# REPORTS TO.., 

# THE U.S. NUCLEAR DATA COMMITTEE 

## Meeting at

## ARGONNE NATIONAL LABORATORY

28-29 NOVEMBER 1973

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## REPORTS TO

THE U.S. NUCLEAR DATA COMMITTEE

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28-29 NOVEMBER 1973

Compiled by
C. D. Bownan, Secretary, USNDC

Chief, Nuclear Sciences Division National Bureau of Standards Washington, D.C. 20234

The reports in this document were submitted to the United States Nuclear Data Committee (USNDC) at the meeting at the Argonne National Laboratory, November $28-29,1973$. The reporting laboratories are those having a substantial effort in measuring neutron and nuclear cross sections of relevance to the U. S. applied nuclear energy program. The material contained in these reports is to be regarded as comprised of informal statements of recent developments and preliminary data. Persons wishing to make use of these data should contact the individual experimenter for further details. The data which appear in this document should be quoted only by permission of the contributor and should be referenced as private communication, and not by this document number. Appropriate subjects are listed as follows:

1. Microscopic neutron cross sections relevant to the nuclear energy program, including shielding. Inverse reactions where pertinent are included.
2. Charged particle cross sections, where they are relevant to 1 ) above, and where relevant to developing and testing nuclear models.
3. Gamma-ray production, radioactive decay, and theoretical developments in nuclear structure which are applicable to nuclear energy programs.
4. Proton and alpha-particle cross sections, at energies of up to 1 GeV , which are of interest to the space program.

These reports cannot be regarded as a complete summary of the nuclear research efforts in the U. S. A number of laboratories, whose research is less programmatically oriented do not submit reports; neither do the submitted reports reflect all the work related to nuclear cross sections in progress at the submitting laboratory. Budgetary limitations have made it mandatory to follow more strictly the subject guidelines described above and therefore to restrict the size of this document.

This compilation has been produced almost completely from master copies prepared by the individual contributors listed in the Table of Contents. It is a pleasure to acknowledge their help in the preparation of these reports.

> C. D. Bowman, Secretary, USNDC Chief, Nuclear Sciences Division National Bureau of Standards Washington, D.C. 20234

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The CINDA-type index which follows was prepared by L. T. Whitehead, Nuclear Data Section, Science and Technology Branch, USAEC Technical Information Center, Oak Ridge, Tennessee


| BE009 | DIFF ELASTIC | DKE | $80+6$ | 15+7 | EXPT | GLASGOW+. TOF. TO BE DONE. 196 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| BE009 | diff inelast | DKE | $80+6$ | 15+7 | EXPT | GLASGOU+.TOF. TO BE DONE. 196 |
| BE009 | N, PROTON | LAS | 14+7 | $15+7$ | EXPT | MENLOVE+.3ES. DELYD $N$ YLD SIGS GVN. 121 |
| B 010 | evaluation | LAS | NDG |  | EVAL | HALE+. NO DATA GIVEN. 119 |
| B 010 | N,ALPHA | GA | 10+3 | $15+6$ | EXPT | FRIESENHAHN. ION CHAMBER. NO DATA. 73 |
| C 012 | total XSECTN | LAS | 16+6 | $18+7$ | EXPT | AUCHAMPAUGH+.TOF. SCINT.CURVE. 116 |
| C 012 | TOTAL XSECTN | NBS | 10+3 | $10+6$ | EXPT | HEATON+.ANAL TBC.NJ DATA. TBP. 130 |
| C 012 | DIff ELASTIC | ABD | 76+6 | 11+7 | EXPT | BUCHER+.SMALL-ANGLE SCAT.ND DATA. 219 |
| C 012 | diff elastic | DKE | $80+6$ | $15+7$ | EXPT | GLASGOW+.TOF. TO BE DONE. 196 |
| C 012 | DIFF INELAST | DKE | $80+6$ | $15+7$ | EXPT | GLASGOW+.TOF. TO BE DONE. 196 |
| C 012 | Inelas gamma | GA | 48+6 | $20+7$ | EXPT | ROGERSt.SIGS FOR 4.44MEV GAM GUN. 74 |
| N 014 | EVALUATION | LAS | NDG |  | EVAL | YOUNG+. NO DATA SIVEN. 119 |
| N 014 | TOTAL ELAST | ORL | 43+6 | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. 141 |
| N 014 | DIFf ELASTIC | ABD | 77+6 | $14+7$ | EXPT | BUCHER+.SMALL-ANGLE SCAT.ND DATA. 219 |
| N 014 | DIff ELASTIC | ORL | 43+6 | 86+6 | EXPT | KINNEY+. NO DATA GIUEN. 141 |
| N 014 | TOT Inelast | ORL | $43+6$ | .86+6 | EXPT | KINNEY+• ND DATA GIUEN. 141 |
| N 014 | DIfF INELAST | ORL | $43+6$ | $86+6$ | EXPT | KINNEY+. ND DATA GIVEN. 141 |
| N 014 | INELAS GAMMA | G A | NDG |  | EXPT | ROGERS+.ND DATA GIVN. GE(LI). 74 |
| N 014 | SPECT NGAMMA | A NL | NDG |  | EXPT | THOMAS+.NEW GE CRYST SPEC.NDG. 23 |
| 0016 | EVALUATION | LAS | NDG |  | EVAL | HALE+. NO DATA GIVEN. 119 |
| 0016 | TOTAL XSECTN | LAS | $16+6$ | $18+7$ | EXPT | AUCHAMPAUGH+.TOF. SCINT.CURVE. 116 |
| 0016 | diff Elastic | $A B D$ | 10+7 | $14+7$ | EXPT | BUCHER+.SMALL-ANGLE SCAT.NO DATA. 219 |
| 0016 | DIfF ELASTIC | YAL | $10+6$ | 40+6 | EXPT | FIRK+.POL AT 9ANGS.20-160DEG.CRUS. 222 |
| 0016 | POLARIZATION | Y AL | $10+6$ | 40+6 | EXPT | FIRK+.PSL AT 9ANGS.20-160DEG.CRUS. 222 |
| 0017 | TOTAL XSECTN | LAS | $16+6$ | $18+7$ | EXPT | AUCHAMPAUGH+.TOF. SCINT.CURVE. 116 |
| 0018 | TOTAL XSECTN | LAS | 16+6 | $18+7$ | EXPT | AUCHAMPAUGH+.TOF. SCINT.CURVE. 116 |
| NA023 | TOTAL XSECTN | YAL | 10+0 | $50+4$ | EXPT | FIRK+.TJF.LINAC.CURVE.TBP IN NSE. 223 |
| NA023 | SPECT NGAMMA | ANL | $28+3$ |  | EXPT | JACKSON+.TO BE CDMPLETED.NO DATA. 24 |


| AL027 | EVALUATION | LAS | NDG |  | EVAL | YOUNG+. NO DATA SIVEN. 1 | 119 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| AL027 | DIfF ELASTIC | ABD | 76+6 | $11+7$ | EXPT | BUCHER+.SMALL-ANGLE SCAT.NO DATA. 2 | 219 |
| AL027 | diff Elastic | DKE | $80+6$ | 15+7 | EXPT | GLASGOWt. TOF. TO BE DONE. 1 | 196 |
| AL027 | NONEL GAMMAS | ORL | $85+5$ | $20+7$ | EXPT | DICKENSt. DIFF GAM PROD SIGS.NDG. 1 | 142 |
| AL027 | DIff InELAST | OKE | $80+6$ | $15+7$ | EXPT | GLASGOUt.TOF. TO BE DONE. 1 | 196 |
| AL027 | N,PROTON | ANL | TR | $10+7$ | EXPT | SMITH+.ACT.LIT(PN)+ D( DN ) NEUTS.NDG | 12 |
| SI | NONEL GAMMAS | ORL | $10+6$ | 20+7 | EXPT | DICKENS+.NAI SPEC.DIFF SIGS.NDG. 1 | 138 |
| S 032 | N,ALPHA | LAS | $40+5$ | 68+5 | EXPT | AUCHAMPAUGH+.VDG.AVG SIG GIVN. 1 | 120 |
| K | TOTAL XSECTN | COL |  | 40+5 | EXPT | SINGH+.TRANS.HI RESOL.NDG.TBP. | 71 |
| K 039 | RESON PARAMS | COL |  | 20+5 | EXPT | SINGH+.TRANS.HI RESOL.NDG.TBP. | 71 |
| K 039 | RESON PARAMS | QRL |  | 10+5 | EXPT | GODD+. ND DATA GIVEN. DRELA: 1 | 142 |
| K 039 | STRENGTH FNC | COL |  | 20+5 | EXPT | SINGH+.SO AND SI VALUES GIVEN. | 71 |
| K 041 | RESON PARAMS | COL |  | 20+5 | EXPT | SINGH+.TRANS.HI RESOL.NDG.TBP. | 71 |
| K 041 | RESON PARAMS | ORL |  | 10+5 | EXPT | GOOD+.9 NEW RESON ES GIVN. NDG. 1 | 142 |
| K 041 | STRENGTH FNC | COL |  | 20+5 | EXPT | SINGH+.SO AND SI VALUES GIVEN. | 71 |
| CA | NONEL GAMMAS | ORL | 70+5 | 20+7 | EXPT | DICKENS+. DIFF GAM PROD SIGS.NDG. 1 | 141 |
| TI | TOTAL XSECTN | ANL | 10+5 | 15+6 | EXPT | BARNARD+.1.5KEU RESOL.NO DATA GUN | 10 |
| TI | DIFF ELASTIC | ANL | 30+5 | 15+6 | EXPT | BARNARD+. $10 K E V$ RESJL. ${ }^{\text {NO }}$ DATA GIVN | 10 |
| TI | NONEL GAMMAS | ORL | 49+6 | 59+6 | EXPT | DICKENS.GE(LI) DET.SPEC+SIGS.NDG. 13 | 138 |
| TI | DIFF INELAST | ANL | 30+5 | $15+6$ | EXPT | BARNARD+. 10 KEV RESJL.NO DATA GIVN | 10 |
| TI046 | N, PROTON | ANL. | TR | 10+7 | EXPT | SMITH+.ACT.LIT(PN)+D( DN ) NEUTS.NDG | 12 |
| T1047 | N, PROTON | ANL | TR | 10+7 | EXPT | SMITH+.ACT.LIT(PN)+D(DN ) NEUTS.NDG | 12 |
| TIO48 | N, PROTON | ANL | TR | 10+7 | EXPT | SMITH+.ACT.LIT(PN)+D(DN ) NEUTS.NDG | 12 |
| CR | TOTAL ELAST | ORL | 41+6 | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. 13 | 139 |
| CR | DIff ELASTIC | ORL | 41+6 | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. 13 | 139 |
| CR | TOT INELAST | ORL | $41+6$ | $86+6$ | EXPT | KINNEY+. NO DATA GIVEN. 13 | 139 |
| CR | DIFF INELAST | ORL | 41+6 | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. 13 | 139 |
| CR052 | TOTAL ELAST | ORL | $64+6$ | $86+6$ | EXPT | KINNEY+. ND DATA GIVEN. 13 | 139 |


| CRC52 | DIFF ELASTIC | ORL | $64+6$ | $86+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 139 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CR052 | TOT INELAST | JRL | 64+6 | $86+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 139 |
| CRO52 | DIFF INELAST | ORL | $64+6$ | $86+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 139 |
| CROS2 | SPECT NGAMMA | RPI | NDG |  | EXPT | ARENDT+.LINAC. TO BE DONE. | 169 |
| MNO55 | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMAWI+.NO DATA GIVEN. | 52 |
| FE | DIFF ELASTIC | ABD | $76+6$ | $11+7$ | EXPT | BUCHER+.SMALL-ANGLE SCAT.NO DATA. | 219 |
| FE | DIFF ELASTIC | ANL |  | $40+6$ | EXPT | SMITH+. NO DATA GIVEN. | 11 |
| $F E$ | DIFF ELASTIC | RPI | $10+4$ | $65+5$ | EXPT | ZUHR+.LINAC.6ANGS 30-150DEG. NDG. | 169 |
| $F E$ | NONEL GAMMAS | GA | $85+4$ | $17+7$ | EXPT | ROGERSt. TBL SIGS 10 NEUT ES. | 73 |
| FE | DIFF INELAST | ANL |  | $40+6$ | EXPT | SMITH+. NO DATA GIVEN. | 11 |
| FE | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMANIt.NO DATA GIVEN. | 52 |
| FE | SPECT NGAMMA | RPI | THR | $+3$ | EXPT | BRDWN+.LINAC.GE(LI) DET. NO DATA. | 168 |
| FE | N, PROTON | ANL |  | $70+6$ | EXPT | SMITH+.ACTIVATIDN. ND DATA GIVEN. | 11 |
| FEO54 | TOTAL XSECTN | RPI | 10+4 | $20+5$ | EXPT | KNOX+.LINAC.TRANS.TU BE DONE. | 170 |
| FE054 | DIFF ELASTIC | ORL | $55+6$ | $85+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 140 |
| FE054 | DIFF INELAST | ORL | $55+6$ | $85+6$ | ExPT | KINNEY+. NO DATA GIVEN. | 140 |
| FE054 | N, GAMMA | RPI | $10+4$ | $20+5$ | EXPT | KNOX+.LINAC.ANAL TBC. NO DATA. | 170 |
| FE054 | SPECT NGAMMA | R PI | ND G |  | EXPT | ARENDT+.LINAC. NO DATA GIVEN. | 169 |
| FE054 | N,PROTON | ANL | IR | $10+7$ | EXPT | SMITH+.ACT.LI7(PN)+D(DN) NEUTS.ND | 12 |
| FE056 | INELAS GAMMA | ANL | NDG |  | EXPT | SMITH.SIGS+ANG DISTR. ND DATA. | 12 |
| FE056 | N, PROTON | ANL | TR | $10+7$ | EXPT | SMITH+.ACT.LI7(PN)+D(DN) NEUTS.ND | 12 |
| FE058 | TOTAL XSECTN | RPI | $10+4$ | $20+5$ | EXPT | KNOX+.LINAC.TRANS.TD BE DONE. | 170 |
| FE058 | N, GAMMA | RPI | $10+4$ | $20+5$ | EXPT | KNOX+.LINAC.ANAL TBC. NO DATA. | 170 |
| C0059 | TOTAL XSECTN | A NL | $20+6$ | $45+6$ | EXPT | GUENTHER + . NDG. SEE ANL/NDM-1. | 10 |
| C0059 | TOTAL XSECTN | LOK | $10+6$ | $16+7$ | EXPT | FISHER+.DEFORM EFFECT.PDL TARGET. | 98 |
| COO59 | DIFF ELASTIC | ANL | $20+6$ | $45+6$ | EXPT | GUENTHER +. NDG. SEE ANL/NDM-1. | 10 |
| C0059 | DIFF INELAST | ANL | $20+6$ | $45+6$ | EXPT | GUENTHER +. NDG. SEE ANL/NDM-1. | 10 |
| C0059 | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMAWIt. CURV OF COUNTS/CHANNEL. | 52 |


| C0059 | N, PROTON | ANL | TR | 10+7 | ExPT | SMITH+.ACT.LIT(PN ) + D ( DN ) NEUTS.NDG |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| NI | TOTAL XSECTN | ANL. | $30+5$ | $40+6$ | EXPT | SMITH+.ANAL TBC. NJ DATA GIVEN. | 11 |
| NI | total elast | ORL | $41+6$ | $86+6$ | EXPT | KINNEY+. ND DATA GIVEN. | 140 |
| NI | diff Elastic | ANL | $30+5$ | $40+6$ | EXPT | SMITH+.ANAL TBC. NJ DATA GIVEN. | 11 |
| NI | diff Elastic | ORL | 41+6 | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. | 140 |
| NI | DIfF ELASTIC | RPI | $10+4$ | $65+5$ | EXPT | ZUHR+.LINAC.6ANGS 30-150DEG. NDG. | 69 |
| NI | NONEL GAMMAS | ORL | 10+6 | $20+7$ | EXPT | DICKENS+.NAI+GE(LI) DET. NO DATA. | 137 |
| NI | total inelas | LRL | $15+7$ |  | EXPT | HANSEN+. INTEGRATD SIG.UCRL-51232. | 84 |
| NI | tot inelast | ORL | 41+6 | $86+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 140 |
| NI | DIFF INELAST | ANL | $30+5$ | 40+6 | EXPT | SMITH+.ANAL TBC. NJ data given. | 11 |
| NI | DIff InELAST | ORL | 41+6 | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. | 140 |
| NI | DIFF INELAST | LRL | $15+7$ |  | EXPT | HANSEN+.CURV+TBL.SEE UCRL-51232. | 84 |
| NI | SPECT NGAMMA | RPI | NDG |  | EXPT | ARENDT+.LINAC. ND DATA GIVEN. | 169 |
| NI 058 | N, PROTON | ANL | TR | 10+7 | EXPT | SMITH+.ACT.LIT(PN)+D( DN ) NEUTS.NDG | 12 |
| NI060 | total Elast | ORL | $41+6$ | 86+6 | EXPT | KINNEY+. ND DATA GIVEN. | 140 |
| NI 060 | DIfF ELASTIC | ORL | $41+6$ | 86+6 | EXPT | KINNEY+. NO DATA GIVEN. | 140 |
| NL060 | DIFF INELAST | ORL | 41+6 | $86+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 140 |
| NI060 | SPECT NGAMMA | RPI | THR | +3 | EXPT | BROWN+.LINAC.GE(LI) DET. ND DATA. | 168 |
| NI061 | TOTAL XSECTN | RPI | 10+4 | 20+5 | EXPT | KNOX+.LINAC.TRANS.TO BE DONE. | 170 |
| NI061 | N,GAMMA | RPI | 10+4 | 20+5 | EXPT | KNOX+.LINAC.ANAL TBC. NO DATA. | 170 |
| NI061 | PHOTONEUTRON | ANL | 12+4 |  | EXPT | JACKSON.UPPER LIMIT NONRESON SIG. | 21 |
| N1064 | TOTAL XSE.CTN | RPI | $10+4$ | 20+5 | EXPT | KNOX+.LINAC.tRANS. TO BE DONE. | 170 |
| NI 064 | N, GAMMA | RPI | 10+4 | 20+5 | EXPT | KNOX+.LINAC.ANAL TBC. ND DATA. | 170 |
| CU | DIfF Elastic | ABD | 76+6 | 11+7 | EXPT | BUCHER+.SMALL-ANGLE SCAT.NO DATA. | 219 |
| Cu063 | TOTAL ELAST | DRL | $55+6$ | $85+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 139 |
| CU063 | DIFF ELASTIC | ORL | 55+6 | $85+6$ | EXPT | KINNEY+. NO DATA GIVEN. 139 | 139 |
| CU063 | TOT INELAST | ORL | 55+6 | $85+6$ | EXPT | KINNEY+. NO DATA GIVEN. | 139 |
| Cu063 | DIFF INELAST | ORL | $55+6$ | $85+6$ | EXPT | KINNEY+. ND DATA GIVEN. 13 | 139 |


| CU065 | TOTAL ELAST | JRL | $55+6$ | $85+6$ | EXPT | KINNEYt. NO DATA | GIVEN. |  | 139 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| cuc65 | DIFF ELASTIC | 3RL | $55+6$ | $85+6$ | EXPT | KINNEY + ND DATA | GIUEN. |  | 139 |
| CUC65 | TOT INELAST | ORL | $55+6$ | $85+6$ | EXPT | KINNEY+* NO DATA | GIVEN. |  | 139 |
| CU065 | DIFF INELAST | ORL | $55+6$ | $85+6$ | EXPT | KINNEY + NO DATA | GIVEN. |  | 139 |
| 2N064 | N,PROTON | ANL | TR | $10+7$ | EXPT | SMITH+.ACT.LI7(PN)+D(DN) NEUTS.NDG 12 |  |  |  |
| AS075 | STRENGTH FNC | NBS | $10+3$ | $60+5$ | EXPT | CAMARDA.TRANS.LINAC. S1 MEASD.NDG 130 |  |  |  |
| BR | STRENGTH FNC | NBS | $10+3$ | $60+5$ | EXPT | CAMARDA.TRANS.LINAC. S1 MEASD.NDG 130 |  |  |  |
| 2R090 | TOTAL XSECTN | ANL |  | $20+7$ | EXPT | POENITZ+. DPTMOD ANAL TBC. NO DATA. 12 |  |  |  |
| 2R090 | STRENGTH FNC | ANL | +6 |  | EXPT | TOOHEY+.SO AND S1 | 1 VALUES | VN.TBP. | 22 |
| 28090 | N, GAMMA | ORL |  | $40+4$ | EXPT | SLAUGHTER+ . VALENC | CY CAPT T | ST. NDG | 143 |
| 2R090 | SPECT NGAMMA | ORL |  | $40+4$ | EXPT | SLAUGHTER+.GE(LI).RESON CAPT. NDG 143 |  |  |  |
| 2R091 | PHOTONEUTRON | ANL. | +6 |  | EXPT | TOOHEY +.WGO MEASD | ( $36 \mathrm{RES.ND}$ | G.TBP. | 22 |
| 2RC92 | TOTAL XSECTN | ANL |  | $20+7$ | EXPT | POENITZ+.OPTMOD ANAL TBC. NO DATA. 12 |  |  |  |
| ZR092 | TOTAL XSECTN | ORL | NDG |  | EXPT | GOOD+. TRANS. ORELA | A. VO DATA | GIVEN. | 244 |
| 2R094 | TOTAL XSECTN | ORL | NDG |  | EXPT | GOOD+.TRANS.ORELA | A. VO DATA | GIVEN. | 144 |
| 2R096 | TOTAL XSECTN | ORL | NDG |  | EXPT | GOOD+.TRANS.ORELA | A.VO dATA | GIVEN. | 144 |
| NB093. | STRENGTH FNC | NBS | $10+3$ | $60+5$ | EXPT | CAMARDA.TRANS.LIN | NAC. S1 ME | EASD.NDG | 130 |
| MO | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMAWIt.NO DATA G | GIVEN. |  | 52 |
| M0092 | TOTAL XSECTN | ANL |  | $20+7$ | EXPT | POENITZ+.OPTMOD ANAL TBC. NO DATA. 12 |  |  |  |
| M0092 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINED+.TRANS.NO D | DATA. TBP | IN AP | 198 |
| M0092 | STRENGTH FNC | DKE | NDG | . | EXPT | PINEOt. S0,S1, S2 MEASD.NDG.TBP AP. 198 |  |  |  |
| M0094 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO+.TRANS.NO D | DATA. TBP | IN AP | 198 |
| M0094 | STRENGTH FNC | DKE | ND G |  | EXPT | PINEO+. SO,S1,S2 MEASD.NDG.TBP AP. 198 |  |  |  |
| M0095 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO+.TRANS.NO D | DATA. TBP | IN AP | 198 |
| MOC95 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. SO,SI,S2 | MEASD.NDG | G. TBP AP | . 198 |
| MOC96 | TOTAL XSECTN | ANL |  | $20+7$ | EXPT | POENITZ+.OPTMOD A | ANAL TBC. | NO DATA. | 12 |
| M0096 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO+.TRANS.NO DA | DATA. TBP | IN AP | 198 |
| M0096 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. SO,S1,S2 | MEASD.NDG | G.TBP AP | . 198 |


| M0098 | TOTAL XSECTN | ANL |  | $20+7$ | EXPT | POENITZ＋．DPTMOD ANAL TBC．ND DATA． 12 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| MOC98 | TOTAL XSECTN | BNL | NDG |  | EXPT | COLE＋．ORELA．TBD TEST VALENCE MOD． 47 |
| M0098 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO＋．TRANS．NO DATA：TBP IN AP 198 |
| M0098 | RESON PARAMS | 8NL | NDG |  | EXPT | COLE＋．ORELA．TBD TEST VALENCE MOD． 47 |
| M0098 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO＋．S0，S1，S2 MEASD．NDG．TBP AP． 198 |
| M0098 | N，GAMMA | ANC | PILE |  | EXPT | SMITH＋．ACT．NO DATA GIVN．CFRMF． 6 |
| M0100 | TOTAL XSECTN | ANL |  | $20+7$ | EXPT | POENITZ＋．OPTMOD ANAL TBC．NO DATA． 12 |
| M0100 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO＋．TRANS．NO DATA．TBP IN AP 198 |
| M0100 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO＋．SO，S1，S2 MEASD．NDG．TBP AP． 198 |
| M0100 | N，GAMMA | ANC | PILE |  | EXPT | SMITH＋．ACT．ND DATA GIUN．CFRMF． 6 |
| RU | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO＋．TRANS．NO DATA．TBP IN AP 198 |
| RU | STRENGTH FNC | DKE | NDG |  | EXPT | PINED＋．SO，S1；S2 MEASD．NDG．TBP AP． 198 |
| RH103 | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO＋．TRANS．NO DATA．TBP IN AP 198 |
| RH103 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO＋．S $0, S 1, S 2$ MEASD．NDG．TBP AP． 198 |
| RH103 | STRENGTH FNC | NBS | $10+3$ | 60＋5 | EXPT | CAMARDA．TRANS．LINAC．S1 MEASD．NDG 130 |
| RH103 | N，GAMMA | RPI | 20＋1 | $10+5$ | EXPT | KNOX＋．LINAC．TBC．VD DATA GIUEN． 168 |
| PD105 | N，GAMMA | RPI | 20＋1 | $10+5$ | EXPT | KNOX＋．LINAC．TBC．NO DATA GIVEN． 168 |
| AG | STRENGTH FNC | NBS | 10＋3 | $60+5$ | EXPT | CAMARDA．TRANS．LINAこ．S1 MEASD．NDG 130 |
| AG109 | N，GAMMA | ANC | PILE |  | EXPT | SMITH＋．ACT．NO DATA GIVN．CFRMF． 6 |
| IN | STRENGTH FNC | NBS | $10+3$ | $60+5$ | EXPT | CAMARDA．TRANS．LINAC．S1 MEASD．NDG 130 |
| SN | DIFF ELASTIC | ABD | 76＋6 | $11+7$ | EXPT | BUCHER＋．SMALL－ANGLE SCAT．NO DATA． 219 |
| SB | STRENGTH FNC | NBS | $10+3$ | 60＋5 | EXPT | CAMARDA．TRANS．LINAこ．S1 MEASD．NDG 130 |
| I 127 | STRENGTH FNC | NBS | 10＋3 | $60+5$ | EXPT | CAMARDA．TRANS．LINAこ．S1 MEASD．NDG 130 |
| I 127 | N，GAMMA | ANC | PILE |  | EXPT | SMITH＋．ACT．NO DATA GIVN．CFRMF． 6 |
| I 129 | N，GAMMA | ANC | PILE |  | EXPT | SMITH＋．ACT．NO DATA GIVN．CFRMF． 6 |
| BA135 | SPECT NGAMMA | BNL | 24＋4 |  | EXPT | RIMAWI＋．GAM SPEC＋IVTENSITY GIVN． 52 |
| LA | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO＋．TRANS．NO DATA．TBP IN AP 198 |
| LA | StRENGTH FNC | DKE | NDG |  | EXPT | PINED＋．SO，S1，S2 MEASD．NDG．TBP AP． 198 |


| LA | STRENGTH FNC | NBS | $10+360+5$ | EXPT | CAMARDA.TRANS.LINAこ. S1 MEASD.NDG 130 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| LA139 | N,GAMMA | ANC | PILE | EXPT | SMITH+. ACT. NO DATA GIVN.CFRMF. 6 |
| ND 143 | SPECT NGAMMA | ANL | THR | Expt | SMITHER+. NO DATA GIVEN. 25 |
| ND145 | SPECT NGAMMA | ANL | THR | EXPT | SMITHER4. NO DATA GIVEN. 25 |
| SM147 | SPECT NGAMMA | ANL | NDG | EXPT | SMITHER+.AVG RESON CAPT SPEC.NDG. 24 |
| SM149 | SPECT NGAMMA | ANL | NDG | EXPT | SMITHER+.AVG RESON CAPT SPEC.NDG. 24 |
| SM152 | RESON PARAMS | BNL | $80+0 \quad 24+2$ | EXPT | COLE+.WN+WG FOR GRESON FROM CAPT. 39 |
| SM152 | SPECT NGAMMA | BNL | -1 | EXPT | COLE+.DIRECT CAPT SPECT SHOWN. 39 |
| EU151 | N, GAMMA | ANC | PILE | EXPT | SMITH+. ACT. NO DATA GIVN.CFRMF. 6 |
| EU151 | N, GAMMA | RPI | $20+1 \quad 10+5$ | EXPT | KNOXt.LINAC. TBC. NO DATA GIVEN. 168 |
| EU153 | N, GAMMA | ANC | Pile | EXPT | SMITH+. ACT. NO DATA GIVN.CFRMF. 6 |
| EU153 | N, GAMMA | RPI | 20+1 10+5 | EXPT | KNOX+.LINAC. TBC. NO DATA GIVEN. 168 |
| T8159 | RESON PARAMS | BNL | $33+0 \quad 98+1$ | EXPT | RIBON+.TABLE OF RESON J VALUES. 48 |
| TB159 | N, GAMMA | ANC | PILE | EXPT | SMITH+. ACT. NO DATA GIVN.CFRMF. |
| TB159 | SPECT NGAMMA | BNL | +0 +2 | EXPT | RIBON+.TABLE OF RESON J VALUES. 48 |
| DY164 | SPECT NGAMMA | BNL | NDG | EXPT | COLE+.DIRECT CAPT.IBC.ND DATA GIVN. 48 |
| H0165 | STRENGTH FNC | NBS | $10+360+5$ | EXPT | CAMARDA.TRANS.LINAC. S1 MEASD.NDG 130 |
| TM169 | N, GAMMA | ANC | PILE | EXPT | SMITH+. ACT. NO DATA GIVN.CFRMF. 6 |
| YB170 | SPECT NGAMMA | BNL | NDG | EXPT | COLE+.DIRECT CAPT.TBC.ND DATA GIVN. 48 |
| HF | TOTAL XSECTN | DKE | NDG | EXPT | PINEO+.TRANS.NO DATA. TBP IN AP 198 |
| HF | STRENGTH FNC | DKE | NDG | EXPT | PINEO+. SO,S1,S2 MEASD.NDG.TBP AP. 198 |
| TA181 | TOTAL XSECTN | DKE | NDG | EXPT | PINEO+.TRANS. NO DATA. TBP IN AP. 198 |
| TA181 | STRENGTH FNC | DKE | NDG | EXPT | PINEO+. SO,SI,S2 MEASD.NDG.TBP AP. 198 |
| TA181 | N, GAMMA | ANC | PILE | EXPT | SMITH+. ACT. NO DATA GIUN.CFRMF. 6 |
| W | TOTAL XSECTN | DKE | ND G | EXPT | PINEO+.TRANS. ND DATA. TBP IN AP, 198 |
| W | STRENGTH FNC | DKE | NDG | EXPT | PINEO+. SO,S1,S2 MEASD.NDG.TBP AP. 198 |
| W | diff Elastic | ABD | 76+6 11+7 | EXPT | BUCHER+.SMALL-ANGLE SCAT.NO DATA. 219 |
| W 182 | EVALUATION | LAS | NDG | EVAL | YOUNG+. NO DATA GIVEN. 119 |


| W 182 | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMAWI+. NO DATA GIVEN. 52 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| +183 | EVALUATION | LAS | NDG |  | EVAL | YOUNG+. NO DATA GIVEN. 119 |
| W 183 | SPECT NGAMMA | ANL | THR |  | EXPT | SMITHER+. W184 LEVEL SCHEME GVN. 25 |
| W 184 | evaluation | LAS | NDG |  | EVAL | YOUNG+. ND DATA GIVEN. 119 |
| W 186 | EVALUATION | LAS | NDG |  | EVAL | YOUNG+. NO DATA GIVEN. 119 |
| W 186 | SPECT NGAMMA | BNL | NDG |  | EXPT | COLE+.DIRECT CAPT.TBC.NO DATA GIVN. 48 |
| W 186 | SPECT NGAMMA | BNL | 24+4 |  | EXPT | RIMAWI+ NO DATA GIVEN. 52 |
| W 186 | SPECT NGAMMA | BNL | THR | $24+4$ | EXPT | CASTEN+. NO DATA GIVEN 66 |
| OS | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO+. TRANS. NO DATA. TBP IN AP. 198 |
| OS | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. SO,S1,S2 MEASD.NDG.TBP AP. 198 |
| IR | TOTAL XSECTN | DKE | NDG |  | EXPT | -PINED+. TRANS. NO DATA. TBP IN AP. 198 |
| IR | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. SO,S1,S2 MEASD.NDG.TBP AP. 198 |
| AU197 | StRENGTH FNC | NBS | 10+3 | $60+5$ | EXPT | CAMARDA.TRANS.LINAC. S1 MEASD.NDG 130 |
| TL | TOTAL XSECTN | DKE | NDG |  | EXPT | PINEO+.TRANS. NO DATA. TBP IN AP. 198 |
| TL | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. SO,S1,S2 MEASD.NDG.TBP AP. 198 |
| PB | DIFF ELASTIC | ABD | 70+6 | $14+7$ | EXPT | BUCHER+.FORWD-ANG DIST AVAIL.NDG. 219 |
| PB206 | N, GAMMA | ORL | $25+3$ | +5 | EXPT | ALLEN+.ORELA. ND DATA GIVEN. 144 |
| PB206 | SPECT NGAMMA | ORL | $25+3$ | +5 | EXPT | ALLEN+.ORELA. NO DATA GIVEN. 144 |
| P8207 | TOTAL XSECTN | LRL | $16+5$ | 51+5 | EXPT | PHILLIPS+.LINAC.TOF.CURV.ANAL TBC. 86 |
| PB207 | TOTAL XSECTN | ORL | $50+6$ | $35+7$ | EXPT | HARVEY+.TRANS.DRELA. ND DATA GIVN 142 |
| PB207 | TOTAL XSECTN | ORL | $17+7$ |  | EXPT | HARVEY+. 16.7MEV RESON NOT SEEN 142 |
| PB207 | N, GAMMA | ORL | $25+3$ | +5 | EXPT | ALLEN+.JRELA. NO DATA GIVEN. 144 |
| P8207 | SPECT NGAMMA | ORL | $25+3$ | +5 | EXPT | ALLEN+.JRELA. NO DATA GIVEN. 144 |
| PB207 | PHOTONEUTRON | ANL |  | 10+6 | EXPT | MEDSKER.GIANT M1 RES SEEN.ND DOORWY22 |
| P8208 | N,GAMMA | ORL | 25+3 | +5 | EXPT | ALLEN+.ORELA. NO DATA GIVEN. 144 |
| P8208 | SPECT NGAMMA | ORL | $25+3$ | 45 | EXPT | ALLEN+.ORELA. NO DATA GIVEN. 144 |
| P8208 | PHOTONEUTRON | ANL | $41+4$ |  | EXPT | JACKSON.NEUT SPEC.SIG GIUN.TBP. 21 |
| B1209 | TOTAL XSECTN | OKE | NDG |  | EXPT | PINEO+.TRANS. NO DATA. TBP IN AP. 198 |


| BI209 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEOt. S0,S1,S2 MEASD.NDG. TBP AP. 198 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| TH229 | FISSN YIELD | ANL | THR |  | EXPT | UNIK+.CURV OF FRAG MASS DIST GVN. 30 |
| TH229 | FISSN YIELD | col | NDG |  | EXPT | FELVINCI+. ORELA. TO BE DONE. 72 |
| TH229 | FRAG SPECTRA | ANL. | THR |  | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GUN. 30 |
| TH232 | TOTAL XSECTN | DKE | ND G |  | EXPT | PINEO+.TRANS. NO DATA. TBP IN AP. 198 |
| TH232 | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. S0,S1,S2 MEASD.NDG. TBP AP. $198{ }^{\text {l }}$ |
| TH232 | STRENGTH FNC | NBS | $10+3$ | $60+5$ | EXPT | CAMARDA.TRANS.LINAこ. S1 MEASD.NDG 130 |
| TH232 | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMAWI+.ND DATA GIVEN. 52 |
| U | TOTAL XSECTN | DKE | NDG |  | EXPT | PINED+.TRANS. ND DATA. TBP IN AP. 198 |
| U | STRENGTH FNC | DKE | NDG |  | EXPT | PINEO+. S0,S1,S2 MEASD.NDG.TBP AP. 198 |
| U 233 | FISSN XSECTN | ANL | $10+5$ | 75+6 | EXPT | MEADOWS.RATIO TO U235NF.CURVE. 13 |
| U 233 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. ND DATA GIUN. 82 |
| U 233 | SPECT FISS G | ORL | THR |  | EXPT | PLEASONTON.AVG GAMMA NUMBER+E GVN 149 |
| U 233 | FISSN YIELD | COL | NDG |  | EXPT | FELVINCI+. ORELA. TO BE DONE. 72 |
| U 234 | TOTAL XSECTN | QRL | +0 | +5 | EXPT | JAMES+.ORELA.TOF.NJ DATA GIVEN. 147 |
| U 234 | RESON PARAMS | ORL | +0 | +4 | EXPT | JAMES+. ORELA.WN+WF MEASD.ND DATA. 147 |
| U 234 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. ND DATA GIVN. 82 |
| U 234 | FISSN XSECTN | ORL | +0 | +5 | EXPT | JAMES+.ORELA.NO DATA GIVEN. 147 |
| U 235 | EVALUATION | LAS | NDG |  | EVAL | STEWART+. ND DATA GIVEN. 120 |
| U 235 | TOTAL XSECTN | NBS | +6 |  | EXPT | SCHWARTZ+. NO DATA GIVN. TBP NSE. 130 |
| U 235 | TOTAL XSECTN | RPI | $50+5$ | $30+7$ | EXPT | GREEN+.PROT RECOIL SPEC.NO DATA. 170 |
| U 235 | RESON PARAMS | LAS |  | $60+1$ | EXPT | KEYWORTH.POL BEAM+TARG.J MEASD. 114 |
| U 235 | RESON PARAMS | ORL |  | 60+1 | EXPT | KEYWORTH+. J FOR 65 RESON. NDG. 148 |
| U 235 | FISSN XSECTN | ANL | 10+5 | 75+6 | EXPT | MEADOWS.RATIO TO U233NF.CURVE. 13 |
| U 235 | FISSN XSECTN | LAS | 10+6 | $60+6$ | EXPT | HANSEN+.TABLE.41ES.TBP NSE. 114 |
| U 235 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. NO DATA GIVN. 82 |
| U 235 | FISSN XSECT | LRL | $30+6$ | $20+7$ | EXPT | CZIRRt. LINAC. TBC. NO DATA GIVN. 81 |
| U 235 | FISSN XSECTN | MHG | $96+5$ |  | EXPT | GILLIAM+. SIG GIVN. 2.3PC ERROR. 128 |


| U 235 | FISSN XSECTN | MHG | $26+5$ |  | EXPT | KNOLLt.ABSOL MEAST TBC.NO DATA. 129 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| U 235 | FISSN XSECTN | JRL | $20+3$ | $10+5$ | EXPT | PEREZ+.ORELA.TOF.TABLE.CFD OTHERS. 146 |
| U 235 | NU | LRL | THR | 15+7 | Expt | HOWE+.PRELIM RESULTS SHOWN.TBC. 81 |
| U 235 | FISSN YIELD | COL | NDG |  | EXPT | FELVINCI+. ORELA. TO BE DONE. 72 |
| U 235 | FRAG SPECTRA | ANL | THR |  | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GVN. 30 |
| U 235 | FISSN YIELD | ANL | THR |  | EXPT | UNIK+.CURV OF FRAG MASS DIST GVN. 30 |
| U 236 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. NO DATA GIVN. 82 |
| U 238 | TOTAL XSECTN | NBS | +6 |  | EXPT | SCHWARTZ+. NO DATA GIVN. TBP NSE. 130 |
| U 238 | total inelas | ANL | 45+4 | 10+7 | EVAL | SMITH.NJ DATA. RESULTS AVAILABLE. 11 |
| U 238 | FISSN XSECTN | ANL | 22+6 | 45+6 | EXPT | WOLF+.RATID DELAYD/PROMPT SIG.CRV. 27 |
| U 238 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. NO DATA GIVN. 82 |
| U 238 | N,GAMMA | BNL | 24+4 |  | EXPT | RIMAWI+.CURV(PART WG)/(E GAM)**3. 52 |
| U 238 | SPECT NGAMMA | BNL | $24+4$ |  | EXPT | RIMAWI+.CURV OF COUNTS/CHANNEL. 52 |
| NP237 | RESON PARAMS | LAS |  | 10+3 | EXPT | KEYWORT'H.POL BEAM+TARG.J MEASD. 114 |
| NP237 | RESON PARAMS | DRL |  | 10+3 | EXPT | KEYWORTH+. J OF INTERMEDIATE STRUC148 |
| PU239 | EVALUATION | LAS | ND G |  | EVAL | STEWART+. NO DATA GIVEN. 120 |
| PU239 | TOTAL XSECTN | NBS | $50+2$ | 10+5 | EXPT | HEATON+.STRUCTURE SEEN.ND DATA. 130 |
| PU239 | TOTAL XSECTN | NBS | +6 |  | EXPT | SCHWARTZ+. NO DATA GIVN. TBP NSE. 130 |
| PU239 | TOTAL XSECTN | RPI | $50+5$ | 30+7 | EXPT | NADOLNY+.TRANS.PRDT RECOIL. NDG. 170 |
| PU239 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. NJ DATA GIVN. 82 |
| PU239 | FISSN XSECTN | MHG | $96+5$ |  | EXPT | KNOLL+. TD BE COMPLETED. ND DATA. 129 |
| PU239 | NU | LRL | THR | $15+7$ | EXPT | HOWE+. TO BE DONE. 81 |
| PU239 | SPECT FISS G | DRL | THR |  | EXPT | PLEASONTON.AVG GAMMA NUMBER+E GUN 149 |
| PU239 | FISSN YIELD | COL | NDG |  | EXPT | FELVINCI+. ORELA. TO BE DONE. 72 |
| PU240 | FISSN XSECT | LRL | THR | 15+7 | EXPT | BEHRENS.LINAC.TOF. NO DATA GIUN. 82 |
| PU24 1 | FISSN XSECT | LRL | THR | $15+7$ | EXPT | BEHRENS.LINAC.TOF. NU DATA GIVN. 82 |
| PU242 | FISSN XSECT | LRL | THR | $15+7$ | EXPT | BEHRENS.LINAC.TOF. NO DATA GIVN. 82 |
| CM245 | FISSN YIELD | ANL | THR |  | EXPT | UNIK+.CJRV OF FRAG MASS DIST GVN. 30 |


| CM245 | FRAG SPECTRA | ANL | THR | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GVN. 30 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| CM246 | FISSN YIELD | ANL | SPON | EXP1 | UNIK+.CURV OF FRAG MASS DIST GVN. 30 |
| CM246 | FISS YIELD | ORL | SPON | EXPT | PLEASONTON+. FRAG MASS DIST MEASD. 150 |
| CM246 | FRAG SPECTRA | ANL | SPON | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GUN. 30 |
| CM246 | FRAG SPECTRA | DRL | SPON | EXPT | PLEASONTON+. MASS+KE DISTR MEASD. 150 |
| CM248 | FISSN YIELD | ANL | SPON | EXPT | UNIK+.CURU OF FRAG MASS DIST GVN. 30 |
| CM248 | FRAG SPECTRA | ANL | SPON | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GVN. 30 |
| CF249 | RESON PARAMS | ORL | 30-1 20+1 | EXPT | DABBS+. 11 NEW RESOV SEEN. ORELA. 148 |
| CF249 | FISSN XSECTN | JRL | NDG | EXPT | DABBS+.JRELA. 11 NEW.RESON SEEN. 147 |
| CF249 | FISSN YIELD | ANL | THR | EXPT | UNIK+.CURV DF FRAG MASS DIST GVN. 30 |
| CF249 | FRAG SPECTRA | ANL | THR | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GVN. 30 |
| CF250 | FISSN YIELD | ANL | SPON | EXPT | UNIK+.CURV OF FRAG MASS DIST GVN. 30 |
| CF250 | FRAG SPECTRA | ANL | SPON | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GUN. 30 |
| CF251 | FISSN YIELD | ANL | THR | EXPT | FLYNN+.RADIDCMEM. MASS DISTR CURV. 36 |
| CF251 | FRAG SPECTRA | ANL | THR | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. 36 |
| CF252 | SPECT FISS G | LRL | SPON | EXPT | DIETRICH+. NAI SPECTR.CURV.TBC. 86 |
| CF252 | FISSN YIELD | ANL | SPON | EXPT | UNIK+.CURV OF FRAG MASS DIST GUN. 30 |
| CF252 | FRAG SPECTRA | ANL | SPON | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GUN. 30 |
| CF254 | FISSN YIELD | ANL | SPON | EXPT | UNIK+.CURV OF FRAG MASS DIST GVN. 30 |
| CF254 | FRAG SPECTRA | ANL | SPON | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GVN. 30 |
| ES253 | FISSN YIELD | ANL | SPDN | EXPT | FLYNN+.RADIDCMEM.MASS DISTR CURV. 36 |
| ES253 | FRAG SPECTRA | ANL | SPON | EXPT | FLYNN+.RADIDCMEM. MASS DISTR CURV. 36 |
| ES254 | FISSN YIELD | ANL | THR | EXPT | UNIK+.CURV OF FRAG MASS DIST GVN. 30 |
| ES254 | FISSN YIELD | ANL | THR | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. 36 |
| ES254 | FRAG SPECTRA | ANL | THP | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GVN. 30 |
| ES254 | FRAG SPECTRA | ANL | THR | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURU. 36 |
| FM254 | FISSN YIELD | ANL | SPON | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. 36 |
| FM254 | FRAG SPECTRA | ANL | SPON | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. 36 |


| FM255 | FISSN | YIELD | ANL | THR | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. | 36 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| FM255 | FRAG | SPECTRA | ANL | THR | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. | 36 |
| FM256 | FISSN | YIELD | ANL | SPDN | EXPT | UNIK+.CURV OF FRAG MASS DIST GUN. | 30 |
| FM256 | FISSN | YIELD | ANL | SPON | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. | 36 |
| FM256 | FRAG | SPECTRA | ANL | SPON | EXPT | UNIK+.FRAG MASS DIST+TOTAL KE GUN. | 30 |
| FM256 | FRAG | SPECTRA | ANL | SPON | EXPT | FLYNN+.RADIOCMEM.MASS DISTR CURV. | 36 |

## NATIONAL REACTOR TESTING STATION, AEROJET NUCLEAR COMPANY IDAHO FALLS, IDAHO

A. NUCLIDE DECAY DATA FOR ENDF/B (Reich, Helmer, Heath, Greenwood)

In recognition of the pressing need for such data in a variety of applications, the scope of ENDF/B has been expanded to include information on the decay properties of radioactive nuclides. Through our participation in the Decay-Heat Task Force of the Fission-Product Subcommittee of CSEWG, we have a major involvement in this project. The first task was to decide upon the data content of this file. After consideration of the potential user applications of radioactive decay data, a file content was proposed which should have applicability in a wide range of practical problems. This proposed content was adopted by CSEWG during its May 1973 meeting at Brookhaven National Laboratory.

The current phase of this effort is the preparation for inclusion in ENDF/B-IV of certain nuclide decay data for a selected group of fissionproduct nuclides relevant to decay-heat calculations in reactor cores. These data include fission yields, half-lives, decay energies and average $\beta$ - and $\gamma$-ray energies. A list of 338 "priority" nuclides for which these data are necessary has been drawn up by the Decay-Heat Task Force.

At present, we have completed a compilation of the total decay energies (i.e., $Q_{\beta}$ values) for these nuclides. Experimental values have been taken primarily from the 1973 revision of the Wapstra-Gove atomic-mass tables ${ }^{1}$ although, where such data have appeared sufficiently recently as not to be included in this compilation, these later data have been used. For those nuclides for which no experimental data exist, the $Q_{\beta}$ values have been taken from the predictions of Garvey et al. ${ }^{2}$

It has been found that $\left\langle E_{\beta}\right\rangle$ and $\left\langle E_{\gamma}\right\rangle$ values can be derived from experimental data for $\sim 180$ of these "priority" nuclides, and this data compilation effort is currently under way.

[^0]
## B. GAMMA-RAY SPECTRA FROM FISSION-PRODUCT NUCLIDES (R. L. Heath)

The compilation of high-quality gamma-ray spectra from fission-product nuclides has been a continuing effort. An emphasis of this activity is
the cataloguing of spectra obtained using $G e(L i)$ spectrometers for use in a variety of fields of both a basic and an applied character. In addition to plots showing the spectra gamma-ray energy and intensity values, obtained in a consistent fashion, are given for all the nuclides studied.

At the present time data are being accumulated for the following fission-product nuclides: ${ }^{94} \mathrm{Y},{ }^{95} \mathrm{Y},{ }^{102} \mathrm{Tc},{ }^{104} \mathrm{Tc},{ }^{143} \mathrm{La},{ }^{146} \mathrm{Ce}$ and ${ }^{146} \mathrm{Pr}$. Detailed data on gross fission-product samples are also being accumulated. Gamma-ray spectra of such samples, from thermal-neutron-induced fission of both ${ }^{235} \mathrm{U}$ and ${ }^{239} \mathrm{Pu}$, have been measured for sample decay times ranging from $\sim 2$ minutes up to essentially infinity.

## C. EVALUATION OF DECAY-SCHEME DATA (R. G. Helmer and R. C. Greenwood)

For several purposes, we have carried out detailed evaluations of the decay data of several isotopes. The isotopes involved include a number which are of interest for neutron dosimetry purposes as well as a number of fission products.

For reaction rate determinations using gamma-ray spectroscopy the parameters needed are the half-lives and the absolute gamma-ray intensities. The uncertainties in these parameters have also been evaluated. The literature surveyed in these evaluations generally include that available up to about April 1973.

The evaluated decay parameters for fourteen isotopes produced by $(n, \gamma)$, ( $n, p$ ) or ( $n, n^{\prime}$ ) reactions are given in Table $C-1$. A similar set of data for ten fission-product isotopes is given in Table C-2.

## TABLE C-1

A SET OF RECOMMENDED HALF-LIVES, GAMMA-RAY ENERGIES AND BRANCHING RATIOS FOR THE NONFISSION MEASUREMENTS

| Radioisotope | $\begin{gathered} \text { Half-Life }{ }^{\text {a }}{ }^{\frac{1}{2}} \\ \hline \end{gathered}$ | $\begin{gathered} \text { Gamma-Ray } \\ \text { Energya }^{\text {a }} \\ (\mathrm{keV}) \\ \hline \end{gathered}$ | $\begin{gathered} \text { Gamma-Ray Branching } \\ \text { Ratioa } \\ (\%) \\ \hline \end{gathered}$ |  |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{27} \mathrm{Mg}$ | 9.46(2) m | $\begin{array}{r} 843.73(4) \\ 1014.44(5) \end{array}$ | $\begin{aligned} & 71.4(5) \\ & 28.6(5) \end{aligned}$ | sum $=100.0$ |
| ${ }^{24} \mathrm{Na}$ | 14.99(2) h | $\begin{aligned} & 1368.52(6) \\ & 2753.98(10) \end{aligned}$ | $\begin{aligned} & 99.99(1) \\ & 99.85(2) \end{aligned}$ |  |
| ${ }^{46} \mathrm{Sc}$ | 83.85 (10) d | $\begin{array}{r} 889.258(18) \\ 1120.516(25) \end{array}$ | $\begin{aligned} & 99.98(1) \\ & 99.99(1) \end{aligned}$ |  |
| ${ }^{47} \mathrm{Sc}$ | 3.39 (4) d | 159.39 (5) | 69.0 (25) |  |
| ${ }^{48} \mathrm{Sc}$ | 43.8(1) h | $\begin{array}{r} 983.4(2) \\ 1037.4(3) \\ 1311.9(3) \end{array}$ | $\begin{aligned} & 99.98(1) \\ & 97.7(3)^{b} \\ & 99.99(1) \end{aligned}$ |  |
| ${ }^{54} \mathrm{Mn}$ | 312.6(3) d | 834.827(21) | 99.978(2) |  |
| ${ }^{59} \mathrm{Fe}$ | 44.6(1) d | $\begin{aligned} & 1099.224(25) \\ & 1291.564(28) \end{aligned}$ | $\begin{aligned} & 55.5(17) \\ & 44.1(12) \end{aligned}$ | sum $=99.6(1)$ |
| ${ }^{58} \mathrm{Co}$ | 71.3(2) d | 810.757(21) | 99.44(2) |  |
| ${ }^{60} \mathrm{Co}$ | $5.268(5) \mathrm{y}$ | $\begin{aligned} & 1173.208(25) \\ & 1332.491(41) \end{aligned}$ | $\begin{aligned} & 99.86(2) \\ & 99.985(1) \end{aligned}$ |  |
| ${ }^{64} \mathrm{Cu}$ | 12.78(5) h | $511.002^{\text {c }}$ | 36.8(16) |  |
| ${ }^{115 m}$ In | 4.50 (2) h | 336.2(1) | 47.0(20) |  |
| 116 m In | 54.10(20) m | $\begin{aligned} & 1293.4(3) \\ & 2112.1(4) \end{aligned}$ | $\begin{aligned} & 83.7(15) \\ & 16.2(15) \end{aligned}$ | sum $=99.93(2)$ |
| ${ }^{198} \mathrm{Au}$ | 2.696(2) d | 411.794 (8) | 95.47 (10) |  |
| ${ }^{239} \mathrm{~Np}$ | 2.355 (4) d | $\begin{aligned} & 228.19(1)^{\mathrm{d}} \\ & 277.60(3) \end{aligned}$ | $\begin{aligned} & 12.5(15)^{\mathrm{d}} \\ & 14.5(15)^{\mathrm{e}} \end{aligned}$ |  |

4

## TABLE C-1 (Cont.)

```
\({ }^{\mathrm{a}}\) The numbers in parentheses indicate the uncertainty (10) in the last
        digit(s).
\({ }^{\mathrm{b}}\) The combined intensity of the \(1037-\mathrm{keV}\) gamma ray and a \(1212-\mathrm{keV}\) gamma
    ray is ( \(99.98 \pm 0.01\) ) \% .
    \(c_{\text {The effective }}\) line-energy of this peak may be lower than this energy due
        to electron binding effects and the finite width of the annihilation
        radiation energy distribution.
\(\mathrm{d}_{\text {There }}\) is also a gamma-ray transition of 226.4 keV which has an intensity
    of \(0.7 \%\).
\({ }^{\text {e }}\) There are also gamma-ray transitions of 272.8 keV and 280.5 keV , but
    both have intensities of less than \(0.1 \%\).
```


## TABLE C-2

A SET OF RECOMMENDED HALF-LIVES, GAMMA-RAY ENERGIES AND BRANCHING RATIOS FOR SELECTED FISSION PRODUCT NUCLEI

| Radioisotope | $\begin{gathered} \text { Half-Life }{ }^{\text {a }} \\ \mathrm{t}_{1}^{1} / 2 \end{gathered}$ |  | $\begin{gathered} \text { Gamma-Ray } \\ \text { Energy }^{\text {a }} \\ \text { (keV) } \\ \hline \end{gathered}$ | $\begin{gathered} \text { Gamma-Ray } \\ \text { Branching Ratio }{ }^{\text {a }}(\%) \\ \hline \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{95} \mathrm{Zr}$ | 64.6(6) | d | 724.184(18) | 43.8(5) |
|  |  |  | 756.715(19) | 54.4(5) |
| ${ }^{97} \mathrm{Zr}$ | 16.85(5) | h | 743.35(5) | 93.3(4) |
| ${ }^{97} \mathrm{Nb}$ | 72.1(7) | m | 657.92 | 98.1(1) |
| ${ }^{103} \mathrm{Ru}$ | 39.45 (10) | d | 497.08(1) | 89 (3) |
| ${ }^{132} \mathrm{Te}$ | 77.9(5) | h | 228.16(6) | 88.5 (60) |
| ${ }^{137} \mathrm{Cs}$ | 29.94(20) | y | 661.638(19) | 85.0 (3) |
| ${ }^{140} \mathrm{Ba}$ | 12.79(1) | $d^{\text {b }}$ |  |  |
| ${ }^{140} \mathrm{La}$ | 40.26(2) | $h^{\text {b }}$ | 1596.18(5) | 95.33(16) |
| ${ }^{144} \mathrm{Ce}$ | 284.4 (4) | d | 133.53(3) | 10.7 (4) |
| ${ }^{144} \mathrm{Pr}$ | 17.28(5) | m | 696.492(19) | 1.49 (15) |
|  |  |  | 2185.608 | 0.77 (4) |

[^1]
## D. INTEGRAL CROSS SECTION MEASUREMENTS (Y. D. Harker)

Since the last report ${ }^{1}$, integral capture cross section measurements using the Coupled Fast Reactivity Measurement Facility (CFRMF) and gamma activation techniques have been completed for those nuclides listed in Table D-1.

TABLE D-1

INTEGRAL CROSS SECTIONS IN THE CFRMF

| Reaction | $\overline{\bar{\sigma}}$ (barns) |
| :---: | :---: |
| ${ }^{98} \mathrm{Mo}(\mathrm{n}, \gamma){ }^{99} \mathrm{Mo}$ | $0.0606 \pm 0.0053$ |
| ${ }^{100} \mathrm{Mo}(\mathrm{n}, \gamma)^{101} \mathrm{Mo}$ | $0.0355 \pm 0.0036$ |
| ${ }^{109} \mathrm{Ag}(\mathrm{n}, \gamma){ }^{110 \mathrm{~m}_{\mathrm{Ag}}}\left(\mathrm{t}_{\frac{1}{2}}=252 \mathrm{~d}\right)$ | 0.029 |
| ${ }^{127} \mathrm{I}(\mathrm{n}, \gamma)^{128} \mathrm{I}$ | 0.293 |
| ${ }^{129} \mathrm{I}(\mathrm{n}, \gamma)^{130} \mathrm{I}$ | 0.182 |
| ${ }^{139} \mathrm{La}(\mathrm{n}, \gamma){ }^{140} \mathrm{La}$ | $0.0199 \pm 0.0024$ |
| ${ }^{151} \mathrm{Eu}(\mathrm{n}, \gamma){ }^{152} \mathrm{Eu}\left(\mathrm{t}_{\frac{1}{2}}=13 \mathrm{y}\right)$ | $1.52 \pm 0.13$ |
| ${ }^{151} \mathrm{Eu}(\mathrm{n}, \gamma){ }^{152 \mathrm{mEu}}\left(\mathrm{t}_{\frac{1}{2}}=9.3 \mathrm{~h}\right)$ | $1.072 \pm 0.086$ |
| ${ }^{153} \mathrm{Eu}(\mathrm{n}, \gamma){ }^{154} \mathrm{Eu}\left(\mathrm{t}_{\frac{1}{2}}=8.6 \mathrm{y}\right)$ | $1.51 \pm 0.12$ |
| $\left.{ }^{159} \mathrm{~Tb}(\mathrm{n}, \gamma)\right)^{160} \mathrm{~Tb}$ | $0.824 \pm 0.066$ |
| ${ }^{169} \mathrm{Tm}(\mathrm{n}, \gamma){ }^{170} \mathrm{Tm}$ | 0.560 |
| ${ }^{181} \mathrm{Ta}(\mathrm{n}, \gamma){ }^{182} \mathrm{Ta}$ | $0.64 \pm 0.04$ |

Most of these nuclides are classified as fission products and the results in Table D-1 will be utilized in the compilation-evaluation of fission-product neutron-cross-section files for ENDF/B. Others, such as Eu and Ta , are being studied primarily as a part of the current interest in their application as control elements in the future generations of fast reactors.

Reactivity measurements in the CFRMF have been completed for those materials listed in Table $\mathrm{D}-2$ and Table $\mathrm{D}-3$.

Present activities include integral cross section measurements similar to those for which results are reported above and also

TABLE D-2
CFRMF REACTIVITY WORTHS OF FISSION PRODUCT ISOTOPES AND STANDARDS

| Material | (\% Enrichment) | Reactivity per Gram ${ }^{\text {a }}$ of Four Sample Diameters ( $\mu \mathrm{k}$ ) |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.27 cm | 1.9 cm | 2.54 cm | 3.175 cm |
| ${ }^{90} \mathrm{ZrO}_{2}$ | (97.85) | -0.1125 | -0.1113 | -0.1194 | -0.1157 |
| ${ }^{91} \mathrm{ZrO}_{2}$ | (89.31) | -0.2345 | -0.2313 |  |  |
| ${ }^{92} \mathrm{ZrO}_{2}$ | (95.36) | -0.2571 | -0.2683 |  |  |
| ${ }^{94} \mathrm{ZrO}_{2}$ | (96.07) | -0.2612 | -0.2649 |  |  |
| ${ }^{95} \mathrm{Mo}$ | (96.45) | -0.2375 | -0.2399 | -0.2368 | -0.2338 |
| ${ }^{96} \mathrm{Mo}$ | (96.76) | -0.1847 | -0.1877 | -0.1837 | -0.1822 |
| $9^{97}$ Mo | (94.25) | -0.2642 | -0.2673 | -0.2647 | -0.2614 |
| $98 \mathrm{Mo}^{\text {b }}$ | (98.30) |  |  | -0.1314 |  |
| ${ }^{98} \mathrm{MoO}_{3}$ | (97.30) | -0.3232 | -0.3200 | -0.3317 | -0.3283 |
| ${ }^{100}$ Mo | (97.42) | -0.1993 | -0.1954 | -0.1964 | -0.1921 |
| ${ }^{147} \mathrm{Sm}_{2} \mathrm{O}_{3}$ | (98.34) | -0.3797 | -0.3762 |  |  |
| ${ }^{149} \mathrm{Sm}_{2} \mathrm{O}_{3}$ | (97.72) | -0.6267 | -0.6124 | -0. 5984 |  |
| ${ }^{152} \mathrm{Sm}_{2} \mathrm{O}_{3}$ | (98.29) | -0.1613 | -0.1599 | -0.1593 | -0.1559 |
| ${ }^{154} \mathrm{Sm}_{2} \mathrm{O}_{3}$ | (98.69) | -0.1519 | -0.1438 | -0.1492 | -0.1396 |
| ${ }^{197} \mathrm{Au}$ |  | -0.3986 | -0.3988 | -0.3972 | -0.3936 |
| ${ }^{197} \mathrm{Au}_{2} \mathrm{O}_{3}$ |  | -0.410 | -0.3856 | -0.3857 | -0.3850 |
| ${ }^{127} \mathrm{I}_{2}$ |  | -0.2336 | -0.2322 | -0.2281 | -0.2244 |
| ${ }^{235} \mathrm{UO}_{2}$ | (93.12) | +1.008 | +0.9952 | +0.9930 | +0.9839 |

[^2]
## TABLE D-3

REACTIVITY WORTHS OF CONTROL MATERIALS IN CFRMF

| Material | (\% Enrichment) | Reactivity per Gram of Four Sample Diameters ( $\mu \mathrm{k}$ ) |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 1.27 cm | 1.9 cm | 2.54 cm | 3.175 cm |
| ${ }^{10}{ }_{B}$ | (92) | -8.742 | -8.145 | -7.681 |  |
| ${ }^{10}{ }_{B}$ | (85) | -8.404 | -7.873 | -7.359 |  |
| $\mathrm{B}_{4} \mathrm{C}$ |  | -2.293 | -2.256 | -2.223 | -2.181 |
| $\mathrm{Eu}_{2} \mathrm{O}_{3}$ |  | -0.7654 | -0.7416 | -0.7376 | -0.7113 |

transmutation measurements to determine capture cross sections of those nuclides where reaction products are stable. Many nuclides which are rated very high on the CSEWG list for desired information fall into the latter category and, therefore, techniques are being developed and will be implemented for these measurements.

[^3]E. DISCREPANCIES BETWEEN MEASUREMENTS OF $\bar{v}$ AND $\eta$ BY THE MANGANESE BATH METHOD (J. R. Smith)

Manganese bath measurements of $\eta$ and $\bar{v}$ are being re-examined in an effort to identify possible sources of the apparent discrepancies. Two aspects of this investigation are being pursued. One is an examination of data taken at the MTR in 1969 from measurements of the strength of a ${ }^{252} \mathrm{Cf}$ source that had preyiously been calibrated at ANL. The second is a review of the corrections to manganese bath experiments. _ Neither study has yet succeeded in isolating a dominant factor in the $\bar{v}-n$ discrepancy.

The source comparison data are rather inconclusive because of limitations in the data taken to calibrate the counting efficiency of the MTR system. Despite these limitations, the data appear to contradict the hypothesis that the MTR $\eta$ values are relatively higher because of systematically higher detection efficiencies.

In the examination of manganese bath corrections, the results of the Bettis Monte Carlo calculations ${ }^{1}$ of the MTR experiment are being studied, along with modified corrections recommended by deVolpi ${ }^{2}$ and Axton ${ }^{3}$. Changes of one or two tenths of a percent may be indicated in a few of the factors, but nothing large enough to account for the discrepancy between $\bar{v}$ and $\eta$ has been seen. In particular, deVolpi's recommendation of a drop of $0.4 \%$ in the MTR $\eta$ values has been found to be due essentially to an erroneous interpretation of the manganese resonance absorption correction.

[^4]
## ARGONNE NATIONAL LABORATORY

## A. FAST NEUTRON PHYSICS

1. Fast Neutron Total and Scattering Cross Sections
a. Cobalt Fast Neutron Cross Sections - Measurement and Evaluation (P. Guenther, P. Moldauer, A. Smith, D. Smith and J. Whalen)

Elastic and inelastic scattering cross sections of cobalt have been measured from incident energies of 1.8 to 4.0 MeV including those for the excitation of states at $1.10 \pm 0.01,1.20 \pm 0.01,1.30 \pm 0.01$, $1.43 \pm 0.01,1.46 \pm 0.02,1.72 \pm 0.02,2.06 \pm 0.02,2.09 \pm 0.02,2.16$ $\pm 0.03,2.35 \pm 0.05$ and $2.50 \pm 0.05 \mathrm{MeV}$. Total neutron cross sections have been measured from $\approx 2.0$ to 4.5 MeV . From the experimental results, and previously reported values, an optical-statistical model has been deduced providing a quantitative description of measured values to 20.0 MeV . The observed excited structures and cross sections are shown consistent with a nuclear structure model based upon a proton hole in the $\mathrm{f}_{7 / 2}$ shell strongly coupled to a spherical core and a solution of previous ambiguities in $J^{\pi}$ assignments is suggested. The available experimental information and the computational model are utilized to provide a comprehensive evaluated data file in the ENDF format suitable for use in fission reactor, fusion reactor and other applied neutronic calculations. The experimental results and the complete evaluation are available in ANL/NDM-1.
b. Neutron Scattering from Titanium (E. Barnard*, J. de Villiers*, P. Moldauer, D. Reitman*, A. Smith and J. Whalen)

Neutron total and elastic and inelastic scattering cross sections of natural titanium have been measured. Total cross sections have been determined from $0.1-1.5 \mathrm{MeV}$ with resolutions of $\gtrsim 1.5 \mathrm{keV}$. Differential elastic and inelastic neutron scattering cross sections were measured from $0.3-1.5 \mathrm{MeV}$ with resolutions of $\gtrsim 10 \mathrm{keV}$. The inelastic neutron excitation of states in ${ }^{46} \mathrm{Ti}(889 \mathrm{keV}),{ }^{47} \mathrm{Ti}(160 \mathrm{keV})$ and ${ }^{48} \mathrm{Ti}$ ( 984 keV ) was observed. The energy-averaged behavior of the measured results can be described in terms of spherical and ellipsoidal optical models and compound-nucleus and direct-reaction processes. It can be shown that both compound-nucleus and direct-reaction processes con-
tribute to the fluctuating cross sections and that comparison of calculated and observed fluctuations gives an improved definition of the energyaverage models. The experimental results, their interpretation and improved version of the ENDF / B evaluated titanium file are reported in ANL/NDM-3.
*Staff of the Pelindaba Laboratory, Transvaal, Republic of South
Africa.
c. Fast Neutron Total and Scattering Cross Sections of Elemental Nickel (A. Smith, P. Guenther, J. Whalen)

Elastic and inelastic scattering and total cross section measurements have been completed in the energy range 0.3 to 4.0 MeV . The inelastic neutron excitation of states at 1.33, 1.45, 2. 15, 2.28, $2.48,2.62$ and 2.73 MeV was observed. A complete analysis extending through the comprehensive evaluation is in progress.
d. Fast Neutron Cross Sections of Iron (A. Smith, P. Guenther, D. Smith and J. Whalen)

Scattering measurements are complete to incident energies of 4.0 MeV . Activation cross sections, ( $n, p$ ) have been determined to $\approx 7.0 \mathrm{MeV}$. The results are being used to formulate an evaluated file covering the energy range $\approx 0.3$ to 20.0 MeV .

$$
\text { e. } \frac{\text { Inelastic Neutron Scattering Cross Sections of }{ }^{238} \mathrm{U}}{\text { (A. B. Smith) }}
$$

Contemporary knowledge of inelastic neutron scattering from ${ }^{238} \mathrm{U}$ was reviewed inclusive of recent data obtained at the ongoing ANL program. An evaluated inelastic scattering data set was deduced from experimental information and theoretical calculation. Particular attention was given to the basic interrelation of total and elastic and inelastic scattering cross sections and to physical reaction mechanisms verified in other contexts. The present evaluated data set suggests that in the region $\mathrm{E}_{\mathrm{n}}=45 \mathrm{keV}$ to 10.0 MeV the accepted standard reference file (ENDF/B, MAT-1158): a) represents the total cross section to within a few percent accuracy, b) underestimates the elastic scattering cross section and, by inference, overestimates the inelastic scattering cross section near threshold and d) overestimates the inelastic scattering cross section by $\geqslant 10 \%$ above $\mathrm{E}_{\mathrm{n}}=\geqslant 1.0 \mathrm{MeV}$. Generally, it is sug-
gested that the desired precise inelastic scattering cross section will be achieved only with a comprehensive physical understanding of fast neutron and other nuclear reactions with heavy-even-deformed nuclei. A momorandum reporting the above work and including evaluated numerical values is available from the author.

## f. Total Neutron Cross Sections (W. Poenitz and J. Whalen)

The continuing program of both monoenergetic and whitesource total cross section measurements has been extended to 20 MeV . The results compliment the ongoing program in partial cross section areas. For example: recent results for $\mathrm{Zr}^{90}, 92$ and $\mathrm{Mo} 92,96,98,100$ and associated detailed scattering measurements are being analyzed in the context of the isospin dependence of the optical potential.
2. Fast Neutron Activation and Dosimetry Measurements (D. Smith

Considerable progress has been made in the measurement of fast-neutron reaction cross sections via activation. Data on the ${ }^{27} \mathrm{Al}$ $(\mathrm{n}, \mathrm{p})^{27} \mathrm{Mg}, 54,{ }^{56} \mathrm{Fe}(\mathrm{n}, \mathrm{p}) 54,56 \mathrm{Mn}, 46,47,48 \mathrm{Ti}(\mathrm{n}, \mathrm{p})^{46}, 47,48 \mathrm{Sc},{ }^{58} \mathrm{Ni}$ $(\mathrm{n}, \mathrm{p})^{58} \mathrm{Co},{ }^{64} \mathrm{Zn}(\mathrm{n}, \mathrm{p}){ }^{64} \mathrm{Cu}$ and ${ }^{59} \mathrm{Co}(\mathrm{n}, \mathrm{p})^{59} \mathrm{Fe}$ reactions, which was acquired using the ${ }^{7} \mathrm{Li}(p, n){ }^{7}$ Be reaction as a neutron source, has been completely processed and cross sections are available for energies from threshold to $\sim 6 \mathrm{MeV}$. Data has also been obtained on each of these reactions for the energy range from $6-10 \mathrm{MeV}$ using the $\mathrm{D}(\mathrm{d}, \mathrm{n})^{3} \mathrm{He}$ neutron source. In addition, the characteristics of the neutron spectra from the particular deuterium gas cell target assembly used in these measurements has been investigated by time-of-flight techniques.
3. Gamma-Ray Production Cross Sections (D. Smith)

A facility for the measurement of gamma-ray production cross sections is now operational providing a capability for precision cross section and angular distribution measurements. The primary objective is the measurement of the yield of discrete lines, predominantly those arising from ( $n, n^{\prime} \gamma$ ) reactions. A large true-coaxial $\mathrm{Ge}(\mathrm{Li})$ detector is used for gamma-ray detection. Time-of-flight techniques are applied to distinguish gamma-ray- and neutron-induced events in the detector. The neutron flux is measured with a fission chamber which is also subjected to a time-of-flight condition to minimize backg round and normalization problems. A series of measure-
ments has been made on this facility to test its operating characteristics, obtain calibrations and determine necessary corrections to be applied to cross section data. In addition, a series of cross section and angular distribution measurements have been made on the ${ }^{56} \mathrm{Fe}$ $\left(n, n^{\prime} y\right)^{56}$ Fe reaction.

## 4. Fission

a. Experimental Studies of Short-Lived Fission Isomers in Reactions Initiated by Fast Neutrons (A. J. Elwyn, F. J. Lynch, F. P. Mooring, and M. Fluss*)

A post-acceleration pulsing system is being utilized along with the pulsed and bunched proton source in the Physics Division 4 MeV Dynamitron high-voltage terminal to study the production of short-lived fissioning isomers in reactions induced by neutrons. The beam from the accelerator is incident on thick Li metal targets, and neutrons from the ${ }^{7} \mathrm{Li}(p, n){ }^{7}$ Be reaction strike foils of the fission samples. Fission events in the foil are detected by ZnO scintillators attached to RCA 8575 phototubes, and the time distribution of fission fragments is determined. The proton-beam pulse shape is monitored continuously during the accumulation of fission events. A great deal of effort has gone into the study and elimination of those experimental conditions that can lead to the existence of false isomer lifetime determinations. Results will be presented as they become available.

* Chemical Engineering Division, ANL
b. $\frac{\text { The } 233}{\text { Meadows) } / 235} \mathrm{U}$ Fission Cross Section Ratio (J. W.

Measurements of the ${ }^{233} \mathrm{U} /{ }^{235} \mathrm{U}$ fis sion cross section ratio have been completed over the energy ranges 0.1 to 3.0 MeV and 4.5 to 7.5 MeV with accuracies of $\sim 1 \%$. Relative masses of the fissile samples were obtained from the alpha activities and also from the relative thermal fission ratios. The results are summarized and compared with other values and with values deduced from ENDF/B-III in Fig. A-1.
5. Standards - Measurements of the ${ }^{6} \mathrm{Li}(\mathrm{n}, a) \mathrm{T}$ Cross Section in the keV Energy Range (W. Poenitz)

The ${ }^{6} \mathrm{Li}(\mathrm{n}, \mathrm{a})$ cross section was measured in the $90-1500 \mathrm{keV}$


Fig. A-1. The ${ }^{233} \mathrm{U} /{ }^{235} \mathrm{U}$ fission cross section ratio. The solid curve is calculated from the ENDF/B-III data file. The data of Lamphere, Pfletchinger and Käppeler, Nesterov and Sm Smirenkin consist of a large number of points closely spaced in energy. Only enough points have been plotted to indicate the trend of these data.
energy range with uncertainties of $3-5 \%$. A lithium glass scintillation detector was used for the measurement of the ( $n, a$ )-reaction rate. Flat response neutron detectors were used to monitor the neutron flux. A calibrated vanadium bath was employed to obtain absolute values. The results were analyzed in terms of the single-level multi-channel $R$-Matrix theory. The measured values are summarized in Table A-1 and the R-Matrix fit illustrated in Fig. A-2. A complete report of this work has been submitted for publication.
6. Methods - Prompt Air-Scattering Corrections for a FastNeutron Fission Detector (D. L. Smith)

Calculational procedures have been developed for determining corrections for air-scattering effects. The present application is to precision flux determinations using fission monitors. The procedures have a wider application and have been used in the correction of fissionisomer measurements. The calculations (and computational program) are described in ANL/NDM-2.
B. CHARGED PARTICLE REACTIONS

1. Reactions Relevant to Controlled Thermonuclear Research
a. Cross Sections for $\mathrm{L}_{\mathrm{i}}$ ght Charged-Particle Reaction on Li (C. R. McClenahan and R. E. Segel)

The cross sections for several reactions involving light charged particles incident on Li have been measured. These results are preliminary, and work is continuing on these reactions. The cross section for ${ }^{7} \mathrm{Li}(\mathrm{d}, \mathrm{p}){ }^{8} \mathrm{Li}$ has been measured from 280 keV to 966 keV using the induced ${ }^{8} \mathrm{Li}$ activity. With the exception of a sharp resonance at 360 keV , the cross section rises monotonically from 71 nb at 280 keV to 146 mb at $764 \mathrm{keV}_{8}$ From there the cross section falls slowly to 131 mb at 966 keV . The ${ }^{8}$ B data activity was used to measure the ${ }^{6}{ }_{\mathrm{Li}}$ $\left({ }^{3} \mathrm{He}, \mathrm{n}\right){ }^{8} \mathrm{~B}$ cross section from threshold at 2.966 MeV to 3.8 MeV . The cross section rises monotonically reaching a value of 7.2 mb at 3.8 MeV . The protons from the reaction ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{p})^{7} \mathrm{Li}$ were measured as a function of energy and angle in order to determine the cross section for this reaction from 0.5 to 3.4 MeV . Protons from reactions feeding the ground state of ${ }^{7} \mathrm{Li}$ as well as those from the first excited states were observed. The ground-state cross section is 51 mb at 0.5 MeV and

TABLE A-1. Results for the ( $n, a$ ) - Cross Section of Lithium-6
$\mathrm{E}_{\mathrm{n}} / \mathrm{keV} \quad \pm \Delta \mathrm{E}_{\mathrm{n}} / \mathrm{keV} \quad \sigma / \mathrm{b} \quad \pm \Delta \sigma / \mathrm{b} \quad \mathrm{E}_{\mathrm{n}} / \mathrm{keV} \quad \pm \Delta \mathrm{E}_{\mathrm{n}} / \mathrm{keV} \quad \sigma / \mathrm{b} \quad \pm \Delta \sigma / \mathrm{b}$

| 91 | 7 | 0.624 | 0.019 | 296 | 7 | 1.522 | 0.064 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 94 | 7 | 0.653 | 0.029 | 298 | 8 | 1.553 | 0.078 |
| 99 | 8 | 0.617 | 0.023 | 347 | 7 | 0.745 | 0.033 |
| 106 | 7 | 0.707 | 0.026 | 389 | 7 | 0.643 | 0.028 |
| 118 | 7 | 0.695 | 0.026 | 390 | 7 | 0.599 | 0.020 |
| 119 | 8 | 0.716 | 0.026 | 398 | 7 | 0.589 | 0.026 |
| 124 | 7 | 0.720 | 0.027 | 398 | 13 | 0.639 | 0.026 |
| 137 | 7 | 0.788 | 0.028 | 407 | 7 | 0.540 | 0.022 |
| 141 | 6 | 0.828 | 0.025 | 417 | 7 | 0.538 | 0.024 |
| 148 | 7 | 0.886 | 0.031 | 428 | 6 | 0.448 | 0.022 |
| 153 | 7 | 0.901 | 0.028 | 439 | 6 | 0.458 | 0.023 |
| 157 | 7 | 0.970 | 0.034 | 467 | 6 | 0.400 | 0.016 |
| 162 | 6 | 1.047 | 0.031 | 491 | 24 | 0.404 | 0.016 |
| 166 | 7 | 1.026 | 0.038 | 499 | 6 | 0.400 | 0.014 |
| 194 | 6 | 1.603 | 0.048 | 499 | 6 | 0.400 | 0.013 |
| 194 | 7 | 1.668 | 0.053 | 503 | 21 | 0.388 | 0.013 |
| 197 | 7 | 1.576 | 0.063 | 508 | 6 | 0.390 | 0.012 |
| 201 | 8 | 1.920 | 0.086 | 547 | 6 | 0.378 | 0.012 |
| 212 | 6 | 2.109 | 0.063 | 552 | 21 | 0.362 | 0.011 |
| 222 | 6 | 2.492 | 0.051 | 595 | 23 | 0.317 | 0.013 |
| 225 | 7 | 2.694 | 0.084 | 597 | 6 | 0.325 | 0.011 |

TABLE A-1 CONTINUED


|  |  |  |  |  |  |  |  |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| 232 | 6 | 2.734 | 0.081 | 600 | 21 | 0.349 | 0.011 |
| 238 | 7 | 3.010 | 0.090 | 653 | 20 | 0.320 | 0.011 |
| 238 | 6 | 2.865 | 0.086 | 699 | 6 | 0.292 | 0.010 |
| 242 | 6 | 2.925 | 0.088 | 704 | 20 | 0.294 | 0.011 |
| 247 | 8 | 3.031 | 0.133 | 751 | 19 | 0.288 | 0.010 |
| 249 | 6 | 2.925 | 0.087 | 798 | 6 | 0.256 | 0.009 |
| 250 | 7 | 2.804 | 0.115 | 805 | 19 | 0.277 | 0.011 |
| 253 | 6 | 2.804 | 0.084 | 904 | 19 | 0.248 | 0.011 |
| 263 | 6 | 2.716 | 0.084 | 999 | 6 | 0.267 | 0.010 |
| 265 | 7 | 2.564 | 0.079 | 1007 | 18 | 0.228 | 0.010 |
| 275 | 6 | 2.443 | 0.076 | 1108 | 18 | 0.234 | 0.009 |
| 295 | 7 | 1.966 | 0.069 | 1308 | 17 | 0.219 | 0.009 |
|  |  |  |  | 1500 | 17 | 0.284 | 0.014 |



Fig. A-2. Comparis on of measured cross sections for the ${ }^{6} \operatorname{Li}(n, a) T$ reaction with the results of an R-Matrix analysis (curves).
rises to 60 mb at 1 MeV . Thereafter the cross section falls slowly to 35 mb at 2.9 MeV , and then rises again reaching 44 mb at 3.2 and 3.4 MeV . The d, $\mathrm{p}_{1}$ reaction cross section rises from 17 mb at 0.5 MeV to 32 mb at 1.2 MeV whereupon it remains nearly constant up through 2.7 MeV . The cross section dips to 28 mb at 2.9 MeV and then rises to 38 mb at 3.2 and 3.4 MeV . The a-particle angular distributions were also measured for the ${ }^{6} \mathrm{Li}(\mathrm{d}, a)^{4} \mathrm{He}$ reaction for deuteron energies between 0.5 and 3.4 MeV . The cross section fell from 32 mb at 0.5 MeV to 16 mb at 2.0 MeV , and it remains nearly a constant 16 mb up through 3.0 MeV . Then it rose to 27 mb at 3.4 MeV .
b. Low-Energy Charged-Particle Induced Cross Sections on Light Nuclei: ${ }^{6}$ Li + d Reactions (A. J. Elwyn, R. E. Holland, F. J. Lynch, L. Meyer-Schützmeister and F. P. Mooring)

A program is being initiated to study reactions which may be of interest in controlled the rmonuclear research. The objectives are to obtain absolute cross sections for charged-particle induced reactions on light nuclei. Initial work will concentrate on reactions initiated by 0.1 to 3.5 MeV deuterons on targets of ${ }^{6} \mathrm{Li}$. It is hoped that prelimi nary experiments will develop those procedures and techniques that will minimize many of the technical problems in such measurements.

## 2. Nuclear Structure Studies

a. Two-Neutron Quasiparticle States Observed in ${ }^{2 \prime} \mathrm{U}$ with the (d, p) Reaction (K. Katori, A. M. Friedman and J. R. Erskine)

Energy levels in the nucleus 236 ${ }^{235} \mathrm{U}(\mathrm{d}, \mathrm{p}){ }^{236} \mathrm{U}$ reaction at bombarding energies from 12 to 16 MeV . The reaction products were analyzed with a split-pole magnetic spectrograph. The strongest transitions are those that lead to two-neutron quasiparticle states. Four rotational bands built upon the $\frac{7}{2}-[743]$ $\pm \frac{1}{2}+[631]$ and $\frac{7}{2}-[743] \pm \frac{5}{2}+[622]$ configurations were identified. The bandheads for the $K^{\pi}=1^{-}, 4^{-}, 3^{-}$, and $6^{-}$bands are found to be at 970 , 1054, 1192, and 1472 keV , respectively. The single-particle cross sections were extracted from the measured cross sections to the members in the rotational bands that involve the $\frac{1}{2}+[631]$ orbital. Disagreement with calculated single-particle cross sections was found similar to the corresponding disagreement for cross sections extracted from the
data on population of this orbital by transfer reactions on even-even targets. Measured energy splittings in both ${ }^{236} U$ and ${ }^{234} U$ are compared with calculated values.
b. Studies of Pairing Excitations in Actinide Nuclei; ${ }^{233} \mathrm{U}$ $237 \mathrm{Pu},{ }^{235} \mathrm{~Np},{ }^{241} \mathrm{Am},{ }^{224} \mathrm{Ra}$ and ${ }^{238} \mathrm{Pu}$ (A. M. Friedman, K. Katori, D. Albright and J. P. Schiffer)

The behavior of a pairing excitation, previously reported in even actinide nuclei, has been explored with two odd-neutron ( ${ }^{235} \mathrm{U}$ and $\left.{ }^{239} \mathrm{Pu}\right)$ and two odd-proton ( ${ }^{235} \mathrm{~Np}$ and ${ }^{243} \mathrm{Am}$ ) targets as well as the even-even targets ${ }^{226} \mathrm{Ra}$ and ${ }^{240} \mathrm{Pu}$. It is found that this behavior is similar to that previously found in even-even actinide nuclei.
c. Study of the ${ }^{96} \mathrm{Mo}(\mathrm{d}, \mathrm{p})^{97} \mathrm{Mo}$ Reaction (L. R. Medsker and J. L. Yntema)

The ${ }^{96} \mathrm{Mo}(\mathrm{d}, \mathrm{p}){ }^{97}$ Mo reaction has been studied with $16-\mathrm{MeV}$ deuterons. Experimental angular distributions were analyzed by use of distorted-wave Born-approximation calculations to determine $\ell$ values and spectroscopic strengths. The results have been compared with previous data and the neutron configurations of ${ }^{97}$ Mo examined in comparison with neighboring molybdenum and zirconium nuclei.

$$
\text { d. Levels in }{ }^{97} \mathrm{Nb} \text { by Means of the }{ }^{96} \mathrm{Zr}\left({ }^{3} \mathrm{He}, \mathrm{~d}\right) \text { Reaction }
$$

(L. R. Medsker)

The $\left.{ }^{96} \operatorname{Zr}^{(3} \mathrm{He}, \mathrm{d}\right){ }^{97} \mathrm{Nb}$ reaction has been studied with $22-\mathrm{MeV}$
${ }^{3}$ He particles. Experimental angular distributions were analyzed by use of distorted-wave Born-approximation calculations to determine $\ell$ values and spectroscopic factors. The results have been compared with previous data on reactions and $\beta$ decay, and the proton configurations of 97 Nb compared with neighboring niobium nuclei and recent theoretical results.
e. Study of ${ }^{166}$ Er by Means of the ( ${ }^{3} \mathrm{He}, \mathrm{d}$ ) and ( $a, t$ ) Reactions (K. Katori, L. R. Medsker, and J. L. Yntema)

Two-proton quasiparticle states in ${ }^{166}$ Er have been studied with ( ${ }^{3} \mathrm{He}, \mathrm{d}$ ) and ( $\left.\mathrm{a}, \mathrm{t}\right)$ reactions on ${ }^{165} \mathrm{Ho}$. Rotational bands built upon quasiparticle states formed by the [523 $\uparrow$ ] proton state coupled with the $[411 \downarrow],[404 \downarrow]$, and [541 $\downarrow$ proton states were identified. For each
rotational band, the cross sections have a characteristic pattern which has been used to identify the band. Assignments were checked by comparing the ratios of ( ${ }^{3} \mathrm{He}, \mathrm{d}$ ) and ( $\mathrm{a}, \mathrm{t}$ ) cross sections for each level.

## C. PHOTONUCLEAR PHYSICS

1. Search for Nonresonant Component in ${ }^{61} \mathrm{Ni}(\mathrm{y}, \mathrm{n})^{60} \mathrm{Ni}$ (H. E.

Recent analysis of ( $\gamma, n$ ) data has suggested the existence of strong nonresonant reaction amplitudes for nuclei in the mass region $A=50-70$. In an effort to confirm this trend we have begun a series of precise measurements of line shapes for low energy s-wave resonances from targets in this region. Nonresonant reaction amplitudes can be estimated from the asymmetries produced by interference between the nonresonant and resonant amplitudes. The first case, the 11.7 keV resonance in ${ }^{61} \mathrm{Ni}(\gamma, n)$, has been studied at the ANL photoneutron threshold facility. The ground state transition accounts for about $10 \%$ of the total radiation width for this state. The resonance shape was studied by observing the photoneutron spectra from a 32 g sample enriched to $92.4 \% 61 \mathrm{Ni}$ with a time-of-flight resolution of $\sim 1 \mathrm{nsec} / \mathrm{m}$. Neutrons were observed simultaneously at $90^{\circ}$ and $135^{\circ}$ to the photon beam. No strong asymmetry has been detected to date. A preliminary analysis has established an upper limit of 1 mb for the non-resonant ( $\gamma, \mathrm{n}$ ) cross section near 12 keV .
2. Background ( $\gamma, n$ ) Cross Section in ${ }^{208} \mathrm{~Pb}$ (H. E. Jackson) ${ }^{208} \mathrm{~Pb}(\gamma, \mathrm{n})$ Measurements of the shape of the 40.7 keV resonance in abstract:

A series of experimental estimates of the nonresonant radiative neutron reaction cross section in ${ }^{208} \mathrm{~Pb}$ have been reported recently. To date, the results from ( $\gamma, \mathrm{n}$ ) studies have been inconsis tent with measurements of neutron-induced reactions. In an effort to resolve this discrepancy, the shape of the $41-\mathrm{keV}$ resonance in the reaction ${ }^{208} \mathrm{~Pb}(\gamma, \mathrm{n}){ }^{207} \mathrm{~Pb}$ has been studied in detail by simultaneous measurements of the photoneutron spectra at $90^{\circ}$ and $135^{\circ}$. A small asymmetry in the resonance shape implies the presence of a background cross section of $1.3_{-0.0}^{+2.7} \mathrm{mb}$. This value can be explained in terms of
contributions from neighboring resonances plus a small direct-reaction component; there is no evidence for anomalous processes. The result is consistent with the most recent data from study of the reaction ${ }^{207} \mathrm{~Pb}$ ( $\mathrm{n}, \gamma_{0}$ ).
3. Giant M1 Resonance in ${ }^{207} \mathrm{~Pb}$ (L. R. Medsker and H. E. Jackson)

Measurements of the reaction ${ }^{207} \mathrm{~Pb}(\gamma, n)$ below 1 MeV have been completed and a paper with the following abstract has been submitted for publication:

The ${ }^{207} \mathrm{~Pb}(\gamma, n)$ reaction has been studied with high energy resolution and photon intensity to determine radiation widths, spins, and parities of resonances. The present data show an intense p-wave strength. A comparison between the measured and calculated integrated M1 strength suggests the existence of a giant M1 resonance in ${ }^{207} \mathrm{~Pb}$. No evidence was found for the photon doorway in ${ }^{207} \mathrm{~Pb}(\gamma, n)$ proposed in earlier studies. This state had been interpreted as a common doorway occurring in both the photon and neutron channels.
4. Valence Component in the Threshold Photoneutron Spectrum of

A study of photoneutron resonances in ${ }^{91} \mathrm{Zr}$ has been completed. The following abstract summarizes the results:

Ground-state radiation widths ( $\Gamma_{Y^{0}}$ ) for thirty-six $p_{3 / 2}$ photoneutron resonances in ${ }^{91} \mathrm{Zr}$ have been measured from $5-325 \mathrm{keV}$ above threshold at the A rgonne National Laboratory threshold photoneutron facility. Reduced neutron widths ( $\gamma_{n}{ }^{2}$ ) for the same resonances were obtained at the Oak Ridge Electron Linear Accelerator (ORELA) facility from total-cross-section measurements on ${ }^{90}$ Zr. A strong correlation ( $\rho=+0.59$ ) is observed between the two sets of widths. Because of a lack of knowledge of the relative phase of the compoundnucleus and valence amplitudes in the individual resonances, the average valence component cannot be deduced from the correlation analysis. However, one can obtain a mean compound-nucleus contribution by studying those resonances where the valence amplitude is expected to be negligible. By using such a procedure, an average valence component is obtained which is in excellent agreement with the average valence strength calculated from the valence model. The s-wave neutron strength function is $S^{0}=(3.9 \pm 0.8) \times 10^{-5}$ and the p -wave strength function is $S^{1}=(3.2 \pm 0.8) \times 10^{-4}$. The reduced photon width
for $E 1$ transition is $\bar{k}(E 1)=3.2 \pm 0.6) \times 10^{-3}$, in agreement with the single-particle reduced width derived from the Weisskopf model. The neutron widths are observed to follow a Porter-Thomas distribution, while the photon widths appear to follow a $\chi^{2}$ distribution with two degrees of freedom.
5. Delbrück and Nuclear Raman Scattering of 10.83 MeV Photons by Deformed and Spherical Heavy Nuclei (H. E. Jackson, K. J. Wetzel and G. E. Thomas)

A beam of monoenergetic $\gamma$-rays, extracted from the CP- 5 reactor, has been used in a high resolution measurement of the differential cross sections for photon scattering by $\mathrm{Tb}, \mathrm{Ta}, \mathrm{Pb}, \mathrm{Bi}, \mathrm{Th}$, and ${ }^{238} \mathrm{U}$. The spectrum of scattered photons was observed with a resolution of $\sim 10 \mathrm{keV}$ in a $\mathrm{Ge}(\mathrm{Li})$ detector whose sensitive volume was $\sim 60 \mathrm{cc}$. For Pb and U extensive measurements of the angular distributions for elastic and inelastic scattering were measured. For scattering angles $\theta<45^{\circ}$ the elastic scattering is dominated by the Delbrück effect. With the possible exception of Ta , for $\theta>90^{\circ}$ (where only nuclear resonances and Thomson scattering are important) both the magnitude and angular dependence of the elastic scattering cross section are in good agreement with the values which follow from the most recent photoabsorption cross sections in the corresponding targets. To an accuracy of $\sim 10 \%$ the elastic and inelastic (Nuclear Raman) scattering for $U$ and Th can be deduced from the simple rotator model using the parameters implied by the photoabsorption data. A trend of Raman scattering to be $10 \%$ weaker than expected is suggested by the data. For Tb and Ta the Raman scattering is substantially weaker than expected.

## D. NEUTRON CAPTURE SPECTROSCOPY

1. High Purity Germanium Spectrometer (G. E. Thomas and

The Ge(Li) detector formerly used in the pair spectrometers of the capture $\gamma$-ray facility at the CP-5 reactor has been replaced with a high purity (intrinsic) germanium detector whose dimensions are $1 \mathrm{~cm} \times 1 \mathrm{~cm} \times 3.5 \mathrm{~cm}$. The detector was fabricated from a single crystal 3.5 cm in diameter. Several incidents have demonstrated its durability. The relative efficiency is the same as that of a Ge(Li) detector of comparable size and the absolute efficiency appears to be
higher. A spectrum generated by neutron capture in nitrogen was observed to demonstrate the excellent spectrometer resolution over a broad energy range. Several new very weak transitions have been detected, one having an intensity of $<0.03 \%$.

* Lawrence Berkeley Laboratory.

2. Capture Spectrum from the 2.85 keV resonance in ${ }^{23} \mathrm{Na}$ (H. E. Jackson and G. E. Thomas)

Measurements of the $\gamma$-ray spectrum from neutron capture in the 2.85 keV resonance in $23^{\mathrm{Na}} \mathrm{Na}$ a in progress. The capture spectrum is generated by irradiation of a sample heavily shielded by ${ }^{10} B$ in the high sensitivity internal target facility of the CP-5 reactor. Capture predominantly in the 2.85 resonance is indicated by a requisite shift in the energies of the transitions observed relative to those observed in thermal capture. The preliminary results suggest that the capture spectrum for the 2.85 keV resonance is similar to that observed in thermal capture.

$$
\text { 3. } \frac{\text { Level Schemes of }{ }^{148} \mathrm{Sm} \text { and }{ }^{150} \mathrm{Sm}}{\text { Bushnell }} \text { (R. R. Goebbert Smither, D. }
$$

Average resonance neutron capture $\gamma$-ray spectra for the reactions ${ }^{149} \mathrm{Sm}(\mathrm{n}, \gamma)^{150} \mathrm{Sm}$ and ${ }^{147} \mathrm{Sm}(\mathrm{n}, \gamma)^{148} \mathrm{Sm}$ have been measured using highly en riched isotope samples in the Argonne ( $n, \gamma$ ) facility at the CP-5 reactor. The relative intensities of the primary $\gamma$-rays were used to identify the spin (two choices) and parity of all the levels below 3 MeV excitation with $\mathrm{J}^{\top}=1^{-}, 2^{-}, 3^{-}, 4^{-}, 5^{-}, 6^{-}$and $2^{+}, 3^{+}, 4^{+}, 5^{+}$. When this data is combined with the previously published thermal neutron capture data on the low-energy portion of the ( $n, \gamma$ ) spectra, the choice of two values for the spin that comes from the average resonance data could be narrowed to one spin value in almost all cases. About 50 levels were identified in each case. The use of enriched samples greatly simplified the spectra over that obtained in the work of Buss and Smither ${ }^{1}$ using a natural Sm sample, and made it possible to identify the two M1 subgroups, transitions to $2^{-}, 5^{-}$states and transitions to $3^{-}, 4^{-}$states, and the E2 group, transitions to $1^{-}$and $6^{-}$states. Many of these states had been missed in the earlier work. ${ }^{1}$ Of particular interest was the verification of $1^{-}, 3^{-}$and $5^{-}$states that had been suggested by inelastic deuteron scattering experiments.


Thermal and average resonance neutron capture $\gamma$-ray spectra have been measured for the ${ }^{143} \mathrm{Nd}(\mathrm{n}, \gamma){ }^{144} \mathrm{Nd}$ and ${ }^{145} \mathrm{Nd}(\mathrm{n}, \gamma)$ ${ }^{146} \mathrm{Nd}$ reaction using natural abundance samples in the Argonne ( $n, \gamma$ ) facility at the research reactor, CP-5. Further experiments are planned using enriched samples. This is part of a continuing program of investigating nuclei near the closed neutron shell $\mathrm{N}=82$.
*Northern Illinois University
5. Levels in ${ }^{184} W$ Based on ( $n, \gamma$ ) and $\beta$-Decay Experiments (R. K. Smither and D. Bushnell ${ }^{*}$ )

The Argonne ( $n, \gamma$ ) facility at the CP-5 research reactor was used to measure the $\gamma$-ray spectrum of ${ }^{183} W(n, \gamma){ }^{184} W$. Both thermal capture and average resonance capture-spectra were measured with capturing samples enriched in ${ }^{183} \mathrm{~W}$. These ( $n, \gamma$ ) results were combined with a series of $\gamma-\gamma$ coincidence studies of the $\gamma$-ray spectrum following the $\beta$ decay of ${ }^{184} \mathrm{Re}$ to develop the level scheme of 184 W . Forty-three states were identified with excitation energies up to 2404 keV . The $\gamma-\gamma$ coincidence studies were performed at Northern Illinois University. The ${ }^{184}$ Re $\beta$-decay source was prepared at the Argonne electron linac using the ${ }^{185} \operatorname{Re}(\gamma, n){ }^{184}$ Re reaction. The average resonance capture data was used to identify all states with $\mathrm{J}^{\pi}=0^{+}, 1^{+}, 2^{+}$up to 2.4 MeV excitation. These levels are fed directly by primary E1 transitions. Many of the primary M1 transitions were also resolved in the average resonance data leading to information about states with $\mathrm{J}^{\pi}=0^{-}, 1^{-}$and $2^{-}$. The high degree of complexity of the $\gamma$ spectra keep this analysis from being complete. The ( $n, \gamma$ ) spectrum in the energy region from 600 to 2400 keV was also measured with a $G e(L i)$ detector at the Argonne ( $n, \gamma$ ) facility. This medium energy data is combined with the high energy $\gamma$ spectrum of primary transitions to generate the level scheme of ${ }^{184} \mathrm{~W}$ shown in Fig. D-1. The ground state rotational band stands out clearly in the


Fig. D-1. The level scheme for 184 ray spectroscopy. A $\gamma$ transition given as a dot-dash line has been placed in the level scheme with a rather poor energy fit. A dashed transition comes from a level whose existence is uncertain. The heavy short arrows located on initial states represent the $E 1$ average resonance primary transitions from the capture state. The short thin arrows signify the M1 primary transitions.
level scheme. Above the pairing gap ( $\sim 1 \mathrm{MeV}$ ) the level scheme becomes quite complicated and probably consists of many overlapping rotational bands. The primary objective of this work is a search for this type of collective nuclear structure in this very complicated region above 1 MeV . The first step is to determine the spin and parity of each level and in this, the work has succeeded quite well. What remains to be done is to fill in the low energy ( $E_{\gamma}$ below 600 keV ) $\gamma$ transition between states and locate the higher spin states. The $\gamma-\gamma$ coincidence studies following $\beta$ decay of ${ }^{184}$ Re made some progress in this direction. The decay scheme derived from the $\beta$-decay work is shown in Fig. D2. Some of the same low spin levels are fed in this level scheme as were fed in the ( $n, \gamma$ ) work shown in Fig. D-1, but the high degree of selectivity of the $\beta$-decay process is evident. Also there are some conflicts in spin and parity assignments that must be resolved.

## * Northern Illinois University

## E. FISSION PHYSICS

1. $\frac{\text { Spontaneous Fission Isomerism }}{\text { J. W. Meadows) }}$ (K. L. Wolf, J. P. Unik and

Approximately forty fissioning isomers are now known from uranium to berkelium, and fission barrier parameters have been determined for many of these cases from isomer excitation functions and half -lives. Most of the fissioning isomers have been found in plutonium and americium isotopes with only three cases for lighter elements -
 $=40 \mathrm{~ns}$ ) was recently discovered at the Argonne 152 cm cyclotron, and the half-life of $238 \mathrm{~m}_{\mathrm{U}}$ has been remeasured at the cyclotron with a result of $295 \pm 15 \mathrm{~ns}$ which is $50 \%$ longer than the previously accepted value. Very little is known about the properties of the uranium isomers since they cannot be studied by the usual charged particle induced compound nuclear reactions such as ( $\mathrm{p}, \mathrm{xn}$ ) , $\mathrm{d}, \mathrm{xn}$ ) and ( $a, \mathrm{xn}$ ) reactions because there are no suitable projectile and target combinations. However, using monoenergetic neutrons as the projectile, the ${ }^{238} \mathrm{U}\left(\mathrm{n}, \mathrm{n}^{\prime}\right)$ reaction has been used in an attempt to measure the excitation energy of the fissioning isomer ${ }^{238 \mathrm{~m}_{\mathrm{U}}}$. Fig. E-1 shows the results of an excitation function taken by measuring delayed fission activity of ${ }^{238 \mathrm{~m}_{\mathrm{U}}} \mathrm{U}$ as a function of neutron energy. The Argonne Fast Neutron Generator was


Fig. D-2. The level scheme of ${ }^{184} \mathrm{~W}$ based on gamma-ray spectroscopy following electron capture decay of ${ }^{184} \mathrm{Re}$.


Fig. E-1. The ratio of the delayed fission cross section of ${ }^{238 \mathrm{~m}} \mathrm{U}$ to prompt fission cross section for a ${ }^{238}$ U target as a function of incident neutron energy. The horizontal lines of the data points represent the calculated full width energy spread of the incident neutrons. The measured half-life in this work was $270 \pm 50 \mathrm{~ns}$. The curve is the result of an evaporation model calculation which takes into account the doublehumped fission barrier.
used to produce a pulsed beam of nearly monoenergetic neutrons with the ${ }^{7} \mathrm{Li}(\mathrm{p}, \mathrm{n})$ reaction. A parallel plate ionization chamber provided fission fragment detection and timing. The curve in Fig. E-1 is a fit to the data with a calculation that gives quantitative fits to most charged particle induced fissioning isomer data. The value of the isomer excitation energy obtained is 2.2 MeV , but the fit to the data is poor with the threshold being much steeper than expected.

## 2. Physical Measurements of Fission Fragment Mass and Kinetic Energy Distributions from ${ }^{230} \mathrm{Th}$ to ${ }^{256} \mathrm{Fm}$ (J. P. Unik, L. E. Glendenin, J. E. Gindler and A. Gorski)

Measurements of Fission-fragment mass and kinetic energy distributions have already contributed a great deal toward our understanding of the fission mechanism. During the past year, considerable effort has been directed toward extending these measurements to heavier fissioning systems and achieving a much higher accuracy than previously obtained. In our most recent study, fragment mass and kinetic energy distributions have been measured for seven cases of the rmal-neutron-induced fission ( $n, f$ ) and six cases of spontaneous fission (sf) ranging from ${ }^{230} \mathrm{Th}$ to ${ }^{256} \mathrm{Fm}$. These data combined with the results of our earlier studies 1,2 now enable us to examine many new aspects of the fission process in detail. The experimental method used in this study is the well-known "double-kinetic energy method" (Ref. 1). By paying careful attention to many experimental and calculational details, accuracies of $\pm 0.1 \mathrm{amu}$ and $\pm 0.2 \mathrm{MeV}$ have been achieved for the calculated fragment masses and kinetic energies. The fissioning systems, as well as the measured moments of the fragment mass and kinetic energy distributions, are listed in Table E1. Many qualitative features of fragment mass divisions in fission are evident in the results of this work for ( $\mathrm{n}, \mathrm{f}$ ) and ( sf ) as shown in Figs. E-2 and E-3, respectively. The average masses of the heavy fragment groups are seen to be nearly constant over the entire range of fissioning nuclides studied. There is an appreciable increase in the yield of symmetric fission fragments for the very heaviest systems. Furthermore, a great deal of fine structure exists in the mass distributions, most notably for the lighter fissioning systems. This fine structure is due to a preferential formation of fragments with even nuclear charges in low-energy fission. The shaded vertical bars in Figs. E-2 and E-3 indicate the calculated masses corresponding to the formation of even-Z fragments based on our earlier charge division results ${ }^{1}$. Many of the general features of the shapes of these mass distributions can now be

TABLE E-1. Summary of Pre-Neutron-Emission Fission Fragment Data ${ }^{\text {a }}$

| Fissioning System | Source Preparation ${ }^{\text {b }}$ | Events <br> Analyzed (x 105) | $\bar{A}_{L}$ | $\bar{A}_{H}$ | $\sigma_{M}^{C}$ | $\bar{E}_{L}$ | $\bar{E}_{H}$ | $\overline{\text { TKE }}$ | $\sigma_{T K E}{ }^{\text {c }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $229 \mathrm{Th}(\mathrm{n}, \mathrm{f})$ | IS | 1.0 | 89.6 | 140.4 | 4.7 | 99.8 | 63.8 | 163.6 | 8.2 |
| ${ }^{2335} \mathrm{U}$ ( $\left.n, f\right)^{\text {d }}$ | $v$ | 3.7 | 95.0 | 139.0 | 5.6 |  |  | 172.1 | 9.9 |
| ${ }^{235} \mathrm{U}(\mathrm{n}, \mathrm{f})$ | $v$ | 2.5 | 96.5 | 139.5 | 5.6 | 101.4 | 70.4 | 171.8 | 10.3 |
| $239 \mathrm{Pu}(\mathrm{n}, \mathrm{f}) \mathrm{d}$ | V | 7.6 | 100.4 | 139.6 | 6.4 |  |  | 177.1 | 11.5 |
| $245 \mathrm{Cm}(\mathrm{n}, \mathrm{f})$ | IS | 1.1 | 105.3 | 140.7 | 6.7 | 105.1 | 79.0 | 184.2 | 11.7 |
| $246 \mathrm{Cm}(\mathrm{sf})$ | IS | 4.3 | 106.0 | 140.0 | 6.3 | 104.5 | 79.4 | 183.9 | 10.6 |
| $248 \mathrm{Cm}(\mathrm{sf})$ | IS | 2.6 | 107.0 | 141.0 | 6.6 | 103.4 | 78.7 | $182.2{ }^{\text {e }}$ | 10.5 |
| $249 \mathrm{Cf}(\mathrm{n}, \mathrm{f})$ | IS | 2.6 | 108.2 | 141.8 | 7.4 | 107.0 | 82.0 | 189.1 | 13.0 |
| $250 \mathrm{Cf}(\mathrm{sf})$ | IS | 3.3 | 107.5 | 142.5 | 6.9 | 106.4 | 80.5 | 187.0 | 11.3 |
| 252 Cf (sf) | T | 2.5 | 108.5 | 143.5 | 7.1 | 105.7 | 80.2 | $185.9$ | 11.6 |
| $254 \mathrm{Cf}(\mathrm{sf})$ | IS | 2.5 | 110.6 | 143.4 | 7.2 | 105.3 | 81.5 | 186.9 | 11.8 |
| $254 \mathrm{Es}(\mathrm{n}, \mathrm{f})$ | IS | . 5 | 112.7 | 142.3 | 8.1 | 108.1 | 86.2 | $194.3$ | 15.9 |
| ${ }^{256} \mathrm{Fm}(\mathrm{sf})$ | IS | . 1 | 113.9 | 142.1 | 7.6 | 109.6 | 88.3 | 197.9 | 14.4 |

astimated relative precision for $\bar{A}_{L}, H, \bar{E}_{L, H}$ and $\overline{T K E}$ are $\pm 0.1$ amu, $\pm 0.2 \mathrm{MeV}$ and $\pm 0.5 \mathrm{MeV}$,
respectively.
${ }^{b} I S=$ isotope separator, $V=$ vacuum volatilization, $T=$ self transfer
${ }^{c}$ Uncorrected for experimental resolution
${ }^{\text {d Data taken from ref. [1] }}$
$e_{\text {Error }} \pm 0.9 \mathrm{MeV}$


Fig. E-2. Primary fragment mass distributions obtained for thermal-neutron-induced fission. All distributions have been corrected for experimental dispersions. The shaded vertical bars indicate the calculated fragment masses associated with the even nuclear charges designated in the figure for ${ }^{239} \mathrm{Pu}(\mathrm{n}, \mathrm{f})$.


Fig. E-3. Primary fragment mass distributions obtained for spontaneous fission. All distributions have been corrected for experimental dispersions. The shaded vertical bars indicate the calculated fragment masses associated with the even nuclear charges designated in the figure for ${ }^{252} \mathrm{Cf}(\mathrm{sf})$.
qualitatively interpreted ${ }^{3}$ as being due to stabilizing shell effects in deformed fission fragments possessing neutron numbers in the vicinity of $\approx 66, \approx 80-90$ and proton numbers of $\approx 42$.

The average total kinetic energy release for many fissioning systems has in the past been correlated with the symmetric-fission Coulomb repulsion parameter $Z_{F}{ }^{2} / A_{F}{ }^{1 / 3}$, i.e.

$$
\begin{equation*}
\overline{\mathrm{TKE}}=\mathrm{B}\left(Z_{F}^{2} / \mathrm{A}_{\mathrm{F}}^{1 / 3}\right)+\mathrm{C} . \tag{1}
\end{equation*}
$$

However, in previous correlations, TKE values with large uncertainties were included as well as data for fissioning systems with widely different excitation energies and angular momentum distributions. The total kinetic energy has previously been shown to be slightly dependent on both excitation energy as well as angular momentum. The TKE values obtained in this work are correlated with the Coulomb repulsion parameter in Fig. E-4. The line in this figure is the result of a leastsquares fit of the ( $\mathrm{n}, \mathrm{f}$ ) data (open circles) to Eq. (1) yielding $B=0.13323$ and $C=-11.64$. For fission data taken at nearly the same low excitation energy and with no angular momentum, it is seen that TKE data can be adequately represented by Eq. (1), generally to within $\pm 1 \mathrm{MeV}$. However, in fitting the data, the TKE value for ${ }^{249} \mathrm{Cf}(\mathrm{n}, \mathrm{f})$ was omitted since it is considerably lower than expected from such a linear fit. The TKE values measured in this work as well as in the work of others indicate a deviation for californium isotopes from this general linear dependence. The first moments of the fragment mass groups for the californium fission also deviate from the smooth dependence with fissioning mass based upon isotopes of other elements. The TKE values measured for spontaneous fission are in all cases less than those measured or interpolated from ( $n, f$ ) data indicating that although there is a stron dampening of the excitation energy, some of the initial excitation energy does appear as additional kinetic energy of the fragments. A more complete summary of this work will soon appear in print. ${ }^{4}$

[^5]

Fig. E-4. Correlation of measured average total kinetic energies ( $\overline{\mathrm{TKE}}$ ) with the symmetric-fission Coulomb replusion parameter $Z_{F}{ }^{2} / A_{F}{ }^{1 / 3}$. Data for thermal-neutron-induced fission are shown as open circles, data for spontaneous fission are shown as solid squares. The fissioning nuclides are indicated for each data point.

3. Radiochemical Investigation of Fission Fragment Mass Distributions (K. F. Flynn, J. E. Gindler, L. E. Glendenin, R. K. Sjoblom, A. J. Gorski and J. P. Unik)

Distribution of fission fragment mass (atter neutron emission) were obtained radiochemically for thermal-neutron-induced fission ( $\mathrm{n}, \mathrm{f}$ ) of ${ }^{251} \mathrm{Cf},{ }^{254} \mathrm{Es},{ }^{255} \mathrm{Fm}$ and spontaneous fission ( $\mathrm{s}, \mathrm{f}$ ) of ${ }^{253} \mathrm{Es},{ }^{254} \mathrm{Fm}$ and ${ }^{256} \mathrm{Fm}$. The important features of these distributions for fission of some of the heaviest nuclides now available may be seen by comparison of the mass-yield curves for the six fissioning systems plotted in Fig. E-5. Of especial importance is the marked decrease observed in the peak-to-valley ratios ( $P / F$ ) of the distributions (enhancement of summetric fission) with increasing mass of the fissioning nucleus for both spontaneous and neutron-induced fission. These results provide support for recently developed models 1,2 of fission based on minimum potential energy and nuclear shell effects. Of particular interest is the nearly symmetrical fission in the case of ${ }^{255} \mathrm{Fm}(\mathrm{n}, \mathrm{f})$ (with a peak-to-valley ratio of only $\sim 2$ ) in view of the recently reported ${ }^{3}$ completely symmetrical fission for ${ }^{257} \mathrm{Fm}$ ( $\mathrm{n}, \mathrm{f}$ ) based on physical measurements. Enhancement of symmetrical fission with the increased excitation energy of $\sim 6 \mathrm{MeV}$ from neutron absorption is also apparent in comparisons of ${ }^{252} \mathrm{Cf}(\mathrm{s}, \mathrm{f})$ with ${ }^{251} \mathrm{Cf}(\mathrm{n}, \mathrm{f})(\mathrm{P} / \mathrm{V}$ decreasing from 600 to 20 ) and of ${ }^{256} \mathrm{Fm}(\mathrm{s}, \mathrm{f})$ with ${ }^{255} \mathrm{Fm}(\mathrm{n}, \mathrm{f})$ ( $\mathrm{P} / \mathrm{V}$ decreasing from 12 to 2 ). Since no experimental information is presently available on neutron emission probabilities as a function of fragment mass, $\bar{\nu}(A)$, for the heaviest fissioning systems of mass $A_{F}>252$, an iterative procedure comparing physical with radiochemical fission yield data based on the method of Terrell ${ }^{4}$ was used to derive such functions for some of the heaviest fissioning systems. The derived function $\bar{\nu}$ ( $A_{F}$ ) for ${ }^{256}$ (sf) (solid curve in Fig. E-5) which gives the best fit of physical measurements of the mass distribution to the radiochemical data is seen to have the same saw-tooth character as the experimental data for ${ }^{252} \mathrm{Cf}(\mathrm{sf})$ (dashed line). Thus, for fission of nuclides heavier than ${ }^{252}$ Cf shell effects continue to play an important role in determining the relative fragment deformation energies.

[^6]

## F. NUCIEAR DATA ON URANIUM ISOTOPES

1. Specific Activity and Half-Life of $\mathrm{U}^{233}$ (A. H. Jaffey, K. Flynn, W. C. Bentley, J. Karttunnen)

The value of the half-life of $\mathrm{U}^{233}$ enters critically into the calculations of fission constants used for reactor calculations. The least squares analysis which leads to "best-values" uses as input data various cross-section ratios, absolute cross-sections (total and fission), nu-values, alpha-values. The best samples for fission counting measurements are typically prepared by electroplating or by some other method not yielding quantitative deposition. The weights of such samples are, in the case of $U^{233}$, usually assayed by alpha-counting in a known geometry. With the $\mathrm{U}^{233}$ half-life value, the alpha count gives the sample mass. In some experiments, the $U^{235}$ samples have been spiked with $U^{233}$ such that the $U^{233}$ alpha-activity dominates, but masswise, the $\mathrm{U}^{235}$ dominates. With a precision mass-spectrometric isotope ratio, alpha counting the sample yields the $\mathrm{U}^{235}$ mass. The measured values of the $U^{233}$ half-life scatter over a range of about $4 \%$, a situation which led us to re-determine it by a method already successfully used for $\mathrm{U}^{235}, \mathrm{U}^{236}, \mathrm{U}^{238}$. The experiment has been completed and the data is being reduced. Preliminary calculations indicate the result to lie about mid-way between the extremes of the previous values.
2. Hyperfine Interaction and Nuclear Moments in Even Uranium Isotopes from Mössbauer Spectroscopy (R. D. Meeker, G. M. Kalvius, B. D. Dunlap, S. L. Ruby and D. Cohen)

Nuclear gamma resonance (Mössbauer effect) measurements have been performed using the $45 \mathrm{keV}, \mathrm{O}^{+} \rightarrow 2^{+}$transition in ${ }^{234} \mathrm{U}$, ${ }^{236} \mathrm{U}$ and ${ }^{238} \mathrm{U}$. Values are obtained for the ratio of quadrupole moments of the ${ }^{2+}$ level in these isotopes

$$
Q(234): Q(236): Q(238)=1: 1.13 \pm 0.09: 1.13 \pm 0.10
$$

and for the magnetic moments of the $2^{+}$level

$$
\mu(234): \mu(236): \mu(238)=1: 0.98 \pm 0.06: 0.94 \pm 0.09 .
$$

No isomer shifts are detected, placing an upper limit on the change in nuclear mean square charge radius of

$$
\left|\Delta\left\langle\mathrm{r}^{2}\right\rangle\right| \leq 2 \cdot 10^{-4} \mathrm{fm}^{2}
$$

for all three isotopes where $\mathrm{fm}=10^{13} \mathrm{~cm}$.

## BROOKHAVEN NATIONAL LABORATORY

## A. NEUTRON PHYSICS

1. Fast Chopper
a) Technical Developments

The neutron flux available at the Fast Chopper has been increased fourfold by a redesign of the in-pile collimator which is located between the chopper and the reactor core. The original collimator was divided by both vertical and horizontal inserts to form an array of square tubes which offered very severe collimation. The new collimator has no horizontal inserts, so that the beam can spread in the vertical direction; external collimation is used to limit the vertical spreading. This more open collimator accepts neutrons from a significantly larger area of the radiating surface of the reactor thimble compared with the previous collimator. The neutron flux at 22 m has been measured by observing the 479 keV $\gamma$-ray from the $10_{B}(n, \alpha Y)$ reaction; it is $\sim 3.7 \times 10^{4} / \mathrm{E} \mathrm{n}-\mathrm{cm}^{-2}-\mathrm{sec}^{-1}-\mathrm{eV}^{-1}$. Standards runs using a tungsten target were made before and after the collimator change; they verify the factor of four flux increase. The standard tungsten runs also show that the background (e.g., Y-rays due to neutron capture in iron and other materials in the room) has increased no more than the same factor of four; thus the use of external collimators to limit the beam size does not add to the room background.

The flux increase makes it possible to consider experiments using a chopper rotor which gives $1 \mu$ sec beam burst, rather than the $5 \mu \mathrm{sec}$ minimum burst width now available. A rotor containing a $1 \mu$ sec slit package is readily interchangeable with the standard rotor, and is presently being tested.
b) Experimental

1. $\frac{\text { Direct Capture S.tudies in } \operatorname{Sm-152}(\mathrm{n}, \mathrm{Y}) \mathrm{Sm}-153}{\text { (G.W. Cole and R.E. Chrien) }}$

Radiative capture in $\mathrm{Sm-152}$ is being studied as part of a continuing investigation of non-statistical effects near the 4-s giant resonance. The Fast Chopper group has previously reported the existence of significant direct neutron capture in Dy-162 ;
$1_{\text {G.W. Cole, S.F. Mughabghab and R.E. Chrien, Proc. Int. Conf. on }}$ Photonuclear Reactions and Applications, B. Berman, ed. (1973).
the present experiment continues these direct capture investigations.
Figure A-1-1 shows the time-of-flight spectrum obtained using a 116 gm target of $\mathrm{Sm}_{2} \mathrm{O}_{3}$, $98 \%$ enriched in $\mathrm{Sm}-152$. The 8.03 eV resonance clearly exhibits a multiple scattering effect. A thin target, consisting of $\sim 1 \mathrm{gm}$ of $\mathrm{Sm}_{2} \mathrm{O}_{3}$ dispersed over $60 \mathrm{~cm}{ }^{2}$, was also used, in order to make a detailed study of the intensity variation of $\gamma$-rays near the 8.03 eV resonance. The time-of-flight spectrum from this thin target is shown in Fig. A-1-2

The observed $\gamma$-ray intensities were normalized by comparison with the thermal cross sections obtained by Bennett et al. ${ }^{2}$ Using Bennett's value of 5868.6 keV for the neutron binding energy in $\mathrm{Sm}-153$, we find general agreement within $\pm 1 \mathrm{keV}$ with the level energies of Ref.2. Table A-1-1 lists the partial radiative widths for E1 transitions to six final states from six resonances, along with the resonance parameters used for the multilevel analysis. The ( $\mathrm{d}, \mathrm{p}$ ) intensities are those of Kenefick and Sheline. ${ }^{3}$ The correlation coefficient $\left\langle\rho\left(\Gamma_{\mathrm{n}}^{\mathrm{O}}, \Gamma_{\gamma \mathrm{i}}\right)\right\rangle=0.44$ is significant above the $95 \%$ confidence level for this sample size.

Multilevel interference fitting has been carried out for these six $\gamma$-rays, including partial widths for the 8.03 eV , 62.2 eV and 87.7 eV resonances. Figure A-1-3 shows the results of one such fit, for the $\gamma$-ray populating the 695.8 keV state. The solid line is the result for zero direct amplitude, while the dashed line shows the best fit including direct capture. Although this state has the largest ( $d, p$ ) intensity of the six, the $\gamma$-ray intensity variation shows little evidence for direct capture; the dashed line was produced with $\sim 0.1 \mathrm{mb}$ of direct cross section at 1 eV .

The existence of arbitrary phase relations between amplitudes for different resonances gives, in general, a range of possible results for the direct amplitude depending upon the relative phases chosen. While it is often possible to choose among the phases by the quality of the resulting fits or the magnitude of the direct amplitude obtained (e.g., very large results for the direct cross section seem unreasonable), the $\mathrm{Sm}-152$ case is not clearcut. The average direct cross section for the 6 final states considered is

[^7]


Fig. A-1-2

Table A-1-1

|  |  | ${ }^{152} \operatorname{Sm}(\mathrm{n}, \gamma) \quad$ Partial Widths (meV) |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $E_{\lambda}(\mathrm{eV})$ | 8.03 | 62.2 | 87.7 | 154.1 | 185.2 | 237.2 |
|  |  | $\Gamma_{n}^{o}(\mathrm{meV})$ | 45.8 | 0.51 | 21.9 | 11.4 | 1.4 | 27.0 |
|  |  | $\Gamma_{Y}(\mathrm{meV})$ | 68 | 65 | 65 | 65 | 65 | 65 |
| $\begin{aligned} & I(d, p) \\ & (\operatorname{Ref} .3) \end{aligned}$ | $J^{\pi}$ | $\mathrm{E}_{\text {exc }}$ |  |  |  |  |  |  |
| 2.5 | $3 / 2^{-}$ | 35.9 | 0.79 | 0.65 | 0.34 | 0.35 | 0.11 | 0.38 |
| 1.8 | $3 / 2^{-}$ | 127.3 | 2.30 | 0.73 | 0.97 | 0.44 | 0.60 | 0.47 |
| 5.9 | $3 / 2^{-}$ | 405.5 | 0.28 | 0.47 | 0.38 | 0.25 | 0.97 | 1.63 |
|  | 3/2 ${ }^{-}$ | 630.2 | 0.65 | 0.19 | 0.079 | 0.15 | 0.086 | 0.10 |
| 13.5 | $1 / 2^{-}$ | 695.8 | 0.41 | 0.43 | -- | 0.79 | 0.10 | . 089 |
| 3.9 | $3 / 2^{-}$ | 750.3 | 0.27 | 0.075 | 0.30 | -- | 0.092 | 0.13 |
|  |  |  |  | $<p\left(\Gamma_{\mathrm{n}}^{\mathrm{O}}\right.$ | $\left.y_{i}\right)^{>}=$ | . 44 |  |  |



Fig. A-1-3
$\sim 0.9 \mathrm{mb}$ at 1 eV if lower limits are chosen, but if upper limits are chosen the average is $\sim 12 \mathrm{mb}$ at 1 eV .

Lane has derived an expression ${ }^{4}$ relating the direct cross section to the partial width correlation coefficient; when evaluated for $\mathrm{Sm}-152$, the expression gives

$$
\sigma_{D}^{o} \approx 27 \rho\left(\Gamma_{\mathrm{n}}^{\mathrm{o}}, \Gamma_{\gamma f}\right) \mathrm{mb}
$$

where $\sigma_{D}{ }^{\circ}$ is the direct cross section at 1 eV . We therefore would prefer a more precise determination of $\sigma_{D}{ }^{\circ}$, in order to make a comparison with Lane's result. The thin target data should be important in refining the analysis, since they provide a second opportunity to study the $\gamma$-ray intensity variation; in particular, the detailed shape of the $\gamma$-ray intensity variation over the 8.03 eV resonance should be a good indicator of relative resonance phases, and should help to remove this ambiguity.

## 2. Direct Capture Studies in Dy-162( $n, Y$ ) Dy-163 (G.W. Cole and R.E. Chrien)

The direct capture investigation in Dy-162 which was referred to in the preceding section is subject to a remaining ambiguity: the Columbia University group has recently proposed 5 that resonances in Dy-162 at 5.43 and 70.7 eV are both doublets. TableA-1-2 lists the resonance parameters 6 which were used in the multilevel analysis already completed, along with preliminary estimates of the doublet parameters. The high resolution chopper rotor, which gives a maximum resolution of $46 \mathrm{nsec}-\mathrm{m}^{-1}$ at 22 m , or $21 \mathrm{nsec}-\mathrm{m}^{-1}$ at the 48 m flight path, will be used to investigate these proposed doublets; the resolution at both 5 eV and 71 eV should be adequate to observe doublets with the suggested spacings.

[^8]
## Table A-1-2

## Resonance Parameters for Dy-162

| Ref. 6 |  | Ref. 5 |  |
| :---: | :---: | :---: | :---: |
| $E_{\lambda}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}^{\mathrm{o}}(\mathrm{meV})$ | $E_{\lambda}(\mathrm{eV})$ | $\left(\Gamma_{\mathrm{n}}^{0}(\mathrm{meV})\right.$ |
|  |  | 5.45 | 9.0 |
| 5.43 | 9.1 | 5.80 | 2.4 |
|  |  | 70.55 | 13.1 |
| 70.7 | 47.1 | 72.10 | 21.2 |

## 3. Validity of the Valence Model in Mo-98 (G.W. Cole, R.E. Chrien, J.A. Harvey* and G.G. Slaughter*)

The success of the valence capture model of Lane and Lynn 7 in the first few p-wave resonances of Mo-98 ${ }^{8}$ led to àn investigation of higher energy resonances in order to study the range of validity of the model. ${ }^{9}$ Capture $\gamma$-ray spectra were recorded at ORELA, using an enriched Mo-98 target with a flight path of 10 m and a nominal resolution of $2.5 \mathrm{nsec}-\mathrm{m}^{-1}$. The neutron widths for the p-wave resonances, which are necessary for valence capture analysis, were originally obtained in a total cross section measurement at ORELA, using a thick ( 0.0434 atom/b) Mo-98 target, a flight path length of 78.2 m and a nominal resolution of $0.06 \mathrm{nsec}-\mathrm{m}^{-1}$.

The total cross section data did not provide the desired precision in the determination of neutron widths, because only one target thickness was used and because difficulties in accounting for experimental backgrounds were encountered. Since the thick target runs were completed, the background conditions for total cross section measurements at ORELA have been considerably improved; therefore a new measurement was undertaken using a thinner target. The target thickness was 0.00428 atom/b, the flight path length was 78.2 m , and the time resolution $0.38 \mathrm{nsec}-\mathrm{m}^{-1}$. The analysis of these results is presently in progress at BNL, and should yield an accurate set of neutron widths which will allow the final determination of the fraction of capture in Mo-98 which proceeds through the valence mechanism.

## *

Oak Ridge National Laboratory, Oak Ridge, Tennessee
7
J.E. Lynn, "Theory of Neutron Resonance Reactions," Clarendon Press, Oxford (1968).

8
S.F. Mughabghab, R.E. Chrien, O.A. Wasson, G.W. Cole and M. R. Bhat, Phys. Rev. Lett. 26, 1118 (1971).

9
G.W. Cole, R. E. Chrien, R. C. Byrd, S. F. Mughabghab, J. A. Harvey, and G. G. Slaughter, Bull. Am. Phys. Soc. 18, 96 (1973).
4. Direct Neutron Capture Survey in the 4-s Giant Resonance

Lane ${ }^{4}$, and Boridy and Mahaux ${ }^{10}$ have shown that the direct reaction cross section between two channels is proportional to the linear correlation coefficient between widths in the two channels. In particular, the direct neutron capture cross section is predicted to be proportional to the correlation coefficient between reduced neutron widths and partial radiative widths. An extensive search for evidence of direct capture of epithermal neutrons is being carried out at the Fast Chopper for target nuclei near the 4-s giant resonance. In addition to $\mathrm{Dy}-162$ and $\mathrm{Sm}-152$, which are mentioned elsewhere in this contribution, Dy-164, Yb-170 and $\mathrm{W}-186$ are under investigation. Data have been obtained for these nuclei, and multilevel analysis of the variation of gamma-ray intensity with neutron energy is in progress.
5. Spins of ${ }^{159} \mathrm{~Tb}$ Resonances and the Absence of Evidence for Nonstatistical Effects (P. Ribon*, G.W. Cole and R.E. Chrien)

A study of the spectra of neutron capture $\gamma$-rays from $\mathrm{Tb}-159(\mathrm{n}, \mathrm{Y})$ was made with the HFBR neutron chopper facility in order to improve the knowledge of the level scheme of 160 Tb and to check the possible existence of nonstatistical effects.

We have determined the spins of most of the neutron resonances below 100 eV (see Table A-1-3). The high energy $\gamma$ rays studied are the direct transitions from the $2^{+}$resonances to $3^{-}$ states (both the ground state and the 156 keV state); for unknown reasons, we saw no transition from the $1^{+}$resonances to the $64 \mathrm{keV}, 0^{-}$ state. 11 Many low energy $\gamma$ rays appeared to be enhanced in the decay from $2^{+}$resonances; this enhancement is easily explained in some cases, such as the $\gamma$ ray corresponding to the transition from the $177 \mathrm{keV} 5^{-}$state to the ground state. 11

* Visiting Physicist from CEN/Saclay

10 E. Boridy and C. Mahaux, Phys. Lett. 45B, 82 (1973).
11 J. Kern, et a1. "Nuclear Levels in ${ }^{160} \mathrm{~Tb}$ ", Helv. Phys. Acta, 46 60 (1973).

Table A-1-3
Spin attribution ${ }^{159} \mathrm{~Tb}$


Ref. 13 BNL 325 Third Edition (1973)

The same results were used in order to check the preliminary results reported by Jain et al. ${ }^{12}$ By numerical integration of the $\gamma$ ray spectra for the resonances, we obtained a ratio $\mathrm{R}^{\prime}$ :

$$
R^{\prime}=\int_{4.5 \mathrm{MeV}}^{6.4 \mathrm{MeV}} \mathrm{n}(\gamma) \mathrm{dE}_{\gamma} / \int_{2.0 \mathrm{MeV}}^{4.5 \mathrm{MeV}} \mathrm{n}(\gamma) \mathrm{dE}_{\gamma}
$$

similar to the ratio $R$ of Ref. 12 and which presents the same variations, thus confirming their results. But the constancy of the ratio $R$ which appears in Jain's results for the five $1^{+}$ resonances (Fig. A-1-4) no longer holds if we introduce our attribution of the spins and if we furthermore remark that the 108 eV and 113 eV resonances are, in fact, some overlap of several resonances which were not resolved in the experiment from which their spins were determined.

To conclude, we confirm the previously observed fluctuations of $R$ (or $R^{\prime}$ ), but there appears to be no evidence for a correlation of this ratio with the resonance spins, or with the neutron widths.

12 A.P. Jain et al. Int. Conf. on Nuclear Structure Study with Neutrons, Budapest, 1972; A.P. Jain, private communication.


## A. 2. The 24 keV Filter Program

(K. Rimawi, O. A. Wasson* and R. E. Chrien)
a) Equipment

Since the previous report, the aperture for the 24 keV filtered beam was increased by removing the remaining tubing on the forecollimatgr in front of the filter. This increased the 24 keV flux to $10^{7} \mathrm{n} / \mathrm{cm}^{2} / \mathrm{sec}$ across an area of approximately $6.45 \mathrm{~cm}^{2}$ when transmitted through 9 inches $\mathrm{Fe}, 14$ inches Al and 2 inches S . The flux was measured by the $10_{B(n, \alpha y)}$ reaction.

The neutron spectrum for the filtered beam is shown in Fig. A-2-1. The beam is seen to have a half maximum full width of 2 keV and to peak at a neutron energy of 24 keV . The flux has been calculated from the measured transmission of the components and assuming a $E^{-1}$ reactor flux dependence. The transmission experiments were carried out at ORELA in May 1973.

## b) Experiments

The program of investigating the 24 keV capture spectra was continued and the spectra of $\mathrm{U}^{238}, \mathrm{~W}^{182}, \mathrm{~W}^{186}$, Co, $\mathrm{Ba}^{135}$, Mn, Fe, Th and Mo were investigated. Some of the results of these investigations are discussed in the following:

1. $\mathrm{Co}^{59}(\mathrm{n}, \gamma) \mathrm{Co}^{60}$

The 24 keV spectrum for $\mathrm{Co}^{59}(\mathrm{n}, \gamma) \mathrm{Co}^{60}$ is shown in Fig. A-2-2. Five resonances are expected to contribute to the capture. These are the resonances at $19.75,21.95,22.51,24.46$ and 25.16 keV . Thus the spectrum represents an average over these resonances. Since the level density is low in this region it is possible to determine which of these resonances contributes strongly to a certain transition from the shift of the gamma peak center relative to that of the gamma ray following thermal neutron capture. Figure A-2-3 shows the transitions to the $5^{+}$ground state, the $2^{+}$state at 58 keV and the $\left(3^{+}\right)$state at 1006 keV . The position of the peak in thermal capture is taken as the zero of the energy scale in each case. The different shifts in the position of the peaks indicates capture in differing resonances. The transition to the ground state is seen to be shifted by $20.2 \pm 0.5 \mathrm{keV}$. The three resonances that may contribute to this transition are the $19.75,21.95$ and 22.51 keV . The latter two have spin 3 and thus are not expected to contribute significantly to this transition. This indicates that the transition is predominantly due to capture in the 19.75 keV level implying a spin 4 for this resonance.

[^9]

Fig. A-2-1


Fig. A-2-2

COUNTS PER CHANNEL



2. $\underline{U}^{238}(n, y) U^{239}$

The high level density in $U^{238}$ leads to a spectrum averaged over several hundred resonances washing out the PorterThomas fluctuations. Both s-wave and p-wave capture contribute to the spectrum.

Figure A-2-4 shows the gamma spectrum obtained. The partial capture cross sections were determined for the individual transitions from this spectrum using the reaction $B 10(n, \alpha \gamma)$ as a standard.

The average partial capture cross sections divided by $\mathrm{E}_{\mathrm{Y}}{ }^{3}$ are shown as a function of $\mathrm{E} Y$ in Fig. A-2-5. The four high energy transitions populate positive parity states and thus are populated by El transitions from p-wave resonances. Spin 5/2+ low lying states are populated only by $3 / 2^{-}$resonances while states with spin $1 / 2$ or $3 / 2$ are reached by both $1 / 2^{ \pm}$and $3 / 2$ resonances via dipole transitions. This leads to smaller cross sections for the $5 / 2^{+}$states as seen in figure. The fact that both negative and positive parity final states have nearly equal cross sections shows that the amount of p-wave capture is nearly equal to the amount of s-wave capture at 25 keV .

The solid lines represent an $E_{\gamma}{ }^{5}$ energy dependence for E1 and M1 strength functions. The photon strength function is seen to be consistent with an $E \gamma^{5}$ dependence as predicted by the tail of the giant dipole resonance.

COUNTS PER CHANNEL

yGgNan TGNNVHO




Fig. A-2-5

## 3. ${\underline{ }{ }^{135} \mathrm{Ba}(\mathrm{n}, \mathrm{y})^{136} \mathrm{Ba}^{*} \text { * }}^{\text {a }}$

The results of an investigation of a possible anomaly in the strength of M1 decay of ${ }^{135} \mathrm{Ba}(\mathrm{n}, \gamma)^{136} \mathrm{Ba}$ resonance capture were described in the Apri1 1973 report to the USNDC. This investigation has been pursued for 24 keV neutron capture where the filtered neutron beam overlaps about 40 s -wave and 80 p-wave resonances. Figure A-2-6 shows the gamma-ray spectrum obtained in this experiment. The intensities for observed transitions to states below 2.6 MeV in ${ }^{136} \mathrm{Ba}$ are given in Table A-2-1. An upper limit for the M-1 strength function of $(15 \pm 4.5) \times 10^{-9} \mathrm{MeV}^{-3}$ is deduced from these data when the contribution of $p$-wave capture is ignored. The p-wave capture contribution to these transitions is known to be small, because transitions to $4^{+}$levels at 1866 and 2053 keV are not observed; these levels would be populated by $E 1$ transitions from $3^{-}$states formed in p-wave capture. This value is consistent with the observed average M-1 strength for all nuclei.

Furthermore, as seen from the table, there is no indication of enhancement for the ground state transition. Thus the enhancement of the ground state transition appears to be limited to the case of the 24 eV resonance. That this enhancement is due to Porter-Thomas fluctuations rather than the existence of a nonstatistical effect seems to be implied by these data.

## 4. Capture Cross Sections

Several capture cross sections at 24 keV have been measured by comparing the induced activity after irradiation with a flux monitor based on the $10_{B}(n, \alpha \gamma)$ reaction, using the ENDF-B-III values for ${ }^{10} \mathrm{~B}(\mathrm{n}, \alpha \gamma)$. Preliminary numbers have been obtained for ${ }^{238} \mathrm{U} \sigma(\mathrm{n}, \gamma)$ by observing the 228 and $278 \mathrm{keV} \gamma$-rays from ${ }^{239} \mathrm{~Np}$ decay and for the $411 \mathrm{keV} \gamma$-ray following ${ }^{198} \mathrm{Au}$ decay. These values are 238U: 424 mb ; ${ }^{197} \mathrm{Au} 702 \mathrm{mb}$. A more careful analysis, including the effect of energy degraded neutrons on the samples, is in process and may modify the above results somewhat. An error analysis is also in progress.

[^10]

Fig. A-2-6

Table A-2-1
Gamma ray intensities from the reaction ${ }^{135} \mathrm{Ba}(\mathrm{n}, \gamma){ }^{136} \mathrm{Ba}$ for $E_{n}=24 \mathrm{keV}$.

|  | $E_{\gamma} g . s .=9120 \mathrm{keV}$ |  |
| :---: | :---: | :---: |
| $\mathrm{E}_{\text {exc }} \mathrm{keV}$ | $\mathrm{J}^{\pi}$ | Intensity <br> Photons $/ 100 \mathrm{n}$ |
| $\mathrm{g.s}$. | $0^{+}$ | $0.54 \pm 0.09$ |
| 817.1 | $2^{+}$ | $1.02 \pm 0.14$ |
| 1549.0 | $\left(2^{+}\right)$ | $0.55 \pm 0.11$ |
| 1575.7 | $\left(0^{+}\right)$ | $0.11 \pm 0.09$ |
| 2080.5 | $(1,2)$ | $0.44 \pm 0.07$ |
| 2127.7 | $(1,2)$ | $0.55 \pm 0.14$ |
| 2219.8 |  | $0.51 \pm 0.09$ |
| $* 2376.8$ |  | $1.43 \pm 0.29$ |
| 2392.2 |  | $1.25 \pm 0.26$ |
| 2533.6 |  | $0.19 \pm 0.07$ |

* 

This transition has not been observed in resonance capture for resonances below 500 eV . However, it has not been possible to identify it with any reasonable background line, it thus is included in the table with this questionable status.

## B. NUCLEAR STRUCTURE

1. Study of Low Spin States in ${ }^{200} \mathrm{Hg}$ (D. Breitig, R. F. Casten

The study of the implications of the ${ }^{200} \mathrm{Hg}$ level scheme deduced earlier has continued and revealed several new points of interest. The level scheme itself accommodates nearly all of the $\gamma$-ray intensity below 3 MeV observed in ( $\mathrm{n}, \gamma$ ) studies and includes $\sim 60$ levels up to 3.3 MeV .

The discovery of a new $0^{+}$state at 1515 keV and the measurement of several new branching ratios has led to a significantly greater degree of agreement between the data and the core coupling calculations of Corvello and Sartoris. Most of the predicted branching ratios are closer to experimental values than was the case when different levels were earlier chosen as candidates for the model states.

The $0^{+}$state at 1029 keV is now seen to be an "extra" $0^{+}$ state not accounted for by the model. It is possible, but only a possibility at present, that it corresponds to a predicted low lying bubble configuration characterized by a reduced central nuclear density. In this regard it is important to map the locations of $0^{+}$levels in neighboring nuclei (see next entry).

The four $1^{-}$levels deduced earlier are now thought to be understood most simply in terms of oblate deformations involving the unique parity $v_{i 13 / 2}$ or $\pi h 11 / 2$ orbits in the form of simple two-quasiparticle, collective octupole or core coupled ( $5^{-} \times 4^{+}$) excitations. This represents an extension and confirmation of the earlier suggestion of oblate shape components of odd nuclei in this region from study of spin isomers.

Finally, a relatively new technique, that of population systematics for spin assignments, has been studied and found to be extremely useful up to an excitation energy of $\sim 2 \mathrm{MeV}$ (see next entry as well).
2. Study of Low Spin States in ${ }^{202} \mathrm{Hg}$ (R. F. Casten, D. Breitig, W. R. Kane and G. Cole)

This study is an outgrowth of the ${ }^{200} \mathrm{Hg}$ investigation, in particular to search for low lying $0^{+}$states and to compare core coupling calculations with the resulting data. An extensive level scheme, consisting almost entirely of new levels, transitions and spin assignments is shown in Fig. B-1. It was deduced from $\gamma$-ray data taken following thermal and resonant neutron capture and includes measurement of primary and secondary radiation, $\gamma-\gamma$ coincidences and angular correlations.

An important tool in making some of the spin assignments was the use of population systematics. These are illustrated for ${ }^{202} \mathrm{Hg}$ in Fig. B-2. Shown are the relative level populations, excluding feeding by primary transitions, as a function of excitation energy. Levels with spins 1,2 deduced without using such population arguments are plotted as open points. Other levels are represented by solid dots. Four of these are a factor of 3-4 below the upper group and are considered therefore to have $J=0, \geq 3$. Combining this new information from our level scheme (primary feeding, deexcitation transitions, $\gamma-\gamma$ coincidences and angular correlations) and with some $\beta$ decay data gives the $\mathrm{J}^{\Pi}$ assignments in Fig. B-1 for the levels at 1119.8, 1311.5, $1562.1,1564.7,1575.6$ and 1643 keV .

Two principal features emerge from the level scheme. First, the distribution in energy of levels in ${ }^{202} \mathrm{Hg}$ differs considerably from that in 200 Hg . The lowest $0^{+}$state is at 1564.7 keV , over 500 keV higher than in ${ }^{200} \mathrm{Hg}$ but close to the $1515 \mathrm{keV} 0^{+}$level in that nucleus. Its preference for decay only to the first $2^{+}$state is also similar to the decay routes for the 1515 keV level. Thus the 1029 keV leve 1 in 200 Hg remains anomalous with no apparent counterpart in ${ }^{202} \mathrm{Hg}$ (see previous entry). The other low spin states in ${ }^{202} \mathrm{Hg}(\mathrm{J}=1,2,3)$ occur several hundred keV lower than their counterparts in ${ }^{200} \mathrm{Hg}$. This behavior is not understood but is probably related to the second feature of interest in 202 Hg . The latter is that the core coupling model, as extrapolated from calculations for $198,200 \mathrm{Hg}$, fails completely in ${ }^{202} \mathrm{Hg}$. There is no state above the first excited state that has a reasonable energy or decay routes and intensities to be a candidate for the core coupled states. Many measured branching ratios from levels tested differ by an order of magnitude or more from the predicted values. There is apparently a significant change in the nuclear structure of the low lying levels between 200 Hg and ${ }^{202} \mathrm{Hg}$.


3. Study of the ${ }^{186}{ }_{W}\left(\mathrm{n}, \mathrm{Y}^{187}{ }^{18}\right.$ W Reaction at 24 keV and the Breakdown of the Nilsson Model (R. F. Casten, D. Breitig, O. A. Wasson, K. Rimawi and R. E. Chrien)

The ( $n, \gamma$ ) reaction at thermal and 24 keV neutron energies was performed on ${ }^{186} \mathrm{~W}$. The purpose was to assign $1 / 2^{-}$or $3 / 2^{-}$spins to levels in ${ }^{187} \mathrm{~W}$ in the $700-1600 \mathrm{keV}$ excitation energy region and thereby to map out the fragmentation of single particle strength in the Nilsson model and the distribution of strength as observed in the (d, p) reaction. This study follows a related one dealing with $179 \mathrm{Hf}, 183,184_{\mathrm{W}}$, and establishes some surprising systematics in the fragmentation. The spectroscopic results were obtained by combining the present results with earlier data. They comprise the assignment of $201 / 2^{-}$or $3 / 2^{-}$ spins between 700 and 1600 keV of which 13 are for levels populated in ( $d, p$ ). This implies the existence of a minimum of 10 low $K$ negative parity rotational bands and at least 7 that have single particle strength. The Nilsson model predicts only four or five of the former and two of the latter. These results are similar to those obtained for ${ }^{179} \mathrm{He}$ and $183,184 \mathrm{~W}$. However, an interesting difference emerges when the summed experimental and theoretical ( $\mathrm{d}, \mathrm{p}$ ) cross sections are compared. The results, in several forms, are summarized in Table B-1 where the footnotes interpret the entries. The main conclusion is that despite the severe fragmentation in all these nuclei nearly all the calculated single particle strength is in fact observed in ${ }^{179} \mathrm{Hf}$ (and also in $177,181_{\mathrm{Hf}}$ from other studies) and in 187 W . However, in $183,184_{\mathrm{W}}$ only a fraction of the strength is found: this fraction is $\sim 60 \%$ in the former and $18-32 \%$ in the latter.

The fragmentation of Nilsson model strength is not predicted by existing calculations, including those including extensive phononparticle coupling. Nor, given the fragmentation, do such calculations account for any marked behavior in the systematics such as is observed. It is possible, but not in the least proved as yet, that both features of the data may be partially explained by enhanced $\Delta N=2$ mixing resulting from the much larger than expected (recently measured) $\beta 4$ shape components near ${ }^{182} \mathrm{~W}$. If the speculation is correct, the same shape components may be important in the interpretation of recent anomalies in the neutron transfers cross sections and in the understanding of backbending phenomena in this mass region.

Table B-1
Distribution, Fragmentation of Nilsson Strength

|  |  | $\mathrm{N}_{-}(\mathrm{d}, \mathrm{p})^{\mathrm{b}}$ | Experimental Cross Sections |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | $\begin{gathered} \operatorname{Max} \sigma \\ (\mu \mathrm{b} / \mathrm{sr}) \end{gathered}$ | $\sum \sigma(n, \gamma), \ell=1$ |  | $\sum_{\ell \neq 3}^{\mathrm{e}}$ |  |
|  |  |  |  | $\sigma \geq 100 \mu \mathrm{~b} / \mathrm{sr}^{\mathrm{c}}$ | a11 $\sigma^{\text {d }}$ |  |  |
| ${ }^{179} \mathrm{Hf}$ | 12 | 9 | $\sim 446$ | 997 | 1440 | 1617 | 1886 |
| 183 W | 9 | 7 | 232 | 585 | 1036 | 1095 | 1848 |
| 184 W | -- | - | 123 | 123 | $<653$ | $<866$ | 2087 |
| ${ }^{185}$ W | -- | - | 391 | 1025 | -- | 1517 | 1800 |
| $187_{W}$ | 11 | 6 | 336 | 1437 | 1656 | 2104 | 1800 |

${ }^{\text {a }}$ Lower limit on number of negative parity rotational bands. Covers energy regions: $1400-2200 \mathrm{keV}$ in ${ }^{179} \mathrm{Hf}$ and $183_{\mathrm{W}}$, and $700-1600$ in $187_{\mathrm{W}}$.
${ }^{\mathrm{b}}$ Same as a) except applies to negative parity bands observed in ( $\mathrm{d}, \mathrm{p}$ ) as well.
${ }^{\text {c }}$ Sum of ( $\mathrm{d}, \mathrm{p}$ ) cross section larger than $100 \mu \mathrm{~b} / \mathrm{sr}$ at $\theta_{\mathrm{L}}=90^{\circ}$, Q -reduced to +3.0 MeV , for states assigned from the ( $n, \gamma$ ) reaction studies as low spin negative parity levels $\left(1 / 2^{-}, 3 / 2^{-}\right.$for odd nuclei, $\mathrm{J} \leq 2$ for $\left.{ }^{184} \mathrm{~W}\right)$. Includes a few states not assigned in ( $n, \gamma$ ) but with ( $d, p$ ) angular distributions suggesting these spin limitations.
d Same as c) except not restricted to large cross sections. Entry for ${ }^{184} \mathrm{~W}$ is upper limit since it includes the described sum of cross sections for states from 1400-2300 keV but also the sum of all cross sections from $2300-2700 \mathrm{keV}$.
e Same as d) except includes all ( $d, p$ ) transitions not definitely ascribable to $\ell_{n} \geq 3$. Included because the entry described under d) for 185 W is not available.
f Summed theoretical cross section from Nilsson model with pairing included.

## C. NATIONAL NEUTRON CROSS SECTION CENTER

Two NNCSC representatives were aided by IAEA funds to attend a 4 Center meeting held in Moscow in June. Substantial progress was made in several areas that included more uniform methods of reporting center statistics, agreement on an input format for the worldwide request list WRENDA, and generalization of EXFOR to include additional data types and multidimensional tables. A problem common to all the centers has been the unavailability of published and other known data sets because the center was unable to obtain the results from the measurer. The NNCSC has over thirty such cases. A few cases have been pursued for over a year. In some instances funding reductions have caused difficulties in the transmission of data.

NNCSC preparation for Volume 1 of BNL 325 containing recommended resonance parameters and thermal cross sections has been completed. Printing and distribution of the book is expected by the end of 1973.

The present concern of CSEWG is development of Version IV of the Evaluated Nuclear Data File (ENDF/B) due for release in early 1974. In ENDF/B-IV the general purpose file will contain data for over 100 materials, the dosimetry file will contain 32 materials, the scattering-law file 10 materials, and the fission product file several hundred nuclides. Special attention has been give to data sets for shielding applications. Over 30 materials will have gamma-production data files that are consistent with the neutron data portion of the file. In addition there are photon-interaction data for all materials. Some of the thermal cross sections will be changed in ENDF/B-IV. For some elements error files will be included.

Statistics for data requested from the NNCSC during the year ending June 30, 1973 are presented in Tables C-1 and C-2. The requests for evaluated data outnumber requests for experimental data. Magnetic tapes are a favored retrieval mode indicating that many requesters are prepared to process the data by computer.
Table C-1
CSISRS Request Statistics
July 1, 1972 - June 30, 1973
Requests for Experimental Data (CSISRS):

1. Requests
a) received ..... 151
b) answered ..... 148
c) number of data sets sent ..... 17,232
d) number of data records sent ..... $1,473,788$
2. Origin of Request
a) Government Agencies ..... 4
b) Educational Institutions ..... 37
c) Industry ..... 30
d) Four-Center (other than format EXFOR) 7
e) National Laboratories ..... 40
f) Internal (NNCSC staff) ..... 33
Total ..... 151
3. Mode of Request
a) Magnetic tapes, varied formats ..... 76
b) Computer 1istings ..... 72
c) P1ots ..... 1,403d) Other
Table C-2
ENDF Request Statistics
July 1, 1972 - June 30, 1973
4. Requests
a) Number of requests ..... 184
5. Origin of Request
a) CSEWG Members (other than ENDF/B, ..... 86i.e., ENDF/A, Doppler broadeneddata, etc.
b) Government Agency ..... 13
c) Educational Institution ..... 30
d) Industry (other than CSEWG) ..... 42
e) Foreign Exchange ..... 13
6. Mode of Request (may be more than 1 per request)
a) Magnetic Tapes ..... 98
b) Computer Listings ..... 51
c) Cards ..... 5
d) Plots ..... 11
e) Other ..... 54

## COLUMBIA UNIVERSITY

## A. NEUTRON SPECTROSCOPY

1. Neutron Resonance Spectroscopy XIV: Potassium, (U. N. Singh, H. I. Liou, G. Hacken, M. Slagowitz, F. Rahn, J. Rainwater, W. Makofske, J. B. Garg)

High resolution transmission measurements using pure natural K metal samples have been completed. The measured total $\sigma$ vs $E$ to 400 keV is given, and resonance parameter evaluations are given for 65 resonances below 200 keV . The isotope assignments, $A=39$ or 41 , are mainly based on recent unpublished measurements of Good and Harvey at ORELA using separated $K$ isotope samples. Values of level strengths, ag ${ }^{n}$, are mainly based on transmission dip area analysis, which with evidence from the resonance shape and peak cross sections permits assignment of $\ell$ and $J$ for most resonances, and $A$ for many of the resonances not identified in the separated isotope measurements: We obtain for the $s$ and $p$ strength functions:

$$
\begin{aligned}
& 10^{4} s_{0}=\left(0.66_{-0.30}^{+0.63}\right),\left(0.78_{-0.41}^{+1.08}\right) \text {, and } 10^{4} S_{1}= \\
& \left(1 . 8 _ { - 0 . 5 } ^ { + 0 . 7 } \text { ) and } \left(2.4_{-0.8}^{+1.3}-\text { for }^{39} \mathrm{~K} \text { and }{ }^{41^{2}} \mathrm{~K}\right.\right. \text {, respectively. }
\end{aligned}
$$

2. Fission Measurements at ORELA, (J. Felvinci \& E. Melkonian)

Because the startup of the improved Nevis synchrocyclotron has been delayed, it was suggested that use be made of the LINAC at Oak Ridge. An exploratory run at ORELA was carried out in June, 1973. Our data-acquisition equipment, as used in the 1968 Nevis run, was transported to ORELA so that both the neutron time-of-flight and the energy of one fission fragment could be recorded event-by-event. Only 20 hrs of good running time on 233 Th and 235 Th were achieved, but demonstrated that the intensity . was adequate for our pur oses and that the background to the fission yield was considerable lower than at Nevis.

At this time (November) our equipment is again at ORELA for a several week run. Measurements will be made on $229 \mathrm{Th},{ }^{233} \mathrm{Th}, 235 \mathrm{Th}$ and 239 Pu . The flux dependence upon energy will be determined with a thin deposit of boron viewed by a surface barrier detector in vacuum.

INTELCOM RAD TECH<br>San Diego, California

## A. NEUTRON CROSS SECTIONS

1. Measurements of the ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha) \mathrm{T}$ and the ${ }^{10} \mathrm{~B}\left(\mathrm{n}, \alpha, \alpha_{0}\right){ }^{7} \mathrm{Li}$ Cross Sections for Neutron Energies from 1 to 1500 keV . (S. J. Friesenhahn)

The ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha) \mathrm{T}$ and ${ }^{10^{0}} \mathrm{~B}\left(\mathrm{n}, \alpha, \alpha_{0}\right)^{7} \mathrm{Li}$ cross sections have been measured between 1 and 1500 keV neutron energy relative to the hydrogen scattering cross section. The present measurements were performed in a large parallel plate ion chamber using self-supporting films in the case of 10 B and evaporated metal deposits in the case of ${ }^{6} \mathrm{Li}$. The present results for $l^{0} \mathrm{~B}$ are in good agreement with previous measurements ${ }^{(1)}$ employing a $\mathrm{BF}_{3}$ detector at this laboratory, but are in dis agreement for neutron energies above $\sim 100 \mathrm{heV}$ with the previous ion chamber results. This discrepancy is apparently due to dead time losses in the previous ion chamber data. The possibility for dead time correction errors have been eliminated in the present data by use of a tagged test pulse which was random in time and which was recorded with the data.

The data analysis for the ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha) \mathrm{T}$ cross section is complete with the exception of the ion chamber response function calculations which are currently in progress. (This work pertinent to request Nos. 18 and 53 in USNDC-6).
2. Measurement of the Continuum Gamma Ray Production Cross Sections for Iron (V. Rogers, C. Hoot and V. Orphan)

The unfolding of previously measured gamma-ray spectra from ( $n, x y$ ) reactions in iron ${ }^{2}$ was corrected for gamma-ray energy degradation in the sample to obtain corrected continum plus discrete-line cross sections. The net effect was to reduce the magnitude of the low gamma energy continuum component, so that the total gamma-ray production

[^11]cross section was reduced by about $5 \%$. The resulting cross sections are listed in Table A-l.
3. Measurement of Gamma-Ray Production Cross Sections for Carbon and Nitrogen (V. Rogers, C. Hoot, V. Verbinski, and V. Orphan)

Measurements of gamma-ray production cross sections for carbon and nitrogen have been continued since the last USNDC report. Table A-2 lists the preliminary experimental values of $\sigma$ ( $n, n^{\prime} \gamma$ ) for the 4. 44 MeV gamma-ray from carbon. High-neutron-energy resolution cross sections have also been obtained for the same gamma ray. The measured cross sections are consistent with other available data.(3)

Final analysis of the discrete and the continuum components of the nitrogen ( $n, x y$ ) cross sections is in progress.

The Ge(Li) spectral response to neutrons was examined further, and a complete response matrix was obtained which included the response functions for neutron energies less than 6 MeV . The additional measurements for $E_{n}<6 \mathrm{MeV}$ yielded spectra which are somewhat dependent upon neutron energy. (This work pertinent to request Nos. 59 and 68 in USNDC-6).

## B. IN TEGR AL EXPER IMENTS

1. Integral Measurements to Test Neutron Scattering and $\gamma$-Ray Production Cross Sections of $\mathrm{Be}, \mathrm{C}, \mathrm{N}, \mathrm{O}$ and Fe (L. Harris, Jr., J.C. Young, D.K. Steinman, L. Schānzler, P. A. Read, W.E. Gober)

Data reduction for the $C$ and $N$ measurements reported earlier has continued. Measurements were made to obtain more accurate $\gamma$-ray efficiencies for the 2 in . x 2 in . NE-2l3 detector. Measured $\gamma$-ray response functions are being parameterized in order to generate a $\gamma$-ray
$\overline{(3)}$ G. L. Morgan, T. A. Lave, J. K. Dickens and F.G. Perey, "GammaRay Production Cross Section of Tantalum and Carbon for Incident Neutron Energies Between 0.007 and $20 \mathrm{MeV}^{\prime \prime}$, Oak Ridge National Laboratory Report ORNL-TM-3702. (February 1972).

Table A-1
$\operatorname{IRON} \sigma(\mathrm{n}, \mathrm{xy})$ AT $125^{\circ}(\mathrm{mb} / \mathrm{sr})$

| $\begin{gathered} E_{Y} \\ (\mathrm{keV}) \end{gathered}$ | NEUTRON ENERGY (MeV) |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0.085 | 1.3- | 2.1- | 3.0 | 4.1. | 5.1 - | 6.15 . | 7.71. | 9.78. | 12.56-16.74 |
| 708 .946 | 41.7 | 69.7 | 85.0 | 97.4 | 89.4 | 96.9 | 90.1 | 86.3 | 82.1 | 58.8 |
| $\therefore 1185$ |  |  |  | 2.1 | 12.0 | 19.7 | 19.6 | 17.1 | 16.6 | 15.6 |
| -1424 |  | 1.2 | 10.1 | 25.7 | 31.4 | 48.3 | 58.2 | 65.9 | 76.1 | 64.1 |
| -1663 |  | 0.8 | 0.3 | 3.8 | 8.4 | 13.3 | 16.8 | 19.4 | 21.6 | 18.8 |
| -1902 |  | 0 | 1.0 | 1.0.9 | 14.5 | 16.8 | 19.9 | 16.2 | 17.1 | 16.1 |
| -2141 |  | 0.1 | 0.1 | 15.2 | 12.9 | 14.8 | 20.9 | 22.9 | 23.8 | 18.9 |
| -2380 |  |  |  | 1.2 | 6.5 | 8.0 | 8.7 | 6.8 | 10.1 | 6.4 |
| -2619 |  |  |  | 3.9 | 8.0 | 6.4 | 10.6 | 12.8 | 13.9 | 8.0 |
| -2858 |  |  |  | 2.1 | 6. 7 | 7.9 | 11.2 | 11.7 | 11.9 | 12.1 |
| -3097 |  |  |  | 0.0 | 4.7 | 6.2 | 5.4 | 5.6 | 8. 0 | 4.2 |
| -3336 |  |  |  | 0.3 | 2.1 | 3.4 | 5.5 | 5.6 | 5.5 | 4.7 |
| -3575 |  |  |  | 1.4 | 2.9 | 4.6 | 6.3 | 8.9 | 11.2 | 8.0 |
| -3814 |  |  |  | 0.6 | 6.9 | 7.6 | 6.9 | 8.0 | 8.0 | 6.0 |
| -4053 |  |  |  |  | 1.0 | 3.6 | 5.7 | 5.3 | 6.5 | 3.4 |
| -4291 |  |  |  |  | 0.1 | 1.4 | 2.9 | 3.0 | 3.8 | 3.3 |
| -4530 |  |  |  |  | 0.1 | 1.1 | 1.6 | 2.1 | 3.7 | 2.6 |
| -4769 |  |  |  |  | 0.2 | 0.6 | 1.6 | 1.6 | 3.9 | 3.1 |
| -5008 |  |  |  |  |  | 0.1 | 1.3 | 1.7 | 2.1 | 1.9 |
| -5247 |  |  |  |  |  |  | 1.1 | 2.1 | 4.0 | 2.8 |
| -5486 |  |  |  |  |  |  | 1.1 | 1.8 | 3.0 | 1.8 |
| -5725 |  |  |  |  |  |  | 1.2 | 1.6 | 4.0 | 3.9 |
| -5964 |  |  |  |  |  |  | 0.9 | 1.9 | 2.6 | 2.3 |
| -6203 |  |  |  |  |  |  | 0.5 | 1.6 | 2.8 | 2.9 |
| -6442 |  |  |  |  |  |  | 0.1 | 1.8 | 3.0 | 1.4 |
| -6681 |  |  |  |  |  |  |  | 1.1 | 3.9 | 3.4 |
| -6920 |  |  |  |  |  |  |  | 1.5 | 2.7 | 2.5 |
| -7159 |  |  |  |  |  |  |  | 0.7 | 2.3 | 2.2 |
| -7398 |  |  |  |  |  |  |  | 0.6 | 1.7 | 1.0 |
| -7637 |  |  |  |  |  |  |  | 0.8 | 0.6 | 1.1 |
| -7875 |  |  |  |  |  |  |  | 0.8 | 0.6 | 0.9 |
| total | 41.7 | 71.8 | 96.5 | 164.6 | 207.8 | 260.7 | 298.1 | 317.2 | 358.1 | 282.2 |
| LINES | 44.3 | 68.4 | 97.8 | 143.3 | 167.7 | 186.8 | 175.2 | 158.0 | 147.2 | 106.1 |
| CONTIN. | 0 | 0 | 0 | 21.3 | 40.1 | 73.9 | 122.9 | 159.2 | 210.9 | 176.1 |
| \% CONT. | 0 | 0 | 0 | 12.9\% | 19.3\% | 28.3\% | 41. $2 \%$ | 50.2\% | 58.9\% | 62.4\% |

Table A-2.
CARBON $\sigma\left(n, n^{\prime} \gamma\right)$ FOR $4.44 \mathrm{MeV} \gamma-$ RAY AT $125^{\circ}$

| $\operatorname{En}(\mathrm{MeV})$ | $\frac{\sigma\left(\mathrm{n}, \mathrm{n}^{\prime} \gamma\right)(\mathrm{mb} / \mathrm{sr})}{}$ |
| :---: | :---: |
| $4.8-5.0$ | 12.0 |
| -6.0 | 16.9 |
| -7.0 | 23.0 |
| -8.0 | 19.2 |
| -9.0 | 23.2 |
| -10.0 | 23.3 |
| -12.0 | 15.3 |
| -14.0 | 7.5 |
| -17.0 | 5.4 |
| -20.0 |  |

response matrix. As soon as this response matrix is tested for unfolding $Y-r a y$ energy spectra, the energy spectra of the secondary $\gamma$-rays from the small liquid nitrogen sample will be unfolded. Secondary $\gamma$-ray energy spectra will be obtained for a number of incident-neutron energy intervals between l. 5 to 15 MeV similar to those used for scattered neutron spectra.

Measurements of incident-neutron dependent count rates due to scattered neutrons and secondary $\gamma$-rays were made at angles of 30 , 55 , 90 and 125 degrees for small samples of $\mathrm{Be}, \mathrm{H}_{2} \mathrm{O}$ and Fe . In addition, energy spectra of scattered neutrons and secondary $\gamma$-rays at 125 degrees were measured for the $\mathrm{H}_{2} \mathrm{O}$ and Fe samples. Data reduction for these measurements is in progress.
2. Integral Concrete and Steel Shielding Experiment (L. Harris, Jr., J. C. Young, D. K. Steinman, L. Schänzler, and W.E. Gober)

A new integral shielding experiment, involving fast-neutron and secondary gamma-ray transport through a thick concrete and steel shield, has been planned and will be performed during the next few months. The geometry for this experiment is shown in Figure B-1.The experiment will be like the 1969 Concrete Shielding Experiment ${ }^{(1,2)}$ with the following differences:
a. Measurements will be made for a single thickness (34.8 in.) of alternating concrete slabs and steel plates. The same 4-in. thick concrete slabs used in 1969 will be used again. The water content will be remeasured to correct for water losses since 1969.
b. 3/16-in. -thick steel plates will be distributed between the concrete slabs as shown in Figure B-2. The resulting shield configuration is 20 wt . per cent steel. Equal thickness plates are used in order to obtain them from the same heat and thus obtain uniform composition from plate-to-plate.
c. The lead detector shield used for the 1969 measurements will not be used in order to simplify the geometry.
d. Detector positions will be at a single distance ( 6 in.) behind the last steel plate in order to reduce the coupling between detector and shield.
e. A ${ }^{3}$ He gas proportional counter (with and without cadmium cover) will be used for thermal neutron measurements.
f. The following measurements will be made on the neutron flight path axis: (l) time-dependent count rates and energy spectra of leakage fast neutrons and secondary gamma rays detected using an NE-213 scintillator ( 2 -in. diameter by 2 in. length) and (2) timedependent count rates for thermal neutrons detected using the ${ }^{3} \mathrm{He}$ gas proportional counter ( $2-\mathrm{in}$. diameter by $6-\mathrm{in}$. length, 4 atmospheres gas pressure).

[^12]

RT-01381C

Figure B-l.Geometry for Concrete and Steel Shielding Experiment


Figure B-2. Concrete and Steel Shield
g. At several positions above and below the neutron flight path axis, the two detectors will be used to measure integral counts due to fast neutrons, ( $n, x y$ ) photons, ( $n, \gamma$ ) photons and thermal neutrons, and thus provide four vertical spatial profiles behind the concrete and steel shield. These profiles will provide experimental data for estimating the influence of the floor on the centerline measurements, and hence indicate if the floor needs to be included in the calculational model for the experiment.
3. Integral Missile Shielding Experiment (L. Harris, Jr., J. C. Young, D.K. Steinman, and W.E. Gober)

Another new integral shielding experiment, this one involving neutron and secondary gamma-ray transport through a missile guidance section, is underway. Attention will be focused on measuring neutronand secondary gamma ray-induced silicon dose at locations inside the missile as a function of incident neutron energies from 1 eV to 20 MeV . In addition, energy spectra of fast neutrons and secondary gamma rays leaking from the missile guidance section will be measured for the same range of incident neutron energies.

## LAWRENCE LIVERMORE LABORATORY

## A. STANDARDS

1. ${ }^{235} \mathrm{U}$ Fission Cross-Section Measurements. (J. B. Czirr and G. S. Sidhu) Relevant to Requests 439, 440, 441 and 442).

A measurement of the ${ }^{235} \mathrm{U}$ fission cross section is in progress at the LLL linac with preliminary data available in the $3-$ to $20-\mathrm{MeV}$ energy range. The fission rate is measured relative to the ( $n, p$ ) scattering cross section using an annular polyethylene radiator and a Li-drifted-Si proton detector. The telescope background measuned with a matching graphite foil arises primarily from the $C(n, \alpha)$ reaction. It is planned to complete data collection for the above energy range shortly.
2. Fission $\bar{V}$ Measurements. (R. E. Howe, T. W. Phillips, and C. D. Bowman*) Relevant to Requests 447 and 503.

Utilizing recent improvements in our electronics and in background conditions, we have measured $\bar{v}$ for 235 U neutron-induced fission in the energy range: $0.5 \mathrm{eV} \leq \mathrm{E}_{\mathrm{n}} \leq 125 \mathrm{eV}$. Fast, spectrum-independent neutron detection was accomplished with the system previously described. 1

Preliminary results of the measurements are shown in Figure A-l. These compare fairly well with recent data from RPI2 and from Saclay. 3 With statistical uncertainties of less than 0.5 percent for many of the resonances in our data, it is possible to make arguments for the presence of some energy-dependent structure for $\bar{v}$ in the resonance region. The 57 data points shown in Figure A-1 have an overall reduced $\chi^{2}$ of 1.41 . Restricting ourselves to the 16 data points with fractional errors less than $0.3 \%$, we find a reduced $\chi^{2}$ of 1.93 . Analysis is currently underway to verify that this structure is not due to any systematic effects related to background events or electronic deadtime corrections.

Using the resonance_spin assignments of Keyworth, ${ }^{4}$ we find an overall difference of $\Delta \nu=\bar{\nu}\left(4^{-}\right)-\bar{v}\left(3^{-}\right)=+0.205 \pm 0.119 \%$ between the
*National Bureau of Standards, Washington, D.C.
$1_{\text {NCSAC }}$ Report, dated 10 November 1971, UCID-15937.
${ }^{2}$ Linear Accelerator Project Progress Report (Oct. 1-Dec. 31, 1972), Rensselaer Polytechnic Institute.
${ }^{3}$ J. Frehaut and D. Shackelton, IAEA-SM-174/47, Third International Conference on the Physics and Chemistry of Fission, Rochester, N.Y. (1973).
${ }^{4}$ G. A. Keyworth et al., Los Alamos Scientific Lab. Rept. No. LA-UR-73-1077 ( $\overline{19} 7 \overline{3}$ ).
respective means of all resonances with spin $4^{-}$and those with spin $3^{-}$. While on the surface this seems to imply some slight spin dependence in $\bar{v}$, these resonances have a reduced $\chi^{2}$ of 1.79 about their common mean. Also, the $J=4$ resonances at 8.79 eV and 19.3 eV are separated by $0.70 \pm 0.18 \%$, which drastically over-shadows the $\Delta \bar{v}$ for resonances of different spin states.

Future plans include completion of $\bar{v}$ measurements for ${ }^{235} \mathrm{U}$ from thermal energy up to 15 MeV , and similar measurements for 239 Pu .

## B. NEUTRON DATA APPLICATIONS

1. Measunement of the $233 \mathrm{u}, 234 \mathrm{U}, 235 \mathrm{u}, 236 \mathrm{U}, 238 \mathrm{u}, 239 \mathrm{pu},{ }^{240 \mathrm{Pu}}$, 241 Pu , and 242 Pu Fission Cross Sections Relative to Various Flux Monitors from Thermal to 15 MeV . (J. W. Behrens) Relevant to Requests $414,501,517,526$, and 527.

Fission cross section measurements for a wide collection of uranium and plutonium isotopes are presently being made at LLL using the $100-\mathrm{MeV}$ Electron Linear Accelerator as a pulsed source for neutrons. The fission cross sections relative to the appropriate flux monitors can be measured as a function of neutron energy from thermal to 15 MeV using the time-of-flight technique. Fission ionization chambers are located at the 34 -meter T.O.F. station on our 250 -meter T.O.F. tube with flux monitors located at both the $34-m e t e r$ and 222 -meter stations. For neutron energies above 1 MeV we will be using a new method for determining absolute fission cross section ratios. This method eliminates the need for determining the absolute masses of fissionable material within our fission chambers. This method is described in detail in UCRI-51478.

To cover the range from thermal to 15 MeV we have chosen a variety of flux monitors. For neutron energies below 100 keV , we are using the $10 \mathrm{~B}(\mathrm{n}, \alpha)$ reaction. From 30 keV up to 15 MeV we are using the $235 \mathrm{U}(\mathrm{n}, \mathrm{f})$ reaction. In addition we are using the $l_{\mathrm{H}}(\mathrm{n}, \mathrm{p})$ above 1 MeV .

Fission cross section ratios $\sigma_{f}(233 U): \sigma_{f}(235 U), \sigma_{f}(238 \mathrm{U}): \sigma_{f}(235 \mathrm{U})$, $\sigma_{f}(239 \mathrm{Pu}): \sigma_{f}(235 \mathrm{U})$ with energy resolution from $2-5 \%$ and total uncertainty of $2-5 \%$ from 1 keV to 15 MeV should be available for publication in Spring of 1974.

> 2. Pulsed Sphere Measurements on ${ }^{235}$ U and ${ }^{239}$ Pu. (J. D. Anderson, J. C. Davis, S. M. Grimes, R. C. Haight, T. T. Komoto, C. M. Logan, J. W. McClure, B. A. Pohl, and C. Wong)

As an extension of the Livermore pulsed-sphere experiments, ${ }^{5}$ measurements have been made on spheres of 235 U and 239 Pu pulsed with neutrons in the 0.3 to 2.7 MeV range. Neutron leakage spectra above the source energy were measured by time of flight. The neutron source was the $\mathrm{T}(\mathrm{p}, \mathrm{n}){ }^{3} \mathrm{H}$ reaction at proton beam energies of 2.5 and 3.5 MeV . At the higher beam energy, the neutron energy varies with angle from 2.7 MeV to $0^{\circ}$ to 0.5 MeV at $180^{\circ}$. At the lower beam energy, the neutron energy varies from 1.7 to 0.3 MeV . In both cases, the intensity of the source is peaked at 00. Three spheres have been studied: 235U (3.145 cm radius), ${ }^{239} \mathrm{Pu}(3.22 \mathrm{~cm})$, and $235 \mathrm{U}(5.925 \mathrm{~cm})$. The last sphere was pulsed only at the lower energy.

In the analysis of these data we have transformed the time-offlight spectra to pseudo-energy spectra. The pseudo-energy, $\varepsilon$, is defined by

$$
\varepsilon=\frac{1}{2} m\left(\frac{d}{t}\right)^{2}\left(1+\frac{3}{4} \beta^{2}\right)
$$

where $t$ is the time-of-flight measured from the source pulse time, $d$ is the (straight line) distance from the source to the detector, and m is the mass of the neutron and $\beta=\frac{d}{t c}$. In the limit of very small spheres this pseudo energy equals the true energy.

Monte Carlo simulations of these experiments have been calculated with the code TART to test various data libraries. In the following discussion, calculations with the ENDF/B-III library are compared with the experiment. The major sensitivity, of course, is to the fission neutron spectrum.

For the ${ }^{235} \mathrm{U}$ spheres, fair agreement obtains between the TART calculation with ENDF/B-III and the experiment both in the magnitude and spectral shape of the emitted neutrons (Fig. B-l). The data above 10 MeV are subject to larger errors than indicated because of uncertainties in the background. On the other hand the 239 Pu comparison (Fig. B-2) shows a significant discrepancy between the slopes of the calculated and measured spectra in the region of good Monte Carlo and experimental statistics, namely from 3 to 8 MeV . The comparisons at $E_{p}=2.5 \mathrm{MeV}$ are similar. If this disagreement is ascribed solely to incorrect fission temperatures in ENDF/B-III, then these temperatures are too high for ${ }^{239} \mathrm{Pu}$ by $0.15 \pm 0.05 \mathrm{MeV}$.

These experiments strongly suggest that the fission temperatures of 239 Pu and 235 U are much closer than stated in ENDF/B-III.

[^13]3. Neutron Spectra from Ni Bombarded with 14 meV Neutrons (L. F. Hansen, J. D. Anderson, S. M. Grimes, J. L. Kammerdiener, T. Komoto, and C. M. Logan) Relevant to Request 184.

The neutron spectrum produced by $14-\mathrm{MeV}$ neutron bombardment of Ni is shown in Fig. A-4. Ring geometry and time-of-flight techniques were used to measure the neutrons. These measurements are described elsewhere, 6 in which the neutron emission spectra are given as a function of angle between $25^{\circ}$ and $130^{\circ}$ in $5^{\circ}$ intervals. The differential neutron spectra were integrated over $1-\mathrm{MeV}$ neutron energy intervals to obtain the integrated cross sections presented in Fig. B-3. The neutron group between 12 and 13 MeV corresponds to the first excited state in Ni and the magnitude of the integrated cross section is 39.5 mb . This is in excellent agreement with the value of 39.4 mb obtained by integrating the differential cross section measured by Stelson et al. ${ }^{7}$ The neutron elastic differential cross section from Kammendienerts measurements were fitted with an optical-model calculation. The best fit to the data was obtained with Bjonklund and Fernbach neutron parameters, which yielded an elastic cross section of $1.09 \pm 0.11 \mathrm{~b}, \mathrm{a}$ total cross section of 2.56 b , and a Wick's limit cross section at $0^{\circ}$ of $2.86 \mathrm{~b} / \mathrm{sr}$. In Table B-l and B-2 the differential cross sections are given for the elastic and inelastic scattering to the first excited state of Ni , respectively.

Calculations are in progress to reproduce the inelastic measured spectra given in Fig. B-3 (excluding the neutrons from the first excited state), including contributions from equilibrium and pre-equilibrium processes.

Table B-l. Differential Elastic Scattering Cross Sections for Ni Bombarded with 14.6 MeV Neutrons

| $\sigma_{\mathrm{cm}}$ | $\mathrm{d} \sigma / \mathrm{d} \Omega(\mathrm{mb} / \mathrm{sr})$ |  |  |
| :---: | :---: | :---: | ---: |
| 26.2 | 331.6 | $\pm$ | 16.6 |
| 36.3 | 52.8 | $\pm$ | 2.6 |
| 46.5 | 24.2 | $\ddagger$ | 1.2 |
| 56.6 | 16.8 | $\ddagger$ | 0.8 |
| 66.6 | 5.09 | $\pm$ | 0.50 |
| 76.7 | 12.0 | $\pm$ | 0.60 |
| 86.7 | 16.2 | $\ddagger$ | 0.80 |
| 96.7 | 12.6 | $\pm$ | 0.60 |
| 111.6 | 4.14 | $\ddagger$ | 0.32 |
| 131.5 | $7.82 \pm$ | 0.51 |  |
| $\sigma_{\text {elastic }}=$ | $1090 \pm 110 \mathrm{mb}$ |  |  |

$\widehat{\sigma}_{\mathrm{J} .}$ L. Kammerdiener, Neutron Spectra Emitted by $239 \mathrm{Pu}, 238 \mathrm{U}, 235 \mathrm{U}, \mathrm{Pb}$, Ni, Al, and C Irradiated by 14 MeV Neutrons, Ph. D. Thesis UCRL-51232.
${ }^{7}$ P. H. Stelson, R. L. Robinson, H. J. Kim, J. Rapaport, and G. R. Satchler, Nucl. Phys. 68, 97 (1965).

Table B-2 Differential Inelastic Scattering Cross Sections to the First Excited Level in Ni ( $E_{n^{\prime}}=12-13 \mathrm{MeV}$ ) Bombarded with 14.6 MeV Neutrons

| $\sigma_{\mathrm{cm}}$ | $\mathrm{da} / \mathrm{d} \Omega(\mathrm{mb} / \mathrm{sr})$ |
| ---: | ---: |
| 26.2 | $13.47 \pm 1.31$ |
| 36.4 | $7.34 \pm 0.70$ |
| 46.5 | $5.67 \pm 0.48$ |
| 56.6 | $3.65 \pm 0.33$ |
| 66.7 | $2.92 \pm 0.27$ |
| 76.7 | $3.03 \pm 0.24$ |
| 86.8 | $2.55 \pm 0.22$ |
| 96.8 | $2.16 \pm 0.11$ |
| 111.7 | $1.28 \pm 0.20$ |
| 131.5 | $1.45 \pm 0.26$ |
| $\sigma=39.5 \pm 2.8 \mathrm{mb}$ |  |

4. Measurements and Calculations of the Neutron Spectra from Concrete Bombarded with $14-\mathrm{MeV}$ Neutrons (L. F. Hansen, J. D. Anderson, J. L. Kammerdiener, T. Komoto, C. M. Logan, and C. Wong.

The neutron spectra emitted from 2.0 and 3.8 mean free paths of concrete for a $14-\mathrm{MeV}$ neutron source have been measured between 14 and 2.0 MeV using the sphere transmission and time-of-flight techniques. 8 The nominal $14-\mathrm{MeV}$ neutron source was obtained from the $\mathrm{T}(\mathrm{d}, \mathrm{n}) 4 \mathrm{He}$ reaction using a $400-\mathrm{keV} \mathrm{D}^{+}$ion beam from the Livermore ICT accelerator (Insulated Core Transformer). The concrete targets were solid spheres of 21.0 - and $35.5-\mathrm{cm}$ radius with a density of $2.35 \mathrm{~g} / \mathrm{cm}^{3}$. The chemical composition of the concrete was. $15.1 \% \mathrm{H}, 55.7 \% \mathrm{O}, 14.9 \% \mathrm{Si}, 3.6 \% \mathrm{Ca}$, $3.2 \% \mathrm{Al}, 3.1 \% \mathrm{C}, 1.8 \% \mathrm{Mg}, 1.3 \% \mathrm{Na}$, and less than $1 \%$ each of $\mathrm{Fe}, \mathrm{K}$, Ti and Mn (the percentages refer to atomic fractions).

Calculations of the measured neutron time-of-flight spectra were carried out with the Monte Carlo neutron transport code TART, using the LLL neutron library. All the elements listed in the chemical composition were included, with the exception of $\mathrm{K}, \mathrm{Ti}$, and Mn which were taken to be Fe. In Fig. B-4, the agreement between measurements and calculations is shown to be quite good for neutron energies $E_{n} \geq 3 \mathrm{MeV}$ (neutron flight time $\leq 400 \mathrm{nsec}$ ). It is interesting to point out that the structure in the spectra is determined mainly by the oxygen. This can be seen in Fig. B-5 where the neutron spectrum from oxygen ${ }^{9}$ is shown for comparison.
${ }^{8}$ C. Wong, J. D. Anderson, P. Brown, L. F. Hansen, J. L.' Kammerdiener,
C. M. Logan, and B. A. Pohl, Livermore Pulsed Sphere Program, UCRL-51144
9. F. Hansen, J. D. Anderson, E. Goldberg, J. L. Kammerdiener,
E. Plechaty, and C. Wong, Nucl. Sci. Eng. 40, 262 (1970).

## C. BASIC SCIENCE

## 1. Neutron Total Cross Section of ${ }^{207} \mathrm{~Pb}$. (T. W. Phillips and B. L. Berman)

The neutron total cross section of ${ }^{207} \mathrm{~Pb}$ has been measured using a separated ${ }^{207} \mathrm{~Pb}$ sample (. 0309 atoms/b). Neutron energies were determined by time of flight over a 250 -meter path using a 6 -nsec pulse from the LLL Linac. Both flight time and pulse height of an event detected in a plastic scintillator were recorded and used to assign the event to a position in a two-dimensional array. The pulse-height information was later used to obtain a dynamic bias thereby removing background events from the data. The neutron total cross section for 207 Pb derived from the transmission data obtained in this manner is shown in the Figures C-l, C-2, and C-3. Presently a multi-level R-matrix fitting procedure is being applied to this data to obtain neutron widths and spin assignments for the observed resonances.

## 2. Spectrum of High-Energy $\gamma$ Rays from ${ }^{252}$ Cf Spontaneous Fission. (F. S. Dietrich, J. C. Browne, W. J. O'Connell and M. J. Kay)

The spectrum of high-energy $\gamma$ rays between 7 and 20 MeV has been measured for ${ }^{252} \mathrm{Cf}$ spontaneous fission using an anti-coincidence shielded $24 \mathrm{~cm} \times 24 \mathrm{~cm} \mathrm{NaI}$ spectrometer. Fission neutrons and prompt fission $\gamma$ rays were separated by their time of flight to the detector. The unfolded NaI spectra are shown in Figure C-4 for three different geometries. These data yield an upper limit of $4 \times 10^{-4}$ gammas/fission-MeV for $14-\mathrm{MeV}$ events of multiplicity two which is in disagreement with a recent measurement of Brooks and Reinesl0 which reported to observe two correlated $\gamma$ rays whose total energy was greater than 14 MeV . A calculation is presently in progress to determine whether the measured $\gamma$-ray spectrum can be explained by the statistical decay of the highly-excited fission fragments.

## 3. Measurement of the ${ }^{26} \mathrm{Mg}(\mathrm{y}, \mathrm{p})^{25} \mathrm{Na}$ Reaction with Monoenergetic Photons. (T. F. Godlove* and B. L. Berman)

An exploratory experiment has been performed in order to determine the feasibility of measuring photonuclear cross sections using monoenergetic photons from positron annihilation in flight as the source of radiation and a large-volume $\mathrm{Ge}(\mathrm{Li}) \gamma$-ray spectrometer to detect the residual radioactivity by counting, between the accelerator beam bursts, the $\gamma$ ray following $\beta$ decay. A l00-g sample of 26 Mg was irradiated with $25-\mathrm{MeV}$ annihilation photons, and the $585-$, $975-$, and $1612-\mathrm{keV} \gamma$ rays from the $\beta$ decay of the 25 Na produced by the $26 \mathrm{Mg}(\gamma, \mathrm{p}$ ) reaction ( $\tau 1 / 2=$

[^14]. W. Brooks and F. Reines, Phys. Rev. C7, 1579 (1973).

59 sec ) were measured with a $90-\mathrm{cc} \mathrm{Ge}(\mathrm{Li})$ detector. Although the backgrounds were low and the $\gamma$-ray peaks were readily apparent in experimental runs of the order of a few hours, the total net count rate was discouragingly low. An expected increase in our positron beam flux of a factor of 5 to 10 times that used in this measurement within the next year or so might make such experinents feasible.

## D. CONTROLLED THERMONUCLEAR RESEARCH APPLICATIONS

1. Study of the $\operatorname{ll} l_{B}(p, \alpha) 8_{B e^{*}+2 \alpha \text { Resonant Reaction. (I. D. Proctor, }}$ H. F. Lutz, and W. Bartolini)

The reaction of ${ }^{1 l_{B}(p, \alpha)}{ }^{8} \mathrm{Be}^{*}+2 \alpha$ has possible applications as a fuel for controlled thermonuclear reactors involving only charged nonradioactive particles. 11 We have employed the tandem van de graaff of the Livermore cyclograaff facility to measure the broad resonance for this reaction proceeding through the first excited state of 8 Be. Data were obtained from 375 keV to 1.25 MeV . The peak cross section occurs near 650 keV laboratory bombarding energy and the FWHM of the resonance is approximately 320 keV . In order to circumvent the line-shape difficulties in interpreting the data we have observed all three alpha particles.

The results of the experiment are shown as the smooth curve in Fig. D-l where we have also plotted the previously measured values of the cross section. Discrepancies of approximately $50 \%$ existed before our measurements, which are believed to have an absolute error of $\pm 12 \%$.

We have also measured the elastic scattering of protons from $1 l_{B}$ at energies between 1 and 4 MeV since this scattering cross section is also needed for fuel plasma calculations.
2. Translation of the LLL Evaluated Nuclear Data Library (ENDL) to the ENDF/B Format. (R. J. Howerton)
The LLL Evaluated Nuclear Data Library (ENDL), as it existed in October 1973, has been translated into the ENDF/B format. Magnetic tapes and documentation (UCID-16376) are available upon request from the Radiation Shielding Information Center at Oak Ridge National Laboratory. Neutron-induced cross sections and related data are given for 73 materials, including partial evaluations for 8 materials and 65 complete evaluations. Photon production cross sections are included for 56 of these materials. The neutron energy range is from $10^{-10}$ to 20 MeV .

Users of evaluated data may be interested in comparing calculations using ENDL with those using ENDF/B-III. The most significant differences should be expected for neutron energies between 5 and 20 MeV . $\mathrm{Il}_{\text {T. Weaver, G. Zimmerman, and L. Wood, UCRL-74191 (unpublished) } 1972 . ~}^{\text {. }}$


ENERGY (EV)
Figure A-1. Relative $\bar{v}$ Measurement. The numbers on the abscissa refer to the incident neutron energy. The asterisk (*) represents $3^{-}$resonances, the plus ( + ) represents $4^{-}$resonances, the box (田) represents resonances with unassigned spins, and the diamond ( $\Delta$ ) represents overlapping resonances of unknown or different spins.


Figure B-2




Figure B-4 Neutron flight time in nanoseconds



Figure C-I




## LOCKHEED PALO ALIO RESEARCH LABORATORY

A. NEUTRON PHYSICS

1. Gross-Fission-Product $\gamma$-Ray Spectroscopy (W. L. Imhof, L. F. Chase, R. A. Chalmers, F. J. Vaughn, and R. W. Nightingale)

Analysis of the fission-product $v$-ray data is continuing. Recent emphasis has been placed on the data from the 5 -h and 5 -min neutron bombardments in order to study activities with half-lives both shorter and longer than those observed from the previously analysed $40-\mathrm{min}$ irradiations.
2. Neutron Cross-Section Measurements with Polarized Targets
(T. R. Fisher, A. R. Poletti, and B. A. Watson)

Measurements of the deformation effect in the ${ }^{59}$ Co+n total cross section have been completed employing the aligned 59 Co target described previously. With $16 \%$ nuclear alignment in the target, the average of five measurements at energies between 1 and 2 MeV was $\Delta \sigma_{\text {def }}=-259$ $\pm 41 \mathrm{mb}$; at 15.9 MeV , the result obtained was $\Delta \sigma_{\text {def }}=-37 \neq 42 \mathrm{mb}$. These results, when interpreted using the first-order DWBA theory, imply a value of $0.39 \pm 0.06 \mathrm{~b}$ for the quadrupole moment of 59 Co , which is in good agreement with the result of other techniques.

## B. CHARGED-PARTICLE REACTIONS

1. Lifetimes of Levels in ${ }^{24} \mathrm{Ne}$ (B. A. Watson, J. A. Becker, and T. R. Fisher)

Lifetimes of levels in ${ }^{24} \mathrm{Ne}$ have been measured employing the $22 \mathrm{Ne}(\mathrm{t}, \mathrm{p})$ reaction at a triton bombarding energy of 2.9 MeV . Using the Doppler-shift-attenuation technique, lifetimes of the 1.98-, 3.87- and 4.76 MeV levels were found to be $0.89+.36,<0.18$ and $3.3+2.1$ psec, respectively. The experimental results are well-reproduced by the shellmodel calculations of Robertson and Wildenthal.
2. Study of Some Proton Unbound ${ }^{26}$ Si States (J. G. Pronko, B. A. Watson* $^{*}$, D. C. Slater*, and E. Kuylman*)

A number of highly excited states of ${ }^{26}$ Si are being investigated by the ${ }^{24} \mathrm{Mg}(3 \mathrm{He}, \mathrm{n})^{26} \mathrm{Si}(\mathrm{p}){ }^{25} \mathrm{Al}$ reaction at a beam energy of

[^15]$\mathrm{E}_{\mathrm{He}} 3=15 \mathrm{MeV}$. Neutrons associated with the formation of the ${ }^{26}$ Si states are detected by means of a NE213 liquid scintillator positioned at a fixed angle of $0^{\circ}$ with respect to the incident beam. Proton groups emitted by the de-excitation of the ${ }^{2} \sigma_{\mathrm{Si}}$ states were observed in time coincidence with the associated neutrons and coincident proton angular correlations were obtained. The ${ }^{26}$ Si states were observed to decay to the ground state and first two excited states of 25 Al . Results obtained from the analysis of preliminary data indicate strong anisotropies for most of the angular correlations. The $8.62-\mathrm{MeV}$ state was found to decay predominantly to the 25 Al ground state and the associated angular correlations indicate that the decay involves protons with orbital angular momentum of $1=1$ and 3 consistent with a spin parity assignment of $J \pi=3^{-}$. From this data this state is believed to be of a ( $\mathrm{d}_{5 / 2, ~ f / 2}$ ) configuration. Assignments for the $8.08,7.41,6.77$ and $6.32-\mathrm{MeV}$ states are being considered.

## 3. The $\gamma$-Ray De-excitation of ${ }^{53} \mathrm{~V}$ Excited States. (J. G. Pronko and J. A. Becker)

The previously unobserved $v$-ray decay modes of the excited states of 53 V were studied using the $51 \mathrm{~V}(\mathrm{t}, \mathrm{py}) 53 \mathrm{~V}$ reaction at a bombarding energy of $E_{t}=2.9 \mathrm{MeV}$. The v-rays were detected with a 4 in . x 4 in. and a 0.6 in. x 1.5 in. $N a I(T l)$ crystals, both of which were in time coincidence with a surface barrier proton detector positioned at $70^{\circ}$ with respect to the beam axis. This angle was chosen on the basis of a maximum in the angular distribution of protons leading to most of the excited states of interest. These experimental results will be compared with the decay schemes of a number of nuclei whose low-lying structure can be attributed to a $\left(f_{7 / 2}\right)^{3}$ configuration.
4. The $\gamma$-Ray De-excitation of 50 Ti States in the Region of $4-\mathrm{MeV}$ Excitation (J. G. Pronko, T. T. Bardin, J. A. Becker, R. E. McDonald and A. R. Poletti)

Nuclear properties of some 50 Ti states in the region of 4 MeV excitation were obtained using the ${ }^{4} 8 \mathrm{Ti}_{i}(\mathrm{t}, \mathrm{p}) 50 \mathrm{Ti}$ reaction at a bombarding energy of $E_{t}=2.9 \mathrm{MeV}$. Angular correlations of $v$-rays were obtained using a spectrometer consisting of five $\mathrm{NaI}(T I)$ counters in time coincidence with an annular particle detector positioned near $180^{\circ}$. A unique spin assignment of $J=2$ was found for the $4.32-\mathrm{MeV}$ state. The $\gamma$-ray branching and mixing ratios for the de-excitation of this state along with branching ratios for a number of other states in this region of excitation were measured.
5. Lifetime Limits for the ${ }^{46} \mathrm{Ca} 2_{I}^{+}$and $0_{2}^{+}$States (J. A. Becker, T. T. Bardin, T. R. Fisher, B. A. Watson and E. K. Warburton*)

Following the ${ }^{44} \mathrm{Ca}(t, p)$ reaction, the spectrum of $p-v$ coincidence pulse heights was measured using 2 -parameter data collection techniques. Preliminary values of $|M|^{2}<2$ and $<9$ were deduced for the ${ }^{45} \mathrm{Ca}$ excited states at $\mathrm{E}_{\mathrm{x}}=1.347$ and 2.423 MeV , respectively, pointing towards marked changes in the deformation of the Ca isotopes with increasing mass number.
6. Nuclear Lifetimes in ${ }^{45} \mathrm{Ca}$ (J. A. Becker, T. T. Bardin, T. R. Fisher, and B. A. Watson)

Levels in ${ }^{45} \mathrm{Ca}$ were produced using the ${ }^{44} \mathrm{Ca}(\mathrm{d}, \mathrm{p})^{45} \mathrm{Ca}$ reaction together with a collinear geometry; a thick metallic foil target of ${ }^{44} \mathrm{Ca}$ was employed as a target. The data are being analyzed for nuclear lifetimes (using the Doppler shift attenuation method) and $\gamma$-ray branching modes.
7. Nuclear Lifetimes in ${ }^{42} \mathrm{Ar}$ (T. R. Fisher, T. T. Bardin, J. A. Becker, and B. A. Watson)
Excitation energies and nuclear lifetimes of states in ${ }^{42}$ Ar have been measured by employing the reaction ${ }^{40} \mathrm{Ar}(t, p){ }^{42} \mathrm{Ar}$ at a triton bombarding energy of 2.8 MeV . Protons were detected by an annular silicon surface barrier counter at an average angle of $174^{\circ}$, and coincident $\gamma$ rays were detected by a $20 \mathrm{~cm}^{3} \mathrm{Ge}(\mathrm{Li})$ counter positioned at angles of 30 and 120 . The extraction of nuclear lifetimes by the Doppler-shiftattenuation technique was made possible by the use of a solid argon target operated at $15^{\circ} \mathrm{K}$. The experimental results are in good agreement with the shell-model calculations of Gloeckner, Lawson, and Serduke.
8. Search For a Low Mass Scalar Boson (D. Kohler, J. A. Becker, and B. A. Watson)

It has been proposed recently by N. K. Sundaresan and P.J.S. Watson that certain muonic $x$-ray energy discrepancies observed by $M$. Dixit et al and A. K. Walton et al can be explained by assuming that the scalar particle required by the Weinberg type guage theories has a mass in the range $0 \leqslant m_{\varphi} \leqslant 22 \mathrm{MeV}$. Two experiments were carried out to check this possibility. The $\mathrm{O}^{+}$to $\mathrm{O}^{+}$decays of 160 (6.05) and ${ }^{4} \mathrm{He}(20.2)$ were used to produce the hypothetical particle with calculable branching

[^16]ratios. No scalar particle production was observed in either of the experiments. The combined result (preliminary) of the two experiments is that the scalar particle, if it exists at all, cannot have a mass in the range $1.025 \mathrm{MeV} \leqslant \mathrm{m}_{\mathrm{p}} \leqslant 19.0 \mathrm{MeV}$.

## 9. Superconducting Nuclear Particle Detectors (B. A. Watson and T. R. Fisher)

Alpha particles incident upon a $\mathrm{Pb}-\mathrm{PbO}-\mathrm{Pb}$ tunnel junctions operated at $4.2^{\circ} \mathrm{K}$ have been observed to produce a pulse when the junction is biased. Further work is being directed toward fabrication of $\mathrm{Nb}-\mathrm{PbO}-\mathrm{Pb}$ junctions which are reported to be stable to temperature cycling.
10. Resonaince Depolarization of $12_{\mathrm{B}}$ (R. E. McDonald and $\mathrm{T} . \mathrm{K}$. McNab)
$12_{B}$ recoils from the reaction ${ }^{l 1_{B}}(\alpha, p)^{12} D_{B}$ at $E_{d}=1.5 \mathrm{MeV}$ and at a recoil angle of $45^{\circ} \pm 5^{\circ}$ have been implanted in a variety of metallic and semi-conductor hosts in a uniform magnetic field. The polarization and alignment of the ${ }^{12} \mathrm{~B}$ were partially destroyed by applying a radiofrequency transverse field at the Larmor frequency. Knight shifts in the F.C.C. metallic hosts $\mathrm{Au}, \mathrm{Pt}, \mathrm{Pd}, \mathrm{Rh}, \mathrm{Cu}, \mathrm{Al}$, and Ag were obtained by comparing resonance frequencies to those in the semiconductor hosts $\mathrm{Si}, \mathrm{Ge}$, and SiC . Depolarization measurements with single-crystal Be hosts show the presence of double-quantum transitions, as do measurements in unannealed metallic and radiationdamaged semiconductor hosts.

## LOS ALAMOS SCIENTIFIC LABORATORY, UNIVERSITY OF CALIFORNIA

## A. STANDARDS

1. Interaction of Fast Neutrons with the Isotopes of Hydrogen and Helium (J. D. Seagrave)

Because of their intrinsic interest, LASL has a continuing program of measurements of the neutron interactions with the isotopes of hydrogen and helium. Recent LASL publications have included studies of neutron interactions with ${ }^{4} \mathrm{He},{ }^{1}$ and of neutron interactions with deuterium and tritium. ${ }^{2}$ As a part of this program, we have recently completed a study of the elastic scattering of neutrons by ${ }^{3} \mathrm{He}$ in the energy range from 8 to 24 MeV . Final values for the integral cross sections are shown in Table A-1 and plotted with other data in Fig. A-1. This presentation supersedes and extends the previous graphical summary given by Seagrave. ${ }^{3}$ New ${ }^{3} \mathrm{He}(\mathrm{n}, \mathrm{p}) \mathrm{T}$ cross sections are derived (by time-reversal calculations)
 ${ }^{3} \mathrm{He}(\mathrm{n}, \mathrm{d}) \mathrm{D}$ cross sections are from various older sources. New measurements at LASL of the $D(d, n){ }^{3} H e$ reaction at higher energies will permit extension of the ${ }^{3} \mathrm{He}(\mathrm{n}, \mathrm{d}) \mathrm{D}$ cross section calculations in a similar manner.

From the integral values of the new elastic cross sections and the calculated ${ }^{3} \mathrm{He}(\mathrm{n}, \mathrm{d}) \mathrm{D}$ and ${ }^{3} \mathrm{He}(\mathrm{n}, \mathrm{p}) \mathrm{T}$ cross sections, together with new total cross section values (see below), it was possible to derive upper limits for the sum of the ${ }^{3} \mathrm{He}(\mathrm{n}, 2 \mathrm{n})$ and ${ }^{3} \mathrm{He}(\mathrm{n}, 3 \mathrm{n})$ reactions.

The differential cross sections are shown in Fig. A-2 and tabulated in Table A-2. Recent work by P. W. Lisowski ${ }^{5}$ has provided $n-{ }^{3} \mathrm{He}$ polarization

[^17]

Fig. A-1. The ${ }^{3} \mathrm{He}$ integral elastic scattering cross sections ( $\sigma_{\mathrm{e} 1}$ ) for neutrons in the energy range $8-24 \mathrm{MeV}$. Cross sections for other neutron interactions with the ${ }^{3} \mathrm{He}$ and earlier measurements of $\sigma_{e l}$ are shown for comparison.

Table A-1
$\mathrm{n}^{3}$ He Integral and Elastic $0^{\circ}$ Differential Cross Sections (in barns)

| Type | $\mathrm{E}_{\mathrm{n}}(\mathrm{MeV})$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | 7.90 | 12.00 | 13.60 | 14.40 | 23.70 |
| $\sigma_{T}{ }^{\text {a }}$ | $\begin{gathered} 1.78 \\ \pm 0.018 \end{gathered}$ | $\begin{gathered} 1.30 \\ \pm 0.020 \end{gathered}$ | $\begin{gathered} 1.17 \\ \pm 0.035 \end{gathered}$ | $\begin{gathered} 1.12 \\ \pm 0.035 \end{gathered}$ | $\begin{gathered} 0.70 \\ \pm 0.055 \end{gathered}$ |
| $\sigma_{e l}\left(0^{\circ}\right)$ Wick ${ }^{\text {b }}$ | 0.43 | 0.35 | 0.32 | 0.31 | 0.20 |
| $\sigma_{e 1}\left(0^{\circ}\right)^{\text {b, }} \mathrm{c}$ | 0.44 | 0.36 | 0.34 | 0.33 | 0.22 |
|  | 1.43 | 1.04 | 0.92 | 0.87 | 0.48 |
| el | $\pm 0.05$ | $\pm 0.03$ | $\pm 0.03$ | $\pm 0.03$ | $\pm 0.02$ |
| $\sigma_{n e}=\sigma_{T}{ }^{-\sigma} e l$ | $\begin{array}{r} 0.35 \\ \pm 0.05 \end{array}$ | $\begin{array}{r} 0.26 \\ \pm 0.04 \end{array}$ | $\begin{array}{r} 0.25 \\ \pm 0.05 \end{array}$ | $\begin{array}{r} 0.25 \\ \pm 0.05 \end{array}$ | $\begin{array}{r} 0.22 \\ \pm 0.06 \end{array}$ |
| $\sigma_{n, p} e^{e}+\sigma_{n, d} f$ | $\begin{array}{r} 0.31 \\ \pm 0.01 \end{array}$ | $\begin{array}{r} 0.24 \\ \pm 0.01 \end{array}$ | $\begin{array}{r} 0.23 \\ \pm 0.01 \end{array}$ | $\begin{array}{r} 0.22 \\ \pm 0.02 \end{array}$ | $\begin{array}{r} 0.15^{\mathrm{C}} \\ \pm 0.02 \end{array}$ |
| $\sigma_{\mathrm{n}, \mathrm{pn}}+\sigma_{\mathrm{n}, 2 \mathrm{n}}$ | $\begin{array}{r} 0.04 \\ \pm 0.05 \end{array}$ | $\begin{array}{r} 0.02 \\ \pm 0.04 \end{array}$ | $\begin{array}{r} 0.02 \\ \pm 0.05 \end{array}$ | $\begin{array}{r} 0.03 \\ \pm 0.05 \end{array}$ | $\begin{array}{r} 0.07 \\ \pm 0.06 \end{array}$ |

ata of Goulding, Stoler, and Seagrave (LA-UR-73-1319).
$b_{\text {Barns/steradian. }}$.
${ }^{c}$ Extrapolated.
$\mathrm{d}_{\text {By integration. }}$
${ }^{e}$ Converted data of McDaniels et al. [Phys. Rev. C6, 1593 (1972)].
$\mathrm{f}_{\text {Adjusted }}$ from data of Brolley et al. [Phys. Rev. 107, 821 (1957)], Goldberg and Leblanc [Phys. Rev. 119, 1992 (1960)], and Van Oers and Brockman [Nucl. Phys. 48, 625 (1963)].

Lab Cross Sections for the Reaction ${ }^{3} \mathrm{He}(\mathrm{n}, \mathrm{n})^{3} \mathrm{He}$ in mb（liquid samples only）

| 7.00 MeV |  | 12.00 MeV | 13.60 MeV | 14.40 MeV | 23.70 MeV |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\cos \theta_{\mathrm{cm}}$ | ${ }^{1}{ }_{1 \mathrm{ab}} \quad \sigma \pm \Delta \sigma$ | ${ }^{1}{ }_{1 a b} \quad \sigma \pm \triangle \sigma$ | ${ }^{1} 1 \mathrm{ab} \quad \sigma \pm \Delta \sigma$ | ${ }^{1 a b} \quad \sigma \pm \Delta \sigma$ | ${ }^{1} 1 \mathrm{ab} \quad \sigma \pm \Delta \sigma$ |
| 0.90 | 19.4 620．$\pm 39$ ． | 19.5 537．$\pm 18$. | 19.4 471．$\pm 17$. | 19.3 436．$\pm 15$ ． | 19．4 267．$\pm 12$ ． |
| 0.80 | 27.9 496．$\pm 25$. | $28.0415 . \pm 18$. | $27.9345 . \pm 13$. | 27.7 341．$\pm 11$. | 27.8 194．$\pm 7$ ． |
| 0.70 | 34.5 421．$\pm 13$ ． | $34.6301 . \pm 7$ ． | $34.6273 . \pm 9$ ． | $34.5265 . \pm 9$ ． | $34.6140 . \pm 6$ ． |
| 0.60 | 40.5 320．$\pm 10$ ． | $40.5228 . \pm 8$ ． | 40.5 209．$\pm 7$ ． | $40.5189 . \pm 7$ ． | $40.596 .8 \pm 5.4$ |
| 0.55 | 43.4 274．$\pm 11$ ． | 43.4 195．$\pm 5$ ． | $43.4172 . \pm 4$ ． | 43.4 166．$\pm 5$. | $43.4 \quad 76.1 \pm 3.5$ |
| 0.40 | 51.2 186．$\pm 8$ ． | $51.3121 . \pm 8$ ． | $51.4106 . \pm 4$ ． | $51.4104 . \pm 4$. | $51.3 \quad 47.4 \pm 3.2$ |
| 0.25 | 58.8 109．$\pm 5$. | $58.975 .2 \pm 4.7$ | $58.8 \quad 69.2 \pm 2.8$ | $58.8 \quad 66.2 \pm 2.6$ | $58.9 \quad 28.1 \pm 1.7$ |
| 0.10 | $66.466 .5 \pm 3.3$ | $66.444 .9 \pm 2.5$ | $66.5 \quad 36.9 \pm 1.8$ | $66.3 \quad 33.0 \pm 1.8$ | $66.3 \quad 17.6 \pm 1.5$ |
| 0.00 | $71.4 \quad 42.4 \pm 1.9$ | $71.6 \quad 27.8 \pm 1.1$ | $71.6 \quad 24.6 \pm 1.1$ | $71.4 \quad 23.7 \pm 1.0$ | $71.510 .5 \pm 1.9$ |
| －0．10 | $76.5 \quad 29.1 \pm 1.3$ | $76.8 \quad 17.6 \pm 1.3$ | $76.8 \quad 17.0 \pm 1.0$ | $76.6 \quad 14.3 \pm 0.8$ | $76.6 \quad 7.44 \pm 0.86$ |
| －0．30 | $87.915 .7 \pm 0.8$ | $87.8 \quad 7.53 \pm 0.39$ | $87.86 .26 \pm 0.31$ | $87.8 \quad 6.08 \pm 0.35$ | $87.8 \quad 5.50 \pm 0.72$ |
| －0．50 | $100.817 .7 \pm 1.2$ | $100.9 \quad 7.31 \pm 0.52$ | $100.85 .94 \pm 0.32$ | $100.7 \quad 5.06 \pm 0.33$ | $100.7 \quad 4.10 \pm 0.73$ |
| －0．60 | $108.422 .3 \pm 1.3$ | $108.411 .4 \pm 0.7$ | $108.48 .53 \pm 0.44$ | $108.5 \quad 7.84 \pm 0.36$ | 108.3 4．33士 0.55 |
| －0．715 | 118.3 29．7士 1.0 | $118.216 .7 \pm 1.0$ | $118.5 \quad 12.4 \pm 0.7$ | $118.5 \quad 12.3 \pm 0.46$ | 118.5 5．46士 0.58 |
| Scale <br> Errors <br> （not i | $\begin{gathered} \pm 3.1 \% \\ \text { cluded above) } \end{gathered}$ | $\pm 2.8 \%$ | $\pm 3.1 \%$ | $\pm 2.8 \%$ | $\pm 2.9 \%$ |



Fig. A-2. The ${ }^{3} \mathrm{He}$ differential elastic scattering cross section for neutrons in the energy range $8-24 \mathrm{MeV}$.
data at $8.0,12.0$, and 17.1 MeV , which superseded earlier work of Behof et al. at 8 MeV and of Büsser et al. at 12 MeV . Lisowski also made phaseshift analyses which give excellent fits to the LASL elastic cross sections and the Duke polarizations and clearly rule out all previous data above 6 MeV as erroneous. Dodder (LASL Group T-9) et al. will use the new data in their four-body energy-dependent analysis.

Total cross sections for the interaction of fast neutrons with hydrogen, tritium, ${ }^{3} \mathrm{He}$, and ${ }^{4} \mathrm{He}$ were measured at LASL many years ago ${ }^{1}$ and also with deuterium. ${ }^{2}$ Recently, in a collaboration with Goulding and Stoler at the Rensselaer Polytechnic Institute Electron Linac, we made improved measurements of the neutron total cross section of ${ }^{3} \mathrm{He}$ and ${ }^{4} \mathrm{He}$ in the MeV energy region. The $n-{ }^{4} \mathrm{He}$ measurements are of value in energy-dependent five-body calculations of the most strongly polarizing nuclear interaction known, and the new $n-{ }^{3} \mathrm{He}$ measurements represent a nearly ten-fold increase in precision over the earlier measurements.

We are also making preparations to measure the neutron total cross section of tritium with Berman at the LLL Electron Linac with apparatus similar to that used at RPI. Because of the extraordinary quantity of tritium involved ( 100 liters, or $250,000 \mathrm{Ci}$ ), dry runs will be made with hydrogen and deuterium for the high-energy measurements ( $0.5-50 \mathrm{MeV}$ ), and with deuterium and ${ }^{3} \mathrm{He}$ for those at low energies $(1-500 \mathrm{keV})$.

## 2. Breakup of Deuterium (J. D. Seagrave)

A preprint of the work of Carlson et al. at UCLA gives results for the p-D total reaction cross section in the energy range $20-50 \mathrm{MeV}$. These results are compared with other measurements and estimates of the neutron reaction cross section in Fig. A-3 (adapted from Carlson et al). It is interesting to note that the asymptotic trend is to approach more nearly $2 / 3 \sigma_{\mathrm{T}}$ than the value of $1 / 2 \sigma_{\mathrm{T}}$ which might be expected from the optical representation under the condition of complete absorption in all channels. Preliminary results of Pauletta and Brooks at the University of Cape Town for $\sigma \mathrm{n}, \mathrm{p}$ in the range $8-22 \mathrm{MeV}$ using a pulse-shape discrimination method lie consistently above this composite picture, and extend above 200 mb at the upper end of the range. The source of this divergence is not clear, but it may involve a flux-measurement problem. The LASL value of $158 \pm 16$ mb (E. R. Graves, 1971) at 14.46 MeV was based on reference to the hydrogen cross section by the inclusion of a known small amount of hydrogen in a deuterated scintillator.

[^18]

Fig. A-3. Break up cross sections of deuterium (after Carlson).
3. Thermal Capture Cross Sections for ${ }^{6} \mathrm{Li}$ and ${ }^{7} \mathrm{Li}$ (E. T. Jurney)
a. Thermal Neutron Radiative Capture by ${ }^{7}$ Li

Values given in Brookhaven National Laboratory report BNL-325 for the thermal neutron radiative capture cross section of ${ }^{7} \mathrm{Li}$ cover the range from $33 \pm 5$ to $44 \pm 10 \mathrm{mb}$. Serious uncertainties also exist in the literature regarding the degree of branching of the gamma rays which deexcite the compound ${ }^{8} \mathrm{Li}$ nucleus directly to the ground state and those which form a 2 -step cascade by decays through the only energy level known to exist between the ground level and the neutron binding energy of ${ }^{8} \mathrm{Li}$. We have measured the energies and intensities of the three prompt gamma rays from the reaction ${ }^{7} \mathrm{Li}(\mathrm{n}, \gamma){ }^{8} \mathrm{Li}$ and from the measurements arrived at new values for both the capture cross section of ${ }^{7} \mathrm{Li}$ and the gamma-ray branching ratio of the subsequent deexcitation of the compound ${ }^{8} \mathrm{Li}$ nucleus.

Gamma rays from a $1.4-\mathrm{g}$ target of $\mathrm{Li}_{2} \mathrm{CO}_{3}$ ( $99.99 \%$ enriched in ${ }^{7}$ Li) placed in the internal target neutron capture facility in the LASL Omega West Reactor thermal column were viewed by a Ge(Li) spectrometer. A separate run with a $0.1-\mathrm{g}$ target of $\mathrm{CH}_{2}$ was made to provide a capture cross section standard; thus the unknown intensities were determined relative to the hydrogen capture cross section, $\sigma_{c}=332 \pm 1 \mathrm{mb}$.

The radiative capture cross section of ${ }^{7} \mathrm{Li}$ was obtained by summing the partial cross sections for producing ${ }^{8} \mathrm{Li}$ deexcitation to the ground level and to the 981 keV level. The result and a comparison with previous measurements are given in Table A-3.

Energies and intensities of the three gamma rays produced by thermal neutron capture in ${ }^{7} \mathrm{Li}$ are given in Table A-4. Although the absolute intensities of the $1052-981$ cascade can be stated only to an accuracy of $\sim 10 \%$, their intensities relative to each other are equal to within $\sim 1 \%$. This equality and the gamma ray branching ratio of $\sim 10 \%$ from the compound capture state places a limit on the $\beta$ decay from the 981 keV level of $\sim 0.1$ per 100 neutrons captured.

## b. Thermal Neutron Radiative Capture by ${ }^{6}$ Li

The recommended value ${ }^{l}$ for the thermal ( $n, \gamma$ ) reaction cross section for ${ }^{6} \mathrm{Li}$ is $45 \pm 10 \mathrm{mb}$. This value is based on the observation of the gamma rays which deexcite the compound ${ }^{7} \mathrm{Li}$ nucleus following neutron

[^19]Table A-3
$\sigma(n, \gamma)$ for Thermal Neutron Capture by ${ }^{7}$ Li
$\sigma(\mathrm{n}, \gamma)(\mathrm{mb})$

## Reference

| $45.4 \pm 3$ | This work. |
| :--- | :--- |
| $40 \pm 12$ | L. Jarczyk, et al. (1961), reported in BNL-325. |
| $40 \pm 8$ | W. Imhof, et al. (1959), reported in BNL-325. |
| $44 \pm 10$ | E. A. Koltypin and V. M. Morozov (1956), reported <br> in BNL-325. |
| $33 \pm 5$ | D. J. Hughes, et al. (1947), reported in BNL-325. |
| $37 \pm 4$ |  |
| Recommended value, BNL-325 |  |

Table A-4
Energies and Intensities of $\gamma$-Rays from Thermal Neutron Capture by ${ }^{7}$ Li

| $\mathrm{E}_{\gamma}(\mathrm{keV})^{\text {a,b }}$ | $\mathrm{I}_{\gamma}(\mathrm{mb})^{\mathrm{b}}$ | $\mathrm{I}_{\gamma}(\gamma / 100 \mathrm{n})^{\mathrm{b}}$ | $\mathrm{I}_{\boldsymbol{Y}}(\mathrm{Y} / 100 \mathrm{n})^{\mathrm{c}}$ | $\underline{\mathrm{I}_{\gamma}(\gamma / 100 \mathrm{n})^{\text {d }}}$ |
| :---: | :---: | :---: | :---: | :---: |
| $980.7 \pm 0.2$ | $4.8 \pm 0.5$ | $10.6 \pm 1$ | 30 | 10.62 |
| $1052 \pm 0.2$ | $4.8 \pm 0.5$ | $10.6 \pm 1$ | 20 | 5.30 |
| $2032.78 \pm 0.28$ | $40.6 \pm 3$ | $89.4 \pm 1$ | 80 | 96.49 |

[^20]capture; Bartholomew ${ }^{1}$ reports deexciting transitions of 7.26 and 6.78 MeV with a combined capture cross section (corrected ${ }^{2}$ ) of $30 \pm 8 \mathrm{mb}$, while Jarczyk et al. ${ }^{3}$ report deexciting gamma rays of $7.26,6.78$, and 2.61 MeV to give a capture cross section of $48 \pm 10 \mathrm{mb}$. The two measurements on which the recommended cross section is based can be said to be in agreement only because of the large quoted individual uncertainties; it is also of interest to confirm the presence reported by Jarczyk et al. ${ }^{3}$ of the 2.61 MeV transition to the first excited state in ${ }^{7} \mathrm{Li}$ at 4.629 MeV and its subsequent decay to the ground state.

The prompt gamma-ray spectrum from a $1.7-\mathrm{g}$ target of $\mathrm{Li}_{2} \mathrm{CO}_{3}$ was measured with the Ge(Li) spectrometer and thermal neutron capture facility at the LASL Omega West Reactor. A target with the two lithium isotopes in their natural abundance was chosen, since the 40.6 mb partial cross section for the 2032 keV transition from capture in ${ }^{7} \mathrm{Li}$ (see Section A.3.a, above) could be used as an intensity standard, thereby eliminating uncertainties in determining the average neutron flux in the target caused by the large ( $n, \alpha$ ) cross section of ${ }^{6}$ Li.

Results of the present experiment are given in Table A-5. The uncertainty shown for $\sigma(\mathrm{n}, \gamma)$ is dominated by the $\pm 3 \mathrm{mb}$ uncertainty in the absolute intensity of the transition in ${ }^{8} \mathrm{Li}$ taken as a standard. Neither member of the $2.61 \rightarrow 4.63 \mathrm{MeV}$ transition reported in Ref. 3 was observed, yet the 2.18 MeV transition following capture in ${ }^{16} 0$ ( $\sigma_{\mathrm{c}} \approx 120$ $\mu \mathrm{b}$ ) was clearly present. It is thus possible to place a limit of $<1 \mathrm{\gamma} / 100$ $n$ on the deexcitation of ${ }^{7} \mathrm{Li}$ via the 4.63 MeV state.

The reaction ${ }^{10} B(n, \alpha){ }^{11} B$ leads to excitation of the 478 keV state in ${ }^{7}$ Li via a $93 \% \quad \alpha$ branching (see Fig. A-4). Deexcitation to the ${ }^{7}$ Li ground state takes place while the recoiling nucleus is in motion, however, and the observed gamma ray is severely Doppler broadened. Figure A-5 shows the 478 keV transition from the ${ }^{6} \mathrm{Li}(\mathrm{n}, \gamma)$ reaction superimposed on a broad pedestal, caused by the broadened gamma-ray deexcitation of the same level in ${ }^{7}$ Li. The area of the broad peak corresponds to a boron impurity of $\sim 18 \mathrm{ppm}$ in the target sample. The peaked appearance of the low-energy shoulder is caused by a 472 keV transition following neutron capture in chlorine, another chemical contaminant in the sample.

[^21]

Fig. A-4. Gamma decay of ${ }^{7}$ Li produced by the ( $n, \gamma$ ) reaction. Also shown is the excitation and decay of the 477.6 keV level in Li by the ${ }^{10} \mathrm{~B}(\mathrm{n}, \alpha)$ reactions.


Fig. A-5. Appearance of the 477.6 keV transition in ${ }^{7} \mathrm{Li}$ when capture takes place in a target containing ${ }^{6} \mathrm{Li}$ and a small amount of ${ }^{10}$ B impurity.

Table A-5

Energies and Intensities of $\gamma$-Rays from the Reaction ${ }^{6} \mathrm{Li}(\mathrm{n}, \gamma){ }^{7} \mathrm{Li}$

| $E_{\gamma}(\mathrm{keV})$ | $\mathrm{E}_{\mathrm{REC}}(\mathrm{keV})$ | $\mathrm{E}_{\text {TRANS }}(\mathrm{keV})$ | I (mb) | $\underline{I}(\gamma / 100 \mathrm{n})$ |
| :---: | :---: | :---: | :---: | :---: |
| $477.6 \pm 0.5$ | 0.02 | $477.6 \pm 0.5$ | $17 \pm 2$ | $44 \pm 5$ |
| $6770.4 \pm 1.5$ | 3.5 | $6773.9 \pm 1.5$ | $15.1 \pm 1.1$ | $39 \pm 1$ |
| $7246.6 \pm 1.5$ | 4.0 | $7250.6 \pm 1.5$ | $23.4 \pm 1.7$ | $61 \pm 1$ |

$\Sigma[\sigma(6773.9)+\sigma(7250.6)]=38.5 \pm 3 \mathrm{mb}=\sigma\left(\mathrm{n}_{\mathrm{th}}, \gamma\right)$
4. Fission Cross Section of ${ }^{235} \mathrm{U}$. (Hansen, Barton, Jarvis, Koontz,

Data reduction of the LASL ${ }^{235} \mathrm{U}$ fission cross section measurements in the $1-6 \mathrm{MeV}$ neutron energy range has been completed and a report is being prepared for submission to Nuclear Science and Engineering. Table A-6 lists the $\sigma_{f}(25) / \sigma_{S}(H)$ ratios as directly determined from the fragment and proton outputs of back-to-back ${ }^{235} \mathrm{U}$ and polyethylene radiators, as well as the $\sigma_{f}(25)$ values based on the Yale evaluation of $\sigma_{S}(H)$.

## B. NEUTRON DATA APPLICATIONS

1. Neutron Polarization Experiments (G. A. Keyworth)

An experiment to determine spins of subthreshold fission resonances in ${ }^{237} \mathrm{~Np}$ has been completed and the results accepted for publication in The Physical Review. The abstract is given below:
"A polarized neutron beam and a polarized target have been used to determine spins of 15 intermediate structure groups observed in the fission of ${ }^{237} \mathrm{~Np}$ below 1 keV and of 94 resonances observed in transmission below 102 eV . The pulsed neutron beam, from the Oak Ridge Electron Linear Accelerator, was polarized by transmission through a dynamically polarized proton sample. The ${ }^{237} \mathrm{~Np}$, in the ferromagnetic compound $\mathrm{NpAl}_{2}$, was cooled by a ${ }^{3} \mathrm{He}-{ }^{4} \mathrm{He}$ dilution refrigerator. Nine individual fine-structure resonances comprising the first group at 40 eV were determined to have the same spin, $J=3$, substantiating the current interpretation of intermediate structure in subthreshold fission in

Table A-6
LASL $\sigma_{f}\left({ }^{235} \mathrm{U}\right)$ Data (Fina1)

| $\mathrm{E}_{\mathrm{n}}(\mathrm{MeV})$ | $\underline{\sigma_{f}(25) / \sigma_{s}(\mathrm{H})}$ | \% Uncert. |  | $\sigma_{s}(H)^{a}$ | $\underline{\sigma_{f}(25)}$ | \% Uncert. |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Stat. | Syst. |  |  | Stat. | Syst. |
| 1.0 | 0.2908 | 0.8 | 0.8 | 4.261 | 1.239 | 0.8 | 1.3 |
| 1.1 | 0.3116 | 1.0 | 0.8 | 4.051 | 1.262 | 1.0 | 1.3 |
| 1.2 | 0.3245 | 0.8 | 0.8 | 3.868 | 1.255 | 0.8 | 1.3 |
| 1.3 | 0.3376 | 0.8 | 0.8 | 3.706 | 1.251 | 0.8 | 1.3 |
| 1.4 | 0.3466 | 1.7 | 0.8 | 3.561 | 1.234 | 1.7 | 1.3 |
| 1.5 | 0.3703 | 0.8 | 0.7 | 3.429 | 1.270 | 0.8 | 1.2 |
| 1.6 | 0.3752 | 0.8 | 0.7 | 3.309 | 1.242 | 0.8 | 1.2 |
| 1.7 | 0.4050 | 1.0 | 0.7 | 3.198 | 1.295 | 1.0 | 1.2 |
| 1.8 | 0.4122 | 1.1 | 0.7 | 3.097 | 1.277 | 1.1 | 1.2 |
| 1.9 | 0.4248 | 1.1 | 0.7 | 3.003 | 1.276 | 1.1 | 1.2 |
| 2.0 | 0.4362 | 0.4 | 0.7 | 2.915 | 1.272 | 0.4 | 1.2 |
| 2.2 | 0.4620 | 0.8 | 0.7 | 2.759 | 1.275 | 0.8 | 1.2 |
| 2.4 | 0.4785 | 1.3 | 0.7 | 2.622 | 1.255 | 1.3 | 1.2 |
| 2.5 | 0.4892 | 1.4 | 0.7 | 2.560 | 1.252 | 1.4 | 1.2 |
| 2.6 | 0.4879 | 0.6 | 0.7 | 2.501 | 1.220 | 0.6 | 1.2 |
| 2.7 | 0.5013 | 0.8 | 0.7 | 2.445 | 1.226 | 0.8 | 1.2 |
| 2.8 | 0.5064 | 0.7 | 0.7 | 2.392 | 1.211 | 0.7 | 1.2 |
| 2.9 | 0.5104 | 0.9 | 0.7 | 2.341 | 1.195 | 0.9 | 1.2 |
| 3.0 | 0.5281 | 0.3 | 0.7 | 2.293 | 1.211 | 0.3 | 1.2 |
| 3.2 | 0.5520 | 1.1 | 0.7 | 2.203 | 1.216 | 1.1 | 1.2 |
| 3.4 | 0.5589 | 1.2 | 0.7 | 2.120 | 1.185 | 1.2 | 1.2 |
| 3.5 | 0.5664 | 0.6 | 0.7 | 2.081 | 1.179 | 0.6 | 1.2 |
| 3.6 | 0.5792 | 1.2 | 0.7 | 2.043 | 1.183 | 1.2 | 1.2 |
| 3.7 | 0.5760 | 1.1 | 0.7 | 2.007 | 1.156 | 1.1 | 1.2 |
| 3.8 | 0.5906 | 1.3 | 0.7 | 1.973 | 1.165 | 1.3 | 1.2 |
| 4.0 | 0.5967 | 0.6 | 0.7 | 1.907 | 1.138 | 0.6 | 1.2 |
| 4.2 | 0.6203 | 1.4 | 0.8 | 1.845 | 1.144 | 1.4 | 1.3 |
| 4.4 | 0.6258 | 1.2 | 0.8 | 1.788 | 1.119 | 1.2 | 1.3 |
| 4.6 | 0.6340 | 1.3 | 0.8 | 1.734 | 1.099 | 1.3 | 1.3 |
| 4.8 | 0.6590 | 1.2 | 0.8 | 1.683 | 1.109 | 1.2 | 1.3 |
| 5.0 | 0.6668 | 1.1 | 0.8 | 1.635 | 1.090 | 1.1 | 1.3 |
| 5.1 | 0.6739 | 0.9 | 0.9 | 1.612 | 1.086 | 0.9 | 1.4 |
| 5.2 | 0.6868 | 1.0 | 0.9 | 1.589 | 1.091 | 1.0 | 1.4 |
| 5.3 | 0.6925 | 1.0 | 0.9 | 1.568 | 1.086 | 1.0 | 1.4 |
| 5.4 | 0.6903 | 0.7 | 0.9 | 1.547 | 1.068 | 0.7 | 1.4 |
| 5.5 | 0.6975 | 1.0 | 0.9 | 1.526 | 1.064 | 1.0 | 1.4 |
| 5.6 | 0.6966 | 1.0 | 0.9 | 1.506 | 1.049 | 1.0 | 1.4 |
| 5.7 | 0.7193 | 1.1 | 0.9 | 1.486 | 1.069 | 1.1 | 1.4 |
| 5.8 | 0.7454 | 2.1 | 0.9 | 1.467 | 1.093 | 2.1 | 1.4 |
| 5.9 | 0.7751 | 1.5 | 0.9 | 1.448 | 1.122 | 1.5 | 1.4 |
| 6.0 | 0.8015 | 1.8 | 0.9 | 1.430 | 1.146 | 1.8 | 1.4 |

${ }^{\text {a }}$ Yale evaluation reported by Stewart, LaBauve, and Young in LA-4574 [ENDF-141, EANDC-141]. As suggested by Stewart, $\sigma_{S}(H)$ is assigned a $1.0 \%$ uncertainty and in the $1-6 \mathrm{MeV}$ range this is assumed to be a systematic uncertainty.
terms of the Strutinsky double-humped deformation barrier. Correlation of these results with existing data on the angular distribution of fission fragments from aligned ${ }^{237} \mathrm{~Np}$ indicates an apparent admixing of transition states, as evidenced by nonintegral values of the projection quantum number, K."

In addition, the results of a preliminary measurement on ${ }^{235} \mathrm{U}$ have been published in the Physical Review Letters with the following abstract:
"A pulsed beam of polarized neutrons and a polarized target have been used to determine the spins of 65 resonances below 60 eV . Comparison of these spin assignments with those determined by less direct methods reveals poor agreement, in general. Interpretation of recent data on the angular distribution of fission fragments from aligned ${ }^{235} U$ with the present spin assignments reveals the absence of the $K=0$ channel and an apparent admixing of transition states."

Additional measurements on ${ }^{235} \mathrm{U}$ with higher neutron polarization and improved statistics will hopefully be undertaken in the near future.
2. Total Cross Sections of ${ }^{16} 0,,^{17} 0,{ }^{18} 0$, and ${ }^{12} \mathrm{C}$ from 1.6 MeV to 18 MeV (G. F. Auchampaugh, C. E. Ragan)

The total cross sections of the three stable oxygen isotopes and carbon have been measured from 1.6 MeV to 18 MeV using time-of-flight techniques with a $1-$ nsec pulsed $15-\mathrm{MeV}$ deuteron beam from the LASL Tandem accelerator bombarding a thick Be target and with a $31-\mathrm{m}$ fight path. A NE- 110 scintillator ( $12.7-\mathrm{cm}$ diam by $2.5-\mathrm{cm}$ thick) mounted on an RCA 8054 phototube was used as the neutron detector. The overall timing resolution was limited by the burst width which varied from 1 to 2 nsec during these measurements. The data are presented in Fig. B-1.
3. MULTI, a FORTRAN Code for Least-Squares Shape Fitting of Neutron Cross-Section Data Using the Reich-Moore Multilevel Formalism (G. F. Auchampaugh)

A LASL report (LA-4633) describing the FORTRAN code MULTI has been written and will be available for distribution in the near future. The present configuration of MULTI requires 40,000 words of central memory (system and user programs and common blocks) and 400,000 words of largecore storage memory. In this configuration MULTI will:
a. Simultaneously fit all four neutron cross sections: Total scattering, fission, and capture.
b. Doppler and resolution broaden all cross sections with a common resolution function which must be well defined and represented analytically.


Fig. B-1. Total cross sections of ${ }^{16} 0,{ }^{17} 0,{ }^{18} 0$, and ${ }^{12} \mathrm{C}$ from 1.6 to 18 MeV .
c. Handle up to 100 resonances which need not be located in the energy region being fitted and therefore can be used to generate a pseudobackground $\mathrm{R}^{\infty}$-type matrix.
d. Handle 0 (with or without the shift and boundary functions), 1 , or 2 fission channels per spin state with a total of ten spin states each representing either $s, p, d, f$, or $g$ wave neutron reactions.
e. Search on up to $150 / \mathrm{N}$ parameters where N is the number of cross sections fitted.
f. Handle $1600 / \mathrm{N}$ data points per cross section.

Running times per iteration on the CDC 7600 (6600) for the largest problem MULTI will handle are less than 10 (60) seconds.

## 4. Cross Section Evaluations for Version IV of ENDF/B

Several evaluations of neutron-induced cross sections are being submitted for Version IV of ENDF/B, as well as to the Defense Nuclear Agency's cross-section library at Oak Ridge. A list of the elements involved is given below, together with a brief description of the most important features of the new data.
a. ${ }^{\mathrm{I}} \mathrm{H},{ }^{3} \mathrm{H}$ (Stewart, LaBauve)

An improved representation of the capture gamma-ray data for ${ }^{1} \mathrm{H}$ was incorporated into the ENDF/B Version III evaluation and an existing ${ }^{3} \mathrm{H}$ LASL data set ${ }^{1}$ was converted to ENDF format.
b. ${ }^{4} \mathrm{He}$ (Nisley, Hale, Young)

A new evaluation based on an R-matrix analysis of the combined $n-{ }^{4} \mathrm{He}$ and $\mathrm{p}-{ }^{4} \mathrm{He}$ systems has been submitted.
c. ${ }^{6}$ Li, ${ }^{7}$ Li (LaBauve, Stewart)

Gamma-ray production data were added to the Version III
evaluations.

[^22]d. ${ }^{10} \mathrm{~B}$ (Hale, Nisley, Young)

A new coupled-channel R-matrix analysis has been incorporated below 1 MeV , and the Version III evaluation at higher energies has been extensively revised and expanded to include gamma-ray production data.
e. ${ }^{14} \mathrm{~N}$ (Young, Foster, Hale)

The existing Version III evaluation was revised to better represent the gamma-ray production measurements of Dickens et al for $E_{n}=$ $1-20 \mathrm{MeV}$.
f. ${ }^{16} 0$ (Hale, Foster, Young)

A coupled channel $R$-matrix analysis for $E_{n}=0-6 \mathrm{MeV}$ has been incorporated in the evaluated data, and extensive improvements were made at higher energies to better describe inelastic neutron scattering and gamma-ray production, including anisotropic angular distributions.
g. ${ }^{27} \mathrm{Al}$ (Young, Foster)

Extensive improvements have been made to the total cross section below 1 MeV and to the inelastic neutron scattering and gamma-ray production data at all energies, based mainly on the ( $n, n^{\prime}$ ) measurements of Kammerdiener ${ }^{2}$ at $E_{n}=14 \mathrm{MeV}$ and the ( $n, x \gamma$ ) measurements of Dickens et al. ${ }^{3}$ for $E_{n}=1-20 \mathrm{MeV}$.
h. ${ }^{182-186} \mathrm{~W}$ (Young)

A new evaluation of gamma-ray production for ${ }^{182} \mathrm{~W},{ }^{183} \mathrm{~W},{ }^{184} \mathrm{~W}$, and ${ }^{186} \mathrm{~W}$ has been incorporated into the recent neutron file evaluations by Rose. ${ }^{4}$
 to Neutron Interactions with Nitrogen for Incident Neutron Energies Between 2 and 20 MeV : Tabulated Differential Cross Sections," Oak Ridge National Laboratory report ORNL-4864 (1973).
${ }^{2} \mathrm{~J}$. L. Kammerdiener, "Neutron Spectra Emitted by ${ }^{239} \mathrm{Pu},{ }^{238} \mathrm{U},{ }^{235} \mathrm{U}, \mathrm{Pb}, \mathrm{Nb}$, Ni, Al, and C Irradiated by $14-\mathrm{MeV}$ Neutrons," Thesis, University of California at Davis (1972).
${ }^{3}$ J. K. Dickens, T. A. Love, and G. L. Morgan, "Gamma-Ray Production Due to Neutron Interactions with Aluminum for Incident Neutron Energies Between 0.85 and 20 MeV : Tabulated Differential Cross Sections," Oak Ridge National Laboratory report ORNL-TM-4232 (1973).
 and ${ }^{186} \mathrm{~W}$ Cross Sections for the ENDF/B Data File," Atomics International report TI-707-130-026 (1973).
i. ${ }^{235} \mathrm{U},{ }^{239} \mathrm{Pu}$ (Stewart, Hunter, LaBauve)

LASL is collaborating with other laboratories ${ }^{1}$ in the evaluation of neutron files for Version IV and is providing complete gamma-ray production data.
5. Decay Data for ENDF/B-IV (T. R. England)

LASL Groups T-2 and CNC-11 have been actively involved in a national task force to include decay data in ENDF/B-IV. This first file represents the cumulative efforts of all task force members.

The file contains decay data for 823 nuclides and 10 sets of direct fission yields each covering 1016 nuclides. All fission cumulative yields and their distribution vs charge have been evaluated. Approximately 300 unstable nuclides were identified as being of particular importance in decay heating and most of these received a new evaluation (based on their order of importance). The remainder use data from recent compilations and theoretical estimates where no measurements exist.

The decay data include: half-lives and uncertainties, the average $\beta$ (and/or other particle emissions) and total $\gamma$ energy, the detailed $\gamma$ line data and emission probabilities, and $\beta$ end-point energies and their branching fractions.
C. BASIC PHYSICS
${ }^{33} \mathrm{~S}(\mathrm{n}, \alpha)$ (G. F. Auchampaugh, W. M. Howard)
The branching ratio $\sigma(n, \alpha) / \sigma(n, \gamma)$ for ${ }^{33} S$ in the interval 50 to 500 keV is important to the astrophysicists in the study of the nucleosynthesis of the isotope ${ }^{36} \mathrm{~S}$. A preliminary measurement was made of the ${ }^{33} \mathrm{~S}(\mathrm{n}, \alpha)$ cross section at the LASL Vertical Van de Graaff accelerator using a thick ( 260 keV ) natural Li target bombarded by all-nsec pulsed beam of 2.4 MeV protons. The data were obtained with conventional time-of-flight techniques. The flight path ${ }_{3}$ was 0.56 m . Four $6-\mathrm{cm}^{2}$ surface barrier detectors were used to detect the ${ }^{33} \mathrm{~S}$ alpha particles. A total of 12.3 mg of $91 \%$ enriched ${ }^{3}{ }^{3} \mathrm{~S}$ was available for these measurements. The cross section was normalized to the ${ }^{10} \mathrm{~B}\left(\mathrm{n}, \alpha_{0}+\alpha_{1}\right)$ cross section. A preliminary average value of $\bar{\sigma}(n, \alpha)=39.2 \pm 0.6$ (stat.) mb was obtained for the energy interval from $\sim 400$ to $\sim 680 \mathrm{keV}$ using a value of 676 mB for the ${ }^{10} \mathrm{~B}\left(\mathrm{n}, \alpha_{0}+\alpha_{1}\right)^{7} \mathrm{Li}$ cross section.

[^23]Further measurements are planned to cover the interval from 50 to 600 keV with $5-\mathrm{kev}$ resolution. A collaborative measurement of the ( $n, \gamma$ ) cross section is planned in the near future at Oak Ridge National Laboratory's ORELA.

## D. NUCLEAR DATA FOR MATERIALS ANALYSIS, SAFEGUARDS, AND ENVIRONMENTAL MATTERS

Delayed Neutron Yield from the ${ }^{9} \mathrm{Be}(\mathrm{n}, \mathrm{p})^{9} \mathrm{Li}$ Reaction for $14.1 \leq \mathrm{E}_{\mathrm{n}} \leq$ 14.9 MeV (R. H. Augustson and H. O. Menlove)

The absolute value of the cross section for the delayed neutron yield from the ${ }^{9} \mathrm{Be}(\mathrm{n}, \mathrm{p})^{9}$ Li reaction for neutron energies of $14.1,14.5$, and 14.9 MeV has been measured. Lithium-9 decays by beta emission with a half-life of 175 msec to excited states of ${ }^{9} \mathrm{Be}$ which ${ }_{8} \mathrm{lie}$ above the neutronbinding energy, resulting in prompt neutron decay to ${ }^{8} \mathrm{Be}$. Thus ${ }^{9} \mathrm{Lj}$, along with ${ }^{17} \mathrm{~N}$, is one of the few nonfission delayed neutron precursors. Previous measurements ${ }^{2}$ of the cross section have had large assigned errors and have differed by orders of magnitude.

The $300-\mathrm{kV}$ Cockcroft-Walton accelerator operating in the pulsed mode provided the neutron irradiation utilizing the D,T reaction. An associated particle technique was used to determine the absolute neutron flux, and the delayed neutrons were detected in a calibrated flat response detector. 3 The half-life of the $\beta$ decay was accurately measured by following the delayed neutron decay. This half-1ife determination enabled a correction to be made to the cross-section value for the length of the irradiation period. Two Be samples, $5.08-\mathrm{cm}$ diam and $0.317-\mathrm{cm}$ thick, were used either singularly or combined for the measurements. Determinations of flux depression across the samples were made using Al activation foils placed in front and in back of the samples.

To determine the half-life of the delayed neutron decay, the ${ }^{9} \mathrm{Be}$ sample was irradiated for approximately one half-life and the decay followed for ten half-lives. The computer fit to the data yielded only one decay constant with a value of $0.175 \pm 0.001 \mathrm{sec}$.

A value for the average delayed neutron energy from the ${ }^{9}$ Be decay was obtained by using the front-to-back ratio of the slab detector as described in Ref. 3. This technique gave an average energy of 500 keV for the ${ }^{9} \mathrm{Be}$

[^24]delayed neutrons, a value much lower than had previously been reported.

For the cross-section measurement the accelerator was pulsed on and off repetitively at a $50 \%$ duty with a total period of 120 msec . A similar irradiation technique to measure the delayed neutron yields from fissionable isotopes has been described by Masters et al. ${ }^{2}$ A $3.6 \%$ correction based on the $175-\mathrm{msec}$ half-life was made in the data analysis for decay of delayed neutrons during the $60-\mathrm{msec}$ irradiation.

The absolute efficiency of the delayed neutron detector was obtained using a ${ }^{238} \mathrm{Pu}-\mathrm{Li}$ source calibrated by the National Bureau of Standards to within $\pm 3 \%$. The average energy of this source is 650 keV , thus lying close to the ${ }^{9}$ Be delayed neutron average energy.

The resulting cross-section values are:

$$
\begin{aligned}
\sigma_{\mathrm{n}, \mathrm{p}}(\text { activation })= & 0.210 \mathrm{mb} \pm 0.013 \text { at } 14.9 \mathrm{MeV} \\
& 0.053 \mathrm{mb} \pm 0.005 \text { at } 14.5 \mathrm{MeV} \\
& <0.004 \mathrm{mb} \text { at } 14.1 \mathrm{MeV}
\end{aligned}
$$

It can be seen that the ${ }^{9} B e(n, p)$ cross section varies quite rapidly in this energy region, possibly explaining the apparent discrepancies between previous values.

## E. CONTROLLED THERMONUCLEAR RESEARCH

1. $D(\vec{d}, \vec{n})^{3}$ He Reaction [Salzman, Ohlsen, Martin; Jarmer (AWU-U of Wyoming) and Donoghue (Ohio State)]

A paper with the above authors and the following abstract, on the angular distribution of the polarization and polarization transfer functions for the $D(d, n)^{3} \mathrm{He}$ reaction has been submitted to Nuclear Physics:

[^25]"Angular distrịbutions, of six polarizațion transfer coefficients $K_{x}^{\mathrm{x}}(\theta), K_{x}^{z}(\theta), K_{z}^{x^{p}}(\theta), K_{z}^{z}(\theta), K_{y}^{y}(\theta)$, and $K_{y y}^{y^{\prime}}(\theta)$; of the four analyz-powers $A_{y}(\theta), A_{x x}(\theta), A_{y y}(\theta)$, and $A_{z z}(\theta)$; and of the polarization function $\mathrm{Py}^{4}(\theta)$, have been measured at $E_{d}=10.00 \mathrm{MeV}$ for the reaction $B(d, n)^{3} \mathrm{He}$. Measurements were made for neutron laboratory angles between 0 and $80^{\circ}$ in $10^{\circ}$ steps. Additionally, the y axis associated quantities were measured at $\theta_{1 \mathrm{ab}}=99^{\circ}$. Most of the coefficients are large at some angles and all show considerable variation with ang1e."
2. ${ }^{4} \mathrm{He}(\overrightarrow{\mathrm{d}}, \overrightarrow{\mathrm{d}})$ Polarization Transfer [Oh1sen, Salzman, Mitchell (EGGG), Gruebler (ETH, Zurich), and Simon (U. Wyoming)]

A paper on this work with the above authors and the following abstract has been submitted to Physical Review C:
'We report measurements of the four analyzing tensors and of up to fourteen polarization transfer coefficients, at each energy and angle studied, for ${ }^{4} \mathrm{He}(\mathrm{d}, \mathrm{d}){ }^{4} \mathrm{He}$ elastic scattering. This number of observables greatly overdetermines the scattering matrix, and many consistency checks are therefore available. These data represent the first measurements of deuteron polarization transfer phenomena. Bombarding energies were in the range 4.8 to $9.0 \mathrm{MeV} . "$
3. Absolute M Matrix Elements for ${ }^{4} \mathrm{He}(\overrightarrow{\mathrm{d}}, \overrightarrow{\mathrm{d}})^{4} \mathrm{He}$ (Salzman and Oh1sen)

A gradient search technique has been used to determine the elements of the ${ }^{4} \mathrm{He}(\overrightarrow{\mathrm{d}}, \overrightarrow{\mathrm{d}})^{4} \mathrm{He}$ scattering matrix at eight energy-angle pairs. The polarization transfer data reported above was the input for this work. This represents the first case, we believe, in which all elements of the scattering matrix are known for such a complex case. However, we are not yet satisfied with the fits, so the writing of a Physical Review Letter has been delayed. We also wish to compare our results to the 6 -nucleon problem analysis being carried out in collaboration with Dodder, Lovoi, and Crosthwaite.




## THE UNIVERSITY OF MICHIGAN

## A. THE PHOTONEUTRON FACILITY (G. F. Knoll)

A facility for the determination of primary neutron cross section standards is now operational in the Phoenix Memorial Laboratory at The University of Michigan. The facility consists of a low neutron background laboratory, a manganese bath neutron source comparator, and equipment for the uniform in-pile activation and routine remote handling of photoneutron sources. The choice of suitable gamma ray emitters is limited to the relatively long lived isotopes ${ }^{24} \mathrm{Na},{ }^{72} \mathrm{Ga}$, and ${ }^{124} \mathrm{Sb}$ because of the length of time required for handling the highly radioactive sources and the restrictions on maximum gamma activity.

Photoneutron sources are prepared by irradiation in the Ford Nuclear Reactor. Uniform activation is assured by continuous rotation of the source during irradiation at the midplane of the core. Specialized handling tools permit complete underwater transfer of the source from the core to the adjacent hot cave where it is inserted into a mobile cask for transfer to the nearby low neutron background laboratory.

The cross section measurements are conducted in a room having a mean radius of 2.3 m . The thick concrete walls required to provide shielding for personnel against the intense gamma activity of the sources required installation of a 2 inch thick anhydrous borax liner to reduce the room return component of the neutron flux. Measurements using a $3_{\mathrm{He}}$ detector and a Pu-Be neutron source show reduction of the relative background count rate from $129 \%$ to $1.5 \%$ due to the borax lining.

A manganese bath neutron source comparator makes possible the absolute determination of the photoneutron yielá, and hence the flux in the vicinity of the source. Two long lived local reference sources have been calibrated by comparison with the National Bureau of Standards source NBS-II, and photoneutron sources are calibrated against these local references.

The manganese sulfate solution is held in a spherical tank of 98.3 cm I.D. with the source supported at the center in a re-entrant tube of 4.6 cm I.D. For the $\mathrm{Na}-\mathrm{Be}$ source - the highest energy photoneutron source used - the neutron leakage from the bath (excluding streaming from the source tube which is directly measured) is estimated to be $0.5 \%$. The solution is constantly mixed by a rapid recirculation of the fluid with a radially inward flow pattern. A fraction of the recirculated flow is passed through a heavily shielded detector chamber in the adjacent room for continuous monitoring of the manganese activity by a NaI detector.

The efficiency of the bath is $2.65 \times 10^{-4}$ counts/neutron, giving more than adequate counting statistics (typically, standard deviation $=0.03 \%$ ).

Reproducibility of $0.1 \%$ has been achieved in neutron source comparisons, and an overall accuracy below $1 \%$ is achieved in the photoneutron source calibrations when the residual uncertainties from all corrections are included.

## B. ABSOLUTE DETERMINATION OF THE ${ }^{235}$ U FISSION CROSS SECTION AT 964 keV

 (D. M. Gilliam, G. F. Knoll)A sodium-beryllium photoneutron source emitting essentially monoenergetic neutrons has been employed to measure the 235 U fission cross section at 964 keV with absolute flux determination. Fission events are recorded by a pair of limited solid angle track-etch detectors. The symmetric arrangement of the source and detectors minimizes geometric uncertainties in the flux determination. Rather thick $U_{3} 0_{8}$ deposits (l.1 mg $\mathrm{U} / \mathrm{cm}^{2}$ ) are allowed by the limited solid angle counting, the oxide masses being known from weighings performed by the supplier. The calculation of the efficiency of the detectors takes into account the anisotropy of the fission fragment emission, using empirical angular distributions. The fission fragment track recorder material is a commercial polyester plastic film. The accumulated tracks are displayed on the screen of a projection microscope and counted by hand. The neutron yield of the source is determined by means of a continuously sampled manganese bath. Because of the short half-life of the ${ }^{24} \mathrm{Na}$ relative to the time required to achieve nearlysaturated manganese activity, careful analysis of the kinetics of manganese activation and mixing delays is required in processing the 56 Mn counting data. The bath counting data are accumulated over a sequence of accurately timed short intervals spanning the entire calibration cycle. The efficiency of the manganese bath is determined relative to the secondary national standard source NBS-II. The average magnitude of the scalar neutron flux over the uranium deposit is determined from the source yield and vacuum streaming calculations which include consideration of the angular and spatial distributions of the photoneutron production and corrections for scattering. Small contributions to the fission rate from wall-scattered neutrons are eliminated by comparison of fission rates at several different source-detector spacings.

The value of the ${ }^{235} \mathrm{U}$ fission cross section determined by the present measurement is

$$
\sigma_{\mathrm{n}, \mathrm{f}}(964 \pm 16 \mathrm{keV})=1.20 \text { barns } \pm 2.3 \% \text { (Sta. Dev.) }
$$

The indicated uncertainty in the neutron energy encompasses the kinematic spread of the photoneutron energy distribution. The $2.3 \%$ estimate of the error is composed of $1.84 \%$ random error and $1.35 \%$ systematic error. Each component is a quadrature sum (square root of the sum of the squares of individual error contributions. Additional measurements have recently been made which should reduce the expected error in our result below $\pm 2 \%$.
C. $\frac{\text { ABSOLUTE FISSION CROSS SECTION OF } 235 \mathrm{U} \text { AT } 261 \mathrm{keV}}{\text { M. C. Davis, J. C. Engdahl) }}$ (G. F. Knoll,

Techniques similar to those described above are now being used to measure the 235 U fission cross section at 261 keV . A spherical ${ }^{24} \mathrm{Na}-\mathrm{D}$ source has been substituted to provide a sharply peaked neutron spectrum with 261 keV median energy. The same pair of fission foils is used to again provide dual geometry, and tracks etched in polyester film serve as the fission detector. The initial fission rate measurements have been made, other measurements are in progress.
D. THE ${ }_{\text {Li }}(n, \alpha)$ CROSS SECTION AT 964 keV (W. P. Stephany, G. F. Knoll)

The photoneutron facility has also been used over the past year to complete an absolute measurement of the $\sigma_{\mathrm{Li}}(\mathrm{n}, \alpha)$ cross section. The same sodium-beryllium neutron source described earlier has been used with a fully depleted "inverse sandwich" silicon detector with LiF deposits on both faces. Target masses were inferred from measured "monitor foils" exposed during the target evaporation. $85-90 \%$ of the reaction products were discernable above the gamma pile-up tail on pulse height spectra recorded during the neutron exposures. Thermal neutron-induced spectra were used to derive the fraction of events lost below the gamma pile-up tail.

Measurements and initial analysis have been completed. A preliminary value of $333 \mathrm{mb} \pm 7 \%$ is indicated pending a more detailed examination of the data and a complete error analysis.
E. $\frac{\text { THE }{ }^{239} \text { Pu FISSION CROSS SECTION AT } 964 \mathrm{keV}}{\text { J. C. Engdahl) }}$ (G. F. Knoll, M. C. Davis,

Work has begun toward the measurement of plutonium fission cross sections using techniques similar to those described earlier for uranium. Dual ${ }^{239} \mathrm{Pu}$ foils of $\sim l \mathrm{mg} / \mathrm{cm}^{2}$ thickness are mounted in a vacuum tight experiment package and the irradiated neutron source put in place by remote manipulators. Initial determinations will be made using the sodium-beryllium source with a median energy of 964 keV .

## NATIONAL BUREAU OF STANDARDS

## A. NEUTRON PHYSICS

1. MeV Total Neutron Cross Sections (R. B. Schwartz, R. A. Schrack, and H. T. Heaton II)

NBS Monograph 138, with the above title, is now in galley proof, with publication hoped for by the end of the year. The monograph will contain cross section curves for twelve normally occurring elements plus the separated isotopes $235 \mathrm{U}, 238 \mathrm{U}$, and 239 Pu . An appendix is included which gives complete details of the experimental technique.

A separate paper on the uranium and plutonium measurements has been prepared for publication in Nuclear Science and Engineering, and is now proceeding through the editorial review process.
2. keV Total Neutron Cross Sections (H. T. Heaton II, J. L. Menke, R. A. Schrack, R. B. Schwartz, and A. D. Carlson)

The measurements of the carbon cross section from 1 keV to 1 MeV have been completed, the data are being analyzed, and a paper is being written. The paper will include our earlier MeV data and hence will describe measurements of the carbon cross section to $1 \%$ accuracy over the range of 1 keV to 15 MeV .

Measurements have been made of the ${ }^{239} \mathrm{Pu}$ total neutron cross section from 0.5 to $\sim 100 \mathrm{keV}$ where data are needed for the new ENDF/B version 4 evaluation. Structure has been observed which has not been reported in previous measurements of this cross section.
3. Average Neutron Transmission Measurements (H. S. Camarda)

A paper entitled, "p-Wave Neutron Strength Function Measurements and the Low Energy Optical Potential" has been accepted for publication in the Physical Review. The abstract follows:
"Using the National Bureau of Standards electron linac and underground time-of-flight facility, precise average neutron transmission measurements have been made in the energy range $1 \mathrm{keV} \leq \mathrm{E} \leq 600 \mathrm{keV}$ on the elements As, $\mathrm{Br}, \mathrm{Nb}, \mathrm{Rh}, \mathrm{Ag}, \mathrm{In}, \mathrm{Sb}, \mathrm{I}, \mathrm{La}, \mathrm{Ho}, \mathrm{Au}$, and Th . The samples were "thick" in that the $s$ wave self-protection was accounted for at low energies. However, the samples were still sufficiently thin that any errors introduced by neglecting $p$ wave self-protection are negligible. The average R-matrix theory was employed in the analysis and the $\ell=0$ scattering length $R^{\prime}$ and the $p$ wave strength function $S_{1}$ were
extracted from the data. The behavior of $S_{1}$ vs mass number $A$ in the region of the 3 maximum was found to vary smoothly with no evidence of any splitting of the resonance. Further, it was found that the predicted behavior of $\mathrm{S}_{1}$ vs A calculated with Moldauer's optical potential, which fits the $\ell=0$ data well, differs significantly from experiment. In particular, experiment indicates $S_{1}$ peaks at a lower mass number and that the maximum is stronger than indicated by the calculations. When the constants of the potential were changed in. order to reproduce the observed behavior of $\mathrm{S}_{1}$, a significant discrepancy with the $\ell=0$ data resulted. The results presented here imply a state dependence of the low energy optical potential. It is noted that more fundamental studies indicate a state dependence of the real potential of the optical model."

## 4. Calculation of Intermediate Energy Standard Neutron Field (ISNF) Facility (A. Fabry* and C. Eisenhauer)

We have calculated the neutron flux spectrum for the center of the ISNF facility. This facility consists of a spherical boron shell 15 mm thick, with a diameter of 12 cm , located in a 30 cm cavity in the (graphite) thermal column. Fission sources are located near the periphery. The spectrum was calculated using ANISN, a multigroup, discreteordinates computer program. Efforts are underway to permit calculation of the response of various types of detectors placed within the facility.
5. Beam Filters (R. B. Schwartz and I. G. Schröder)

The scandium filters from the MTR have arrived, and the collimators, manganese scatterer, etc., are under construction. The filter should be ready to install by the next reactor shut-down. The calculated intensity of the 2 keV neutron beam produced by the filter is $\sim 10^{6}$ $\mathrm{n} / \mathrm{cm}^{2} / \mathrm{sec}$. By using as a source a manganese scatterer placed at the center of a through tube, it is calculated that the higher energy neutron flux will be less than $5 \%$ of the 2 keV flux.

## B. PHOTONUCLEAR PHYSICS

1. Measurement of the ${ }^{3} \mathrm{He}(\mathrm{Y}, \mathrm{d})$ Cross Section from 10 to 21 MeV (W. R. Dodge)

We have measured the ${ }^{3} \mathrm{He}(\mathrm{e}, \mathrm{d})$ cross section from 10 to 21 MeV and from these measurements deduced the ${ }^{3} \mathrm{He}(\gamma, d)$ cross section. 1 The magnitude and average shape of the ${ }^{3} \mathrm{He}(\gamma, d)$ cross section provide information

[^26]primarily about rescattering effects in the final (continuum) state. Structure in the ${ }^{3} \mathrm{He}(\mathrm{r}, \mathrm{d})$ cross section would provide evidence for the existence of excited states in the ${ }^{3} \mathrm{He}$ ground state. Two recent experiments have given evidence for such structure. ${ }^{2,3}$ Our measurement of the $3^{\mathrm{He}}(\gamma, \mathrm{d})$ cross section is consistent with a structureless, smooth cross section and did not reproduce the reported structure. 2,3 Our absolute cross section is fitted by the theoretical calculation of Barbour and Phillips ${ }^{4}$ and Hendry and Phillips ${ }^{5}$ in which the final state is described by a wave function which is a solution of the Faddeev equations in the separable approximation.
2. Measurement of the ${ }^{2} H(\gamma, p)$ Cross Section from 4.5 to $40 \mathrm{MeV}{ }^{*}$ (W. R. Dodge)

In 1971 Tieze et a1 ${ }^{6}$ published experimental data which gave evidence for deviations of as much as $20 \%$ for the ${ }^{2} H(\gamma, p)$ cross section from the celebrated and widely accepted theoretical cross section of Partovi. Other corroborating experimeptal results were published by Weissman and Schultz ${ }^{7}$ and Baglin et al. Since the deuteron is the simplest and hence presumably the best understood nuclear system, deviations from theoretical predictions by this amount are indeed serious. Furthermore, the deuteron photodisintegration cross section has served as a standard cross section for many photodisintegration cross section measurements, and if incorrect will require readjustment of these cross sections. We are currently making a very careful measurement of the electrodisintegration cross section under conditions which will allow the ${ }^{2} \mathrm{H}(\mathrm{e}, \mathrm{p})$ cross section to be extrapolated to the ${ }^{2} \mathrm{H}(\mathrm{\gamma}, \mathrm{p})$ cross section with minimum uncertainty. Our preliminary $90^{\circ}$ differential cross section values at excitation energies of $5.5,6.8,8.0,10.0,12.0$ and 15.0 MeV
${ }_{\text {Rel evant }}$ to Request No. 588, USNDC-6.
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are $.265 \pm .016, .231 \pm .014, .194 \pm .012,149 \pm .009, .120 \pm .007$, and $.084 \pm .005 \mathrm{mb} / \mathrm{sr}$. The theory of Partovi predicts . 271, . 237, . 206, . 135 and $.103 \mathrm{mb} / \mathrm{sr}$ at these excitation energies.

## C. APPLIED NUCLEAR PHYSICS

1. Radioactivity Decay Schemes (A. T. Hirshfeld and D. D. Hoppes)

NBS-prepared gamma-ray emission rate standards have been used to determine the efficiency of a $G e(L i)$ system at 24 different energies from 60 to 1840 keV . Efficiencies at 19 points above 270 keV are fit to a simple analytic function of the energy with a mean deviation of $1 \%$, using present decay scheme information and calibrations. After a few remaining efficiency determinations have been made, the resulting function will be used to evaluate gamma-ray branchings in silver - 110 m , silver - 108m, antimony - 125, and barium - 133.

## D. ACCELERATOR TECHNOLOGY

1. Induction Linear Accelerator Development (J. E. Leiss and M. Wilson)

Theoretical and experimental studies have been underway at NBS for about 2-1/2 years directed toward the design of high current induction linear accelerators. The objectives have been directed toward reducing cost and complexity of these accelerators relative to previous technology, particularly as might be required for higher energy, longer pulse accelerators than previously available.

Proof of the success of these studies have recently been demonstrated by the initial operation of a test accelerator operating with a 450 keV injector, and 400 keV additional induction acceleration, obtained from two induction cores. Beam pulse lengths of about 1.7 microseconds, and beam currents of about 900 amperes have been achieved. Beam transmission from the injector cathode to the end of the accelerator is about 90 percent. Higher energies can be readily achieved by addition of more accelerating cores.

These successful beam tests demonstrate the validity of a number of new innovations in the design of induction accelerators which make this type of accelerator practical for specialized applications. They also demonstrate the validity of special beam dynamics computer programs developed for accelerators operating in this very high current regime.

## E. DATA COMPILATION

1. X-Ray Attenuation Coefficient Information Center (J. H. Hubbell and W. J. Veigele*)

A set of theoretical coherent and incoherent scattering factors $F(q, Z)$ and $S(q, Z)$ for elements $Z=1-100$ to arbitrarily high $q$-values ( $q=$ momentum transfer in units of $\sin (\theta / 2) \lambda$, inverse angstroms) has been assembled for inclusion in the ENDF/B tape system and will comprise File 27, MT 502 and 504, heretofore vacant. These values are still being tested against experimental values from the literature, in collaboration with Veigele at Kaman.

The presently assembled values consist of Pirenne "exact" values for $Z=1$, R. T. Brown configuration-interaction values for $Z=2$ to 6 , and D. T. Cromer non-relativistic SCF Hartree-Fock values for $Z=7-100$. For $q$-values above $10.0 \AA^{-1}, Z=2$ to 100 , the asymptotic expression for $F(q, Z)$ given by Bethe and Levinger, as suggested by Pratt, Gavrila and Tsing, is used. These values of $F(q, Z)$ and $S(q, Z)$ will also be submitted for publication in the Journal of Physical and Chemical Reference Data.

## F. FACILITIES

1. Above-Ground Neutron Time-of-Flight Faci1ity (C. D. Bowman, S. Penner, A. D. Carlson, and J. L. Menke)

A considerable amount of progress has been made on this facility since the last USNDC status report. Electron beams are now routinely transported to both the 5 foot high and 8 foot high target positions. The 5 foot target will provide neutron beams for the 5 and 20 meter stations and the 8 foot target will be used for the 60 and 200 meter stations. The 5 meter station is now completely operational. The 20,60 and 200 meter facilities are now under construction and should be completed in early 1974. A number of additional beam parts are available for expansion in the future. Experiments are now being prepared for this facility.
2. 3 MV Van de Graaff Facility (M. M. Meier, G. P. Lamaze, and A. D. Carlson)

The 3 MV Van de Graaff accelerator has been operating satisfactorily since the most recent USNDC status report. Most down time has been due to routine source replacement at $\sim 100 \mathrm{hr}$ intervals. A threefold increase in analysed, plused beam was realized in a recent test of the effect of a quadrupole doublet at the accelerator exit. Since the

[^27]quadrupole used in the test is ordinarily part of the beam transport system, permanent implementation of this improvement will have to await fabrication of a duplicate quadrupole.

An associated particle apparatus for keV neutron flux normalization is being assembled in the low scatter experimental area. This device, similar to that described by Liskien and Paulsen, monitors neutron flux from the $T(p, n)^{3} \mathrm{He}$ reaction by detecting the associated ${ }^{3} \mathrm{He}$ nuclei. Charged particle time of flight and energy, as well as electrostatic deflection are used to eliminate elastically scattered protons and unwanted reaction products. The apparatus now being installed will cover the energy range from 100 to 500 keV with an estimated yield on the order of 100 neutrons/second in the associated cone. The system is designed so that a simple modification will extend the range to 1 MeV .

The Datacraft 6024/5 computer and magnetic tape unit have arrived. Software development and interfacing to CAMAC for data acquisition are underway and on-line operation is anticipated in the near future.

OAK RIDGE NATIONAL LABORATORY
A. NEUTRON DATA APPLICATIONS SUBCOMMITTEE
A.1. Nonfission

1. $\frac{\text { Multilevel Effects in the Unresolved Resonances Region of }}{\text { the Cross Sections of Fissile Nuclides*,** (G. de Saussure }}$

For the specification of the cross sections of the fissile isotopes in the neutron energy region of unresolved resonances, the singlelevel formalism is often used while an analysis of the cross sections in the resolved region indicates that a multilevel formula may be more appropriate. In this paper we compare the statistical properties of the cross sections generated using the single-level formalism with those obtained by a multilevel formulation. The multilevel parameters were chosen so as to give the same average cross sections as the single-level formalism. The comparison indicates that there are small but significant differences between the statistical properties of the cross sections obtained with the multilevel formalism and those obtained with the single-level formula. The differences are probably too small, particularly when Doppler broadening is considered, to affect reactor calculations.

[^28]2. The Transformation of a Set of Multilevel Resonance Parameters

Into an Equivalent Set of Single-Level Pseudoparameters and a "Smooth Background"* (G. de Saussure and R. B. Perez)

A method is described to transform a set of multilevel resonance parameters into an equivalent set of single-level pseudoparameters and a "smooth background". The method utilizes a Kapur-Peierls expansion of the cross sections and does not necessitate "refitting" of the data. It is illustrated by an example.
\# To be published in Nuclear Science and Engineering.
3. $\frac{\text { Integral Neutron Scattering Measurements on Iron from } 1 \text { to }}{20 \mathrm{MeV} *, * * \text { (G. L. Morgan, T. A. Love and F. G. Perey) }}$

The spectrum of neutrons scattered through $90^{\circ}$ by a thick ( $\approx 1$ mean free path) annulus of iron has been measured as a function of the incident neutron energy over the range from 1 to 20 MeV . The measurements
were made for an incident neutron beam with smooth energy dependence and with an incident beam structured by an iron filter (also $\approx 1 \mathrm{~m} . \mathrm{f} . \mathrm{p}$. ). The results of the measurement are presented in forms suitable for comparison to calculations based on the evaluated neutron data files.

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    Abstract of ORNL-TM-4193
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    Relevant to request No. 150.
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4. Is There Still a Nitrogen Cross-Section Discrepancy?* $* *$ (F. G. Perey and J. K. Dickens)

For several years there have been great uncertainties as to which nitrogen neutron cross-section set should be used for neutron transport of $14-\mathrm{MeV}$ neutrons in air. Various discrepancies were found between microscopic cross-section measurements and difficulties experienced in calculating correctly results of integral experiments. Most neutron air transport calculations have been performed using either the nitrogen crosssection set of Straker (1969) or the Young-Foster (1970) set. These two cross-section sets differ by about a factor of two in gamma-ray production cross sections around 14 MeV . In this short note we review the status of these evaluated cross-section sets on the basis of recent work and conclude that the Young-Foster evaluation, MAT 4133 Mod 2, is more consistent with all the available information and should be preferred over the Straker set.

[^29]5. Gamma-Ray Production Due to Neutron Interactions with Nickel for Incident Neutron Energies Between 1.0 and 20 MeV : Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with nickel have been obtained for neutron reactions for neutron energies between 1.0 and 20 MeV . These data were obtained using two different experimental systems: (a) $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{dE}$ values were obtained for $\theta_{\gamma}=125$ deg using a NaI spectrometer. These data are presented as gamma-ray production group cross-section values of $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{dE}$ for $0.7 \leq \mathrm{E}_{\gamma} \leq 10.5 \mathrm{MeV}$, with gamma-ray intervals ranging from 20 keV for $\mathrm{E}_{\gamma} \leq 1 \mathrm{MeV}$ to 160 keV for $\mathrm{E}_{\gamma} \sim 9 \mathrm{MeV}$. Neutron energy intervals varied from 0.5 MeV for $\mathrm{E}_{\mathrm{n}}=1$ to 8 MeV to 3 MeV for $\mathrm{E}_{\mathrm{n}}=14$ to 20 MeV . (b) Discrete line values ${ }^{\mathrm{n}} \mathrm{f} \mathrm{d} \sigma / \mathrm{d} \omega$ for transitions due $\mathrm{t}_{\mathrm{n}}$ neutron interactions with nickel were obtained at $\theta_{\gamma}=55$ or 125 deg for $E_{n}=4.85,5.4$, and 5.9 MeV using $\mathrm{Ge}(\mathrm{Li})$ spectrometers.

[^30]6. Gamma-Ray Production Cross Sections Due to Neutron Interactions

Interactions of neutrons with titanium have been studied by measuring gamma-ray production cross sections. For a sample of natural titanium, spectra were obtained for incident mean neutron energies $E=$ $4.9,5.4$ and 5.9 MeV with gamma-ray detector systems utilizing coaxial Ge(Li) detectors. Nearly monoenergetic neutrons were obtained from the $d(d, n)$ reaction using deuterons obtained from the (pulsed) ORNL 5-mV Van de Graaff Accelerator. Time of flight was used with the detector to discriminate against pulses due to neutrons and background radiation. Gammaray identification was aided by obtaining several spectra for samples enriched in the isotopes ${ }^{46} \mathrm{Ti}$ and ${ }^{48} \mathrm{Ti}$, and new information on the level structures of these two isotopes was obtained. Absolute differential cross sections for production of gamma rays were obtained and are reported. These cross sections have been compared, where possible, with previous ( $n, n^{\prime}$ ) measurements and with cross sections derived from the current ENDF/B evaluation.

[^31]7. Gamma-Ray Production Due to Neutron Interactions with Silicon for Incident Neutron Energies Between 1.0 and 20 MeV : Tabulated Differential Cross Sections* (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with silicon have been obtained for neutron energies between 1.0 and 20 MeV . The cross-section values were obtained using a NaI spectrometer. These data consist of (a) neutron and gammaray production group cross-section values of $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{dE}$ for $\theta_{\gamma}=125$ and 90 deg and for $0.7 \leq \mathrm{E}_{\gamma} \leq 10.5 \mathrm{MeV}$, with gamma-ray intervals ranging from 20 keV for $\mathrm{E}_{\gamma} \leq 1 \mathrm{MeV}$ to 160 keV for $\mathrm{E}_{\gamma} \approx 9 \mathrm{MeV}$ and with neutron energy intervals varying from 0.25 MeV for $\mathrm{E}_{\mathrm{n}}=1.0$ to 2.0 MeV to 3 MeV for $\mathrm{E}_{\mathrm{n}}=$ 14 to 20 MeV ; and (b) values of do/dwfor $E_{\gamma}=1.78 \mathrm{MeV}$ for $\theta_{\gamma}=125 \mathrm{deg}$ and for $\mathrm{E}_{\mathrm{n}}$ between threshold and 9.6 MeV .

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*Abstract of ORNL-TM-4389.
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8. Natural Titanium Neutron Elastic- and Inelastic-Scattering Cross Sections from 4.07 to $8.56 \mathrm{MeV}^{*}$ (W. E. Kinney and F. G. Perey)

Measured cross sections per atom of natural titanium for neutron elastic and for inelastic scattering to levels in ${ }^{48} \mathrm{Ti}$ for
incident neutron energies between 4.07 and 8.56 MeV are given and compared with previous results. ENDF/B III Mat 1144 angular distributions are in reasonably good agreement with experimental results at angles less than 40 degrees but differ by as much as an order of magnitude at larger angles. The ENDF/B III Mat 1144 angle-integrated elastic-scattering cross sections agree within experimental uncertainties with experimental results at energies below 6.44 MeV but rise $20 \%$ above measured values at 8.56 MeV . ENDF/B III Mat 1144 inelastic-scattering cross sections to discrete levels in ${ }^{48} \mathrm{Ti}$ are in poor agreement with experimental data because of the predominance of continuum inelastic scattering in ENDF/B III Mat 1144. An evaporation model of inelastic scattering to the continuum is found to be valid for inelastic scattering to levels of excitation energy greater than 6 MeV but is questionable for inelastic scattering to levels of lower excitation energy.

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*Abstract of ORNL-4810.
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9. ${ }^{63} \mathrm{Cu}$ and ${ }^{65} \mathrm{Cu}$ Neutron Elastic- and Inelastic-Scattering Cross Sections from 5.50 to $8.50 \mathrm{MeV}^{*}, * *$ (W. E. Kinney and F. G. Perey)

Measured neutron elastic- and inelastic-scattering cross sections for ${ }^{63} \mathrm{Cu}$ and ${ }^{65} \mathrm{Cu}$ between 5.50 and 8.50 MeV are presented and compared with elastic data of Holmqvist and Wiedling and with ENDF/B III Mat 1085 and 1086. Our elastic differential cross sections are in fair agreement with those of Holmqvist and Wiedling in shape. Our angleintegrated differential elastic cross sections are systematically higher by as much as $20 \%$ than those of Holmqvist and Wiedling above 5 MeV , a situation similar to that found in comparing the two sets of data for other elements. ENDF/B III Mat 1085 and 1086 angular distributions underestimate the elastic forward peak below 20 deg . When compared with experimental results and display unphysical fluctuations due to the use of a Legendre series of order 20 where order 9 is the highest required by the data. An evaporation model with temperature ranging from 0.8 and 1.05 MeV reasonably describes inelastic scattering to levels in the residual copper nuclei of excitation energy above 3.2 MeV .

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    *Abstract of ORNL-4908.
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    Relevant to request No. 201.
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> 10. Natural Chromium and ${ }^{52}$ Cr Neutron Elastic and Inelastic Cross Sections from 4.07 to $8.56 \mathrm{MeV}^{*}$,** (W. E. Kinney and F. G. Perey)

Measured neutron elastic- and inelastic-scattering cross sections for natural chromium between 4.07 and 8.56 MeV and for ${ }^{5}{ }^{2} \mathrm{Cr}$ between 6.44 and 8.56 MeV are presented and compared with the elastic


#### Abstract

differential cross sections of Holmqvist and Wiedling and with ENDF/B Mat 1121. Our elastic differential cross sections are in fair agreement with those of of Holmqvist and Wiedling. Our angle-integrated differential elastic cross sections are systematically higher by as much as $17 \%$ than those of Holmqvist and Wiedling above 4.6 MeV , a situation similar to that found in comparing the two sets of data for other elements. The ENDF/B III Mat 1121 elastic angular distributions are found to be in poor agreement with experimental results from 4 to 8.5 MeV though the ENDF/B III Mat 1121 angle-integrated differential elastic cross sections agree within experimental uncertainties with our results over this energy range. An evaporation model of inelastic scattering to levels of excitation energy in the residual nucleus below 6 MeV is found to be of questionable validity.


[^32]11. $\frac{\text { Natural Nickel and }{ }^{60} \text { Ni Neutron Elastic- and Inelastic- }}{\frac{\text { Scattering Cross Sections from } 4.07 \text { to } 8.56 \text { MeV }}{} \text { (W. E. Kinney and F. G. Perey) }}$

Measured neutron elastic- and inelastic-scattering cross sections for natural nickel between 4.07 and 8.56 MeV are presented and compared with the elastic differential cross sections of Holmqvist and Wiedling and with ENDF/B III Mat 1123. Our elastic differential cross sections are in general agreement with those of Holmqvist and Wiedling but our angle-integrated elastic- and inelastic-scattering cross sections at 4.34 and 4.92 MeV are given and compared with our previous results from 6 to 8.5 MeV and with our natural nickel results. Agreement is shown to be excellent. Inelastic-scattering cross sections to the 1.450 MeV level in ${ }^{58} \mathrm{Ni}$ are computed from the natural nickel and ${ }^{60} \mathrm{Ni}$ data. An evaporation model of inelastic scattering to levels of excitation energy in the residual nucleus below 6 is found to be of questionable validity.

Abstract of ORNL-4807.
** Relevant to request Nos. 182, 183 and 184.
12. ${ }^{54} \mathrm{Fe}$ Neutron Elastic- and Inelastic-Scattering Cross Sections from 5.50 to $8.50 \mathrm{MeV}^{*}, * *$ (W. E. Kinney and F. G. Perey)

Measured ${ }^{54} \mathrm{Fe}$ neutron elastic scattering and cross sections for inelastic scattering to 7 discrete levels or groups of levels in ${ }^{54} \mathrm{Fe}$ in the incident neutron energy range from 5.50 to 8.50 MeV are presented. The elastic data are in good agreement with our previously reported natural iron results. Inelastic scattering to the 1.409 MeV level shows evidence
of direct reaction contributions at the higher incident neutron energies. ENDF/B III Mat 1180 natural iron cross sections for inelastic scattering to the 1.409 MeV level in ${ }^{54} \mathrm{Fe}$ are higher by a factor of two than our data. Cross sections for inelastic scattering to levels in the residual nucleus of excitation energy greater than 4.29 Mev are presented as continuum cross sections. It is found that an evaporation model of continuum inelastic scattering is adequate above 6.2 MeV excitation energy but is questionable in describing inelastic scattering to lower-lying levels.

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    * Abstract of ORNL-4907.
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    Relevant to request No. 147.
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13. Nitrogen Neutron Elastic- and Inelastic-Scattering Cross Sections from 4.07 to $8.56 \mathrm{MeV}^{*}$,** (W. E. Kinney and F. G. Perey)

Measured nitrogen neutron elastic and inelastic cross sections at incident neutron energies from 4.34 to 8.56 MeV are presented and compared with previous results. Our elastic data are systematically lower than the data of Bostrum et al. and systematically higher than the data of Bauer et al. But generally agree with the data of Chase et al. and Phillips. Our angle-integrated differential inelastic scattering cross sections are in reasonable agreement with previous results. Agreement of our data and ENDF/B III Mat 1133 is reasonable.
*Abstract of ORNL-4805.
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Relevant to request Nos. 64 and 65.
14. Gamma-Ray Production Due to Neutron Interactions with Calcium for Incident Neutron Energies Between 0.7 and 20 MeV : Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with calcium have been obtained for neutron energies between 0.7 and 20 MeV for $\theta_{\gamma}=125 \mathrm{deg}$. The $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{dE}$ values were obtained using a NaI spectrometer. These data consist of gamma-ray production group cross-section values of $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{dE}$ for $0.7 \leq \mathrm{E}_{\gamma} \leq 10.5 \mathrm{MeV}$, with gammaray intervals ranging from 20 keV for $\mathrm{E}_{\gamma} \leq 1 \mathrm{MeV}$ to 160 keV for $\mathrm{E}_{\gamma} \approx 9 \mathrm{MeV}$. Neutron energy intervals varied from 0.5 MeV for $\mathrm{E}_{\mathrm{n}} \leq 9 \mathrm{Mev}$ to 3 MeV for $\mathrm{E}_{\mathrm{n}} \geq 14 \mathrm{MeV}$.

[^33]
## 15. Gamma-Ray Production Due to Neutron Interactions with Aluminum for Incident Neutron Energies Between 0.85 and 20 MeV : Tabu1ated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with aluminum have been obtained for neutron energies between 0.85 and 20 MeV for $\theta_{\gamma}=125$ and 90 deg . The $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{dE}$ values were obtained using a NaI spectrometer. These data consist of neutron and gamma-ray production group cross-section values of $d^{2} \sigma / d \omega d E$ for $0.7 \leq E_{\gamma}$ $\leq 10.5 \mathrm{MeV}$, with gamma-ray intervals ranging from 20 keV for $\mathrm{E}_{\gamma} \leq 1 \mathrm{MeV}$ to ${ }^{\mathrm{r}}$ $\overline{1} 60 \mathrm{keV}$ for $\mathrm{E}_{\gamma} \approx 9 \mathrm{MeV}$. Neutron energy intervals varied from $0 . \overline{2} \mathrm{MeV}$ for $\mathrm{E}_{\mathrm{n}}=0.85$ to 1.5 MeV to 3 MeV for $\mathrm{E}_{\mathrm{n}}=14$ to 20 MeV .
${ }_{* *}^{*}$ Abstract of ORNL-TM-4232.
Relevant to request Nos. 96, 97 and 98.

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\text { 16. } \frac{\text { Neutron Resonances in }{ }^{39} \mathrm{~K} \text { and }{ }^{41} \mathrm{~K} *}{\text { Harvey and N. W. Hill) }} \quad \text { (W. M. Good, J. A. }
$$

Resonance parameters derived from high-resolution neutron transmission studies at the NEVIS Synchrocyclotron of pure $K$ metal are to be published soon. ${ }^{1}$ Assignment of the observed resonances to the ${ }^{39} \mathrm{~K}$ and ${ }^{41} \mathrm{~K}$ isotopes was materially assisted by data on these separated isotopes obtained at ORELA. Although the Oak Ridge measurements were performed on the compounds ${ }^{39} \mathrm{KCl}$ and ${ }^{42} \mathrm{KCl}$, no difficulty was encountered below 100 keV in differentiating the ${ }^{39} \mathrm{~K}$ and the ${ }^{41} \mathrm{~K}$ resonances from the ${ }^{35} \mathrm{Cl}$ and ${ }^{37} \mathrm{Cl}$ constituents on account of the high resolution employed in the measurements. We report the results of our measurements on ${ }^{39} \mathrm{~K}+\mathrm{n}$ and ${ }^{41} \mathrm{~K}+\mathrm{n}$ in order to complete the picture of the resonance properties of these nuclides below $\approx 100 \mathrm{keV}$ and in particular to record additional resonances in ${ }^{41} \mathrm{~K}$ at 4.012 , $28.31,42.35,57.81,58.20,63.22,67.04,68.29$, and 70.45 keV . These resonances are obscured in a natural sample by resonances in the $93 \%$ abundant ${ }^{39} \mathrm{~K}$.
${ }^{\star}$ To be presented at the Bloomington APS Meeting, November 1-3, 1973.
${ }^{1}$ U. N. Singh et al., submitted for publication, Phys. Rev.
17. $\frac{\text { Neutron Total Cross Section of }{ }^{207} \mathrm{~Pb} \text { from } 5 \text { to } 35 \mathrm{MeV}^{*}}{\text { (J. A. Harvey, W. M. Good, N. W. Hill and R. Schindler }{ }^{1} \text { ) }}$
. Recently a "resonance peculiarity" 2 has been reported in the neutron total cross section of ${ }^{207} \mathrm{~Pb}$ at 16.7 MeV and it was suggested that it might be an isobaric analog resonance. To verify the existence of this resonance we have made neutron transmission measurements upon a ${ }^{207} \mathrm{~Pb}$ sample ( $253 \mathrm{gm}, 1 \mathrm{in}$. diam, $1 / \mathrm{N}=6.865$ ) from 5 to 30 MeV at ORELA. Bursts of neutrons were produced by a Be target irradiated with bremsstrahlung from
a Ta converter. With an 78.185 meter flight path and 5 nsec electron bursts, the neutron energy resolution was $0.5 \%$ at 16 MeV . A NE-110 plastic detector (3 in. diam, 3 in. long) was used. No detailed structure was observed in the entire energy range. Measurements at $\mathrm{LLL}^{3}$ from 16.3 to 17.1 MeV have also failed to observe this resonance.
*To be presented at the Bloomington APS Meeting, November 1-3, 1973.
Summer Student Trainee from University of Rochester
${ }_{3}^{2}$ B. A. Benetzky et al., Journal of Nucl. Phys. 17, No. 1, (1973) p. 21. H. H. Barschall, private communication.
18. Test of Valency Neutron Capture in ${ }^{90} \mathrm{Zr}(\mathrm{n}, \mathrm{Y})^{91} \mathrm{Zr}^{*}$, ${ }^{* *}$ (G. G. Slaughter and 0. A. Wasson ${ }^{1}$ )

As a continuing investigation of the influence of single particle components in the $\gamma$ ray decays of the $p$-wave neutron resonances for nuclei located near the peak of the p-wave neutron strength function, we report resonant neutron capture $\gamma$ ray measurements on the closed neutron shell target nucleus, ${ }^{90} \mathrm{Zr}$. The experiment utilized the 11 m flight path of the ORELA facility. Capture $\gamma$ ray spectra were obtained for 13 resolved resonances for $\mathrm{E}_{\mathrm{n}}<40 \mathrm{keV}$ with a $\mathrm{Ge}(\mathrm{Li})$ detector. The resonance at 4.01 keV neutron energy is assigned as $\mathrm{p} 3 / 2$ based on the observation of a strong primary $\gamma$ ray to the $5 / 2^{+}$ground state of ${ }^{91} \mathrm{Zr}$. Previous measurements ${ }^{1}$ of the ${ }^{91} \mathrm{Zr}(\gamma, \mathrm{n}){ }^{90} \mathrm{Zr}$ reaction indicate a significant single particle component for the ground state $\gamma$ ray decay width. A test of this component for transitions to $s 1 / 2$ and $d 3 / 2$ final states will be presented.
*To be presented at the Bloomington APS Meeting, November 1-3, 1973. R. E. Toohey and H. E. Jackson, Bull. Am. Phys. Soc. 18, 591 (1973). ** Relevant to request No. 249.
19. ADLER-III: A Program to Calculate Cross Sections from ADLERADLER Resonance Parameters* (R. Q. Wright)

ADLER-III is a revision and extension of the ADLER program described in "ENDF/B Processing Codes for the Resonance Region," BNL-50296 (ENDF 148) by M. R. Bhat. The program calculates total, capture, and fission cross sections according to the Adler-Adler formalism using the corresponding parameters from file 2 of ENDF/B data. Doppler broadening is provided through the use of the $\Psi$ and $\phi$ functions. The program can read the resonance parameters from an ENDF/B tape ( $B C D$ mode) or the resonance parameters may be input on cards if desired.

[^34]
## 20. Neutron Capture Cross Sections of the Stable Lead Isotopes* (B. J. Allen, T R. L. Macklin, R. R. Winters, $^{2}$ and C. Y. Fu)

Neutron capture yields for several samples of separated lead isotopes were obtained at the Oak Ridge Electron Linear Accelerator, in the neutron energy range above 2.5 keV . These were analyzed for resonance capture areas and parameters. The data are included in a new evaluation of lead cross-section data.

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* To be published in Physical Review C.
1
Present address: Australian Atomic Energy Commission, Lucas Heights,
Australia.
2
Present address: Denison University, Granville, Ohio.
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21. Total Neutron Cross Sections of the Isotopes of Zirconium* (W. M. Good, J. A. Harvey and N. W. Hill)

Transmission measurements have been made on the isotopes of Zr as part of the program to up-date total cross-section information utilizing ORELA's superior energy resolution.

The ${ }^{92,94,96} \mathrm{Zr}$ measurements were made upon both thick and thin samples of the respective oxides at 80 meters under two conditions:
a) 30 ns electron burst and ${ }^{6} \mathrm{Li}-\mathrm{glass}$ detector,
b) 5 ns electron bursts and $\mathrm{NE}-110$ detector. The data are in process of analysis.

Metallic samples of ${ }^{90,91} \mathrm{Zr}$ were measured last year in collaboration with R. Toohey, ANL. These measurements were made under the following conditions:
a) 80 meters, 30 ns electron bursts, ${ }^{6}$ Li-glass detector,
b) 200 meters, 30 ns electron bursts, NE-110 detector.

Figure 1 is a plot of the cross sections of ${ }^{90} \mathrm{Zr}$ under condition a).

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## A.2. Fissionable Nuclei Studies

1. Measurement of the ${ }^{235} \mathrm{U}$ Fission Cross Section at the ORELA 150-Meter Flight-Path Station for Neutron Energies Between $\frac{2 \mathrm{keV} \text { and } 100 \mathrm{keV}{ }^{*} \text { (R. B. Perez, G. de Saussure, E. G. }}{\text { Silver R. W. Ingle }}$ Silver, R. W. Ingle and H. Weaver)

Comparison of the ${ }^{235}$ U Fission Cross-Section Results (Preliminary) at the ORELA 150-Meter Flight-Path Station With the ENDF/B-III (a) and Sowerby (b) Evaluations

| Energy <br> Interyal <br> kev) | ORELA $(\mathrm{c})$ <br> (barns) | ENDF/B-III <br> (barns) | Percent <br> Difference | Sowerby <br> (barns) | Percent <br> Difference |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $2 .-3$. | 5.450 | 5.585 | +2.5 | 5.486 | +.7 |
| $3 .-4$. | 4.946 | 4.942 | -.1 | 4.866 | -1.6 |
| $4 .-5$. | 4.405 | 4.427 | +.5 | 4.391 | -.3 |
| $5 .-6$. | 3.953 | 3.981 | +.7 | 3.943 | -.3 |
| $6 .-7$. | 3.351 | 3.559 | +6.2 | 3.471 | +3.8 |
| $7 .-8$. | 3.317 | 3.335 | +.5 | 3.373 | +1.7 |
| $8 .-9$. | 3.051 | 3.059 | +.3 | 3.071 | +.7 |
| $9 .-10$. | 3.170 | 3.200 | +.9 | 3.165 | -.2 |
| $10 .-20$. | 2.510 | 2.741 | +9.2 | 2.550 | +1.6 |
| $20 .-30$. | 2.156 | 2.323 | +7.7 | 2.231 | +3.5 |
| $30 .-40$. | 2.044 | 2.205 | +7.8 | 2.011 | -1.6 |
| $40 .-50$. | 1.930 | 2.031 | +5.2 | 1.908 | -1.1 |
| $50 .-60$. | 1.885 | 1.977 | +4.9 | 1.871 | -.7 |
| $60 .-70$. | 1.839 | 1.880 | +2.2 | 1.809 | -1.6 |
| $70 .-80$. | 1.760 | 1.807 | +2.7 | 1.714 | -2.6 |
| $80 .-90$. | 1.684 | 1.742 | +3.4 | 1.681 | -.2 |
| $90 .-100$. | 1.634 | 1.684 | +3.0 | 1.632 | -.1 |

(a) T. A. Pitterle, et al., ENDF/B-III, Mat. 1157; WARD-4210T4-1 (1972).
(b) To be published. Private communication to T. A. Pitterle, March 1972.
(c) The total uncertainties in this data are estimated to be $\pm 7 \%$.

[^36]2. Neutron Fission and Total Cross Section of ${ }^{234} \mathrm{U}$
(G. D. James, ${ }^{1}$ J. W. T. Dabbs, J. A. Harvey, N. W. Hill and R. H. Schindler ${ }^{2}$ )

Neutron time-of-flight fission and total cross-section measurements have been performed at ORELA using fission fragment detection from 181 mg of ${ }^{234} \mathrm{U}$ in a fast ionization chamber, a flight path length of 20.14 m and neutron pulse widths of $3.5 \mathrm{~ns}, 5.5 \mathrm{~ns}, 8 \mathrm{~ns}$ and 28 ns for the fission cross-section determination and a 5.69 g sample of ${ }^{234} \mathrm{U}_{3} \mathrm{O}_{8}$ giving $6.45 \times 10^{-3} 234 \mathrm{U}$ atoms/barn, a flight path length of 78 m and neutron pulse width of 28 ns for the total cross-section measurements. The fission cross section was measured relative to the yield from 20.5 mg ${ }^{235} \mathrm{U}$. All the 118 fine structure resonances observed below 1500 eV have been analyzed to give the neutron and fission widths. In addition to the peak at 640 eV demonstrated by James and Slaughter, ${ }^{3}$ the energy dependence of the fission widths shows evidence of a second narrow intermediate structure peak at 1134 eV . The fission cross section is rich in structure blending from class I levels at low energy through class II levels at about 20 keV to fluctuations due to class II levels up to 1 MeV . Below 14 keV there is clear evidence for groups of levels with increased fission cross section at $600 \mathrm{eV}, 1134 \mathrm{eV}, 4575 \mathrm{eV}, 7845 \mathrm{eV}, 11886 \mathrm{eV}(?)$, and 13072 eV giving $D_{I I}=2.1 \pm 0.3 \mathrm{keV}$. Near a supposed vibrational resonance at 325 keV , the fluctuation peaks first noted at Harwe $11^{4}$ are confirmed with improved statistical accuracy.

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Visiting scientist from AERE, Harwell.
2
3}\mathrm{ Summer research student from University of Rochester.
G. D. James and G. G. Slaughter, Nucl. Phys. Al39, 471 (1969).
G. D. James, A. Langsford and A. Khatoon, Progress Report AERE-NR/NP 19, p.16.
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3. Neutron Fission Cross Section of ${ }^{249} \mathrm{C} f *$ * $* *$ (J. W. T. Dabbs, C. E. Bemis, N. W. Hill, G. D. James, M. S. Moore ${ }^{2}$ and A. N. Ellis ${ }^{2}$ )

It has been known for some time that ${ }^{249} \mathrm{Cf}$ has a very large fission resonance integral. Previous work, primarily that of Silbert at LASL, has failed to account for this large integral above 20 eV .

Time-of-flight measurements of the neutron-induced fission cross section of ${ }^{249} \mathrm{Cf}$ have been performed at ORELA, using an ultrapure $128 \mu \mathrm{~g}$ sample of ${ }^{249} \mathrm{Cf}$ and compared with that of a $458 \mu \mathrm{~g}$ sample of ${ }^{235} \mathrm{U}$ measured simultaneously on the same flight path. Identical diffused junction fission fragment detectors were used. An $\alpha$-particle count rate on $10^{7} / \mathrm{sec}$ caused substantial deterioration of the ${ }^{249} \mathrm{Cf}$ detector during each overnight run. A total of $\sim 7 \times 10^{5}$ Cf fission events were recorded. The present results are comparable in resolution to those obtained by Silbert at LASL above 20 eV , in which an underground nuclear explosion served as the pulsed neutron source.

Eleven new resonances were found between 0.3 eV and 20 eV , including a very large resonance at 0.71 eV of total width $\sim 0.15 \mathrm{eV}$ and $\sigma_{0} \sim 4000 \mathrm{~b}$. This resonance accounted for $\sim 75 \%$ of the total fissions recorded, and also accounts for the large resonance integral.
*Presented at the Third Symposium on the Physics and Chemistry of Fission, Rochester, N. Y., August 13-17, 1973.
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${ }_{2}$ Visiting scientist from AERE, Harwell.
Los Alamos Scientific Laboratory, Los Alamos, New Mexico **

Relevant to request Nos. 573.

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\text { 4. } \frac{\text { Intermediate Structure in the Electron Induced }{ }^{285} \mathrm{U}}{\frac{\text { Cross Sections }}{\text { and R. B. Perez })}}
$$

Recently there has been clear experimental evidence of large fluctuations in the neutron induced ${ }^{235} \mathrm{U}$ cross sections. The WaldWolfowitz and Levene-Wolfowitz statistical tests have been applied to some ${ }^{235} \mathrm{U}$ total fission and capture cross-section data and also to mockedup cross sections. The results of these tests have shown with a large degree of significance the presence of intermediate structure in the fission channels. It is then surmised that the structure in the ${ }^{235} \mathrm{U}$ cross sections is due to phenomena associated with the double-trumped Strutinsky fission barrier at large nuclear deformations.

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* To be presented at the San Francisco ANS Meeting, November 12-15, 1973
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    Visiting scientist from AERE, Harwell
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5. $\frac{\text { Spin Determination of Resonances in the Neutron-Induced }}{\text { Fission of }{ }^{235} \mathrm{U}^{*}, \text { N }^{*}}$ F. T. Seibel, ${ }^{\text {I }}$ J. W. T. Dabbs and N. W. Hill)

A pulsed beam of polarized neutrons and a polarized target have been used to determine the spins of 65 resonances below 60 eV . Comparison of these spin assignments with those determined by less direct methods reveals poor agreement, in general. Interpretation of recent data on the angular distribution of fission fragments from aligned ${ }^{235} \mathrm{U}$ with the present spin assignments reveals the absence of the $K=0$ channel and an apparent admixing of transition states.
*To be published in Physical Review Letters.
University of California, Los Alamos Scientific Laboratory, Los Alamos, N. M. Relevant to request No. 439.
6. Spin Determination of Intermediate Structure in the Subthreshold Fission of ${ }^{237} \mathrm{~Np}^{*}$ (G. A. Keyworth, ${ }^{1}$ J. R. Lemley, ${ }^{2}$ C. E. Olsen, ${ }^{\text {I F. T. Seibel, }}$ J. W. T. Dabbs and N. W. Hill)

A polarized neutron beam and a polarized target have been used to determine spins of 15 intermediate structure groups observed in the fission of ${ }^{237} \mathrm{~Np}$ below 1 keV and of 94 resonances observed in transmission below 102 eV . The pulsed neutron beam, from the Oak Ridge Electron Linear Accelerator, was polarized by transmission through a dynamically polarized proton sample. The ${ }^{237} \mathrm{~Np}$, in the ferromagnetic compound $\mathrm{NpAl}_{2}$, was cooled by a ${ }^{3} \mathrm{He}-{ }^{4} \mathrm{He}$ dilution refrigerator. Nine individual fine structure resonances comprising the first group at 40 eV were determined to have the same spin, $J=3$, substantiating the current interpretation of intermediate structure in subthreshold fission in terms of the Strutinsky double-humped deformation barrier. Correlation of these results with existing data on the angular distribution of fission fragments from aligned ${ }^{237} \mathrm{~Np}$ indicates an apparent admixing of transition states, as evidenced by nonintegral values of the projection quantum number, $K$.

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*}\mathrm{ To be published in Physical Review.
University of California, Los Alamos Scientific Laboratory, Los Alamos, N. M.
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7. Prompt Gamma-Rays Emitted in the Thermal-Neutron Induced Fission of ${ }^{23} \mathrm{U}$ and ${ }^{29} \mathrm{Pu}^{*}, * *$ (Frances Pleasonton)

The average number and average energy of gamma rays emitted within $\sim 5$ nsec after fission have been determined as functions of fragment mass and as functions of total kinetic energy. They were obtained from a 4-parameter experiment that recorded, event-by-event, correlated energies of gamma rays and of fission-fragment pairs and the time, relative to fission, at which a gamma ray was detected. For ${ }^{233} U\left(n_{t h}, f\right)$ the average total number and energy emitted per fission were found to be $6.31 \pm 0.3$ and $6.69 \pm 0.3$ MeV , respectively, giving an average photon energy of $1.06 \pm 0.07 \mathrm{MeV}$. The results for ${ }^{239} \mathrm{Pu}\left(n_{t h}, f\right)$ given in the same order, are $6.88 \pm 0.35,6.73 \pm 0.35$ MeV , and $0.98 \pm 0.07 \mathrm{MeV}$.

[^37]8. Fragment Mass and Kinetic Energy Distributions from the Spontaneous Fission of ${ }^{246} \mathrm{Cm}^{*}$ (Frances
Pleasonton, Robert L. Ferguson, Franz Plasil and C. E. Bemis, Jr.)

Energies of coincident fission fragments from a thin, spontaneously-fissioning ${ }^{246} \mathrm{Cm}$ source were measured with silicon surfacebarrier detectors. Pre-neutron-emission mass and total kinetic energy distributions were deduced from the data. The average pre-neutron-emission fragment total kinetic energy $\bar{E}_{\mathrm{K}}$ was found to be 184.2 MeV , in agreement with ${ }^{245} \mathrm{Cm}(\mathrm{n}, \mathrm{f})$ results. The mass distribution has a peak-to-valley ratio of 142 , and is similar to those from other spontaneously-fissioning nuclei. Fine structure in the mass distributions from ${ }^{245} \mathrm{Cm}(\mathrm{n}, \mathrm{f}),{ }^{246} \mathrm{Cm}(\mathrm{sf})$ and ${ }^{250} \mathrm{Cm}(\mathrm{sf})$ appears to be associated with fragments of mass $\approx 144$ amu. Predictions for $\bar{E}_{\mathrm{K}}$ from fission systematics were not found to describe adequately the observed $\mathrm{E}_{\mathrm{K}}$ values for the spontaneous fission of Cm isotopes.
${ }^{*}$ Physical Review C8, 1018 (1973).
9. $\frac{\text { Potential Energy Surface for the Fission of the Super- }}{\text { heavy Nucleus }{ }^{298} \mathrm{X}_{184}^{\text {* }}}$ (M. G. Mustafa and H. W. Schmitt)

The asymmetric two-center model has been used to calculate the potential energy surface of the superheavy nucleus ${ }_{114}^{298} \mathrm{X}_{184^{4}}$. Four shape variables, including two for asymmetric degrees of freedom, were used to describe the nuclear shape. The minimum-potential-energy path for fission follows reflection-symmetric shapes from the ground state to beyond the second barrier; in this region the surface becomes soft and a variety of paths becomes available. For lesser elongations, asymmetric shapes are briefly preferred; for greater elongations, symmetric shapes are preferred. The paths converge in the main, steeply-descending scission valley, for which the liquid drop term dominates and reflection-symmetric shapes are slightly preferred.

[^38]10. Fragment Kinetic Energy in ${ }^{18} 0$-Induced Fission of ${ }^{232} \mathrm{Th}$ and ${ }^{246} \mathrm{Cm}^{*}$ (Robert L. Ferguson, Franz Plasil, Hartwig Freiesleben, ${ }^{1}$ C. E. Bemis, Jr., and H. W. Schmitt)

On the basis of a static scission model, Schmitt and Mosel have predicted that fragment total kinetic energies, $E_{K}$, are larger than those expected from Viola's fission systematics when $255<\mathrm{A}<280$. In a
search for this effect, $E_{K}$ was measured in ${ }^{18} O$ bombardments of ${ }^{232}$ Th and ${ }^{246} \mathrm{Cm}$. Correlated energies of fission fragment pairs were measured with silicon surface barrier detectors; fragment mass and total kinetic energy distributions were deduced. For $102.5 \mathrm{MeV}{ }^{18} \mathrm{O}$ ions, the average pre-neutron-emission fragment total kinetic energy, 〈E ${ }^{\text {y }}$, was found to be 187 MeV for the ${ }^{232} \mathrm{Th}$ case and 198 MeV for the ${ }^{246 \mathrm{Cm}}$ case. The corresponding Schmitt-Mosel predictions are 186 MeV for ${ }^{2}{ }^{32} \mathrm{Th}$ and 258 MeV for ${ }^{246} \mathrm{Cm}$ and Viola's predicted values are 185 MeV for ${ }^{232} \mathrm{Th}$ and 203 MeV for ${ }^{246} \mathrm{Cm}$. It is probable that the predicted high $E_{K}$ value for ${ }^{246} \mathrm{Cm}$ was not observed because shell effects, which are responsîle for the high predicted kinetic energies, have disappeared at the relatively high excitation energies encountered in this work.

* Physical Review C8, 1104 (1973).

On leave of absence from Fachbereich Physik, Universität Marburg, Germany.
B. BASIC SCIENCE SUBCOMMITTEE

## B.1. General

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\text { 1. } \frac{\text { Potassium-48* }}{\text { Tirse11 }} \text { ) (S. Raman, L. G. Multhauf }{ }^{1} \text { and K. C. }
$$

We have produced ${ }^{48} \mathrm{~K}$ for the first time. This activity was produced by irradiating $96.8 \%$ enriched ${ }^{48} \mathrm{Ca}$ with $14-\mathrm{MeV}$ neutrons ( $>10^{12}$ neutrons/sec) at the Livermore high-flux facility. The halflife is $\approx 9 \mathrm{sec}$. The atomic and mass number assignments are based on the observation of the $3833-\mathrm{keV} \gamma$-ray known to be in ${ }^{48} \mathrm{Ca}$. The enriched ${ }^{48} \mathrm{Ca}$ material was in the form of $\mathrm{CaCO}_{3}$. The oxygen content produced $7-\mathrm{sec}$ ${ }^{16} \mathrm{~N}$ activity which interfered with the measurements. Therefore, new measurements with ${ }^{48} \mathrm{Ca}$ metal are now in progress.

[^39]2. Anomalous Effects in Back Angle Inelastic Scattering of $\alpha$-Particles from $2+$ Levels in ${ }^{60} \mathrm{Ni}^{*}, * *$ (D. C. Hensley, C. B. Fulmer, M. B. Lewis, C. C. Foster, ${ }^{1}$ N. M. $0^{\prime}$ Fallon, ${ }^{1}$ S. A. Gronemeyer, ${ }^{1}$ W. W. Eidson, ${ }^{2}$ and R. G. Rasmussen ${ }^{2}$ )

We measured $\sigma(\theta)$ for elastic and inelastic scattering of 40.1 $\mathrm{MeV} \alpha$-particles from ${ }^{60} \mathrm{Ni}$ over the range $\theta=150^{\circ}-190^{\circ}$. The $180^{\circ}$ cross section for inelastic scattering from the $2+2 n d$ excited state at 2.16 MeV is an order of magnitude larger than that for the $2+1$ st excited state at 1.33 MeV or for the $0+$ ground state. In addition the measured angular distribution for the 2nd excited state is in phase with that for the ground state but of opposite phase to that for the first excited state. Preliminary predictions from the direct channel-channel coupling code JUPITOR of Tamura indicate that the possible two-phonon character of the 2nd $2+$ level can be tested in a very sensitive manner by comparing predictions with back angle measurements of the inelastic channels.

[^40]3. Isotope Effect in 40 MeV Elastic Alpha Scattering from ${ }^{28} \mathrm{Si}^{29}{ }^{29} \mathrm{Si}$ and ${ }^{30} \mathrm{Si}^{*}, * *$ (C. C. Foster, ${ }^{1}$ N. M. $0^{\top}$ Fallon, ${ }^{1}$ S. A. Gronemeyer, ${ }^{1}$ C. B. Fulmer, D. C. Hensley, W. W. Eidson, ${ }^{2}$ and R. G. Rasmussen ${ }^{2}$ )

With a 40 MeV alpha beam from ORIC, we measured elastic $\sigma(\theta)$ between 155 and 190 degrees for ${ }^{28},{ }^{29},{ }^{30}$ Si. $\sigma(\theta)$ peaks at $180^{\circ}$ for each target. $\sigma\left(180^{\circ}\right)$ for the ${ }^{28} \mathrm{Si}$, in which the $\mathrm{d}_{5 / 2}$ shell is filled, and for ${ }^{29} \mathrm{Si}$ is larger by an order of magnitude than that for ${ }^{30}$ Si. This feature of our data supports the idea of shell structure dependence proposed by Oeschler et al. ${ }^{3}$

* To be presented at the Bloomington APS Meeting, November 1-3, 1973. **
This work supported in part by the NSF.
1
University of Missouri, St. Louis
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${ }_{3}$ Drexel University
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Phys. Rev. Lett. 28, 694 (1972).

4. Excitation of Giant Resonances in ${ }^{144,154}$ Sm by Inelastic Proton Scattering* (D. J. Horen, F. E. Bertrand and M. B. Lewis)

The continuum region of nuclear excitation in the vicinity of the giant dipole (GDR) and giant quadrupole (GQR) resonances has been studied in ${ }^{144} \mathrm{Sm}$ and ${ }^{154} \mathrm{Sm}$ using $67-\mathrm{MeV}$ protons from ORIC in order to search for any effect nuclear deformation might have on GQR. In ${ }^{144} \mathrm{Sm}$ broad peaks are observed at $\approx 15.5 \mathrm{MeV}$ and 13.0 MeV , and in ${ }^{154} \mathrm{Sm}$ similar structure is found at $\approx 16.1$ and 12.4 MeV . The higher excitation energy peaks occur at the position of the GDR, ${ }^{1}$ while the lower excitation peaks appear at the energy expected for the GQR. ${ }^{2}$ Preliminary analysis indicates that the GDR plus GQR cross sections are similar for the two isotopes. If, as is known from photo-nuclear work, the GDR is split for ${ }^{154} \mathrm{Sm}$, it appears that there is no large difference in the shape of the GQR peak for the two isotopes.

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## 5. Excitation of Giant Resonances via Inelastic Scattering of Polarized Protons* (D. C. Kocher, F. E. Bertrand, E. E. Gross, R. S. Lord and E. Newman)

Using the $60-\mathrm{MeV}$ polarized proton beam from ORIC and a broad-range magnetic spectrograph with nuclear emulsions, we have measured the analyzing power and the cross section in the giant resonance region of the nuclear continuum for the ${ }^{58} \mathrm{Ni}\left(\overrightarrow{\mathrm{p}}, \mathrm{p}^{\prime}\right)$ reaction. Comparison of the data for $\theta_{\mathrm{L}}=12^{\circ}-35^{\circ}$ with DWBA predictions shows clearly that the giant resonance at $E{ }^{L} \approx 63 / \mathrm{A}^{1 / 3} \mathrm{MeV}\left(16.5+0.5 \mathrm{MeV}\right.$ in ${ }^{58} \mathrm{Ni}$ ) is predominantly E 2 in character. We have observed a resonance at $E_{X} \approx 13.5 \mathrm{MeV}$ which is also best described as an E2 excitation. Measurements on the ${ }^{90} \mathrm{Zr}\left(\overrightarrow{\mathrm{p}}, \mathrm{p}^{\prime}\right)$ reaction are in progress. Spectra for ${ }^{40} \mathrm{Ca}\left(\mathrm{p}, \mathrm{p}^{\prime}\right)$ and ${ }^{20{ }^{8}} \mathrm{~Pb}\left(\mathrm{p}, \mathrm{p}^{\prime}\right)$ up to 40 MeV of excitation have also been obtained.

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*To be presented at the Bloomington APS Meeting, November 1-3, 1973.
Nuclear Information Research Associate.
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From a study of stopping $\mathrm{K}^{-}$meson interactions in a variety of elements located in a hydrogen bubble chamber, we find evidence for the existence of a substantial neutron halo in the periphery of heavy nuclei.

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*To be published in Nuclear Physics.
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    The University of Tennessee, Knoxville, Tennessee.
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    7. The Reaction \({ }^{6} \mathrm{Li}\left({ }^{3} \mathrm{He}, \mathrm{t}\right)\) and the Solar Neutrino Puzzle* \({ }_{\text {(M. L. Halbert, D. C. Hensley and H. G. Bingham) }}\)
    A search for a \({ }^{3} \mathrm{He}+{ }^{3} \mathrm{He}\) resonance just above threshold was made by means of the reaction \({ }^{6} \mathrm{Li}\left({ }^{3} \mathrm{He}, \mathrm{t}\right){ }^{6} \mathrm{Be} *\) with \(46.3-\mathrm{MeV}{ }^{3} \mathrm{He}\). No resonance was found; the \(\mathrm{c} . \mathrm{m}\). cross section is \(\leq 1.6 \mu \mathrm{~b} / \mathrm{sr}\) at \(8.4^{\mathrm{o}} \mathrm{c} . \mathrm{m}\). This corresponds to an upper limit on the spectroscopic factor for \({ }^{6} \mathrm{Be} * \rightarrow\) \({ }^{3} \mathrm{He}+{ }^{3} \mathrm{He}\) of .0003 to .001 , depending on the parameters adopted for a DWBA calculation. The maximum possible effect of such a resonance on the production of high-energy solar neutrinos is too small to explain the discrepancy between solar-model predictions and the experimental results of Davis et al.
    [^42]8. A Test of Isospin Conservation by a Comparison of $\frac{{ }^{3} \mathrm{H}\left({ }^{3} \mathrm{He},{ }^{4} \mathrm{He}\right)^{2} \mathrm{H} \text { and }{ }^{3} \mathrm{He}\left({ }^{3} \mathrm{He},{ }^{4} \mathrm{He}\right) 2 \mathrm{p} \text { at } 16.0 \mathrm{MeV} \text { c.m. }}{\text { (W. J. Roberts, }{ }^{1} \text { E. E. Gross and E. Newman) }}$

The absolute differential cross sections for the reactions (A) ${ }^{3} \mathrm{H}\left({ }^{3} \mathrm{He},{ }^{4} \mathrm{He}\right)^{2} \mathrm{H}$ and (B) ${ }^{3} \mathrm{He}\left({ }^{3} \mathrm{He},{ }^{4} \mathrm{He}\right) 2 \mathrm{p}$ have been measured at $16.0 \mathrm{MeV} \mathrm{c} . \mathrm{m}$. Using final-state interaction theqry, we have extracted the cross section for leaving the di-proton in the ${ }^{1} S$ state for reaction ( $B$ ). Conservation of isospin requires this cross section to have twice the magnitude and the same angular distribution as reaction (A). Isospin conservation also requires that reaction (A) be symmetric about $90^{\circ} \mathrm{c} . \mathrm{m}$. At $16.0 \mathrm{MeV} \mathrm{c} . \mathrm{m}$. we find deviations from $90^{\circ}$ symmetry for reaction (A) which are consistent with lower energy data. In addition, we report deviations from isospin conservation for the comparison test. However, using a simple singlenucleon transfer model, we are able to qualitatively account both for the deviation from $90^{\circ} \mathrm{c} . \mathrm{m}$. symmetry for reaction (A) and for the deviation from the factor of two in the ratio of the yield of reaction (B) to that of reaction (A).

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\({ }_{1}^{*}\) To be published in Physical Review \(C\).
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9. Evidence for a Neutron Halo in Heavy Nuclei from Antiproton Absorption* (W.M. Bugg, G. T. Condo, E. L. Hart, ${ }^{\text {T H. O. Cohn }}$ and R. D. McCulloch)

From a study of stopping antiprotons in a variety of elements located in a hydrogen bubble chamber, we find evidence for the existence of a neutron fringe in heavy nuclei.

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* Phys. Rev. Lett. 31, 475 (1973).
    The University of Tennessee, Knoxville, TN.
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10. Complete Hydrogen and Helium Particle Spectra from 30to $60-\mathrm{MeV}$ Proton Bombardment of Nuclei with $A=12$ to 209 and Comparison with the Intranuclear Cascade Model*,** (F. E. Bertrand and R. W. Peelle)

Differential cross sections for the production of proton, deuteron, triton, helium-3, and alpha particles from as many as ten targets ( $\mathrm{A}=12-209$ ) were measured using $29-, 39-$, and $62-\mathrm{MeV}$ incident protons. The particles were detected, with $\approx 0.2-\mathrm{MeV}$ (FWHM) energy resolution for protons, over a secondary energy range of $\approx 2-6$ to 62 MeV in a total absorption telescope composed of three solid-state detectors. Representative results are shown for cross sections differential in energy and angle, as well as
for angle- and energy integrated cross sections. For incident $60-\mathrm{MeV}$ protons the integral magnitude of the nonevaporation charged-particle production is found to be $\sim 10^{2} \mathrm{~A}^{1 / 3} \mathrm{mb}$. Fewer protons but more complex particles were measured for carbon and oxygen targets than expected from $A^{1 / 3}$ dependence for either component alone. The continuum cross sections for $z=1$ particles at a given angle ( $\mathrm{mb}-\mathrm{sr}^{-1}-\mathrm{MeV}^{-1}$ ) are nearly independent of incident energy when measured with incident protons in the $30-$ to $60-\mathrm{MeV}$ energy range. Nonevaporation production of complex particles ( $\mathrm{A} \geq 2$ ) is $25-40 \%$ of that for protons.

The proton spectra have been compared with predictions from the intranuclear cascade model. Differential spectral predictions compare well with the measured spectra for angles in the range $\sim 25-60$ degrees, and relatively poor predictions for small and large angles are more favorable when reflection and refraction by the potential well are included. Evidence is given that predictions for backward angles are greatly improved by allowing proton scattering from nucleon pairs within the model nucleus, but the A-dependent underprediction at extreme forward angles is not understood at all. The calculated angle-integrated spectra reproduce the measured spectral shape but consistently predict $\approx 30 \%$ too few nonevaporation protons for targets with $\mathrm{A} \geq 27$.
${ }^{*}$ Physical Review C8, 1045 (1973). ** Relevant to request No. 633.
11. Levels in ${ }^{146,147,148} \mathrm{Gd}$ Observed Following the Decay of Their Terbium Parents; New Isotope, ${ }^{146} \mathrm{~Tb}^{*}$ (E. Newman, K. S. Toth, D. C. Hensley and W-D. Schmidt-Ott ${ }^{1}$ )

The decay schemes of the following terbium isotopes were investigated: $2.3 \pm 0.2-\mathrm{min}^{148} \mathrm{~Tb}, 1.9 \pm 0.1-\mathrm{min}$ and $1.6 \pm 0.1-\mathrm{h}{ }^{147} \mathrm{~Tb}$, and a previously unreported $23 \pm 2-\mathrm{sec}$ nuclide assigned to ${ }^{146} \mathrm{~Tb}$. These radioactivities were produced by bombarding ${ }^{141} \mathrm{Pr}$ with ${ }^{12} \mathrm{C}$ ions accelerated in the Oak Ridge Isochronous Cyclotron. Both singles and coincidence gammaray spectra measurements were made. Our data for $2.3-\mathrm{min}{ }^{148} \mathrm{~Tb}$ are in excellent agreement with the recently published results of Bowman, Haenni, and Sugihara. We also confirm their discovery of a new, $1.9-\mathrm{min}$, highspin isomer in ${ }^{147} \mathrm{~Tb}$ and provide additional information concerning its decay properties. Levels in ${ }^{147} \mathrm{Gd}$ populated by this (presumably $\mathrm{h}_{11 / 2}$ ) ${ }^{147} \mathrm{~Tb}$ state are: 997.6, $9 / 2^{-}$; 1397.7, (9/2 $)$; (1778.9); and 1797.8, (9/2 ${ }^{-1}$ ) keV Contrastingly, the $1.6-\mathrm{h}$ low-spin (probably d $5 / 2$ ) ${ }^{147} \mathrm{~Tb}$ isomer was found to populate the following ${ }^{147} \mathrm{Gd}$ levels: $0,752^{2} ; 1152.2,3 / 2^{-} ; 1292.0,\left(3 / 2^{+}\right)$; 1411.5, $\left(1 / 2^{+}\right)$; 1699.2; 1759.1; and 1846.6, $\left(5 / 2^{-}\right) \mathrm{keV}$. The assignment of the new $23-\mathrm{sec}$ activity to ${ }^{146} \mathrm{~Tb}$ is based primarily on the fact that five of its gamma rays have been observed by Kownacki et al. in a ${ }^{144} \mathrm{Sm}(\alpha, 2 \mathrm{n} \gamma)$ study. Levels in ${ }^{146} \mathrm{Gd}$ seen in the decay of ${ }^{146} \mathrm{~Tb}$ (probable spin of 3 ) are as follows: 1579.5, $2^{+}$; 2658.4, $4^{+}$; 2982.4, $6^{+}$; 2996.9; 3099.4; (3139.6); and 3313.4 keV . In contrast to the results of Kownacki et al. gamma rays either feeding or de-exciting their tentatively proposed $3^{-1}$ level at 1584.5 keV were not observed.

[^43]12. Reactions Induced by Alpha Particles on ${ }^{3} \mathrm{He} *$ (M. L. Halbert, A. van der Woude, ${ }^{1}$ and N. M. O'Fallon ${ }^{2}$ )

A prominent peak is observed in the forward-angle spectra of alpha particles if ${ }^{3} \mathrm{He}$ is bombarded $63.7,71.7$, or $81.4-\mathrm{MeV}$ alphas. The energy of the peak is consistent with a sequential decay process involving the $2.18-\mathrm{MeV}$ state of ${ }^{6} \mathrm{Li}$. At 71.7 MeV , proton spectra measured at back angles show that the cross sections for formation of ${ }^{6}$ Li* (2.18) agree with the intensity of the prominent alpha peak. The peak shape and position imply that the alpha particles are preferentially emitted forward with respect to the original ${ }^{6} \mathrm{Li}$ * direction. Two other peaks are observed in some of the alpha spectra, one of them possibly the result of a sequential decay involving ${ }^{5} \mathrm{Li}$.

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*To be published in Physical Review.
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        13. Widths of Analog States in Heavy Elements from ( \(p, n\) )
                Spectra* (H. W. Fielding, S. D. Schery, \({ }^{2}\) D. A.
                Lind, \({ }^{2}\) C. D. Zafiratos, \({ }^{2}\) and C. D. Goodman)
                The ( \(\mathrm{p}, \mathrm{n}\) ) reaction on targets of \({ }^{197} \mathrm{Au},{ }^{206} \mathrm{~Pb},{ }^{207} \mathrm{~Pb}\),
    ${ }^{208} \mathrm{~Pb},{ }^{209} \mathrm{Bi}$, and ${ }^{232} \mathrm{Th}$ has been studied to obtain the widths and reaction Q-values of the isobaric analog of the ground state of these targets. The widths obtained for the targets of 208 Pb and ${ }^{209} \mathrm{Bi}$ are inconsistent with previously quoted ( $p, n$ ) values but show much closer agreement with those found by ( $\mathrm{p}, \mathrm{np}$ ) experiments. Values for the widths are as follows: ${ }^{197} \mathrm{Au}, 158 \pm 35 ;{ }^{206} \mathrm{~Pb}, 220 \pm 35 ;{ }^{207} \mathrm{~Pb}, 236 \pm 35 ;{ }^{208} \mathrm{~Pb}, 277 \pm 35 ;{ }^{209} \mathrm{Bi}, 299 \pm 35$; and ${ }^{232} \mathrm{Th}, 315+30 \mathrm{keV}$.

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## B.2. Heavy Ion Induced Studies

> 1. $\frac{\text { On the Interference Between Direct Nuclear and Coulomb }}{\text { Excitation with Alpha Particles on }{ }^{154} \text { Sm, }{ }^{165} \mathrm{Er} \text { and }{ }^{182} \mathrm{~W}^{*}}$ (C.E. Bemis, Jr., P. H. Stelson, F. K. McGowan, W. T. Milner, J. L. C. Ford, Jr., R. L. Robinson and W. Tuttle ${ }^{1}$ )

Striking destructure interference effects were observed in the ${ }^{4}$ He excitation of the $2^{+}$and $4^{+}$ground band rotational states in deformed even ${ }^{154} \mathrm{Sm},{ }^{166} \mathrm{Er}$ and ${ }^{182} \mathrm{~W}$. The E2 and E4 transition moments and charge deformation parameters, $\beta_{20}^{C}$ and $\beta_{40}^{C}$ are given.
*To be published in Phys. Rev. C.
U. S. Public Health Service Fellow in Radiological Health Physics from the University of Tennessee, Knoxville.
2. Reaction List for Charged-Particle-Induced Nuclear Reactions $Z=1$ to 98 (H to Cf), July 1972 - June 1973* (F. K. McGowan and W. T. Milner)

This reaction list for charged-particle-induced nuclear reactions has been prepared from the journal literature for the period from July 1972 through June 1973. Each published experimental paper is listed under the target nucleus in the nuclear reaction with a brief statement of the type of data in the paper. The nuclear reaction is denoted by $A(\underline{a}, b) B$, where $M_{a} \geq$ (one nucleon mass). There is no restriction on energy. Nuclear reactions involving mesons in the outgoing channel are not included. Theoretical papers which treat directly with the analysis of nuclear reaction data and results are included in the reaction list.
*Submitted to Atomic Data and Nuclear Data Tables for publication.

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\text { 3. } \frac{\text { Charged-Particle Reaction List, 1948-1971* }}{\text { McGowan and W. T. Milner) }} \text { (F. K. }
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This reaction list for charged-particle-induced nuclear reactions has been prepared from the journal literature for the period from 1948 through June 1971. It consists of material from a major collection and two supplements which appeared in Nuclear Data Tables. This material has been reorganized into a single list for presentation here. New indexes and appendixes for the integrated unit have been prepared. Supplements to
this compendium will appear annually in Nuclear Data Tables and will be collected eventually into another volume not overlapping with this one. There has not been a uniform treatment for all Z-values and all types of reaction data for the period 1948 to 1971. The exact coverage is:

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\begin{array}{ll}
\mathrm{Z}=1 \text { and } 2 \text { ( } \mathrm{H} \text { and He) } & \text { May 1969-June } 1971 \\
\mathrm{Z}=3 \text { to } \mathrm{Z}=99 \text { (Li to Es) } & 1948 \text {-June } 1971 \\
\text { Coulomb Excitation } & 1956 \text {-June 1971 } \\
\text { Theoretical Analysis } & \text { July 1970-June } 1971 .
\end{array}
$$

Each published experimental paper is listed under the target nuclei in the nuclear reactions studied with a brief statement of the type of data presented for the reaction. Reactions covered can be described by $A(a, b) B$, where $M_{a} \geq$ (one nucleon mass). Reactions involving mesons in the outgoing channel are not included. There is no restriction on energy. Since July 1970 theoretical papers which treat directly with the analysis of nuclear reaction data and results which have been included in the reaction list.

Published in Atomic and Nuclear Data Reprints, Volume 2, Academic Press
(1973).

> 4. $\frac{\text { E2 and E4 Transition Moments and Equilibrium Deformations }}{\text { in the Actinide Nuclei** }}$ (C. E. Bemis, Jr., F. K. McGowan, J. L. C. Ford, Jr., W. T. Milner, P. H. Stelson and R. L. Robinson)

Precision Coulomb excitation experiments using ${ }^{4} \mathrm{He}$ ions have been performed in the actinide region ( $230 \geq \mathrm{A} \geq 248$ ) by the observation of elastic and inelastically scattered projectiles using a split-pole magnetic spectrometer equipped with a position-sensitive proportional detector. Twelve even-A targets from ${ }^{230} \mathrm{Th}$ to ${ }^{248} \mathrm{Cm}$ have been investigated and the reduced quadrupole matrix element, $<2| | \mathrm{M}(\mathrm{E} 2)| | 0\rangle$, and the reduced hexadecapole matrix element, $\langle 4||M(E 4)||0\rangle$, have been determined from the experimental excitation probabilities of the $0^{+}, 2^{+}$and $4^{+}$states in the ground -state rotational bands. The values of $B(E 4,0 \rightarrow 4)$ range from 167 single-particle units for ${ }^{234} \mathrm{U}$ to essentially zero single-particle units for $244,246,248 \mathrm{Cm}$. Model dependent deformation parameters, $\beta_{20}$ and $\beta_{40}$, are extracted from the measured E2 and E4 transition moments for distributions of nculear charge represented by deformed Fermi distributions and by a deformed homogeneous distribution.

[^45]5. ( ${ }^{6} \mathrm{Li},{ }^{3} \mathrm{He}$ ) and ( $\left.{ }^{6} \mathrm{Li}, \mathrm{t}\right)$ Reactions on ${ }^{12} \mathrm{C}$ at 60 MeV * (H. G. Bingham, M. L. Halbert, D. C. Hensley, E. Newman, K. W. Kemper ${ }^{1}$ and L. A. Charlton ${ }^{1}$ )

The ${ }^{12} \mathrm{C}\left({ }^{6} \mathrm{Li},{ }^{3} \mathrm{He}\right)$ and ${ }^{12} \mathrm{C}\left({ }^{6} \mathrm{Li}, \mathrm{t}\right)$ reactions have been measured at an incident energy of 60 MeV . Several mirror states in $A=15$ up to 18 MeV in excitation were strongly populated. These states, except for slight excitation energy differences, agree with those from the $\left({ }^{10} \mathrm{~B},{ }^{7} \mathrm{Li}\right)$ and $\left({ }^{10} \mathrm{~B},{ }^{7} \mathrm{Be}\right)$ measurements by Nagatani et al. ${ }^{2}$ Negative parity states are weakly populated relative to the positive parity states. Based on the relative strengths, the experimental measurements would favor an assignment of $9 / 2^{+}, 11 / 2^{+}, 13 / 2^{+}$to states at $10.74,13.12$ and 15.49 MeV and $10.52,12.86$ and 15.05 MeV in ${ }^{15} \mathrm{~N}$ and ${ }^{15} 0$, respectively. But shell model predictions ${ }^{3}$ for high spin states ( $\leq 13 / 2$ ) to not agree very well with these assignments. Measured angular distributions for these states were analyzed using a finite range DWBA formalism.

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\({ }^{*}\) To be presented at the Bloomington APS Meeting, November 1-3, 1973.
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Florida State University.
K. Nagatani, D. H. Youngblood, R. Kenefick and J. Bronson, Phys. Rev.
    Letters 31, 250 (1973).
3
    J. B. McGrory, private communication.
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        6. \(\frac{\text { A Study of the }\left({ }^{16} 0,{ }^{15} \mathrm{~N}\right) \text { Reaction at Small Angles* }}{\text { (J. B. Ball, }{ }_{\mathrm{i}} \text { Sinclair, S. S. S. Larsen, }{ }^{1} \text { F. Videbaek, }}\)
    and Ole Hansen ${ }^{1}$
The forward angle dependence of the $\left({ }^{16} 0,{ }^{15} \mathrm{~N}\right)$ reaction
on targets of ${ }^{26} \mathrm{Mg},{ }^{30} \mathrm{Si}$, and ${ }^{48} \mathrm{Ca}$ has been studied with incident ${ }^{16} \mathrm{O}$
energies ranging from 45 to 60 MeV at the Super-FN tandem accelerator of
the Niels Bohr Institute. The ${ }^{15} \mathrm{~N}$ ions corresponding to the ground and
low-lying excited levels in the final nuclei were detected by means of
solid-state position-sensitive counters placed in the focal plane of a
magnetic spectrograph. With this system, cross-section measurements were
obtained as far forward as $7^{\circ}$ in the center-of-mass system. In all cases
sizeable forward angle cross sections are observed for the ${ }^{26} \mathrm{Mg}\left({ }^{16} 0,{ }^{15} \mathrm{~N}\right)$
reaction at 45 MeV , the ground and first-excited state angular distribu-
tions show a sharp rise forward of $15^{\circ}$ (c.o.m.) that is not reproduced by
present DWBA calculations.

[^46]> 7. Elastic Scattering of ${ }^{16} \mathrm{O}$ by ${ }^{16} \mathrm{O}^{*}$ C. B. Fulmer, S. Raman, M. J. Saltmarsh, A. H. Snell and P. H. Stelson)

Pronounced structure in excitation functions for ${ }^{16} 0+{ }^{16} 0$ elastic scattering has been observed by the Yale group for c.m. energies up to 38 MeV . To see whether this remarkable structure persists at higher energies, we have measured the cross section at $90^{\circ} \mathrm{c} . \mathrm{m}$. for relative energies from 37 to 74 MeV ( $\sim 6$ times the Coulomb barrier). Two counters were used in coincidence. The targets were 60 to $110 \mu \mathrm{~g} / \mathrm{cm}^{2} \mathrm{SiO}_{2}$; they withstood beam currents of 30 particlena for many hours without damage. Violent oscillations in the cross section as a function of energy were observed, the peak-to-valley ratio being as much as 80 . Their width and spacing are larger than for the data of Ref. 1 . The cross section shows a strongly decreasing trend, roughly a factor of 5 for each 10 MeV increase in c.m. energy. No set of published optical-model parameters gives an adequate representation of the data.

[^47]8. High-Spin States of ${ }^{39} \mathrm{~K}$ via the ${ }^{28} \mathrm{Si}\left({ }^{16} \mathrm{O}, \alpha \mathrm{p} y\right){ }^{39} \mathrm{~K}$ Reaction* (H. J. Kim, R. L. Robinson and W. T. Milner)

Nuclear properties of the excited states populated via the ${ }^{28} \mathrm{Si}\left({ }^{16} \mathrm{O}, \alpha \mathrm{p}\right){ }^{39} \mathrm{~K}$ reaction were investigated by studying the yields, angular distributions and coincidence relations for in-beam $\gamma$ rays. The incident ${ }^{16} 0$-ion energy range was $26-42 \mathrm{MeV}$. A level scheme based on these $\gamma$-ray studies will be presented. Two noteworthy aspects of the levels populated by the present ${ }^{16} 0$-ion induced reaction are: 1) none of the numerous established levels above 4 MeV were observed, and 2) $\gamma$ rays from many levels above the $\alpha$ - and proton-separation energies are observed. Both observations are consistent with the level spins being rather high. As expected for the $\gamma$ rays from highly spin-aligned nuclear states, most of the prominent in-beam $\gamma$ rays have rather pronounced angular distributions. If we make the usual stretched spin assumption, then the following spins are suggested by the angular distributions: $7 / 2,9 / 2,11 / 2,13 / 2$, and 15/2 for the $2.812-, 3.596-, 3.942-, 4.699-$, and $4.829-\mathrm{MeV}$ states, respectively.

[^48]9. Coulomb-Nuclear Interference in ${ }^{22} \mathrm{Ne}+{ }^{88} \mathrm{Sr}$ Inelastic Scattering* (E. E. Gross, H. G. Bingham, M. L. Halbert, D. C. Hensley, and M. J. Saltmarsh)
${ }^{22} \mathrm{Ne}$ beams from the ORIC cyclotron were used to measure the elastic and inelastic excitation functions for ${ }^{22} \mathrm{Ne}$ ions scattered from $a^{88} \mathrm{Sr}$ target at $155^{\circ}$ and $175^{\circ}$ Lab. The measurements spanned the energy range from 49 to 65 MeV Lab. In addition, the angular distribution for elastic scattering at 65 MeV was obtained. A strong Coulomb-Nuclear interference effect ${ }^{1}$ was observed in the excitation of the first $2^{+}$state of ${ }^{88} \mathrm{Sr}(1.835 \mathrm{MeV})$ and ${ }^{22} \mathrm{Ne}(1.275 \mathrm{MeV})$. The positions of the interference minima at $175^{\circ} \mathrm{Lab}$, in terms of the classical distance or closest approach, were found to occur at 11.6 fm and 11.8 fm respectively. A global search on all the elastic-scattering data determined the following six-parameter optical potential: $\mathrm{V}_{\mathrm{o}}=21.5 \mathrm{MeV}, \mathrm{r}_{\mathrm{o}}=1.3 \mathrm{fm}, \mathrm{a}_{\mathrm{O}}=0.58 \mathrm{fm}, \mathrm{W}=7.37$ $\mathrm{MeV}, \mathrm{r}^{\prime}=1.4 \mathrm{fm}, \mathrm{a}^{\prime}=0.36 \mathrm{fm}$. With this optical potential, the inelastic data could then be accounted for with a collective model DWBA calculation.

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* To be presented at the Bloomington APS Meeting, November 1-3, 1973.
F. Videbaek, I. Chernov, P. R. Christensen, and E. E. Gross, Phys. Rev.
    Letters 28, 1072 (1972).
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10. Coulomb Excitation of Ground Bands in $160,162,164$ Dy with ${ }^{20} \mathrm{Ne}$ and ${ }^{35} \mathrm{Cl}$ Ions* (R. O. Sayer, E. Eichler, Noah R. Johnson, D. C. Hensley and L. L. Riedinger ${ }^{1}$ )

Multiple Coulomb excitation of states up to $J^{\pi}=12^{+}$
in the ground band was measured to test the rigid-rotor prediction for intraband $\mathrm{B}(\mathrm{E} 2)$ ratios. The deexcitation gamma rays were observed in singles and in the particle-gamma coincident mode following excitation by ${ }^{20} \mathrm{Ne}$ or ${ }^{35} \mathrm{C} 1$ ions from the Oak Ridge Isochronous Cyclotron. B(E2) values were extracted by comparing experimental excitation probabilities with theoretical values calculated with the Winther-de Boer computer code. An unexpected result is that the $B(E 2 ; 4 \rightarrow 6)$ values for ${ }^{162,164} \mathrm{Dy}$ are $15 \pm 5 \%$ smaller than the rotational values. However, the most striking variation of $B(E 2)$ with spin occurs for ${ }^{160} \mathrm{Dy}$. We find $B(E 2) \exp / B(E 2)$ rotational
$=0.77 \pm 0.05,0.94 \pm 0.06$, and $1.29 \pm 0.14$ for the $4 \rightarrow 6,6 \rightarrow 8$, and $8 \rightarrow 10$ transitions, respectively. The $10 \rightarrow 8$ transition in ${ }^{160}$ Dy is significantly faster than rotational even when our approximate quantal correction of $6 \%$ is not included in the analysis.

[^49]11. Absolute Cross Sections for the ${ }^{58,60} \mathrm{Ni}\left({ }^{16} 0, \mathrm{X}\right)$

Reactions* (R. L. Robinson, H. J. Kim and J. L.
C. Ford, Jr.)

The absolute cross sections for a variety of reactions resulting from bombardment of ${ }^{58},{ }^{60} \mathrm{Ni}$ with $38-, 42-$, and $46-\mathrm{MeV}{ }^{16} \mathrm{O}$ ions were determined from yields of gamma rays observed from the decay of resulting radioactivities and from yields of in-beam gamma rays. The strongest reactions are $\left({ }^{16} 0, p n\right),\left({ }^{16} 0,2 p\right)$, and $\left({ }^{16} 0, \alpha p\right)$. Other identified reactions are $\left({ }^{16} 0, p\right),\left({ }^{16} 0,2 n\right),\left({ }^{16} 0, \alpha\right),\left({ }^{16} 0, \alpha n\right),\left({ }^{16} 0,2 \alpha\right),\left({ }^{16} 0,2 p n\right)$, $\left({ }^{16} \mathrm{O}, 3 \mathrm{p}\right)$, $\left({ }^{16} \mathrm{O},{ }^{12} \mathrm{C}\right)$, and $\left({ }^{16} \mathrm{O},{ }^{15} \mathrm{~N}\right)$. At the higher projectile energies, the total cross sections are in reasonable agreement with the reaction cross sections based on an optical-model calculation. The relative yields of the reaction products were compared to predictions for statistical decay of a compound nucleus system by neutron, proton, and alpha-particle emission. This model does account for the general features of the experimental data; in particular it correctly predicts that charged-particle emission strongly competes with neutron emission.

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* To be published in Physical Review C.
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\begin{aligned}
& \text { 12. } \frac{\text { Levels in }{ }^{72} \text { Se Populated by }{ }^{72} \mathrm{Br}^{*}}{\text { J. H. Hamilton, }{ }^{2} \text { R. L. Robinson, H. J. Kim and J. L. }} \begin{array}{l}
\text { C. Ford, Jr.) }
\end{array} \text { (W. E. Collins, }
\end{aligned}
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The level structure of ${ }^{72} \mathrm{Se}$, was investigated via the decay of ${ }^{72} \mathrm{Br}$, produced in the ${ }^{58} \mathrm{Ni}\left({ }^{16} 0, \mathrm{pn}\right)$ reaction. Thirty-two transitions were assigned to ${ }^{72}$ Se on the basis of half-life, energy, and/or relative gamma-ray yields for different beam energies with eighteen transitions confirmed by coincidence data. Thirty-two transitions are placed into the decay scheme which consists of the following levels: $862.0,2^{+} ; 936.8,0^{+}$; $1316.7,2^{+} ; 1636.8,4^{+}$; 1876.0; 1998.4,1, $2^{+} ; 2150.3,\left(2^{+}\right) ; 2371.6,\left(2^{+}\right) ; 2433.2$; 2586.2 ; 2965.6; 3124.1; 3225.9 ; and $3239.5-\mathrm{keV}$. The half-1ife of ${ }^{72} \mathrm{Br}$ was measured to be $1.31 \pm 0.04 \mathrm{~min}$.

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*To be published in Nuclear Physics.
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    Physics Department, Vanderbilt University, Nashville, TN.
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13. Study of the ${ }^{10} \mathrm{~B}\left({ }^{16} 0, \alpha\right){ }^{22} \mathrm{Na}$ Reaction* (J. Gomez del Campo, T. J. C. Ford, Jr., R. L. Robinson, P. H. Stelson, and S. T. Thornton ${ }^{2}$ )

States in ${ }^{22} \mathrm{Na}$ were populated using the ${ }^{10} \mathrm{~B}\left({ }^{160} 0, \alpha\right)$ reaction. Excitation functions were measured in the energy range $\mathrm{E}_{\mathrm{c} . \mathrm{m} .}=15.4$ -
17.7 MeV for 47 excited states in ${ }^{22} \mathrm{Na}$ from 0 to 14 MeV excitation. Angular distributions were measured at a bombarding energy of 46 MeV for a number of the excited states and were observed to be symmetrical around $90^{\circ}$ (c.m.). Fluctuation analyses of the excitation functions were made, and the results indicated a statistical compound nucleus process for the reaction mechanism. Hauser-Feshbach calculations gave good agreement with the data and provided strong evidence for proposed high-spin members of the ground-state rotational band, and the $\mathrm{K}=0^{+}, \mathrm{T}=0$ band in ${ }^{22} \mathrm{Na}$.

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    Instituto de Fisica, UNAM, Mexico 20, D.F., supported in part by
    Instituto Nacional de Energia Nuclear, Mexico.
2
    University of Virginia, Charlottesville, Virginia.
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14. Excitation of Rotational Bands in \({ }^{20} \mathrm{Ne}\) by the
    \({ }^{{ }^{10} B\left({ }^{16} 0,\right.}{ }^{6}\) Li) Reaction* (J. L. C. Ford, Jr.,
    J. Gomex del Campo, \({ }^{1}\) R. L. Robinson, P. H. Stelson,
    and S. T. Thornton \({ }^{2}\) )
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    States in \({ }^{20} \mathrm{Ne}\) were populated by the \({ }^{10} \mathrm{~B}\left({ }^{16} \mathrm{O},{ }^{6} \mathrm{Li}\right)\)
    reaction, and levels were observed up to 11 MeV in excitation energy.
Excitation functions at $7^{\circ}$ were measured from 44.4 to 46 MeV in 400 keV
intervals. The reaction appears to be predominantly due to compound nucleus formation, and good agreement was found comparing the measured cross sections with Hauser-Feshbach calculations. The observed level structure agrees with the known band structure of ${ }^{20} \mathrm{Ne}$.

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* To be published in Physical Review.
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    University of Virginia, Charlottesville, Virginia.
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    15. States in \({ }^{24} \mathrm{Mg}\) Populated by the \({ }^{10} \mathrm{~B}\left({ }^{16} \mathrm{O}, \mathrm{d}\right)\) and
    \({ }^{12} \mathrm{C}\left({ }^{16} 0, \alpha\right)\) Reactions* (J. L. C. Ford, Jr.,
    J. Gomex del Campo, R. L. Robinson, P. H. Stelson,
        and S. T. Thornton \({ }^{2}\) )
    States in \({ }^{24} \mathrm{Mg}\) were populated by the \({ }^{10} \mathrm{~B}\left({ }^{16} \mathrm{O}, \mathrm{d}\right)\) and
    \({ }^{12} \mathrm{C}\left({ }^{16} 0, \alpha\right)\) reactions. Excitation functions at \(7^{\circ}\) for many of the levels were measured for bombarding energies between 40 and 46 MeV for the \({ }^{16} \mathrm{O}+{ }^{12} \mathrm{C}\) reaction, and from 44 to 46 MeV for the \({ }^{16} \mathrm{O}+{ }^{10} \mathrm{~B}\) reaction. The reactions appear to be predominantly due to compound nucleus formation,
    and general agreement was found comparing the measured cross sections with Hauser-Feshbach calculations. The experimental cross sections for the members of the $K=0^{+}$and $K=2^{+}$rotational bands are particularly well reproduced by the calculations up through the $8^{+}$states.

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*To be published in Nuclear Physics.
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Instituto de Fisica, UNAM, Mexico 20, D.F., supported in part by
Instituto Nacional de Energia Nuclear, Mexico.
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    University of Virginia, Charlottesville, Virginia.
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16. Population of High Spin States in ${ }^{22} \mathrm{Na}$ by Means of the ${ }^{10} B\left({ }^{16} 0, \alpha\right)$ Reaction* (J. Gomez del Campo, ${ }^{1}$ J. L. C. Ford., Jr., R. L. Robinson, P. H. Stelson, J. B. McGrory, and S. T. Thornton ${ }^{2}$ )

Strong selectivity has been observed in the population of states in ${ }^{22} \mathrm{Na}$ up to high excitation energies. Angular distributions were measured, and a comparison with Hauser-Feshbach calculations allow us to select strong candidates for the high spin members of the $K=3^{+}$, $T=0$ and $K=0^{+}, T=0$ bands in ${ }^{22} \mathrm{Na}$.

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    Instituto de Fisica, UNAM, Mexico 20, D.F., supported in part by
    Instituto Nacional de Energia Nuclear, Mexico.
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    University of Virginia, Charlottesville, Virginia.
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C. BIOMEDICAL APPLICATIONS SUBCOMMITTEE

1. $\frac{\text { Calculations Related to the Application of Negatively }}{\text { Charged Pions in Radiotherapy: Absorbed Dose, LET }}$

Calculations using a Monte Carlo radiation transport code and a model for cell inactivation have been carried out to estimate the spatial distributions of the absorbed dose, LET spectra, and the cell survival, RBE, and OER for $T-1$ human kidney cells produced by a beam of negatively charged pions incident on a slab of tissue.

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## D. ISOTOPES SUBCOMMITTEE

## 1. Developments in the ORNL Program* (L. O. Love)

The status of the ORNL effort to computerize the electromagnetic separators used in stable isotope separation is presented. The effectiveness of the Oak Ridge $180^{\circ}$ sector with computer-assisted operation is discussed, and a plan to install computer equipment for data acquisition and operation assistance on an adjacent calutron is summarized. Computer equipment in use with the sector and some of the problems associated with it are compared with the benefits expected from a computerized calutron system. Once this effectiveness is demonstrated on the pilot calutron, similar equipment will be applied in the operation of 16 calutrons starting with data acquisition and then adding operational control.

Collections involving high-purity isotopes are reviewed, giving comparison of isotopic purities from various charge compounds and feed systems. In mercury separation, a feed of elemental mercury from a water-heated reservoir promoted rapid start-up time, while platinum-metals feeds from the elements with chlorine trifluoride produced improvement in all phases of the operational process.
*Presented at the Eighth International Conference on Low Energy Ion Accelerators and Mass Separators, Billingehus, Skövde, Sweden, June 12-15, 1973.

## 2. Process Efficiencies in Calutron Separations* (L. 0.

One motive for understanding and improving the efficiency of an electromagnetic separator is that in specific separations involving multiple passing or in separations involving radioactive feeds, process efficiency largely determines the ultimate cost of the collected sample. So dramatic is this effect that all avenues accessible to improvement of efficiency should be pursued vigorously.

This paper is a survey of the process efficiency experiences gained in electromagnetic separation of over 60 elements for approximately 250 isotopes with the Oak Ridge calutrons. The data presented is from almost two and three-quarter million separator hours involving over forty thousand runs. Operating parameters from selected series of collections with minimum, maximum and average values related to process efficiencies are given for each element. Opinion will be offered in an attempt to explain the variations from run to run, and to identify the parameters which are thought to place upper limits on the efficiencies we achieve.
*Presented at the Eighth International Conference on Low Energy Ion Accelerators and Mass Separators, Billingehus, Skövde, Sweden, June 12-15, 1973.

## RENSSELAER POLYTECHNIC INSTITUTE

## A. CROSS SECTION MEASUREMENTS

1. Neutron Capture Cross Sections of ${ }^{105} \mathrm{Pd},{ }^{151} \mathrm{Eu},{ }^{153} \mathrm{Eu}$ and ${ }^{103_{\mathrm{Rh}}}$ * (H. D. Knox ${ }^{* *}$, A. Sanislo, R. W. Hockenbury and R. C. Block)

Capture measurements have been made on the above isotopes covering the region from 20 eV to about 100 keV . Linac running conditions were 550 pps and a pulse width of 66 ns . The time-dependent background was determined by using black resonance filters of $\mathrm{S}, \mathrm{Al}, \mathrm{Na}$ and Mn .

The detector efficiency will be determined from pulse-height vs. time-offflight data for each sample. In order to obtain another normalization, transmission data have also been taken over the same energy range. The transmission measurement will thus provide a normalization as well as a check on the resonance parameters in the resolved resonance region.

The Harvey-Atta code will be used to analyze resonances in the transmission data and a combination of the two sets of results will give a normalization for the keV capture cross section.

[^51]2. Radiative Capture in ${ }^{60} \mathrm{Ni}^{*}$ and $\mathrm{Fe}^{*}$ in the Thermal to Low KeV

## Range

(P. H. Brown, R. C. Block and J. R. Tatarczuk)

The spectrum of $\gamma$-rays given off following radiative neutron capture in 60 Ni and Fe has been studied as a function of neutron energy. The RPI Linac is used as the neutron source and the neutron energy is determined by the time-of-flight method (with a resolution of $8 \mathrm{nsec} / \mathrm{m}$ ) using a lithium-drifted germanium ( $\mathrm{Ge}(\mathrm{Li})$ ) detector. The $\gamma$-ray resolution obtained with the $\mathrm{Ge}(\mathrm{Li})$ detector is 12 keV full-width at half-maximum (FWHM) for an $8 \mathrm{MeV} \gamma$-ray and 4 key FWHM for a $1 \mathrm{MeV} \gamma$-ray. The intensities of prominent $\gamma$-rays in the ${ }^{60} \mathrm{Ni}$ and Fe capture spectrum were measured as a function of neutron energy from thermal to low keV neutron energies. In addition the partial capture cross sections for these prominent $\gamma$-rays were measured in the low eV to low keV neutron energy range. The results, which show a dominance of the spectrum by only a few high energy $\gamma$-rays, are discussed in terms of the experimental observables due to compound nucleus (statistical) capture and single-particle (nonstatistical) capture.

[^52]3. Natural $\mathrm{Ni}(n, \gamma)^{*}$ and ${ }^{54} \mathrm{Fe}^{*}(\mathrm{n}, \gamma)$ Spectra Data Acquisition (S. E. Arendt, E. J. Winhold and R. C. Block)

Using the RPI Linac and the PDP-9 data acquisition system, an experiment was performed to determine the spectrum of emitted gamma rays as a function of neutron energy following neutron capture in natural nickel (approx. 430 gms.) and a separated ${ }^{54} \mathrm{Fe}$ isotope (approx. 65 gms. )

The natural nickel data accumulation required 60 hours of Linac time with Linac beam parameters as follows: width 11 nsec , repetition rate 550 Hz , and average current $36 \mu \mathrm{~A}$. The ${ }^{54} \mathrm{Fe}$ data accumulation required 45 hours of Linac time with Linac beam parameters as follows: width 66 nsec , repetition rate 500 Hz , and average current $135 \mu \mathrm{~A}$. For both samples 38 neutron time-of-flight regions were obtained, each containing 4096 channels of gamma ray pulse height data.

Data on ${ }^{52}$ Cr will next be obtained and analysis on all three samples will be forthcoming.
*Req. Nos. 195, 164
4. Differential Elastic Scattering Cross Sections of keV Neutrons from Iron* and Nickel* (R. Zuhr and K. Min)

Final analysis of the six angle differential elastic scattering data for natural iron and nickel has been completed. As previously reported, these measurements were made relative to a lead standard at angles from 30 to $150^{\circ}$. Time-of-flight methods, using the RPI Linac as a pulsed neutron source, gave energy resolution of 3 nanoseconds per meter throughout the desired energy range of 10 to 650 kilovolts.

All the cross sections were corrected for multiple scattering, which is appreciable because of our use of relatively thick samples, by using the method of Lane and Miller. This is a combined Analytic-Monte Carlo approach which includes scattering through fourth order.

Finally the data were fitted with Legendre Polynomial expansions.

[^53]5. Capture and Total Cross Sections of ${ }^{54,58^{*}} \mathrm{Fe}$ and ${ }^{61,64 *} \mathrm{Ni}$ (H. D. Knox, M. Costello, N. N. Kaushal, R. W. Hockenbury and R. C. Block)

Analysis of the low resolution data is partly complete. Higher resolution capture data has been taken on ${ }^{61} \mathrm{Ni}$ and ${ }^{54} \mathrm{Fe}$ using the greater neutron intensity available after installation of the Model 12 Electron Gun. This set of data covers the range 10 to 200 keV . Linac conditions were 11 ns pulse width, 500 pps and a channel width of $7.7 \mathrm{~ns} .$, with an overall timing resolution including moderator effect of about $0.8 \mathrm{~ns} /$ meter. High resolution transmission measurements are planned, to supplement the capture data.

Req. Nos. 169, 173, 187, 200
6. Total Neutron Cross Section of ${ }^{235} \mathrm{U}$

The total neutron cross section of ${ }^{235}$ U was determined from 0.5 to about 30 Mev using a proton recoil scintillator on the 250 meter flight path.

Between 0.7 and 10 Mev , the present data have a statistical error $\circ f \pm 1 \%$ and are in agreement, within the error ( $1 \%$ ), of Heaton and Schwarz and also with the data of Glasgow and Foster.

The results of Smith and Whalen from about 0.7 to 1.4 Mev lie slightly lower (about $1-1 / 2 \%$ ) than the present results.
7. Total Neutron Cross Section of ${ }^{239}$ Pu (K. A. Nadolny, F. L. Green and P. Stoler)

Transmission measurements were made on ${ }^{239}$ Pu from 0.5 to 30 Mev . A proton recoil liquid scintillation detector was used at the 250 meter flight path. Linac running conditions were: (1) pulse width of 20 ns and (2) 500 pps , repetition rate.

The results have been compared to those of Foster and Glasgow. The agreement is within statistical errors in the range l-15 Mev. Between 0.5 and about 1.4 Mev , the data of Ref. l lie above the present data but the difference is within the statistical errors of the measurements.

1. Smith and Whalen, private communication, NNCSC.

## B. INTEGRAL CHECKS OF CROSS SECTION DATA

1. Measurement and Analysis of Fast and Intermediate Neutron Spectra in a Bulk Sodium Assembly
(A. N. Mallen, E. R. Gaerttner, N. N. Kaushal and
B. K. Malaviya)

The first phase of the measurement and analysis of fast neutron spectra in a large bulk sodium assembly has been completed. The spectra were measured by the time-of-flight technique, using a special oilcooled neutron target coupled to the RPI LINAC as a pulsed neutron source; the energy range of the measurements extended from 10 eV to 10 MeV .

Comparison theoretical spectra were generated from energy-dependent transport theory with up to $\mathrm{P}_{8}$ anisotropic scattering. Calculated spectra based on data from the ENDF/B-I and ENDF/B-3 files for sodium have been compared with experiment and differences among cross-section files have been assessed.
T. W. BONNER NUCLEAR LABORATORIES - RICE UNIVERSITY

## A. NEUTRON PHYSICS

1. Organic Scintillator Neutron Detector Efficiency: A Comparison of Experimental Results with Predictions (Plasek, Miljanić, Valković, Liebert, and Phillips)

Absolute efficiency points in the neutron energy range $2-10 \mathrm{MeV}$ were taken for a $7.62 \mathrm{~cm} \times 12.75 \mathrm{~cm} \mathrm{NE}-218$ liquid organic scintillator, utilizing the $d\left(d, \mathrm{He}^{3}\right) \mathrm{n}$ reactions. The results were compared with two theoretical efficiency predictions: (1) Program "DETEFF" and (2) Program OSS. The agreement with DETEFF was quite good; however, the predictions of OSS varied considerably from the experimental points, both in absolute magnitude and in shape. This work has been published in Nucl. Instru. \& Meth. 1ll, 251-252 (1973).
2. Spatial Localization Effects in the ${ }^{2} H(d, p d) n$ Reaction (von Witsch, Mutchler, Phillips, and Miljanić)

A phenomenological explanation is proposed for the pronounced peaks observed in some coincidence spectra of the $\mathrm{2}_{\mathrm{H}}(\mathrm{d}, \mathrm{pd}) \mathrm{n}$ reaction at low relative energies in the protonneutron system. It has been shown that the density of states formalism of Phillips, Griffy, and Biedenharn which includes explicitly the fact that the $p-n$ system is produced in a spatially localized state can describe the observed spectral shapes with the pure, isospin allowed, ${ }^{3} S_{1}$ proton-neutron final-state interaction. In addition, the model satisfactorily describes the case of low relative energy between the deuteron and neutron. This work has been published in Phys. Rev. C8, 403 (1973).
3. Spatial Localization Effects in the ${ }^{2} H(d, p d) n$ Reaction (Mutchler, Andrade, Hudomalj, Miljanić, and Phillips)
The reaction ${ }^{2} H(d, p d) n$ has been studied with kinematical conditions corresponding to small relative energies in the $n-p$ system at bombarding energies of $E_{d}=6.5-10.0 \mathrm{MeV}$. The data were fit with the density of states formalism of Phillips, Griffy, and Biedenharn ${ }^{1}$ (PGB), which includes

[^54]explicitly the fact that the $p-n$ system is produced in a spatially localized state. In this energy range the PGB prediction fits the data while the usual Watson-Migdal form does not. The radius of the system was extracted and found to obey the relation $A^{2}=A_{0}^{2}+K^{2}$ where $A_{O}=3.58 \mathrm{fm}$ and $\lambda$ is the wavelength at the $d-d^{*}$ system in the center of mass system. Good agreement for $A$ was found with the previous results (see A.2. of this report) at higher energies and different kinematically conditions.
4. Experimental Program for the 5.5 MeV Van de Graaff

The klystron-bunched beams $1_{\mathrm{H}},{ }^{2} \mathrm{H},{ }^{3} \mathrm{He},{ }^{4} \mathrm{He}$ produced by the Rice University 5.5 MeV Van de Graaff accelerator are being used to perform experiments using time-of-flight techniques. Of particular interest has been the production of a secondary neutron beam from the $D(d, n){ }^{3}$ He reaction for performing neutron-induced reaction studies. Development of this technique is aimed at measuring selected cross sections from the Los Alamos report LA-5253-MS, "Compilation of Requests for Nuclear Data" with emphasis on those reactions relevant to the controlled thermonuclear fusion programs.
5. Fission Studies (T. Zabel and G. C. Phillips)

Present work concerning fission is involved with the simultaneous measurement of mass and charge of individual fission fragments by a combined ToF-x-ray technique. Effort is now being made to produce heavy ion beams of $\mathrm{Cl}, \mathrm{Br}$, and I in the EN tandem Van de Graaff accelerator to test feasibility, and later to determine efficiency.

## B. FEW-BODY PROBLEMS

1. Deuteron Break-up Reactions and Mass-3 Excited States (Plasek, Valković, Liebert, Miljanić, and Phillips)

Analyses of proton-neutron and proton-proton coincidence spectra corresponding to the $p+d \rightarrow p+d^{*}$ mechanism in the $p+d \rightarrow p+p+n$ reaction have been completed. The cross section results obtained in the two different detection geometries are self-consistent over a wide range of bombarding energies and detection angles. The spectral shapes were fit using final state interaction theory and matrix elements were calculated. The excitation functions are smoothly decreasing with bombarding energy and show no evidence for structure in the mass-3 system. Angular distributions in the range
$\theta \mathrm{d}^{*} \mathrm{C} . \mathrm{M}_{\mathrm{C}}=50^{\circ}-80^{\circ}$ show a pronounced forward-angle peaking for bombarding energies $\sim 7-8 \mathrm{MeV}$ with a smooth transition to essentially flat angular distributions around 12 MeV .
2. Quasi-Free Scattering in the ${ }^{6}$ Li $(d, d d){ }^{4}$ He Reaction at Low Bombarding Energies (Miljanić, Zabel, Liebert, G. C. Phillips, and V. Valković)

Deuteron-deuteron quasi-free scattering contributions
in the $6 \mathrm{Li}(\mathrm{d}, \mathrm{dd}) 4_{\mathrm{He}}$ reaction have been measured for deuteron bombarding energies 6-1l MeV. The plane wave impulse approximation does not give a satisfactory description of the measured spectra. The introduction of a radial cut-off gives a better agreement in the shape and absolute magnitude. Extracted clustering probabilities and widths of momentum distributions are compared with results from other quasi-free scattering reactions on 6 Li . This work has been accepted for publication in Nuclear Physics.
3. Quasi-Free Reactions of $6_{\text {Li }}+d$ at Low Bombarding Energies (Miljanić, J. Hudomalj, Andrade, Mutchler, and Phillips)
${ }^{6} \mathrm{Li}_{\mathrm{L}}(\mathrm{d}, \mathrm{dd}) \alpha,{ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{d} \alpha) \mathrm{d}$, and ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{tp}) \alpha$ reactions are studied at low bombarding energies and in the conditions which emphasize quasi-free reaction mechanism. Experimental data show that quasi-free contributions are still important for bombarding energies below 10 MeV . These results are being compared with the predictions of the modified plane wave impulse approximation.
4. Final State Interactions in Deuteron-Induced ThreeBody Reactions on KLi $_{\text {L }}$ (Miljanić, Hudomalj, Andrade, and Phillips)

Six different pairs of charged particles were detected from the deuteron-induced three-body reactions on $6_{\text {Li. }}$ contributions from the sequential reactions through the intermediate states of ${ }^{4} \mathrm{He},{ }^{5} \mathrm{He},{ }^{5} \mathrm{Li},{ }^{6} \mathrm{Li},{ }^{7} \mathrm{Li}$, and ${ }^{7} \mathrm{Be}$ are observed. The final state coulomb interactions between different charged particles are also studied.
5. A Study of the Reaction Mechanisms in the ${ }^{7}$ Li $(d, n \alpha) \alpha$ Reaction (Furić, Miljanić, Mutchler, and Phillips)

Several neutron-alpha coincidence spectra were accumulated at 10 MeV deuteron bombarding energy. Neutrons were identified through the Pulse Shape Discrimination technique. Neutron detector efficiency was measured using the
$d+d \rightarrow n+{ }^{3}$ He reaction. Strong peaks corresponding to the ${ }^{5} \mathrm{He}_{\mathrm{g} . \mathrm{s}}$. and 2.9 MeV excited state of 8 Be were observed in the spectra. The search was made to establish the quasi-free mechanism corresponding to the $d+t \rightarrow n+\alpha$ reaction on the triton cluster in the 7 Li nucleus. A minimum was observed in the spectrum where the spectator alpha particle energy is close to zero. This is in agreement with the $L=l \alpha-t$ relative wave function. Further data will be accumulated in order to examine the existence of the quasi-free mode more rigorously.
6. Rescattering of $\alpha$ on $d$ in the reaction $p+9_{\mathrm{Be} \rightarrow \mathrm{d}+{ }^{8} \mathrm{Be} \rightarrow}^{\mathrm{d}+\alpha+\alpha}$ $\underline{\alpha+\alpha+\alpha}$ (E. V. Hungerford and T. M. Williams)

By detecting the $d$ and the $\alpha$ going away from the deuteron in coincidence, it should be possible to observe a decrease in counts when the angle between the other $\alpha$ and the deuteron approaches $0^{\circ}$ in the C.M. system. At a slightly higher energy in which rescattering cannot occur, this drop in coincidences should not be observed.
7. A Search for Rescattering in the $d+10_{B \rightarrow 3} \rightarrow 3$ Reaction (Valković, Miljanić, Liebert, and Phillips)

The reaction ${ }^{10} \mathrm{~B}(\mathrm{~d}, \alpha \alpha)^{4}$ He has been studied under kinematic conditions appropriate for the observation of the rescattering process $\mathrm{d}_{\mathrm{l}} \mathrm{lO}_{\mathrm{B}} \rightarrow 8_{\mathrm{Be}}{ }^{*}+\alpha_{1} \rightarrow \alpha_{2}+8_{\mathrm{Be}_{\mathrm{g} . \mathrm{s}} \rightarrow \alpha_{1}+\alpha_{2}}$ $+\alpha_{3}$. The experiment has been performed as a study of the excitation curve for the sequential decay $d+10_{B} \rightarrow \alpha_{2}+8_{B e g . s . ~}^{\text {. }}$ $\rightarrow \alpha 1+\alpha 2+\alpha 3$. The bombarding energy interval was chosen such that the first step in the rescattering process was the formation of 8 Be * resonances at 16.63 and 16.93 MeV . Coincidence and single counter spectra were analyzed.
8. Energy Dependence of the cross section of the $11_{B}(p, \alpha \alpha){ }^{4} \mathrm{He}$ Reaction (Miljanić, Valković, Rendic, and Phillips)

The $\alpha-\alpha$ coincidence spectra from the $\operatorname{ll}_{B}(p, \alpha \alpha){ }^{4}$ He reaction have been measured in the bombarding energy interval $8.5 \leqslant E_{p}$ $\leq 9.5 \mathrm{MeV}$. The bombarding energies were chosen such that the rescattering process involving the first step formation of the $8_{\text {Be* }}$ ( 16.63 MeV ) state was allowed. The angular settings of the two alpha-particle detectors were chosen in such a way as to observe the $\alpha-\alpha$ final state interaction in the $8_{B e *}(2.9 \mathrm{MeV})$ state. The observed structure in the excitation curves was analyzed.
9. $\frac{(160, n p)}{\left(\text { Phillips, Plasek, Liebert, Wheeler, Miljanic }\left(16{ }_{0}, n \alpha\right) \text { Reactions on Some Light Nuclei }\right.}$ Valković)

Nuclear reactions with three particles in the final state resulting from the bombardment of $9 \mathrm{Be}, 10_{\mathrm{B}},{ }^{12} \mathrm{C}$, and 13C targets with 30 and $36 \mathrm{MeV} 160(5+)$ ions have been studied. Neutron-proton and neutron-alpha particle coincidences have been measured for the geometry $\theta_{p, \alpha}=\theta_{n}$. Transitions to ground and excited states of residual nuclei have been observed. The obtained results were analyzed in terms of different final state interactions between the particles in the outgoing channel.
10. ${\text { 160 Induced Three-Body Reactions on }{ }^{6} \text { Li }}^{\text {Li }}$ ( $\oplus$. Miljanić, T. Zabel, and G. C. Phillips)

160 ions with energies $30 \leq \mathrm{E} \leq 36 \mathrm{MeV}$ were used to bombard a 6 LiH target. Different pairs of charged particles from the resulting three-body reactions were detected. Sequential reactions through many intermediate states were observed. Special attention was focused on the ${ }^{6} \mathrm{Li}\left(160,14_{N_{0}} \alpha\right) \alpha$, ${ }^{6} \mathrm{Li}\left(160,{ }^{16} \mathrm{O}_{0} \alpha\right) \alpha,{ }^{6} \mathrm{Li}\left(16 \mathrm{O},{ }^{17} \mathrm{O}_{\mathrm{OP}}\right) \alpha$, and ${ }^{6} \mathrm{Li}(16 \mathrm{O}, 17 \mathrm{O} 1 \mathrm{p}) \alpha$ reactions.

## C. POLARIZATION STUDIES

1. $\frac{\overrightarrow{\mathrm{d}}+3 \overrightarrow{\mathrm{He}} \text { Elastic Scattering }}{\mathrm{G} . \text { Ohlsen and R. Hardekopf }} \begin{aligned} & \text { (D. May } \\ & \text { (LASL) }\end{aligned}$. Baker (Rice)

Analyzing powers and spin-correlation parameters have been measured for $d-3 H e$ elastic scattering at energies $E_{d=4}$ to 12 MeV at $\theta_{\mathrm{Cm}}=49.5^{\circ}, 95.3^{\circ}$, and $120.0^{\circ}$. The LASL polarized beam was incident on a polarized 3 He target constructed at Rice. The geometry of the experiment permitted the measurement of the parameters: $A T A_{y}, A_{y y}, A_{x x}, A_{z z}, C_{y, y}, C_{y Y}, y^{\prime}$
 essentially ready to be submitted for publication in Nuclear Physics.)
2. $\vec{p}+3 \overrightarrow{H e}$ Elastic Scattering (D. May, S. Baker (Rice), G. Ohlsen and R. Hardekopf (LASL)

Analyzing powers and spin-correlation parameters have been measured for polarized protons elastically scattered from polarized 3 He at energies $\mathrm{E}_{\mathrm{p}}=8.8$ and 6.8 MeV at $\theta_{\mathrm{Cm}}=39.6^{\circ}$, 76.80 , 109.50, and 136.80. The parameters measured in this experiment were $A_{y}, A_{y}^{T}, C_{y, y}$, and $C_{x, x}$. The completion of results of a phase shift search which includes these data will
complete this work. It appears that $C_{Y} y$ and $C_{x} x$ data at 7 and 9 MeV do improve greatly the precision with which the $\epsilon(-1)$ coupling parameter is determined in $p-3 \mathrm{He}$ elastic scattering.
3. Polarized Beam for the Texas A\&M Cyclotron (D. May and S. D. Baker)

Components are ordered and are arriving now for assembly at Rice.
 Biegert (Rice) and A. Bocher (Texas A\&M)

Construction of equipment is underway.

## D. NUCLEAR SPECTROSCOPY

1. Tests of $G$ Parity and Isospin Conservation by Nuclei $\beta$ Decay (E. V. Hungerford III)

A system has been designed and constructed to measure the ft-values of short-lived $\beta$ decay isotopes. Comparison of the ft-values between isospin multiplets gives a test of $G$ parity and isospin.
2. The $f 5 / 2$ Resonance in $4 l_{\text {Sc }}$ (T. Jurgensen and C. M. Class)

An optical-model parameterization of the scattering of protons by 40 ca has been obtained that describes well both low energy ( $E_{p} \leq 5 \mathrm{MeV}$ ) structural features of $4 l_{\mathrm{Sc}}$ and the higher energy ( $\mathrm{E}_{\mathrm{p}} \underset{2}{ } 12 \mathrm{MeV}$ ) scattering cross sections and polarization. An interesting implication of the parameterization is that it locates the $£ 5 / 2$ shape-elastic resonance at $E p \simeq 6.5 \mathrm{MeV}$. This result furnishes a key to understanding the behavior of both the proton-capture and -scattering cross sections in the neighborhood of this energy that heretofore have been intractable to analysis. In particular it is seen, with the help of the Lane-Robson formalism, that the scattering cross section is accounted for, in the main, by the coupling between the shape resonance and a half-dozen strong $f 5 / 2$ compound nucleus resonances. Further work is in progress to refine this description of the cross sections.

## 3. The Magnetic Moment of $4 l_{\text {Sc }}$ (R. Dougherty and C. M. Class)

The method of measurement of the magnetic moment of the ground state of the ${ }^{4 l_{S c}}$ nucleus $\left(E_{\max }\left(\beta^{+}\right)=5.5 \mathrm{MeV}, \tau 1 / 2=\right.$ 0.6 sec ) involves the detection of nuclear magnetic resonance as a relaxation of beta-decay anisotropy due to the polarization of the scandium recoil nuclei when produced with the $40 \mathrm{Sc}(\mathrm{d}, \mathrm{n})$ stripping reaction. The hardware and experimental procedure for the measurement has proved capable of measuring beta-decay asymmetries as low as $2 \%$. Of concern at the present time is the various polarization relaxation processes operative in the recoil stopping media.

## 4. Re-analysis of Some Neutron Angular Distributions (C. M. Class)

Angular distributions, measured at deuteron energies below the Coulomb barrier, for neutrons emitted in the ${ }^{40} \mathrm{Ca}$ $(\alpha, n)$ reaction leading to the ground ( $J^{\pi}=7-/ 2$ ) and first excited ( $J^{\pi}=3^{-} / 2$ ) states of $4 I_{\text {Sc }}$ are not satisfactorily described by standard distorted-wave calculations. The difficulty seems to be with the parameterization of the neutron scattering potential. Early results indicate that ad hoc values of these parameters can be found to yield fits in good agreement with the data.
5. $\frac{40 \mathrm{Ca}(\alpha, \alpha) 38_{\mathrm{K}} \text { and Isospin }}{\text { and Univ. of Wisconsin) }}$ (H. Vernon Smith, Jr. (Rice

The ${ }^{40} \mathrm{Ca}\left(\mathrm{d}, \alpha_{0}, 1,2,4\right)^{38 \mathrm{~K}}$ reactions for $4.00 \mathrm{MeV} \leq \mathrm{E}_{\mathrm{d}} \leq$ 4.6l MeV has been investigated. The $\alpha_{1}$ and $\alpha_{4}$ transitions are isospin-forbidden. The resonant-like structures observed in the $\alpha_{0}, \alpha_{1}, \alpha_{2}$, and $\alpha_{4}$ transitions are consistent with Ericson theory. However, a portion of the $\alpha 1$ data can be fitted with a few interfering Breit-Wigner resonances. The level parameters for the corresponding 42 Sc levels have been extracted. This work has been submitted for publication in Nuclear Physics.
6. Proton Spin Flip at 12 MeV for Nuclei Near the Neutron Shell Closure, $N=28$ (J. Ellis, E. Hungerford, and W. Sweeney)

Spin-flip angular distributions for the nuclear pairs 48.50 Ti and $54,56 \mathrm{Fe}$ have been measured using the ( $\mathrm{p}, \mathrm{p}^{\prime} \gamma$ ) correlation method. These data are compared to collective model DWBA calculations using a distorted spin-orbit potential
of the full Thomas form. The spin-flip angular distribution data for ${ }^{54} \mathrm{Fe}$ exhibit two peaks of nearly equal magnitude while the data for 56 Fe and $48,50 \mathrm{Ti}$ more closely resemble the usual single large peak at back angles predicted by DWBA calculations. This work has been published in Nuclear Physics A210, 557-567 (1973).

## E. NUCLEAR THEORY

1. Symmetrization of Arbitrary 3-Particle Wave Functions (J. E. Beam)

A proper treatment of the quantum mechanical 3-body problem for identical particles requires symmetrization (for bosons) or antisymmetrization (for fermions) of the wave function. If one introduces parameter coordinates ${ }^{l}$ then the complete (anti) symmetrization can explicitly be carried out on kernel functions of known form, independently of the form of the particle-particle interaction or of the corresponding unsymmetrized wave function. If the parameter coordinate functions are chosen to be Dirac delta functions, one can obtain a useful angular momentum decomposition which reduces the 6-dimensional parameter coordinate integrals to 2-dimensional ones.
2. On the Possible Observation of the Triangle Graph Through Interference with Pole Graphs (I. M. Duck and V. Valković)

Rescattering processes, represented by triangle diagrams, have been studied for some time, since they have been assumed to be capable of producing peaks in measured cross sections. Such processes have been extensively discussed as different versions of the Peierls mechanism. It has been shown that the original version of the Peierls mechanism with the same initial and final state should not occur, although a modified Peierls mechanism, involving two different resonances, makes the rescattering possible. It has been shown that the

[^55]singularities of such graphs are on the physical boundary if, and only if, the diagrams can be interpreted as describing classical processes in space-time. Several examples of possible three-body peaks generated by rescattering have been discussed in high-energy physics. However, it was shown by Schmid that triangle graphs do not produce peaks in the total transition rate, but may in the differential cross sections. It seems that the contribution of the rescattering process has not yet been experimentally identified directly. All attempts to identify such rescattering graphs experimentally have searched for the contribution of the graph itself. This paper considers the interference of rescattering graphs with pole graphs and has been accepted for publication in II Nuovo cimento.
3. $\frac{\text { Search for Rescattering Singularities (I. M. Duck }}{\text { and } V \text {. Valković) }}$

A critical evaluation of experimental claims to have observed the classical-rescattering triangle graph singularity in low energy nuclear physics has been completed and reported on at an APS meeting (Seattle) and a further report presented to the International Conference on Nuclear Physics (Munich). A paper is being prepared for publication.

## F. APPLIED PHYSICS

1. X-ray Production by Protons of $2.5-12 \mathrm{MeV}$ Energy (Liebert, Zabel, Miljanić, Larson, Valković, and Phillips)

Characteristic K-shell x-rays produced by proton bombardment of $\mathrm{Mn}, \mathrm{Fe}, \mathrm{Ni}, \mathrm{Cu}, \mathrm{Zn}, \mathrm{Y}, \mathrm{MO}, \mathrm{Ag}$, and Cd targets have been observed for incident energies between 2.5 and 12 MeV . Absolute cross-sections for $\mathrm{K}-$ shell ionization have been determined and compared to the predictions of the PWBA and BEA theories. The BEA theory is found to give better agreement at lower bombarding energies and higher $Z$, while the PWBA fits the data better at lower $Z$ and higher bombarding energies. $L_{\alpha}, L_{\beta}$, and $L_{\gamma}$ cross-sections for $P b$ are also presented as a function of energy between 2.5 and 12 MeV . This work has been accepted for publication in Physical Review.
2. Study of L-Shell Ionization Cross Section for Pd, Ag, Sn, and Sb for Incident Proton Energies in the Range of 3 to 12 MeV and for Oxygen Ions in the Range of 15 to 40 MeV (Chaturvedi, Liebert, Miljanić, Zabel, Wheeler, and Phillips)

Absolute L-shell ionizations were measured for the thin targets of Pd , $\mathrm{Ag}, \mathrm{Sn}$, and Sb at l MeV increments for incident protons in the range from 3 to 12 MeV . Similar measurements were also made for the Oxygen ions at 5 MeV increments in the range of 15 to 40 MeV . The L x-rays were measured with a high resolution (175 eV at 5.9 keV ) $\mathrm{Si}(\mathrm{Li})$ detector. The experimental cross sections are seen to compare quite well with the predictions of both the Plane Wave Born Approximation (PWBA) and the Binary Encounter Approximation (BEA).
3. Trace Element Analysis of Blood Serum (Liebert, Zabel, Chaturvedi, Miljanić, Phillips, Valković, Wheeler (Rice), and M.J. Hrgov̌ic, M.D. (Diagnostic Clinic, Houston)

We are studying normal blood serum and serum obtained from patients with malignant lymphoma. From an investigation of many samples from a composite batch of normal blood bank donors sera we have tested the charged particle induced x-ray emission technique for trace element analysis. Our present accuracy is in the $5-15 \%$ range for traces in the range of l-3 ppm. Comparison of patients' conditions with trace element levels in blood serum is now in progress. This paper and F.4. below, were chosen by the A.I.P. as of interest to Science Writers for the media.
4. Trace Element Analysis of Mouse Tissue (Wheeler, Liebert, Miljanić, Phillips, Valković, Zabel (Rice) and Withers and Milas (M.D. Anderson Hospital and Tumor Institute)

The liver and spleen of normal mice and mice with transplantable fibrosarcoma have been studied. We have found that mice with advanced fibrosarcoma can be distinguished from normal mice by changes in contents of several trace elements. Encouraged by these results we will study the changes in trace element concentrations which occur from the time the sarcoma is implanted in a mouse until the sarcoma has reached an advanced stage.
5. Comparison of Proton Induced X-ray Emission, X-ray Fluorescence, and Atomic Absorption Techniques for Trace Element Analysis of Blood Serum (Wheeler, Liebert, Miljanić, Phillips, Valkovit, Zabel (Rice) and P. Ong (M.D.Anderson Hospital \& Tumor Institute)

Independent measurements of trace element content in 100 samples of human blood serum have been performed. A comparison of results for copper levels in the sera indicates that atomic absorption gives the best results, followed by $x-r a y$ fluorescence and proton induced x-ray emission. We are currently attempting to improve all phases of the proton induced x-ray emission technique. This paper has been submitted to Applied Spectroscopy.
6. Trace Element Analysis Along Human Hair (Valković, Liebert, Miljanić, Phillips, Wheeler, and Zabel)

We have examined ll-inch long samples of women's hair at $3 / 4$-inch intervals, representing a growth of approximately two years. In all cases we have found substantial elemental variations with length. The origin of these variations is uncertain but would seem to be due in large part to external sources. We conclude that a much larger sampling of subjects is necessary before any accurate conclusions are possible. This work has been published in NATURE 243, \#5409 (1973).
7. Automated Analysis of X-ray Spectra (R. B. Liebert and R. M. Wheeler)

Two programs have been written for the IBM-1800 computer which allow automated on-line analysis of $x$-ray spectra produced by bombardment of biological targets with heavy charged particles. Program STRIP is used to analyze standard spectra by a non-linear least squares technique to obtain $K_{\alpha} / K_{\beta}$ ratios. relative yields with respect to dopant elements, and relative widths of $x-r a y$ lines as a function of $x-r a y$ energy. Program SPEEL uses these results to do fast on-line analysis by a linear least squares routine while new data are collected. Comparison with STIP output allows results to be expressed directly in parts per million.
8. Trace Element Analysis by Proton Bombardment of Aerosols (Boustany, Liebert, Wheeler, Valkovic, and Phillips)

Preliminary development work has been done to develop targets for proton-induced x-ray fluorescence which will minimize evaporation of trace elements and be compatible with mass production techniques. Aerosols produced from $\mathrm{Fe}\left(\mathrm{NO}_{3}\right)_{3}$ solu-
tions have been bombarded with 3 MeV proton beam in a helium atmosphere and a sensitivity of the order of 1 ppm for a 20 minute run at 200 namps has been observed. Variation of the beam energy and aerosol geometry to optimize proton energy loss, target uniformity, and self-absorption is expected to improve this sensitivity figure.

## 9. Trace Element Analysis Using Proton Induced X-ray Emission Spectroscopy (Valković, Liebert, Zabel, Larson, Miljanić, Wheeler, and Phillips)

A system for trace element analysis by proton-induced x-ray emission spectroscopy has been developed at the Bonner Nuclear Laboratories. Some characteristic problems have been considered and applications to the study of trace element concentrations in environmental and biological targets have been studied. This work has been accepted for publication in Nuclear Instruments \& Methods.
10. Trace Element Analysis of Seawater and Fish Samples by Proton Induced X-ray Emission Spectroscopy (Alexander, Biegert, Jones, Thurston, Valković, Wheeler, Wingate, and Zabel)

Proton induced x-ray emission spectroscopy has been used for trace element analysis of seawater and fish (troutSalmo gairdneri) samples. To test the applicability of the technique for large-scale analysis of seawater and fish samples, the consistency of results from equivalent samples was checked. Also, a volatilization study was made at several different beam intensities to determine the effects of the beam on trace elements in the samples. The reproducability of the results was found to be within acceptable limits. This work has been submitted for publication to the Int. Jour. of Applied Radiation and Isotopes.
11. Contribution to a Book on Trace Elements (T. Zabel)

Holiday House is publishing a book on trace elements for young people. A number of captioned photographs have been supplied to the edition to describe the Rice trace element research.

## G. INSTRUMENTATION

1. $\mathrm{He}^{-}$Ion Source for the Rice Tandem (R. Y. Rodgers and E. V. Hungerford)

A Li exchange $\mathrm{He}^{-}$ion source has been contructed for the Rice tandem accelerator. About 0.5 microamp of $\mathrm{He}^{-}$has been obtained. Replacement of the oven and heater control should allow this current to be increased by at least a factor of two.
2. Two-Lab Data Acquisition Capability (BONER) on IBM-1800 (B. J. McCabe Smith and H. V. Jones)

Coding recognizing the additional hardware requirements of the two-lab situation has been implemented and tested for the one-lab case. The second lab will be simulated for debugging purposes until the second lab's experimental control unit (ECU) hardware is complete. Programming for the PDP-11/ IBM 1800 magnetic tape compatibility is near completion, lacking only de-bugging. Programming for additional BONER diagnostic capability (in the face of the system's increasing complexity) is near completion, but has been shifted to "stand-by" until two-lab has been implemented and become stable. General systems maintenance and user program support underway as usual. Cards to implement a higher modification level of IBM's TSX operating system have been ordered.

## 3. A Multi-Wire Proportional Counter (MWPC) Photon Camera (G. W. Pfeufer and G. C. Phillips)

We are engaged in the development of a MWPC photon camera for use in localizing the Bragg peak energy deposition in the treatment of tumors with high LET radiation. By localizing the source of gamma-rays from the target in the reaction $19 \mathrm{~F}(\mathrm{p}, \alpha, \mathrm{\gamma}){ }^{160}$ using the $6-M V$ Van de Graaff accelerator, existing counter systems are being presently tested for application in this program. Since the counters are relatively insensitive to photons, the gammarays are converted to an electron-positron pair in a suitable foil. The electron and positron are detected in two consecutive $x-y$ counters. Using computerized ray tracing, based on these coordinates, the point of conversion can be determined. The bi-section of these rays is taken as the photon direction which can be traced back to the target. These preliminary studies will indicate the resolution to be expected from the system and disclose paths of further development.
4. 6-MV Van de Graaff Accelerator (J. R. Risser)

It is increasingly practical to use the accelerator for experiments to above 4 MeV due to improved conditioning of the accelerator tube and improvement in beam-defining equipment. It appears finally that the design characteristics are achievable. With further conditioning of the accelerator tube, energies of 5 MeV and above appear attainable. Neither the ion optics of the terminal nor design of the extended pressurizing tank appear to introduce limitations. Pulsebunching of deuterons and protons have been achieved and appears satisfactory. For protons, 2 ns pulse widths and 1 microampere average beams ( $10^{6} \mathrm{sec}^{-1}$ repetition rate) have been obtained.

## 5. Charged Particle Mass Identification by Energy-Time-of-Flight Technique (Andrade, Rendić, Otte, and Phillips)

The energy-time-of-flight technique-for charged particle mass identification has been successfully used in the mass range from mass 1 to 12 and in the energy range from 0.5 MeV to ll MeV. As an illustration of the usefulness of the technique, the results of the analysis of the reactions produced by 12 C nuclei bombarded by deuterons at 12 MeV are presented. The pulsed and bunched beam facilities of the Rice tandem Van de Graaff were used and particles resulting from the bombardment were detected with a silicon surface barrier solid state detector. The energy and time-of-flight parameters were processed using an IBM 1800 real time computer with an A.D.C. resolution of 1024 channels for each parameter. Twenty-six energy peaks from the $12 \mathrm{C}(\mathrm{d}, \mathrm{y}) \mathrm{Y}$ reaction were identified, while, for comparison, the free energy spectrum provides only ten peaks. This work has been published in Nuclear Instruments \& Methods 113 (1973).

## T. W. BONNER NUCLEAR LABORATORIES - RICE UNIVERSITY

## A. PION PHYSICS

1. Pion Small-Angle Multiple Scattering at Energies Spanning the (3,3) Resonance (Mayes, Lee, Allred, Goodman (Univ. Houston); Mutchler, Hungerford, Scott, and Phillips(Rice Univ.)

The small-angle multiple scattering of positive and negative pions has been measured for $\mathrm{C}, \mathrm{Al}, \mathrm{Cu}$, and Pb targets throughout an energy range spanning the $(3,3)$ resonance. The measurements were made using two-dimensional multiwire proportional counters placed in the pion beam. All previous multiple scattering data for electrons and protons as well as these new data for pions are used to recalculate the empirical terms in the Moliere theory of multiple scattering. A second-order Born approximation multiple scattering theory has been devised for spin zero particles. The modified Moliere theory gives a better fit to the experimental data than the second-order Born calculation. Because the updated Molieré theory contains much simpler equations and give closer agreement with experiment, it is recommended in place of the more sophisticated theory for the interpretation of new experimental data. A paper describing this work has been submitted to Physical Review.
2. $\quad \pi^{ \pm}{ }^{16} 0$ Small Angle Scattering at 155, 180, and 213 MeV (Mutchler, Fletcher, Coulson, Hungerford, Gabitzsch, Phillips (Rice); Mayes, Lee, Goodman, and Allred (Univ. Houston)
$\pm$ We have determined $\operatorname{Ref} f_{N}\left(0^{\circ}\right)$ by measuring the small angle $\pi^{ \pm}-160$ scattering in the coulomb-nuclear interference region (40-110) at 155,180 , and 213 MeV . In the region the difference of the $\pi^{+}$and $\pi^{-}$scattering directly determines the sign and magnitude of $\mathrm{Ref}_{\mathrm{N}}\left(0^{\circ}\right)$. This information, plus the $I_{m} f_{N}\left(0^{\circ}\right)$ obtained from total cross section data via the optical theorem, completely determines the nuclear scattering amplitude at $0^{\circ}$. The small angle scattering of $\pi^{+}$from 12 C and 9 Be have also been measured over a larger angular range (50-20 ) . These data are being analyzed. This experiment will be continued at LAMPF as approved Experiment \#80.
3. $\pi \pm$ Nuclear Total Cross Sections Around the 3/2, 3/2 Resonance (Gabitzsch, Coulson, Fletcher, Hungerford, Mann, Mutchler, Phillips (Rice Univ.) Mayes, Hogstrom, Lee, Allred, and C. Goodman (Univ. of Houston)
$\pi \pm$ total cross sectirns heve been measured for the nuclei $9 \mathrm{Be}, 12 \mathrm{C}, 16 \mathrm{O}$, and 27 Al . $\pi^{+}$energies were 115 , 130, 155, 180, 195, and 210 MeV , while $\pi^{-}$measurements were taken at 155 and 210 MeV . Data were collected using multi-wire proportional counters (MWPC) which allowed for good angular resolution at small angles. Electrons were rejected with a gas cerenkov detector and the muon impurity was measured using the target out pion decay distributions. Preliminary analysis of the small angle scattering distributions and total cross sections indicate that the $3 / 2,3 / 2$ resonance shifts to lower energies as the atomic number increases. Furthermore, coulomb effects in $\pi^{+}$and $\pi^{-}$data are observed in the form of a slight difference in the $\pi^{+}$ $T^{-}$total cross section for a given target. This work has been accepted for publication in Physics Letters. This experiment will be continued at LAMPF as approved Experiment \#80.
B. NUCLEON PHYSICS AT INTERMEDIATE ENERGIES

1. Proton Induced Deuteron Break-up at 600 MeV
(Furić, Fletcher, Gabitzsch, Mutchler, Witten, Phillips (Rice Univ.); Mayes, Lee, Warneke, Hudomalj, Gram, Allred, and Goodman (Univ. of Houston)

The $D(p, p p) n$ reaction was studied using a deuterium gas target in the proton beam at the SREL 600 MeV synchrocyclotron. The trajectories of the two charged particles were determined with MWPC. The momentum of one proton was measured by a magnetic spectrometer; the time-offlight of the other proton was also recorded. Good angular and momentum resolution with a large solid angle was achieved through the use of large MWPCs. The momentum spectra obtained in the symmetric 400-410 geometry exhibited strong quasi-free scattering features. The momentum transfer dependence was examined in the range $0-200 \mathrm{MeV} / \mathrm{C}$. The spectra obtained in the $41^{\circ}-61^{\circ}$ geometry had a pronounced maximum corresponding to the neutron-proton final state interaction. This was the first observation of that effect in this energy
region. The $p-p$ elastic scattering data accumulated with the same equipment and the Monte Carlo simulation of the experiment will be used for the absolute normalization and final analysis of the data, which are now in progress. This experiment will be continued at LAMPF as approved Experiment \#81.
2. Neutron-Proton Final State Interaction in p-d Breakup at $E_{p}=585 \mathrm{MeV}$ (Furić, Fletcher, Gabitzsch, Mutchler, Witten, and Phillips (Rice Univ.); Hudomalj, Lee, Gram, Mayes, Allred, and Goodman (Univ. of Houston)

The three-body break-up spectra concerning the reaction $D(p, 2 p) n$ were accumulated at the SREL synchrocyclotron. The angular resolution of each arm in this two-arm experiment was 0.40. The momentum of one proton was measured by a magnetic spectrometer. The momentum resolution was l.5\%. The kinematical conditions for two protons (410-610) were chosen so that the observation of the neutron-proton Final State Interaction (FSI) was possible. The enhancement in the spectrum corresponding to the effect was observed. This was the first report on the $n-p$ FSI above $E_{p}=200 \mathrm{MeV}$. Qualitative features of the spectra can be explained with the Goldberger-watson formula. The simple pole graph term, normalized to the lower energy data predicts the value of the cross section too low by an order of magnitude. This work has been accepted for publication in Physics Letters. This experiment will be continued at LAMPF as part of approved Experiment \#81.

## C. THEORY

1. The Effects of Nuclear Distortion on the Elastic Scattering of Pions from Oriented and Unoriented Nuclei (E. V. Hungerford III)

It is shown that nuclear distortions may introduce small fluctuations in the systematic determination of optical model parameters for pion elastic scattering from nuclear mass neighbors. In addition the measurement of $\pi \pm$ total cross sections from oriented nuclei should provide a sensitive way to look for proton or neutron shape distortions. This work has been submitted for publication in Nuclear Physics.
2. DAMIT: A Small Computer Optical Model Code for Pion Scattering (E. V. Hungerford III)

A Fortran computer code for the optical model calculation of pion nucleus scattering has been written for small computer systems. The code is operational on both an IBM-1800 and a PDP-ll data acquisition computer. It allows calculation with both the Laplacian and Kisslinger optical models using either a modified Gaussian or a Fermi nuclear density. The code gives results in agreement with other pion optical model codes. This work has been published in Nuclear Instruments and Methods III (1973) 509-517.

## 3. Generalization of the Sakata-Taketani Equation to Arbitrary Spin (R. F. Guertin)

The Sakata-Taketani spin -0 and -1 equations for a massive particle have been generalized to arbitrary integer or half-odd integer spin $0^{-}$. Although the theory is covariant, it is not manifestly covariant. However, there are only $2(2 j+1)$ components in the wavefurction, in contrast to the extra components that always appear in a manifestly covariant theory. Second quantization appears to require Bose statistics for any spin. A paper is in preparation to be submitted to the Journal of Mathematical Physics.
4. Electromagnetic Interactions for a Proposed Spin $-1 / 2$ Boson Equation (R. F. Guertin and John B. Cone)

Electromagnetic interactions have been introduced into a spin $-1 / 2$ Boson equation proposed by Guertin and Guth using minimal coupling. The covariance of this theory has not been proven. Nevertheless, one can evaluate the energy levels for a coulomb potential and a constant homogeneous magnetic field, and in the appropriate limits for a certain arbitrary parameter, one obtains the usual results for both the Klein-Gordon equation and the Dirac equation.
5. Static Bootstrap Model for the $\mathcal{\rho}$ Meson Trajectories (R. F. Guertin and Bertrand Chang)

A static bootstrap model for the $\rho$ meson trajectory in which the $n$th particle on the trajecter is obtained selfconsistently in the two-particle channel consisting of a $\pi$ meson and the $n^{t h}$ particle on the $\pi$ trajectory has been attempted. The isospin and angular momenta crossing matrices have been found to be inconsistent with the conjectured result.

## 6. Dibaryon Resonance Production in PP Scattering (V. S. Bhasin and I. M. Duck)

The angular distributions of negative pions produced in proton-proton collisions in the energy range of one to four GeV bombarding energy is calculated assuming the production of a low energy dibaryon resonance between the $\Delta$ (1236) and a proton. Triangle amplitudes involving $\pi^{\circ p} \rightarrow \pi^{-} \Delta^{++}$and $\pi^{-} p \rightarrow \pi^{-p}$ plus pion exchange, evaluated in the Yao approximation, dominate the triangle exchange amplitude and produce differential cross sections comparable to those for $\mathrm{pp} \rightarrow \pi \mathrm{d}$. This work has been accepted for publication in Nuclear Physics.
7. Estimate of $\sigma_{\text {inel }} / \sigma_{\text {el }}$ in Backward p-d Scattering at l.0 GeV. (V.S. Bhasin, I. Duck, and V. Valkovic)

Some estimates have been made of the inelastic contributions in proton-deuteron scattering at 1.0 GeV due to deuteron break-up when one of the outgoing protons is observed in the backward direction. Based on the mechanism due to exchange of a nucleon as well as an isobar we compute $[(d \sigma / d \Omega)$ inel $/(d \sigma / d \Omega)$ el $]$ at $\theta_{C . M}=180^{\circ}$ taking account of both the spin singlet and triplet channels and keeping the relative energy of the scattered pair rather low. It is found that in the simple nucleon exchange mechanism the offshell effects in the two-body amplitude due to the presence of hard-core in the singlet and tensor forces in the triplet channels manifest themselves in enhancing the inelastic contribution. On the other hand, the contributions of the resonance exchanges wherein the two-body amplitudes appear essentially on-shell get suppressed especially if the scattered pair is observed at rather low relative energy.

## 8. Rescattering Effects in Backward Proton-Deuteron Scattering at Intermediate Energies (V.S. Bhasin)

We study backward proton-deuteron scattering at intermediate energies ( $1.0-1.5 \mathrm{GeV}$ ) by considering a rearrangement process where the incident projectile picks up a neutron of the target leaving the target proton behind. By collecting terms up to second order in the multiple-scattering series and by employing the approximations suited to a high-energy large angle scattering behavior, we obtain the expression for the scattering amplitude similar (but not identical) to the one used by the Glauber model for small-angle scattering at these energies. We find that the double-scattering terms, in which the incident proton scatters with the neutron in the forward direction and then sends the target proton back, contribute most significantly. The lowest-order "pickup" and the
single-scattering terms become important if one includes the tensor component in the deuteron wave function. The calculated differential cross section (particularly at intermediate angles) is found to be in reasonable agreement with experimental data.
9. Pion Production in the Reaction $p d \rightarrow t \pi$ (V. S. Bhasin and I. M. Duck)

The Yao-Barry model is extended to the reaction $p d \rightarrow t \pi$ and provides a description of the cross section for incident proton energies from 340 to 670 MeV in terms of a single parameter, the triton nd wavefunction evaluated at the origin. The results are competitive with the predictions of the Ruderman model for the energy dependence of the forward cross section and show much larger backward cross sections. This work is published in Physics Letters 46B (1973) 309.
10. Exotic Nuclei and Resonance Production (I.M. Duck, V. S. Bhasin, and John Brown)

Calculations are in progress to investigate reaction mechanisms for production of $\Delta-P$ resonances at $G e V$ energies. So far, we have production cross sections and angular distributions for resonances with spin 1 or $2, J^{\pi}=0^{-}, 1^{-}, 2^{-}, 3^{-}$, $1^{+}$, and $2^{+}$produced in $p p \rightarrow \pi^{-}+\left(\Delta+{ }^{++} p\right)$ by a pion exchange mechanism. The evaluation of the pion exchange triangle amplitude which is supposed to be dominant is underway.

## D. APPLIED PHYSICS (INTERMEDIATE ENERGY)

## 1. Pion Dosimetry

Preparation for approved LAMPF experiment \#83, "Investigation of Multi-Wire Proportional Counters for Treatment Volume Visualization" (G. C. Phillips, Spokesman), and experiment \#84, "Quality of Meson Radiation Fields" (G. C. Phillips, Spokesman) has continued. Experiment \#83 collaborators, G. D. Oliver, Jr. (Edward Mallindkrodt Institute of Radiology, Washington University School of Medicine), Walter Grant (M.D. Anderson Hospital \& Tumor Institute), and M. C. Taylor (Columbia Scientific Industries), have received funding from N.I.H. for their part in this work. The experimental system has been designed and test runs will be started in November, 1973 on the P3 line at LAMPF as a parasite experiment. The work will continue in 1974 at LAMPF.

## 2. LAMPF Pion Beam Line ( $\mathrm{P}^{3}$ ) Calibration

Calibration of the Pion Beam Transport System (approved LAMPF experiment \#79) was prepared in collaboration with Dr. Robert Macek for running in the summer or fall of 1973. Tests of the $p^{3}$ beam line commenced in September, October, and November of 1973.
3. Observation of Muonic X-rays from Bone (M. C. Taylor, L. Coulson, and G. C. Phillips)

The muonic x-ray, which results from the capture of a negative muon into orbit around a nucleus to form a "muonic atom," may be a useful diagnostic probe. The x-ray transition energies are about 200 times the energies from electronic transitions - the carbon $\mathrm{K}_{\alpha}$ energy is of the order of 75 keV . Thus, muonic x-rays from light elements have considerable penetrating power and can escape from bulky media. Experimental results for negative muons stopped in bone are presented to demonstrate the potential of the technique for observing elements in the range from carbon to calcium in biological specimens. Advantages and disadvantages of this technique with respect to other methods of elemental analysis are discussed. This work published in Radiation Research 54, 335 (1973).

## E. INSTRUMENTATION

1. Instrument Trailer - The Rice Portable Laboratory
(W. P. Madigan, J. A. Buchanan, G. C. Phillips, and J. Windish)

In January, 1973 the outfitting of the instrumentation trailer was completed. The data processing system installed includes a PDP-ll/20 central processor with two magnetic tape units, line printer, teletype, and disc drive. In addition, there are four standard relay racks of nuclear instrumentation. Airconditioning and heating are provided by two 3-ton units mounted externally on the nose of the trailer. A suspended acoustical-tile ceiling is used as the airconditioning supply duct. The walls are covered with plywood paneling from the floor to a height of four feet. From four feet to the ceiling the walls are covered with acoustical tile which dampens the considerable noise generated by the instrumentation. Built into the nose of the trailer are a bed, book shelves, a desk, and a refrigerator providing a study-rest area for long-running experiments. Fire protection is provided by a Halon 1301 system which is actuated by two smoke detectors.

All exposed wood surfaces are painted with Albi 107A fireretardant coating. On July l, the trailer was pulled to Los Alamos, a distance of 1,000 miles, with absolutely no damage to the computer, nuclear instrumentation, or trailer. This clearly proves the feasibility of transporting the trailer to distant accelerator facilities to conduct experiments in medium and high energy physics. The trailer and systems have been operating successfully at LAMPF since July。 1973.
2. $30^{\prime \prime} \times 30^{\prime \prime}$ Multi-Wire Proportional Chamber (W. P. Madigan, E. Harmening, G. C. Phillips, and J. Windish)

The $30^{\prime \prime} \mathrm{x} 30^{\prime \prime}$ MWPC to be used at the National Accelerator Laboratory in cooperation with the Stanford group headed by R. Hofstadter and Z. G.T. Guiragossian is scheduled for completion on November 30 , 1973. It will have a useful active area of $30^{\prime \prime} \mathrm{x} \mathrm{30"} ,\mathrm{an} \mathrm{x-coordinate} \mathrm{plane} \mathrm{(304} \mathrm{wires)}$, $y$-coordinate plane (304 wires), an amplifier/discriminator readout for each wire, and a tapped delay line readout on each coordinate plane. The support frame for the chamber is designed to mesh with the support frame for the Stanford $30^{\prime \prime}$ dia. NaI crystals.
3. $\frac{12 " \text { Diameter MWPC Stands }}{\text { P. DeVries, and E. W. Surles) }}$ (W. Madigan, C. Belcher,

In August, six new MWPC stands were completed for use at LAMPF. They provide a vertical adjustment of $\pm 9$ inches and a transverse adjustment of $\pm 1$ inch. The MWPCs can be mounted singly or two at a time on a stand, permitting, e.g., the insertion of two counters between two closely-spaced magnets in a transport system. The stands have been in service at LAMPF since July, 1973.
4. Cryogenic Target Chamber (M. Furic, W. P. Madigan, P. DeVries, and G. C. Phillips)

Fabrication of the $13^{\prime \prime}$ diameter cryogenic scattering chamber to be used in the Rice-Univ. of Houston approved proton scattering expeximent \#81 at LAMPF is underway. The chamber will accommodate liquid hydrogen and liquid deuterium targets and will contain two retractable scintillation screens to ensure proper centering of the incident beam. Side windows will permit observation angles from $15^{\circ}$ to $165^{\circ}$ and $195^{\circ}$ to $345^{\circ}$ with respect to the incident beam direction. The top flange will fit to the standard Los Alamos cryogenic refrigerator. Completion of the chamber is scheduled for December 15, 1973.
5. Target Chamber for LAMPF Experiment \#80 (T.M. Williams, Mutchler, Phillips, Hungerford, Witten, and Madigan)

A target chamber and collimator for LAMPF Exp. \#80 is being designed. This chamber can be used for small angle scattering (down to $5^{\circ}$ ). The particle exit windows will extend from $5^{\circ}$ to $30^{\circ}$ on one side and from $10^{\circ}$ to $160^{\circ}$ on the other side of the beam. This will allow for coincidence measurements and/or parasite experiments to be run using this chamber.
6. Technique for Alignment and Placement of MWPCs (Hungerford, Williams, Flick, Madigan, and Phillips)

A system for the alignment of Multi-Wire Proportional Counters with respect to a magnet is being designed using a mirror in the magnet and aligning the magnet with a transit equipped with auto-reflection target. The mirror can then be rotated to make an accurate turn through any desired angle. This will allow correct placement of MWPCs behind the magnet.
7. RICE--A Multi-Processor Acquisition and Analysis System Incorporating CAMAC (H.V. Jones, Buchanan, Mann, McGrath, and M.N. Jones)

A two-processor data acquisition and analysis system incorporating CAMAC. The processors are a conventional minicomputer and a micro-programmed $I / O$ processor which effects a programmable interface between the mini-computer and CAMAC. This work has been published in IEEE Trans. on Nuclear Science, Vol. NS-20, No. 1, February, 1973.
8. PDP-11 Systems Development (David Mann)

A data acquisition system using a PDP-ll/20 (soon to be an $11 / 45$ ) and a "MIOP" (micro-programmed I/O processor) is being used to tune the $P^{3}$ line at LAMPF. Fast calculations of various beam parameters allow coarse tuning of the beam using one-dimensional and two-dimensional on-line displays. Fine tuning of the beam is performed using a fast on-line optimizer program plus several tuning criterion. The magnets in the $p^{3}$ line can be periodically read by the computer to verify magnet stability.
9. Development of MWPC Readout in CAMAC (J. Buchanan)

The readout modules (in NIM) for the Rice Multi-Wire Proportional Counters (MWPC) have been redesigned into CAMAC format. In addition certain logic operations as well as
analogue and digital arithmetic operations can be performed at these modules to further improve the rejection of unwanted data.
10. Utilization of an Accelerator Beam's Micro-structure

Methods of using the detection of cerenkov light to view the micro-structure of an accelerator beam, such as that at LAMPF, have been discussed. In particular, the correlation integral of an accelerator synchronized clock signal and the detected signal as a function of the location of the detector in the beam can be used with the methods of Fourier spectroscopy to yield information about the phase space of the beam. A system such as this could be used as a beam monitor, to measure time-of-flight, and possibly to determine the pion to muon ratio in a pion beam. Another promising method involves the use of a high-speed camera with an $X$ and $Y$ sweep synchronized by a clock pulse to form a circular trace from the detected light pulses. A microdensitometer could then be used to determine the relative intensities of the interesting segments of the trace.

## TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

## A. NEUTRON AND FISSION PHYSICS

1. Fast Neutron Differential Cross Sections, 8-15 MeV (D. W. Glasgow, J. R. Boyce, D. E. Epperson, F. O. Purser, K. Stelzer,* G. Mack, ** J. Clement; additional participants when measurements are underway: N. R. Roberson, R. L. Walter, C. R. Gould, E. J. Ludwig, M. Divadeenam, E. G. Bilpuch, H. W. Newson)

The absolute accuracy obtainable in the measurement of fast neutron differential cross sections, spanning the incident neutron energy range $8-15 \mathrm{MeV}$, is principally limited by: a) experimental sensitivity and instabilities, b) undertainty in the determination of the background under or near the peaks in neutron time-of-flight spectra, c) uncertainty in the energy dependence of the neutron detection efficiency which is the major source of error in the normalization to the $n-p$ scattering cross section, and d) uncertainty in the finite sample size corrections to the measured cross sections.

The nearly completed TUNL neutron time-of-flight facility should exhibit the capability for reducing the above limitations and allow measurements of differential cross sections with magnitudes as small as 1 millibarn/steradian to better than $5 \%$ absolute accuracy. Accordingly we plan to initiate a comprehensive program of measurements of elastic and inelastic scattering cross sections. Tentatively we plan to start with ${ }^{12} \mathrm{C}$ and ${ }^{27} \mathrm{Al}$ which are priority I in the USNDC request list and continue with ${ }^{9} \mathrm{Be},{ }^{1} \mathrm{H}$ also of priority I. The program will also endeavor to anticipate and satisfy requests from DCTR for data pertinent to the design of a prototype fusion reactor.

A gamma ray detecting system is also under construction. When completed it might be possible to study $n-\gamma$ correlations for which there is some demand in the request list.

Accurate neutron scattering cross sections are also of interest from a fundamental point of view. In the past studies of the isospin dependence of the nucleon-nucleus optical potential have focused on ( $p, p$ ) scattering experiments.

[^56]The accuracy associated with ( $n, n$ ) scattering experiments is now starting to approach that of the ( $p, p$ ) work. Consequently, accurate neutron differential elastic-scattering cross sections obtained in an energy and mass region where the optical model is applicable should advance the knowledge of the isospin dependence of the optical potential. In addition, the extension of the measurements over a wide range of nuclei should illuminate more clearly the competition between direct and compound nuclear reaction mechanisms.
2. Resolved Neutron Cross Sections And Intermediate Structure (J. G. Malan,* J. Clement, B.-H. Choi, ** W. F. E. Pineo, M. Divadeenam, E. G. Bilpuch, H. W. Newson)

A paper based on the $\mathrm{Sr}+\mathrm{n}$ resolved cross section data and their interpretation in terms of the R -Matrix theory is in progress. Experimental reduced widths will be compared to both $2 \mathrm{p}-1 \mathrm{~h}$ and particle-vibration model predictions.

A paper entitled "Intermediate Structure: ${ }^{28} \mathrm{Si}$ " is in the final stages of preparation for submission to Annals of Physics. The experimental resonance reduced widths are compared both to shell-model $2 p-1 h$ doorway predictions and to the optical model predicted quantity $\int S_{\ell j} d E$. Limitations of these models are discussed.

The results of the R -Matrix analysis of ${ }^{209} \mathrm{Bi}$ partially resolved data have been included in a paper to appear (see Section A-12b) in Annals of Physics.

An R-Matrix interpretation of ${ }^{60} \mathrm{Ni}$ neutron cross section data has been completed. A paper ${ }^{\prime}$ discussing the details of analysis and comparison to particlevibration model predictions was presented at the last Washington APS meeting.

An R-Matrix fit to ${ }^{58} \mathrm{Ni}$ neutron cross section data is being completed using our R-Matrix code. The cross sections were generated by subtraction of ${ }^{60} \mathrm{Ni}$ cross sections from natural Ni data.
3. Averaged Cross Sections, Strength Functions, and Intermediate Strucfure (W. F. E. Pineo, M. Divadeenam, E. G. Bilpuch, H. W. Newson)

Part II of our series on Strength Functions and Average Total Cross Sections has been submitted to Annals of Physics. An abstract was included in TUNL-IX.

Part III of the series is nearly ready for submission. The abstract follows:

> "Neutron cross sections measurements on the separated isotopes $92,94,95,96,98,100 \mathrm{Mo}$ and remeasurements on natural Ru , Rh, La, $\mathrm{Hf}, \mathrm{Ta}, \mathrm{W}, \mathrm{Ir}, \mathrm{Os}, \mathrm{TI}, \mathrm{Bi}, \mathrm{Th}$, and U were made with improved techniques to minimize inscattering background transmission measurements. The average cross section method (Duke Method) was employed to estimate s-, $\mathrm{p}-$, and d-wave strength functions and R' from the measured average cross sections referred to above in addition to earlier Duke measurements, and published Wisconsin measurements. The results are compared with both spherical and collective optical potential model calculations. p-wave strength functions are in good agreement with the collective model predictions, whereas only qualitative agreement is found with the collective model calculations in the case of s-wave strength functions. d-wave strength functions indicate two broad giant resonances at $\mathrm{A}=60$ and $160 . "$
4. Charged-Particle Fission (F. O. Purser, J. R. Boyce, D. E. Epperson, E. G. Bilpuch, H. W. Newson, H. W. Schmitt*)
a. Analysis of Fission Cross-Section Measurements

The total fission cross-section data for proton-induced fission of the uranium isotopes has been analyzed with a statistical model to determine neutron to fission branching ratios. A paper containing the data and the results of the analysis has been completed and is being submitted for publication.
b. Mass And Kinetic Energy Measurements

This program has been inactive for this report period. It will be resumed during the next period.

[^57]
## c. Cross-Section Measurements

Measurements of fission-fragment angular distributions for proton-induced fission have been completed for ${ }^{233} \mathrm{U},{ }^{234} \mathrm{U},{ }^{235} \mathrm{U}$ and ${ }^{236} \mathrm{U}$ for incident proton energies between 7.0 and 13.0 MeV . Addition of this low-energy angular distribution data to that previously measured completes a data set for these four isotopes for initial excitation energies ranging from just below the onset of second chance fission to well above the fourth chance fission region. Computer analysis of the data with our statistical decay model is in progress to determine the excitation energy dependence of the anisotropy and $\mathrm{K}^{2}$ for individual fissioning nuclei.
5. A Selectively Excited And Distorted (SEXD) Liquid Drop Model (H. W. Newson)

This model has been generalized to include both liquid-like and Fermi gas-like phenomena in such a way that shell effects via the $2 p-1 h$ mechanism impose selection rules on the conventional LDM. One can now understand the fragment properties without abandoning the latter model.
6. Cross-Section and Polarization in $\left({ }^{3} \mathrm{He}, \mathrm{n}\right)$ Reactions from ${ }^{12} \mathrm{C}$ and ${ }^{13} \mathrm{C}$ from 8 to 22 MeV (T. C. Rhea, R. A. Hardekopf; P. W. Lisowski, J. M. Joyce, ** R. Bass, ${ }^{+}$R. L. Walter)

Final calculations have been made and no suitable set of parameters was found which could describe the elastic scattering and polarization data for ${ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He},{ }^{3} \mathrm{He}\right){ }^{13} \mathrm{C}$ and the cross section and polarization for ${ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{\mathrm{o}}\right){ }^{15} \mathrm{O}$. For ${ }^{12} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{\mathrm{o}}\right)$ suitable DWBA results were obtained in the $18-22 \mathrm{MeV}$ range using ${ }^{12} \mathrm{C}\left({ }^{3} \mathrm{He},{ }^{3} \mathrm{He}\right){ }^{12} \mathrm{C}$ optical-model parameters published earlier. A publication summarizing our findings is being prepared. This work was reported at the Washington, D.C. American Physical Society Meeting and comprised the major part of the thesis of T. C. Rhea. The abstract from this thesis follows:
"Neutron polarization and cross section angular distributions from $0^{\circ}$ to $120^{\circ} \mathrm{c} . \mathrm{m}$. have been measured for the ${ }^{12} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{\mathrm{o}}\right){ }^{14} \mathrm{O}$ reaction with ${ }^{3} \mathrm{He}$ bombarding energies from 8 to 22 MeV in 2 MeV steps and for the ${ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{0}\right){ }^{15} \mathrm{O}$ reaction at 12,16 , and 20 MeV . The neutron polarimeter utilized

[^58]a spin-precession solenoid and $120^{\circ}$ scattering from ${ }^{4} \mathrm{He}$ gas in a scintillator cell.

DWBA calculations showed significant agreement with the 20 and $22 \mathrm{MeV}{ }^{12} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{\mathrm{o}}\right)$ data although it is evident that effects other than those described by the DWBA are present. Below 20 MeV the polarization data vary quickly with energy, and the results of the calculations are unsatisfactory. Comparison of ${ }^{12} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{\mathrm{o}}\right)$ and ${ }^{12} \mathrm{C}\left(\mathrm{t}, \mathrm{p}_{\mathrm{o}}\right)$ cross-section and polarization data at 16 MeV indicates that the same mechanism dominates both reactions and that the differences in the coulomb effects for the two reactions are small. Even though the DWBA has successfully described 4 to $6 \mathrm{MeV}{ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{0}\right)$ cross sections and polarizations, no agreement was found for the present data. The need for coupled-channel calculations is suggested.

In order to derive optical model parameters to use in the ${ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}_{0}\right)$ DWBA calculations, the cross section and forward-angle polarization of ${ }^{13} \mathrm{C}+{ }^{3} \mathrm{He}$ scattering at 19.3 MeV were measured. The data are similar to 20 MeV ${ }^{12} \mathrm{C}+{ }^{3} \mathrm{He}$ scattering data, and, as would be expected then, the ${ }^{13} \mathrm{C}$ optical model parameters that were obtained in this work were similar to those found previously for ${ }^{12} \mathrm{C} .{ }^{1 "}$
7. Polarization Produced in The ( $d, n$ ) Reactions on ${ }^{9} \mathrm{Be}$ and ${ }^{11} \mathrm{~B}$ (J. Taylor, G. Spalek,** Th. Stammbach, ${ }^{+}$R. L. Walter)

No further progress on DWBA calculations have been made. Perhaps some progress toward understanding our observations will be initiated when ( $\vec{d}, n$ ) reactions are studied in the near future, using pulsed beams if this proves to be possible.

[^59]8. Neutron Polarizations Produced by the Breakup of Polarized Deuterons on D and ${ }^{4} \mathrm{He}$ (P. W. Lisowski, R. Bird, T. B. Clegg, R. L. Walter)

The polarization produced at a reaction angle of $0^{\circ}$ in the breakup of pure vector-polarized deuterons on $D$ and ${ }^{4} \mathrm{He}$ has been measured from 9 to 15 MeV incident deuteron energy. Preliminary results indicate that the neutron polarization is constant for the neutrons in the upper $2 / 3$ of the continuum spectrum over the incident deuteron energy range and that $\mathrm{K}^{\mathrm{y}}$ is large, perhaps as large as 0.9 , implying very little loss of spin information fyr the neutron.
9. Neutron Scattering Studies Using Polarized Neutrons Produced by Polarized Deuteron Beams (P. W. Lisowski, T. C. Rhea, C. E. Busch, T. B. Clegg, R. L. Walter)
a. $\quad{ }^{3} \mathrm{He}(\overrightarrow{\mathrm{n}}, \overrightarrow{\mathrm{n}})$ Reaction

Polarization angular distributions previously obtained at 8, 12, and 17 MeV have been incorporated in phase-shift and optical-model parameterizations. There parameterizations have been made using all of the currently available $n-{ }^{3} \mathrm{He}$ total cross-section, differential cross-section, and polarization data. A report on these data was given at the Washington meeting of the American Physical Society.
b. $\quad{ }^{4} \mathrm{He}(\vec{n}, n)$ Reaction

Asymmetry angular distributions which were previously obtained at 14 and 17 MeV by scattering polarized neutrons from a ${ }^{4} \mathrm{He}$ gas scintillator have been incorporated in an R -matrix analysis and in an optical-model formulation. The $R$-matrix analysis encompasses most of the available $n-{ }^{4} \mathrm{He}$ and $p-{ }^{4} \mathrm{He}$ cross section and polarization data. The resulting $R$-matrix parameters yield phase shifts which provide an excellent representation of both systems for energies below 20 MeV . A report on these data was given at the Washington meeting of the American Physical Society.
10. $\frac{\text { Transfer Polarization Studies in }(\vec{p}, \vec{n}) \text { Reactions }}{\text { T. Doiron, }}$ (P. W. Wyrd, Lisowski,

Polarization transfer coefficients $K_{y}^{y}$, have been deduced from measurements of the neutron polarization produced at a reaction angle of $0^{\circ}$ in $(\vec{p}, \vec{n})$ reactions on several nuclei. Beams of 20 to 100 nA of typically $80 \%$ polarized protons were used. The outgoing neutron polarizations were measured by scattering from a high-pressure ${ }^{4} \mathrm{He}$ gas scintillator. Statistical uncertainties in the calcu-
lated values of $K Y$ were about 0.05 .
a. $D(\vec{p}, \vec{n}) p p$ Reaction

Neutron polarizations have been measured for proton energies from 9 to 15 MeV . Geometry, multiple-scattering, and energy-average analyzingpower corrections need to be calculated before final values are obtained, but preliminary results indicate a nearly constant energy dependence of the transfer coefficient of the final-state interaction neutrons and a similar energy dependence of opposite sign for the polarization transfer of the quasi-elastic neutrons.
b. $\quad{ }^{11} \mathrm{~B}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}}),{ }^{13} \mathrm{C}(\overrightarrow{\mathrm{p}}, \vec{n})$, and ${ }^{9} \mathrm{Be}(\overrightarrow{\mathrm{p}}, \vec{n})$

Polarization transfer coefficients have been measured for ${ }^{9} \mathrm{Be}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}})$ for proton energies from 4 to 15 MeV . A comparison of the preliminary results of this experiment with the ${ }^{11} \mathrm{~B}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}})$ and ${ }^{13} \mathrm{C}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}})$ polarization transfer coefficients previously obtained from 8.5 to 15 MeV shows little similarity.

The KY values fluctuated considerably with energy reaching a maximum of 10.8 in the case of ${ }^{13} C(\vec{p}, \vec{n})$ and 0.5 in the case of ${ }^{11} B(\vec{p}, \vec{n})$. For ${ }^{9} \mathrm{Be}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}})$, the transfer is approximately constant above 12 MeV with a value about +0.4 . The value of $K Y$ decreases below 12 MeV and changes sign around 9 MeV reaching a value of approximately -0.2 near 6 MeV . Below 6 MeV the sign reverses again, rising to about +0.4 at 5 MeV .
c. $\mathrm{Cu}(\overrightarrow{\mathrm{p}}, \vec{n})$

The neutron polarization produced at $0^{\circ}$ bombarding a natural copper target with polarized protons has been obtained at 14.3 MeV . The polarization transfer coefficient deduced from these evaporation neutrons as a function of continuum neutron energy are consistent with zero polarization transfer. In this experiment the statistical accuracy varied from $\pm 0.05$ to $\pm 0.008$ as a function of decreasing neutron energy.

$$
\text { 11. Polarization Transfer at } 0^{\circ} \text { in the } D(d, n) \text { Reaction (P. W. Lisowski, }
$$

The $0^{\circ}$ polarization transfer coefficient $K y$, and the $0^{\circ}$ analyzing power $A_{z z}$ have been measured for the $D(d, n)$ reaction for deuteron energies as low as 500 keV . These results must be additionally corrected for geometry and multiple-scattering effects, but preliminary results indicate that the polarization transfer remains near its value at higher energies even though the $0^{\circ}$ analyzing
power for $D(d, n)$ is not constant below 2.5 MeV . These data and those obtained previously provide a comprehensive set of $0^{\circ}$ polarization transfer coefficients and $0^{\circ}$ analyzing powers for incident deuteron energies from 0.5 to 15.0 MeV . Typical statistical accuracies of 0.01 and 0.02 were obtained for the $K Y$ and $A_{z z}$ values respectively. A report on the data will be given at the Bloomington meeting of the American Physical Society.
12. Theoretical Investigation of Neutron Cross Section Measurements (M. Divadeenam, B.-H. Choi,* W. P. Beres, ** S. Ramavataram, ${ }^{+}$ K. Ramavataram, ${ }^{+}$A. Lev,** R. Y. Cusson, H. W. Newson)
a. Shell Model
(1) Even-Odd Compound Nuclei
${ }^{28} \mathrm{~S}_{\mathrm{i}+\mathrm{n}}$ : A paper ${ }^{1}$ entitled ${ }^{28} \mathrm{~S} \mathrm{i}+\mathrm{n} \mathrm{s}$ - and p -wave $2 \mathrm{p}-1 \mathrm{~h}$ Doorways" was presented at the Spring 1973 Washington American Physical Society meeting.

A short paper ${ }^{2}$ entitled "On the Relevance of the SingleParticle Component of a Doorway State for Evaluating the Nuclear Escape Width" was submitted to the Munich Conference. A simple scheme is proposed in which the roles of both the $s-p$ - and $2 p-1 h$ components of a doorway are considered in evaluating the total nuclear escape widths. This scheme has been tested for $5 / 2^{-}$ resonances in the compound nucleus ${ }^{29} \mathrm{Si}$. A very restricted bas is of $2 \mathrm{p}-\mathrm{Ih}$ states and single neutron reproduces the experimental situation below 2 MeV neutron energy. A paper in the future will incorporate these findings.

The $2 \mathrm{p}-\mathrm{lh}$ calculations for Pb isotopes are in progress.
${ }^{40} \mathrm{Ca}^{+} \mathrm{n}$ and ${ }^{48} \mathrm{Ca}^{+} \mathrm{n}$ : Our previous 2 p - Ih doorway calculations on ${ }^{40} \mathrm{Ca}+\mathrm{n}$ and ${ }^{48} \frac{\mathrm{Ca}}{}{ }^{+} \mathrm{n}$ are being extended to $d$-wave resonances. A paper ${ }^{3}$ based on these findings will be presented at the forthcoming Bloomington Nuclear

[^60]Physics division meeting.

## (2) Odd-Odd Compound Nuclei

${ }^{89} \mathrm{Y}+\mathrm{n}$ : The shell-model program that was previously used to predict $s$-wave $3 p-1 h$ resonance states ${ }^{1}$ in ${ }^{90} \mathrm{Y}$ is being generalized to calculate matrix elements of the type

$$
\begin{aligned}
& <p n\left|V_{12}\right| p^{\prime} n^{\prime}> \\
& \left.<p n\left|V_{12}\right| p^{\prime} n_{1} n_{2} n_{3}^{-1}\right\rangle \\
& \left.<p n\left|V_{12}\right| n^{\prime} p_{1} p_{2} p_{3}^{-1}\right\rangle \\
& \left.<p n_{1} n_{2} n_{3}^{-1}\left|V_{12}\right| p^{\prime} n_{1}^{\prime} n_{2}^{\prime} n_{3}^{\prime-1}\right\rangle \\
& \left.<n p_{1} p_{2} p_{3}^{-1}\left|V_{12}\right| p^{\prime} n_{1}^{\prime} n_{2}^{1} n_{3}^{-1}\right\rangle \\
\text { and } \quad & <n p_{1} p_{2} p_{3}^{-1}\left|V_{12}\right| n^{\prime} p_{1}^{\prime} p_{2}^{\prime} p_{3}^{-1}>
\end{aligned}
$$

to form a secular matrix and subsequent diagonalization to predict doorway energies and wave functions. The resulting wave functions will be used to calculate neutron total cross sections employing a formalism which incorporates both the Lane-Robson Generalized Calculable theory and the Feshbach doorway concept.
${ }^{207} \mathrm{~Pb}+\mathrm{n}$ : The Kuo-Brown and True et al. ${ }^{208} \mathrm{~Pb}$ wave function for different $J^{\pi}$ will be used to interpret the neutron resonance structure observed in ${ }^{207} \mathrm{~Pb}+\mathrm{n}$ experiments. ${ }^{2}$
b. Particle-Vibration Model
(1) Even-Odd Compound Nuclei
${ }^{40} \mathrm{Ca}^{+} \mathrm{n}$ and ${ }^{48} \mathrm{Ca}^{+} \mathrm{n}$ : In the case of ${ }^{41} \mathrm{Ca}$ compound nucleus, the shell model cannot predict any negative parity states if excitations more complex than $2 p-1$ are not considered. However the particle-vibration model is suitable to handle the negative parity doorways. Compound nuclei ${ }^{41} \mathrm{Ca}$ and ${ }^{48} \mathrm{Ca}$ are being considered to predict s -, p - and d-wave particle-vibration doorway escape widths. These predictions will be compared to the corresponding experimental results in a talk (see 12a) to be presented at the forthcoming Bloomington meeting.
${ }^{206} \mathrm{~Pb}+\mathrm{n}$ and ${ }^{208} \mathrm{~Pb}+\mathrm{n}$ : A paper entitled "Nuclear Spreading Widths of Particle-Vibration Resonances in ${ }^{-207} \mathrm{~Pb}$ and ${ }^{209} \mathrm{~Pb}$ has been published in

[^61]Phys. Rev. C8, 1223 (1973). The abstract follows:
> "The nuclear spreading widths of the ${ }^{207} \mathrm{~Pb}$ and ${ }^{209} \mathrm{~Pb} \mathrm{1/2-}$ doorway resonances are calculated in a particle-vibration model. The hallway states are of the particle-two-phonon type. The fine structure in ${ }^{207} \mathrm{~Pb}$ is essentially due to the availability of many hallways (some with large matrix elements) and their proximity to the doorway. The ${ }^{207} \mathrm{~Pb}$ and ${ }^{209} \mathrm{~Pb} 1 / 2^{+}$doorway spreading widths are found to be in line with the experimental situation."

A paper entitled "Imaginary Optical Potential for the Compound Nucleus ${ }^{209} \mathrm{~Pb} "$ has been published in Phys. Review Letters 30, 355 (1973). The abstract follows:
"A nonlocal energy-dependent imaginary optical potential for s-wave neutrons incident on ${ }^{208} \mathrm{~Pb}$ is calculated in the intermediate structure model with particle-vibration coupling. The energy dependence is studied in the range of $0-12 \mathrm{MeV}$. The absorption cross section is calculated and compared to experiment below 2.6 MeV , the inelastic threshold. The agreement is quite good. The radial dependence is also investigated."

Similar calculations for higher partial waves have been performed and the results will be included in a paper that is in preparation.

## (2) Even Mass Compound Nuclei

${ }^{207} \mathrm{~Pb}+\mathrm{n}$ and ${ }^{209} \mathrm{Bi}+\mathrm{n}$ : A paper entitled "Intermediate Struc-
ture: Particle-Vibration States" has appeared in Annals of Physics 80, (1973). The abstract follows:
"The weak coupling particle-vibration model is extended to low-lying neutron resonances in certain even-even or odd-odd nuclei by coupling the extra particle to core excited states of the odd mass target. The odd hole or particle in

> the target is treated as a passive spectator. ${ }^{208} \mathrm{~Pb}$ and ${ }^{210} \mathrm{Bi}$ are studied as test cases and the calculated resonance quantities are in good general agreement with the average features of high resolution experiments. The resonances in ${ }^{208} \mathrm{~Pb}$ and ${ }^{210} \mathrm{Bi}$ are related to the same intrinsic doorway in ${ }^{209} \mathrm{~Pb}$. The ${ }^{210} \mathrm{Bi}$ data is presented here for the first time."
c. Particle-Rotation Model
${ }^{28} \mathrm{Si}+\mathrm{n}$ : A paper entitled "Rotator-Particle p-wave Neutron Resonances in the Compound Nucleus ${ }^{29}$ Si"has been submitted for publication. The abstract follows:
"Neutron continuum resonance states in the compound nucleus ${ }^{29} \mathrm{Si}$ are generated in the framework of the rotator-particle strong coupling model and neutron elastic escape widths for these resonance levels are calculated making use of a quadrupole interaction. The predicted resonance energies of the band-mixed levels and their neutron escape widths corresponding to $1 / 2^{-}$and $3 / 2^{-}$ are in general agreement with the experimental p-wave resonances. A real Woods-Saxon potential with spinorbit term is used for the continuum neutron."

In addition, preliminary findings of this study were presented at the last Washington American Physical Society meeting. ${ }^{1}$
13. Computer Program MODSNOOP for Strength Functions And Single Particle Reduced Widths (B.-H. Choi, M. Divadeenam)

MODSNOOP is being used to predict strength functions and s.p. reduced widths. No modifications have been done since the last report.

[^62]
## B. DEVELOPMENT

1. Accelerator Improvements (F. O. Purser, J. R. Boyce, H. W. Newson, E. G. Bilpuch, R. L. Rummel, M. T. Smith, J. D. Moses, D. E. Epperson, G. E. Mitchell, R. O. Nelson)
a. Tandem Accelerator

The low energy extension of the tandem has been extensively modified to accept a HVEC chopper-buncher system to produce pulsed beams. In Cyclo-Graaff operation, the buncher can be removed from the system to meet the beam optics requirements of the injector cyclotron. Completion of testing of the pulsed beam system and initial data runs are expected during the month of October.
b. Injector Cyclotron

A new cooling manifold has been installed in the lower magnet coil assembly and tested satisfactorily. The cyclotron has been re-assembled and operational tests will be performed at the end of the current maintenance period which has involved extensive modifications to beam line hardware between the injector cyclotron and the FN tandem.
2. Pulsed Beams (F. O. Purser, H. W. Newson, N. R. Roberson, R. O. Nelson, T. B. Clegg, D. E. Epperson, R. A. Hilko, J. Clement, D. W. Glasgow, G. Mack,* K. Stelzer**)
a. Mass Identification of Charged Particles by Time-of-Flight

This program has been inactive for this report period.
b. Neutron Time-of-Flight System

Mechanical installation of the neutron spectrometer system has been completed. The five-ton main detector shield and collimator, the central spectrometer table and monitor detector shield are in place and have been satisfactorily tested. The angular carriage for the main detector traverses an elevated iron track which is co-planar to within $\pm 0.030^{\prime \prime}$ and allows measurements at laboratory scattering angles ranging from $+20^{\circ}$ to $-160^{\circ}$. The maximum time-of-flight

[^63]path obtainable is 4 meters.
An analysis of the beam transport system for time-of-flight operation has been completed. A fully achromatic solution was achieved using the code TRANSPORT written at SLAC and modified at TUNL to be more convenient for use with proton and deuteron beams. The achromatic solution produced less than $5 \%$ beam spread after transport through two $90^{\circ}$ analyzing magnets and a single $70^{\circ}$ switching magnet with a resulting beam transport related pulse length of 0.3 cm , or less than 0.17 nsec at 2 MeV . The final attainable burst width on target should then depend only on the capability of the buncher and chopper and not on the beam handling optics.

Beam handling and vacuum hardware for the neutron target leg are being completed and will be installed by mid-October. An all ceramic and metal beam line will be used to minimize background neutrons arising from the $C(d, n)$ reactions.

Necessary cabling, electrical power, and electronics for neutron time-of-flight measurements are in place and are currently being tested.
3. Polarized Source Improvements (T. B. Clegg, T. A. Trainor, P. W. Lisowski, R. L. Byrd, D. Rickel, T. Spratlin)

The polarized source has continued to be used during a major portion of the accelerator time by many varied experimental groups. During one period in July and August, 23 days of continuous operation were scheduled. Polarized beam intensities have improved considerably with the installation of the new singleaperture duoplasmatron. The best accelerated beam currents observed during the period were 250 nA of polarized deuterons and 180 nA of polarized protons during the initial tests when the duoplasmatron was installed. During later use for experiments accelerated beams of $\sim 180 \mathrm{nA}$ of deuterons and $\sim 120 \mathrm{nA}$ of protons have been obtained for several days on several occasions. Beam polarizations have been between $75 \%$ and $85 \%$ of the theoretical maximum.

Three separate papers are being prepared for publication describing the construction details and methods of operation of the polarized source.

In more detail the contributions and improvements in the polarized source operation in the last six months are as follows:
(1) The new duoplasmatron was developed since, as mentioned in the last report, the multiaperture duoplasmatron tried previously was not successful
when installed on the polarized source. The multiaperture source was redesigned with an expansion cup, extraction electrode, and decel electrode, each with a single aperture through which the beam passes. The actual geometry of these electrodes is very similar to that used on the polarized source at Los Alamos. The new duoplasmatron operates stably with arc currents up to 25 amperes. Initial difficulty with erosion by melting inside the hole in the tip of the intermediate electrode has been overcome by putting a cylindrical tube molybdenum insert in this hole. Difficulty with internal sparking in the duoplasmatron across an epoxy electrode has been overcome by replacing the epoxy insulator with one made of Pyrex. With the installation of the new duoplasmatron, the entire electronics rack for the duoplasmatron has been replaced resulting in a much neater system.
(2) An extensive polarized source manual has been written explaining how to turn the source on, tune it for optimum performance, turn the source off, and change the duoplasmatron filament. This has been the major effort toward trying to acquaint newcomers with the polarized source and make it easy for them to operate.
(3) Digital voltmeter readout of all the coil currents and various quench plate and deflection plate voltages for the polarized source has been provided. This allows conveniently for monitoring the main coil current which provides the spin-filter magnetic field. The DVM reading tells immediately which magnetic substate is being selected for the output beam from the source.
(4) Electrical insulation has been provided for the cesium canal and a power supply has been added to bias this canal between $\pm 32$ volts. Biasing the cesium canal has been shown at LASL to increase the output beam intensity by up to $10 \%$ under some conditions.
(5) Nickel gauze is now being used for filaments in the duoplasmatron instead of the platinum gauze used earlier. If their lifetime compares well with that for the platinum filaments, the cost of replacing filaments can be considerably reduced.
(6) Work has started on a permanent solid-state remote control system for computer control of source parameters to make quench-ratio measurements to determine the beam polarization, to flip the spin direction by changing the direction of all the coil currents for the spin-filter and argon charge-exchange regions, and to change the magnetic substate selected by the spin filter. Although a rudimentary system which allows computer control of these functions already exists, the new system employing LED's, fiber optic, and phototransistor units to couple information from the computer to the high voltage frame of the polarized source
will eliminate many annoying problems.
4. Hardware And Software for Tensor Polarization Experiments (R. F. Haglund, Jr., R. J. Eastgate, T. B. Clegg, C. E. Busch)

After considerable design modification, the automatic chamber rotation system has been assembled. Preliminary bench testing of the logic circuitry has been satisfactory, and assembly of the entire system on the $52^{\circ}$-leg rotating chamber is in progress. A clutch for the drive motor--which will begin to slip at a torque just slightly higher than that required to rotate the chamber--is being installed as an added precaution against dragging cables and other similar mishaps.

The data-taking program DMASS for the 16 K upper memory of the DDP-224 $\beta$-computer has been enlarged and modified to include particle identification of up to 3 particle types. The on-line data analysis includes 4 -point background subtraction, and calculation of the beam polarization from a quench ratio produced by the polarized ion source, to use in the extraction of the tensor analyzing powers. The program can automatically initiate the quench, change the spin sub-state, and flip the quantization axis through $180^{\circ}$ at the polarized ion source; automatic chamber rotation will be incorporated when the hardware installation is complete and has been tested. An off-line analysis version of DMASS is being made for the 12 K DDP-224 a-computer, as only one group in each particle spectrum can be analyzed on-line. A users' guide to this somewhat complex program has also been compiled.

A paper describing this work is to be presented at the Southeastern Section meeting of the American Physical Society in Winston-Salem.
5. Beam Optics Calculations for The Low-Energy End of The Tandem Accelerator (T. B. Clegg, E. Edney)

An investigation of the transmission of the polarized beam through the tandem accelerator showed that it was peaked at $\sim 75 \%$ for terminal voltages of 2-3 MV and decreased steadily to $\sim 40 \%$ as the terminal voltage was raised to 8 MV . To remedy this optics calculations were performed using the off-line DDP224 computer with the interactive display oscilloscope. The results showed that another lens was needed in the beam line close to the low-energy end of the accelerator tank. An einzel lens has been installed at what seems to be the most favorable place during the time when the low energy beam line was being modified to install the chopper-buncher system.
6. $\frac{\gamma \text {-ray Scattering Chamber }}{\text { G. E. Mitchell) }}$ (T. Dittrich, J. F. Wimpey, E. G. Bilpuch,

The p, $\gamma$ chamber in the 3 MV laboratory was modified to accomodate $3^{\prime \prime} \times 3^{\prime \prime} \mathrm{NaI}$ detectors at forward angles of $30^{\circ}$ and $60^{\circ}$. Previously these detectors looked at the chamber through a $5^{\prime \prime}$ diameter flange connecting the chamber to the Faraday cup. This flange was removed and another one installed about $10^{\prime \prime}$ downstream of the chamber. Also, a new air cooled Faraday cup was designed and constructed.

The chamber support bracket was modified to increase the available room above beam line for shielding purposes.

A table was designed which supports about $1 / 2$ ton of lead shielding for the four $3^{\prime \prime} \times 3^{\prime \prime} \mathrm{NaI}$ detectors, yet is versatile enough to allow any combination of a $\mathrm{Ce}(\mathrm{Li})$ detector and NaI detectors around the $\mathrm{p}, \gamma$ chamber.

Lead collars were cast to shield the NaI detectors from background radiation. These provide a minimum shielding of two inches of lead around each NaI crystal. The collars can also be used with the $\mathrm{Ge}(\mathrm{Li})$ detector.
7. New Quadrupole and Steerer Power Supplies for The 3 MeV Laboratory
(T. Dittrich, D. Outlaw, K. Wells, E. G. Bilpuch, G. E. Mitchell)

The quadrupole and steerer power supplies in the 3 MeV laboratory have been replaced with a new system constructed from well-regulated, remotely controlled Lambda power supplies. This new system removes many of the instabilities previously observed in the proton beam, as well as some of those observed in the $\mathrm{HH}^{+}$control beam. This system is also easier to use and should prove more reliable.
8. Gamma Ray Polarimeter (J. R. Williams, R. O. Nelson, C. R. Gould, D. R. Tilley)

A five-crystal, NaI Compton polarimeter has been constructed and its polarization sensitivity experimentally determined over the energy range 0.5 to 4.4 MeV by using gamma rays of known linear polarization. The results are in good agreement with sensitivity calculations made by a computer program which averages the Klein-Nishina scattering cross section over the finite geometry of the polarimeter. The instrument has been used in particle-gamma ray coincidence measurements in the reaction ${ }^{26} \mathrm{Mg}(a, p \gamma)^{29} \mathrm{Al}$. (See Sec. B.8) An abstract describing this work has been submitted to the Southeastern Section American Physical Society
meeting in Winston-Salem.
9. Development of a High Resolution System for The 4 MeV Van de Graaff Accelerator (D. Flynn, F. O. Purser, E. G. Bilpuch, H. W. Newson, G. E. Mitchell, L. W. Seagondollar)

A variety of improvements have been made in these areas: (1) target chamber, (2) electronics, (3) analyzer-homogenizer.
(1) A detector mount and collimation system was designed and fabricated. This system holds four detectors at $90^{\circ}, 105^{\circ}, 122^{\circ}$ and $160^{\circ}$. The beam collimation system was rebuilt to achieve much tighter collimation.
(2) Electronics for 4 parallel counting systems have been obtained. A system involving a teletype and tape punch has been established for recording the scalar readings.
(3) The energy calibration is very strongly dependent on the analyzer temperature. In addition, the energy calibration varies for as much as 12 hours after the beam is initially placed in the analyzer. These present problems are more severe than those observed with the high-resolution system on the 3 MV accelerator, due to a major difference in analyzer design. These improvements (and tests) formed the bulk of the efforts on the 4 MV high resolution system. The primary efforts are still towards improving stability and reliability of the components.
10. Homogenizer Modernization (D. Outlaw, T. Dittrich, J. D. Moses, E. G. Bilpuch, G. E. Mitchell)

Preliminary tests are underway to update the homogenizer system in the 3 MeV laboratory. The current version which is now undergoing tests consists of a high-gain differential amplifier coupled to a target-voltage driver from the Tandem system, ${ }^{1}$ as well as modifications to the existing equipment. Preliminary results indicate better resolution than the previous homogenizer, in addition to increased reliability. Work is continuing to complete the design for a new homogenizer based on these tests.

[^64]11. High Resolution on The Tandem Accelerator (E. G. Bilpuch, F. O. Purser, J. D. Moses, H. W. Newson, T. D. Hayward,* G. E. Mitchell, D. A. Outlaw, R. O. Nelson)

High resolution measurements on the tandem have been greatly improved with the addition of the direct extraction source. With vastly increased beam currents, tighter collimation was possible and the overall resolution reduced. In addition, the asymmetry previously observed is now sharply reduced. Data on ${ }^{92}$ Mo were taken with this system (see section B.l.f.). A paper describing results with the new system has been accepted by Nuclear Instruments and Methods-"Note on High Resolution Measurements With a Tandem Accelerator".

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12. Beam Transport Computer Code Development (J. Clement, F. O. Purser, J. R. Boyce)
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The computer code TRANSPORT/360 written at SLAC has been modified to be more suitable for use on a tandem accelerator. First the acceleration calculation, which formerly handled only fully-relativistic particles, was changed to handle non-relativistic projectiles as well. A new arbitrary, symmetricalfocusing element has been added. This new element may be used for first order calculations involving such elements as Einzel, or gap lenses. Finally the code was modified to print the energy whenever it prints the momentum of a particle. This increases the usefulness of the code for cases where $E$ is not equal to Pc. The modified version of TRANSPORT was then used to calculate the tandem optics for beams injected at high energies from the cyclotron.

## c. THEORY

1. $\frac{{ }^{9} \mathrm{Be}\left(\mathrm{p}, \mathrm{p}_{0}\right) \text { and }{ }^{9} \mathrm{Be}\left(\mathrm{p}, \mathrm{p}_{2}\right)^{9} \mathrm{Be} \text { and The Structure of }{ }^{9} \mathrm{Be} \text { (H. J. Votava, } \text { W. J. Thompson**) }}{}$ (H)

Inactive.
2. Excited-State-Threshold Resonance Effects in ${ }^{9} \mathrm{Be}\left(\mathrm{p}, \mathrm{p}_{0}\right)^{9} \mathrm{Be}$ and ${ }^{9} \mathrm{Be}(\mathrm{p}, \mathrm{n})^{9} \mathrm{~B}$ (H. J. Votava, W. J. Thompson)

Inactive.

[^65]3. Proton Optical-Model Potential Near The Coulomb Barrier (J. S. Eck (Kansas State University)), W. J. Thompson)

Inactive.
4. Compound Elastic Scattering and Tensor Polarizations (R. J. Eastgate, W. J. Thompson)

Inactive.
5. Comparison of $(d, t)$ or $\left(d,{ }^{3} \mathrm{He}\right)$ Vector Analyzing Powers with Those for (d,d) (S. K. Datta, W. J. Thompson)

Inactive.
6. Reaction Mechanism Studies in ${ }^{24} \mathrm{Mg}\left(\alpha, \alpha^{\prime} \gamma\right)^{24} \mathrm{Mg}$ (G. S. McNeilly, W. I. van Rij, N. P. Heydenberg ((Florida State University)), W. J. Thompson)

Inactive.
7. Cluster Effects in Elastic a Scattering Using a New a - a Interaction (W. J. Thompson)

Inactive.
8. Computer Codes for Large Configuration-Space Shell-Model Calculations (S. Maripuu)

The Oak Ridge-Rochester shell-model codes are presently being installed at the TUCC computer. With these programs it will be possible to calculate various observables in a large shell-model basis, e.g., excitation energies, gammaray transition probabilities, log ft values for $\beta$-decay, static multipole moments and spectroscopic factors for nucleon transfer reactions.

A super-large configuration space program which makes use of the m -scheme for the construction of the shell-model basis states is already in use. So far this program can only calculate eigenvalues.

## 9. Computer Codes for Analysis of Fission Data (J. R. Boyce, R. Bass, F. O. Purser)

Two computer codes, developed at TUNL, are being used to analyze proton-induced fission cross section data taken at TUNL. However, both programs have been written so that neutron-induced fission cross sections can also be analyzed. The first, MERLIN, utilizes mass- and energy-dependent optical model parameters to calculate total reaction cross sections for incident protons or neutrons over an energy range $0.125 \mathrm{MeV} \leq \mathrm{E}_{\mathrm{p}} \leq 40.0 \mathrm{MeV}$. Preliminary results indicate that for proton energies below the Coulomb barrier the reaction cross section calculated by using conventional optical-model parameters does not properly describe the compound nucleus formation cross section. The reaction cross section is empirically modified to obtain the compound nucleus cross section used in obtaining "experimental" fission probabilities, $\sigma_{F}$ (exp.)/ $\sigma_{c}$ (o.m.).

The second code, PHROG, is based on a statistical decay model which assumes either fission or neutron emission as primary decay channels. Contributions to the total fission probability from first through third chance fission are calculated for a compound nucleus with initial excitation energy E*. Recent modifications have made it possible to utilize any one of three level density prescriptions (Fermi gas, constant temperature, or Gilbert and Cameron') in the calculations of the channel decay widths $\Gamma_{n}$ and $\Gamma_{\mathrm{f}}$. Parameters for the two level densities used can be varied independently thus introducing a flexibility not present in the original version. The results of this code are compared to the results of MERLIN to obtain a self consistent set of fission thresholds and $\Gamma_{\mathrm{N}} \Gamma_{\mathrm{f}}$ curves for the isotopes studied and over the energy range $0 \leq \mathrm{E}^{*} \leq 30 \mathrm{MeV}$.
10. Proton $2 p-1 h$ and Particle-Vibration Doorways (M. Divadeenam, W. P. Beres, A. Lev, H. R. Weller, E. G. Bilpuch, H. W. Newson, K. Ramavataram)
${ }^{40} \mathrm{Ca}^{+} \mathrm{p}$ : The ${ }^{41} \mathrm{Sc}$ compound nucleus is being considered for predicting $2 p-1 h$ and Particle-Vibration doorway escape widths to compare with the experimentally observed resonance structure in ${ }^{40} \mathrm{Ca}$ proton scattering experiments. The shell model ( $2 p-1 h$ ) can only predict positive parity states for ${ }^{41}$ Sc however the Particle-Vibration Model can predict both positive and negative parity states.

[^66]${ }^{208} \mathrm{~Pb}+\mathrm{p}$ : The latter model is being applied to the ${ }^{208} \mathrm{~Pb}$-plus-proton case to calculate the spreading widths of the antianalog states $\left(2 g_{9} / 2, ~ i_{11 / 2}, ~ j_{15 / 2}\right.$, $3 d_{5 / 2}, 4 s_{1 / 2}, 2 g_{7 / 2}$ and $3 d_{3 / 2}$ ) which are in the continuum region. A paper giving details of the calculation and comparison with the available experimental results will be written for publication.
${ }^{28} \mathrm{Si}+\mathrm{p}$ : The ${ }^{28} \mathrm{Si}+$ proton case is being considered for calculating $2 p-1 h$ doorway energies and their elastic escape widths. In addition the scheme outlined in ref. 1 will be applied to $1 / 2^{-}, 3 / 2^{-}$and $5 / 2^{-}$spins in ${ }^{29} \mathrm{P}$ compound nucleus. The predicted results will be compared to the published experimental data and also with the results obtained by Ramavataram's group at Laval University.
${ }^{14} \mathrm{C}+\mathrm{p}$ : The compound nucleus ${ }^{15} \mathrm{~N}$ has been considered to predict $2 p-1 h$ doorway energies for $j^{\pi}=1 / 2^{+}, 3 / 2^{+}, 5 / 2^{+}, 1 / 2^{-}$and $3 / 2^{-}$. Analogs of $2 \mathrm{~s} 1 / 12$ and $1 d_{5} / 2{ }^{15} \mathrm{C}$ states are almost unfragmented while the analog of the $1 d_{3} / 2{ }^{15} \mathrm{C}$ parent state is fragmented. Elastic proton escape widths are calculated up to 6.0 MeV proton energy. Details of comparison of experiment with theory will be presented at the forthcoming Bloomington meeting.
11. A Core-Plus-Particle Model and Shell Model Investigation of Ni Isotopes (M. Divadeenam, C. R. Gould and K. Ramavataram)
${ }^{57,59} \mathrm{Ni}$ : We are extending the application of the True and Thankappan's Model to study ${ }^{57} \mathrm{Ni}$ and ${ }^{59} \mathrm{Ni}$ levels. These nuclei have been investigated in this laboratory. (See Section B-9.) Both positive and negative parity states will be considered to study their gamma decay properties.
12. Self-Consistent K-Matrix Model Calculation for Finite And Super Heavy Nuclei (R. Y. Cusson, H. W. Meldner (U.C.S.D.)), M. S. Weiss (Livermore)), H. P. Trivedi)

A paper describing this work has been submitted to Nuclear Physics. The abstract follows:
"The Brueckner-Hartree Fock Theory is used to obtain an expression for the (reaction) K-matrix in nuclear matter as a sum of separable terms. A two-term model consisting of a

[^67]zero-range repulsive and density dependent form plus a finite range non-renormalized part is used in an averaged local-density approximation for finite nuclei. Realistic values for the nuclear matter parameters lead to realistic values for the binding energies radii and single-particle properties of finite nuclei. An extrapolation to super heavy nuclei is presented and a discussion of fission properties in this model is given."
13. Computer Codes for High Accuracy Single Particle States (R. Y. Cusson, E. G. Bilpuch, H. P. Trivedi, D. Kolb)

A Ph.D. dissertation on this topic is now in preparation by H. P. Trivedi.
14. Single-Particle Wavefunctions and Energies for Stripping and Pickup Reactions (R. Y. Cusson, G. R. Satchler ((ORNL)))

The reported sensitivity of one-particle transfer reactions to the precise value of the sp energy has been taken into account our realistic shell-model sp potential codes by allowing small adjustments ( $\leq 1 \%$ ) in the nuclear force parameters. These small changes affect only the exponential tail at large distance and maintain the structure at near the nuclear surface. A paper describing these results is being written.

## 15. Realistic Single Particle Hamiltonian for Fission Calculation (D. Kolb R. Y. Cusson, H. W. Newson, H. W. Schmitt ((Oak Ridge)))

A paper has been submitted to Nuclear Physics. The abstract follows.
"A low order approximation to the Brueckner-Goldman density-dependent single-particle reaction matrix is used. The effective single-particle hamiltonian is non-local and depends on a smeared density. The isospin dependence, spin-orbit, center-of-mass and Coulomb corrections are performed in a realistic manner. A large orthogonal (spherical/deformed) oscillator basis or a non-orthogonal basis consisting of two overlapping harmonic oscillators is used to diagonalize the hamiltonian in an iterative self-consistent scheme. The nonlocality, the density dependent terms and the Coulomb terms are expanded in Gaussian forms by using a linearized high speed technique. Results for the total B.E., s.p. energies,
quadrupole moments, radii, proton and neutron density distributions of light nuclei are found to be in good agreement with experiment. Fission effects in the reactions ${ }^{8} \mathrm{Be} \rightarrow \alpha+\alpha$ and ${ }^{32} \mathrm{~S} \rightarrow{ }^{16} \mathrm{O}+{ }^{16} \mathrm{O}$ are studied."
16. New Deep Minima in The Fission Curve of ${ }^{236} \mathrm{U}$ (R. Y. Cusson, D. Koll ${ }^{*}$ H. W. Schmitt ((ORNL)))

Using the realistic Meldner-69 reaction matrix and the atomic physics technique of Molecular Orbitals, a new third minimum in the fission curve of ${ }^{236} \mathrm{U}$ has been identified. It lies 75 MeV below the gnd state; has a deformation parameter of $\beta \cong 1.1$ and is shaped roughly like two half-meshed spheres; it has a 10 MeV deep, 3 Fermi thick barrier for escape in to the fission continuum. Because of overlap factors the transition rate from the ground state is $\sim$ zero. Heavy ion reactions to observe this new possibly metastate form of ${ }^{236} U$ are being discussed
17. Coriolis Anti-Stretching in ${ }^{20} \mathrm{Ne}$ and a Widths (H. C. Lee and R. Y. Cusson)

Inactive.
18. Applications of Group Theory to Rotational Bands in Nuclei (L. C. Biedenharn, R. Y. Cusson, O. L. Weaver (Kansas State University))) Inactive.
19. Do Protons and Neutrons Have Internal Rotational Vibrational Excitations? (L. C. Biedenharn, R. Y. Cusson, O. L. Staunton) Inactive.

## RADIATION LABORATORY

## A. NEUTRON PHYSICS

The new small-angle scattering collimator has been extensively tested. The overall background level is approximately a factor of four lower than that attainable with the old collimator. A particularly meaningful way to characterize the improvement is to note that our signal-to-background ratio for an H 0 sample with the new collimator is comparable with the signal-to-background ratio obtained with a lead scatterer and the old collimator. A detailed description of the smallangle scattering technique has been published. ${ }^{1}$

1. Small-Angle Elastic Scattering of Fast Neutrons (W.P. Bucher, C.E. Hollandsworth, and J. Youngblood) Relevant to USNDC-6 Requests 64,65 , and 69

Measurements have been completed for the scattering of 10.95 and 14.00 MeV neutrons from nitrogen and 10.95 and 14.10 MeV neutrons from oxygen. These measurements supplement existing nitrogen and oxygen data at larger angles.

To provide information on the behavior of the forward scattering in the vicinity of structure in the total cross sections, several additional small-angle scattering measurements were carried out: Nitrogen at $7.65,7.88$, and 8.11 MeV ; and Oxygen at $10.25,10.75$, and 11.25 MeV . The nitrogen measurements span a maximum in the total cross section and the oxygen measurements are centered about a minimum. These data are currently being processed.
> 2. Small-Angle Elastic Scattering of Fast Neutrons from $\mathrm{Be}, \mathrm{C}, \mathrm{Al}$, Fe, $\mathrm{Cu}, \mathrm{Sn}$, and W (W.P. Bucher, C.E. Hollandsworth, A. Niiler, and J. Youngblood) Relevant to USNDC-6 Requests 44, 45, 56, 57, $58,88,147,148,182$ and 381

Absolute cross sections for the small angle scattering of 7.55 MeV neutrons from the above seven elements are now available on request. Further measurements have been started at 11 MeV neutron energy. With the increased sensitivity provided by the new small-angle collimator, it appears that inelastic scattering measurements are also feasible.
3. Forward-Angle Elastic Scattering Cross Sections for Pb (W.P. Bucher, C.E. Hollandsworth, and J. Youngblood)
${ }^{1}$ Nucl. Instr. Methods, 111237 (1973).

An angular distribution of the Elastic Scattering of 7.00 MeV neutrons from Pb has been measured in ring geometry. These data as well as angular distributions at $11.0,12.5$, and 14.0 MeV have been processed and are available.
B. BREAKUP NUCLEONS FROM THE D+d REACTION (A. Niiler and Y.S. Park)

The cross section of breakup nucleon production from the $D+d$ reaction has been measured from $10-16 \mathrm{MeV}$ in the angular range $0^{\circ}$ to $80^{\circ}$. Proton cross sections have been measured at $10,12,14$ and 16 MeV in the angular range of $10-80^{\circ}$ using $\mathrm{E}-\mathrm{AE}$ silicon surface barrier detector telescopes. Neutron spectra have been measured with a recoil-proton telescope at $0^{\circ}$ and $10^{\circ}$ at 12 and 16 MeV . Energy distributions of the breakup nucleons are obtained at all measured angles. The proton and neutron results are in very good agreement with each other. In addition, these data agree well with recent Lawrence Livermore Laboratory neutron results but both of these cross sections are $60 \%$ higher at 16 MeV than extrapolations of other earlier measurements.

Knowledge of the cross sections and energy distributions of neutrons from the $D+d$ reaction is important to the planning of cancer therapy by fast neutron irradiation.
C. ERODED GUN BORE SURFACE DIAGNOSTICS (A. Niiler, T.J. Rock and J.E. Youngblood)

Gun barrel erosion and the resulting wear limited lifetime for most high performance gun barrels has been a long standing problem for the Army. Characterization of some elements in the surfaces which have been exposed to the erosive environments of burning propellants is expected to provide new information about the erosion mechanism. Most of the high-performance propellants in use today burn at temperatures where iron oxide is formed in preference to the nitrides and carbides of iron. Thus the bore surface can be characterized in terms of the depth profile of oxygen immediately under the surface and extending to depths of several microns. This depth profiling of oxygen can be done by using the ${ }^{16} \mathrm{O}\left(\mathrm{d}, \alpha_{0}\right)^{14} \mathrm{~N}$ reaction at deuteron energies which may be less than 1 MeV . As long as the $\alpha$-particles are detected on the same side of the sample as where the deuterons enter, the a energy spectrum uniquely identifies the oxygen depth concentration profile. Several hundred Angstrom depth resolution can readily be obtained with high resolution
silicon surface barrier detectors. At increased deuteron energies, carbon and nitrogen can be similarly profiled.

## D. SENSITIVITY OF ATMOSPHERIC NEUTRON TRANSPORT TO PERTURBATIONS IN THE NITROGEN CROSS SECTIONS (A. Niiler, W.B. Beverly and N.E. Banks)

The effect of the uncertainties in the neutron cross sections of Nitrogen on the transport of neutrons through uniform air to 10 mean free paths has been studied. The base set of Nitrogen cross sections was taken as the ENDF/B-III evaluated set. The elastic cross section was allowed to vary within the $10 \%$ assigned uncertainty limits while at the same time keeping the total cross section invariant. Consequently, any change in the elastic was followed by a change in the inelastic or absorption or both so as to keep the total constant. Elastic angular distributions were perturbed by varying the $2^{\text {nd }}$ and $3^{r d}$ Legendre coefficients ( $a_{1}$ and $a_{2}$ ) so as to give more or less pronounced forward peaking and minima. In one case, the total cross section was allowed to increase by $2 \%$. All perturbations were applied over the 5.5 to 14 MeV energy range and a point isotropic 14 MeV neutron source was used. Calculations were done by the correlated sampling Monte Carlo code SAMCEP.

The most pronounced effect on the neutron transport, more than a factor of 2 at 1500 meters, was found for scattered neutron energies in the $6-9 \mathrm{MeV}$ energy bin for the following cross section perturbation conditions. Total remained unchanged. Elastic was increased by the full $10 \%$. The full elastic change was compensated for by equal changes in the absorption and inelastic cross-sections. The change to the inelastic total was equally portitioned among all the inelastic levels. The elastic angular distributions were changed by increasing $a_{1}$ by $+20 \%$ and $a_{2}$ by $+10 \%$.

YALE UNIVERSITY
A. FAST NEUTRON POLARIZATION STUDIES (F.W.K. Firk, J.E. Bond, G.T. Hickey, R.J. Holt, R. Nath and H.L. Schultz.)

1. Polarization of Neutrons in $n^{16} 0$ Scattering

A systematic, high-resolution study of the polarization of neutrons elastically scattered from ${ }^{16} 0$ has been completed at nine angles and at energies between 1 and 4 MeV . The experiment used the absolutely calibrated source of polarized neutrons from the reaction ${ }^{12} C(n, \vec{n})^{12} C$. The results have been analyzed using a general R-function reaction theory and the total and differential cross sections have been predicted. Excellent agreement is obtained between the predictions and the most recent measurements. A complete phase shift analysis has also been carried out. The measured polarizations are shown in Fig. A-1.

## 2. Polarization of Neutrons in $n-{ }^{4} \mathrm{He}$ Scattering

Preliminary measurements of the polarization of neutrons elastically scattered from a liquid He target have been made at six angles and at energies between 2 and 5 MeV using the technique outlined above. The data are being analyzed and assessments of the effects of multiple scattering and of finite geometry are being made before further measurements are undertaken.
B. SLOW NEUTRON STUDIES (F.W.K. Firk and J. Seltzer*)

1. A Study of the 2.8 keV Neutron Resonance of Sodium and an Analysis of the Total Neutron Cross Section up to 50 keV
[^68]The following is the abstract of a paper accepted for publication in Nuclear Science and Engineering:
'The total neutron cross section of sodium has been measured in the vicinity of the 2.8 keV resonance with the high resolution time-of-flight spectrometer associated with the Yale University $70-\mathrm{MeV}$ electron linear accelerator. The spin of the resonance is unambiguously identified to be $J=1$. A least-squares analysis of the cross section has been carried out up to an energy of 50 keV using a model that takes into account the effects of local and distant levels. The observed total cross section is well-described throughout the entire range with a spin-independent interaction radius of 5.8 fm and with reasonable values of the R-functions (distant level effects) for both spin states. The resonance energy, the neutron width and the effective nuclear radii derived from the analysis are, respectively:
$\mathrm{E}_{\mathrm{R}}=2805 \pm 30 \mathrm{eV}, \Gamma_{\mathrm{nR}}=376 \pm 15 \mathrm{eV}, \mathrm{a}_{\mathrm{J}=1}=5.3 \mathrm{fm}$ and
$a_{J=2}^{(E)}=5.7+\left[2 \times 10^{8} /(E+18500)^{2}\right] \mathrm{fm} . "$ The fit to representative data points is shown in Fig. B-1.
C. ACCELERATOR IMPROVEMENTS (H. L. Schultz, P. Jewett)

The original 100 KV Cockcroft-Walton Freon pressurized DC power supply system for the electron gun has been replaced by a home-constructed pulsed supply of pulse width $0.5 \mu \mathrm{sec}$. This allows injection voltage up to 130 KV to be attained. The gridded high current ARCO Model 12 gun is turned on by a 20 ns pulser which is located in the high voltage terminal box. This new system, besides achieving higher injection voltage, eliminates the Freon corrosion problem experienced with the original DC unit, is much easier to service, and has been highly reliable. A substantial improvement in beam current in the 20 ns mode, approaching a factor of two, has been achieved.


Fig. A-1


Fig. B-1


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[^2]:    a Grams of the metallic component of the sample material.
    ${ }^{\mathrm{b}}$ Solid metal sample 2.159 cm diameter $\times 2.108 \mathrm{~cm}$ length.

[^3]:    $\mathrm{I}_{\text {Report }}$ to the U.S. Nuclear Data Committee Meeting at Oak Ridge National Laboratory, compiled by H. E. Jackson, USNDC-7 (June 18-20, 1973).

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    Relevant to request Nos. 192,193,195 and 196.

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    Relevant to request Nos. 110, 111 and 112.

[^32]:    Abstract of ORNL-4806.
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    Relevant to request Nos. 129 and 130.

[^33]:    *Abstract of ORNL-TM-4252.
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[^36]:    *Relevant to request Nos. 439, 440, 441 and 442.

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    ${ }^{* *}$ Final report of $A-11$ in previous USNDC progress report (ORNL-TM-4204), USNDC-7.

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[^39]:    ${ }^{*}$ To be presented at the Bloomington APS Meeting, November 1-3, 1973. 1
    Lawrence Livermore Laboratory

[^40]:    *To be presented at the Bloomington APS Meeting, November 1-3, 1973. **

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    Department of Physics and Astrophysics, University of Colorado, Boulder, Colorado.

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[^50]:    *Abstract of ORNL-TM-4294.

[^51]:    ${ }^{*}$ Req. Nos. 377, 339, 305
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