# THE U.S. NUCLEAR DATA COMMITTEE 

JUNE 1974

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## REPORTS TO

## THE U.S. NUCLEAR DATA COMMITTEE

JUNE 1974

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

PREFACE

The reports in this document were submitted to the United States Nuclear Data Committee (USNDC) in June 1974. The reporting laboratorles 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 ilsted 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 Dr. Charles L. Dunford, National Neutron Cross Section Center, Brookhaven National Laboratory, Upton, New York.







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

## A. NUCLEAR DECAY DATA COMPILATION AND EVALUATION EFFORTS

1. Nuclide Decay Data for ENDF/B-IV (Reich, Helmer, Putnam)

The compilation of data on the decay properties of radioactive nuclides for Version IV of the Evaluated Nuclear Data File (ENDF/B) is continuing. At the present time, experimental decay data on 199 radioactive nuclides have been prepared for inclusion in this file.

Of these, 181 nuclides are fission products and are "priority" nuclides for summation-type calculations of the decay-heat source term in reactor cores. Their data will be included as one of the subsets of nuclear data in the Fission-Product File of ENDF/B-IV. The remaining 19 nuclides - ${ }^{3} \mathrm{H},{ }^{187} \mathrm{Re}$ and selected actinides - will be incorporated into the General-Purpose File of ENDF/B-IV.

A list of these 199 nuclides is given in Table A-1.
The nuclides are arranged on the file in order of increasing atomic number ( $Z$ ). For a given Z-value, the nuclides are arranged in order of increasing mass number (A). Isomers (arbitrarily restricted to excited states with half-lives $\lambda 0.1 \mathrm{sec}$.) are treated as separate cases and appear on the file immediately following their associated ground state (when these latter are radioactive). In addition to $Z$, the chemical symbol, A and an "isomer tag", the following information is given for each nuclide. A number of comment cards are included which give references from which the listed data were taken together with relevant remarks concerning specific aspects of the data and/or how they were treated. The half-life, its uncertainty and the various decay modes of the nuclide are given. These decay modes presently include $\beta^{-}, \beta^{+}$and/or electron-capture, isomeric-transition, alpha-particle, delayed-neutron and spontaneous fission. For each such mode, the associated branching ratio and its uncertainty as well as the available decay energy (where defined) and its uncertainty are listed. For each radiation type, the energies and intensities (and their uncertainties) of the individual transitions are given, together with a normalization factor to convert relative intensities to absolute intensities. In addition, intensityweighted average energies and their uncertainties are included for $\beta^{ \pm}$, $\gamma$ and $\alpha$ transitions. For the individual $\gamma$-ray transitions, provision is made for inclusion of their total internal-conversion coefficients and uncertainties.

List of nuclides (as of March, 1974) for which decay data have been prepared for inclusion in ENDF/B-IV.

| 非 | Z | A | \# | Z | A | 非 | Z | A |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | $\mathrm{H}-3$ | 2 | 32 | GE- 79 | 3 | 33 | AS-80 |
| 4 | 33 | AS-81 | 5 | 33 | AS - 82 | 6 | 33 | AS- 82M |
| 7 | 34 | SE- 83 | 8 | 34 | SE- 83M | 9 | 34 | SE- 84 |
| 10 | 35 | BR- 84 | 11 | 35 | BR- 84M | 12 | 35 | 8R-85 |
| 13 | 35 | BR-86 | 14 | 35 | BR-87 | 15 | 36 | KR-85 |
| 16 | 36 | KR-85M | 17 | 36 | KR-87 | 16 | 36 | KR-88 |
| 19 | 36 | KR-89 | 20 | 36 | KR-90 | 21 | 36 | KR-91 |
| 22 | 36 | KR- 92 | 23 | 37 | RB-88 | 24 | 37 | RB-89 |
| 25 | 37 | RB- 90 | 26 | 37 | RB- 90M | 27 | 37 | RB-91 |
| 28 | 37 | RB-92 | 29 | 38 | SR-89 | 30 | 38 | SR-90 |
| 31 | 38 | SR-91 | 32 | 38 | SR- 92 | 33 | 38 | SR-93 |
| 34 | 38 | SR-94 | 35 | 39 | $\gamma-90$ | 36 | 39 | Y- 90M |
| 37 | 39 | $Y-91$ | 38 | 39 | $Y-91 M$ | 39 | 39 | $Y-92$ |
| 40 | 39 | $Y-93$ | 41 | 39 | $\mathrm{V}-94$ | 42 | 39 | $Y-95$ |
| 43 | 39 | $Y-97$ | 44 | 40 | 2R-95 | 45 | 40 | 2R-97 |
| 46 | 40 | 2R-99 | 47 | 41 | NB- 95 | 48 | 41 | NB-95M |
| 49 | 41 | NB-97 | 50 | 41 | NB- 97 M | 51 | 41 | N8-98 |
| 52 | 41 | NB- 98M | 53 | 41 | NB-99 | 54 | 41 | NB- 99M |
| 55 | 41 | NB-100 | 56 | 41 | NB-101 | 57 | 42 | MJ- 99 |
| 58 | 42 | MO-101 | 59 | 42 | MO-1 02 | 60 | 43 | TC- 99M |
| 61 | 43 | TC-101 | 62 | 43 | TC-102 | 63 | 43 | TC-102 M |
| 64 | 43 | TC-103 | 65 | 43 | TC-104 | 66 | 43 | TC-105 |
| 67 | 44 | RU-103 | 68 | 44 | RU-105 | 69 | 44 | RU-106 |
| 70 | 44 | RU-107 | 71 | 44 | RU-108 | 72 | 45 | RH-103M |
| 73 | 45 | RH-104 | 74 | 45 | RH-104M | 75 | 45 | RH-105 |
| 76 | 45 | RH-105M | 77 | 45 | RH-106 | 78 | 45 | RH-106M |
| 79 | 45 | RH-107 | 80 | 45 | RH-108 | 81 | 45 | RH-108M |
| 82 | 45 | RH-110 | 83 | 45 | RH-110M | 84 | 46 | PD-109 |
| 85 | 46 | PD-109M | 86 | 46 | PD-111 | 87 | 46 | PO-111M |
| 88 | 47 | AG-109M | 89 | 47 | AG-111 | 90 | 47 | AG-111M |
| 91 | 47 | AG-112 | 92 | 49 | IV-118 | 93 | 49 | 1N-118M |
| 94 | 49 | $1 \mathrm{~N}-120$ | 95 | 49 | IN-120M | 96 | 50 | SN-125 |
| 97 | 50 | SN-125M | 98 | 50 | SN-127 | 99 | 50 | SN-127M |
| 100 | 50 | SN-128 | 101 | 50 | SN-132 | 102 | 51 | SB-125 |
| 103 | 51 | SB-127 | 104 | 51 | SB-128 | 105 | 51 | SB-128M |
| 106 | 51 | SB-129 | 107 | 51 | S8-139 | 108 | 51 | S8-130M |
| 109 | 51 | SB-131 | 110 | 51 | SB-132 | 111 | 51 | S8-132M |
| 112 | 51 | S B-133 | 113 | 51 | S8-134 | 114 | 51 | SB-134M |
| 115 | 52 | TE-125M | 116 | 52 | TE-127 | 117 | 52 | TE-129 |
| 118 | 52 | TE-129M | 119 | 52 | TE-131 | 120 | 52 | TE-131M |
| 121 | 52 | TE-132 | 122 | 52 | TE-133 | 123 | 52 | TE-133M |
| 124 | 52 | TE-134 | 125 | 53 | 1-131 | 126 | 53 | I-132 |
| 127 | 53 | I-133 | 128 | 53 | 1-134 | 129 | 53 | I-134M |
| 130 | 53 | I-135 | 131 | 53 | I-136 | 132 | 53 | I-136M |
| 133 | 54 | XE-131M | 134 | 54 | XE-133 | 135 | 54 | XE-133M |
| 136 | 54 | XE-135 | 137 | 54 | XE-135M | 138 | 54 | XE-137 |
| 139 | 54 | XE-138 | 140 | 54 | XE-139 | 141 | 55 | CS-134 |
| 142 | 55 | CS-134M | 143 | 55 | CS-136 | 144 | 55 | CS-137 |
| 145 | 55 | CS-138 | 146 | 55 | CS-138M | 147 | 55 | CS-139 |
| 148 | 55 | $C S-140$ | 149 | 56 | $B A-137 \mathrm{M}$ | 150 | 56 | 6A-139 |
| 151 | 56 | BA-140 | 152 | 56 | BA-141 | 153 | 56 | BA-142 |
| 154 | 57 | LA-140 | 155 | 57 | LA-141 | 156 | 57 | LA-142 |
| 157 | 58 | CE-141 | 158 | 58 | CE-143 | 159 | 58 | CE-144 |
| 160 | 58 | CE-145 | 161 | 58 | CE-146 | 162 | 59 | PR-143 |
| 163 | 59 | PR-144 | 164 | 59 | PR-144M | 165 | 59 | $P R-145$ |
| 166 | 59 | PR-146 | 167 | 59 | PR-147 | 168 | 59 | PR-148 |
| 169 | 59 | PR-149 | 170 | 60 | NO-147 | 171 | 60 | ND-149 |
| 172 | 60 | ND-151 | 173 | 61 | PM-147 | 174 | 61 | PM-148 |
| 175 | 61 | PM-148M | 176 | 61 | PM-149 | 177 | 61 | PM-151 |
| 178 | 61 | PM-152 | 179 | 61 | PM-152M | 180 | 61 | PM-153 |
| 181 | 62 | SM-153 | 182 | 63 | EU-156 | 183 | 75 | RE-187 |
| 184 | 90 | TH-232 | 185 | 91 | PA-233 | 186 | 92 | U-233 |
| 187 | 92 | U-234 | 188 | 92 | U-235 | 189 | 92 | U-236 |
| 190 | 92 | U-238 | 191 | 90 | NP-237 | 192 | 94 | PU-238 |
| 193 | 94 | PU-239 | 194 | 94 | PU-240 | 195 | 94 | PU-241 |
| 196 | 94 | PU-242 | 197 | 95 | AM-241 | 198 | 95 | AM-243 |
| 199 | 96 | CM-244 |  |  |  |  |  |  |

The format in which these data are prepared and stored on magnetic tape at our laboratory is not that in which they appear in ENDF/B but rather is one which is more readily interpretable by nuclear physicists. (A program to convert these data from our format to that of ENDF/B has been written by personnel of the National Neutron Cross-Section Center at BNL.) A detailed discussion of our format and of the data content of the file is given elsewhere. ${ }^{1}$
2. The Gamma-Ray Spectrum Catalogue - A User Data File (R. L. Heath)

The Gamma-Ray Spectrum Catalogue has been a continuing effort at the National Reactor Testing Station for many years. The purpose of this effort is to provide a collection of experimental $X$-ray and gamma-ray spectra for general laboratory use in the analysis of data obtained with laboratory gamma-ray spectrometers.

A new edition of the Gamma-Ray Spectrum Catalogue has recently been issued. The second volume of this edition which has been released is devoted to the presentation of experimental pulse-amplitude spectra obtained with $\mathrm{Ge}(\mathrm{Li})$ and $\mathrm{Si}(\mathrm{Li})$ spectrometers. As in the previous edition (IDO-16880) issued in 1964, this edition presents experimental spectra for over 300 individual radionuclides. The application of highresolution gamma-ray spectrometry for quantitative isotopic analysis requires a precise knowledge of the energies and intensities of major gamma rays emitted in the decay of a given isotope. For this reason the catalogue effort has included the development of techniques for the measurement of energies and intensities using Ge(Li) spectrometry. The data presented for each nuclide includes tabulated experimental values for gamma-ray energies and intensities with associated experimental error. A brief description of experimental methods and equipment employed to obtain these data is presented together with tables of measured values of gamma rays adopted for energy calibration of the gamma-ray spectrometers used to obtain these data.
3. Evaluation of Decay-Scheme Data (R. G. Helmer, R. C. Greenwood)

A re-evaluation of selected decay data for several isotopes has been carried out. 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

[^0]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 A-2. A similar set of data for ten fission-product isotopes is given in Table A-3.

## B. NUCLEAR-STRUCTURE STUDIES

1. Energy Levels of ${ }^{155} \mathrm{Gd}$ and ${ }^{157} \mathrm{Gd}$ Populated by the ( $\mathrm{n}, \gamma$ ) Reaction Using 24.5 keV Neutrons (Greenwood, Reich, Chrien*, Rimawi*)

The nuclei ${ }^{155} \mathrm{Gd}$ and ${ }^{157} \mathrm{Gd}$ have been extensively investigated using charged-particle reactions and nuclear-decay studies. While these studies have provided valuable insights into the structure of these nuclei, there are still serious gaps in our knowledge. Neutron capture $\gamma$-ray studies can provide much additional interesting information about the energy-level structure of these nuclei, particularly regarding the distribution and location of states having spins of $1 / 2$ and $3 / 2$. Because of the very large thermal-neutron capture cross sections of the neighboring isotopes ${ }^{155} \mathrm{Gd}$ and ${ }^{157} \mathrm{Gd}$ and the fact that most ( $\mathrm{n}, \gamma$ ) reaction studies are carried out using thermal neutrons, little such data presently exist, primarily because of the lack of isotopically enriched samples of sufficiently high isotopic purity. The only information currently available is that for the ${ }^{156} \mathrm{Gd}(\mathrm{n}, \gamma)$ reaction. ${ }^{1}$ In view of the experimental difficulties associated with the studies of these nuclides by thermalneutron capture, we have undertaken a series of experiments using a $24.5-\mathrm{keV}$ neutron beam obtained through the iron-aluminum-sulfur filter on the HFBR. ${ }^{2}$ An additional advantage of using this filtered neutron beam results from its finite neutron energy width ( $\approx 2 \mathrm{keV}$ ). In consequence, the resultant ${ }^{154} \mathrm{Gd}(\mathrm{n}, \gamma)$ and ${ }^{156} \mathrm{Gd}(\mathrm{n}, \gamma)$ spectra represent an average over $\sim 130$ and $\sim 42$ resonances, respectively, which gives a reasonable "averaging out" of the statistical fluctuations in the partial radiation widths (i.e., primary capture $\gamma$-ray intensities). Consequently, a significant population of all final states with spins of $1 / 2$ and $3 / 2$ occurs, with those states of negative parity being more strongly populated by primary transitions if s-wave capture predominates. Somewhat surprisingly, in view of the fact that the s-wave strength function is at a maximum and the p-wave strength function is at a minimum in this mass region, we find that the p-wave contribution to the capture $\gamma$-ray spectrum

[^1]TABLE A-2

RECOMMENDED NUCLEAR DECAY DATA FOR NON-FISSION NUCLEI

| Isotope | Half-Life |  | $\begin{aligned} & \text { Gamma-Ray } \\ & \text { Energy (keV) } \end{aligned}$ | ```Gamma-Ray Intensity (%)``` |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{24} \mathrm{Na}$ | 15.00(2) | h | $\begin{aligned} & 1368.60(3) \\ & 2753.98(10) \end{aligned}$ | $\begin{aligned} & 99.993(2) \\ & 99.84(3) \end{aligned}$ |
| ${ }^{27} \mathrm{Mg}$ | 9.46(2) | m | $\begin{array}{r} 843.73(4) \\ 1014.44(5) \end{array}$ | $\left.\begin{array}{l} 71.4(5) \\ 28.6(5) \end{array}\right\} \text { sum }=99.964(4)$ |
| ${ }^{46} \mathrm{Sc}$ | 83.85 (10) | d | $\begin{array}{r} 889.258(18) \\ 1120.516(25) \end{array}$ | $\begin{aligned} & 99.984(6) \\ & 99.987(6) \end{aligned}$ |
| ${ }^{47} \mathrm{Sc}$ | 3.39 (4) | d | 159.39(5) | 69.0(25) |
| ${ }^{48} \mathrm{Sc}$ | 43.8(1) | h | $\begin{array}{r} 983.4(2) \\ 1037.4(2) \\ 1311.8(4) \end{array}$ | $\begin{aligned} & 99.987(2) \\ & 97.5(3) \\ & 99.992(2) \end{aligned}$ |
| ${ }^{54} \mathrm{Mn}$ | 312.6(3) | d | 834.827(21) | 99.97(2) |
| ${ }^{58} \mathrm{Co}$ | 71.23(15) | d | $810.757(21)$ | 99.44(5) |
| ${ }^{59} \mathrm{Fe}$ | 44.6(1) | d | $\begin{aligned} & 1099.224(25) \\ & 1291.564(28) \end{aligned}$ | $\left.\begin{array}{l}55.5(17) \\ 44.1(12)\end{array}\right\}$ sum $=99.6(1)$ |
| ${ }^{60} \mathrm{Co}$ | 5.268(5) | y | $\begin{aligned} & 1173.208(25) \\ & 1332.464(30) \end{aligned}$ | $\begin{aligned} & 99.86(2) \\ & 99.986(2) \end{aligned}$ |
| ${ }^{64} \mathrm{Cu}$ | 12.701(7) | $h$ | $511.002^{\text {a }}$ | $36.8(16)^{\text {b }}$ |
| $115 \mathrm{~m}_{\mathrm{In}}$ | $4.50(2)$ | h | 336.2 (1) | 47.(2) |
| 116 m In | 54.03(20) | m | $\begin{aligned} & 1293.4(3) \\ & 2112.1(4) \end{aligned}$ | $\left.\begin{array}{l}83.4(15) \\ 16.5(15)\end{array}\right\} \quad$ sum $=99.94(1)$ |
| ${ }^{198} \mathrm{Au}$ | 2.696(2) | d | 411.794(8) | 95.48(10) |
| ${ }^{239} \mathrm{~Np}$ | 2.355 (4) | d | $\begin{aligned} & 228.19(1) \\ & 277.60(3) \end{aligned}$ | $\begin{aligned} & 12.0(4) \\ & 15.2(5) \end{aligned}$ |

a The effective energy of this peak may be lower than this due to electron binding effects and the finite width of the annihilation radiation energy distribution.
b
This intensity assumes conversion of all positrons to photon pairs.

## TABLE A-3

RECOMMENDED NUCLEAR DECAY DATA FOR FISSION PRODUCT NUCLEI

| Isotope | Half-Life |  | $\begin{gathered} \text { Gamma-Ray } \\ \text { Energy (keV) } \end{gathered}$ | $\qquad$ |
| :---: | :---: | :---: | :---: | :---: |
| $9^{5} \mathrm{Zr}$ | 64.4(5) | d | $\begin{aligned} & 724.184(18) \\ & 756.715(19) \end{aligned}$ | $\left.\begin{array}{l} 44.2(5) \\ 54.8(5) \end{array}\right\} \text { sum }=99.0(5)$ |
| $103^{\text {Ru }}$ | 39.43(10) | d | 497.08(1) | 89.(3) |
| ${ }^{132} \mathrm{Te}$ | 77.9(5) | h | 228.16(6) | 88.5(60) |
| ${ }^{137} \mathrm{Cs}$ | 30.03(15) | y | 661.638(19) | 85.0(3) |
| 140 Ba | 12.79(1) | $\mathrm{d}^{\text {a }}$ |  |  |
| ${ }^{40} \mathrm{La}$ | 40.26(2) | $\mathrm{h}^{\text {a }}$ | 1596.18(5) | 95.33(16) |
| ${ }^{144} \mathrm{Ce}$ | 284.4(4) | d | 133.53(3) | 10.7(4) |
| $144^{4} \mathrm{Pr}$ | 17.28(5) | m | $\begin{array}{r} 696.492(19) \\ 2185.608(46) \end{array}$ | $\begin{aligned} & 1.49(15) \\ & 0.77(4) \end{aligned}$ |

a The ratio $\mathrm{T}_{\frac{1}{2}}(\mathrm{Ba}) /\left[\mathrm{T}_{\frac{1}{2}}(\mathrm{Ba})-\mathrm{T}_{\frac{1}{2}}(\mathrm{La})\right]$, which is also the ratio of the ${ }^{140} \mathrm{La}$ to $14{ }^{2} \mathrm{Ba}$ activities at equilibrium, is therefore 1.15096(12).
is comparable to that from s-wave capture. This feature of the reaction complicates the analysis, in that it makes unambiguous parity assignments for the final states difficult to achieve on the basis of primary $\gamma$-ray intensity considerations alone. However, this amplification of the primary transitions to the positive-parity states (as compared to the case of only s-wave capture) allows with reasonable certainty the observation of all the $1 / 2^{+}$and $3 / 2^{+}$states, as well as those with $I^{\pi}=5 / 2^{+}$. Hence, in these spectra all final states with $I^{\pi}$ of $1 / 2^{-}, 1 / 2^{+}$ $3 / 2^{-}, 3 / 2^{+}$and $5 / 2^{+}$are strongly populated. In order to discriminate between final states with positive and negative parity, additional experiments are in progress to measure averaged ${ }^{154} \mathrm{Gd}(\mathrm{n}, \gamma)$ and ${ }^{156} \mathrm{Gd}(\mathrm{n}, \gamma)$ spectra using lower energy neutrons (obtained by transmission through a thick ${ }^{10} \mathrm{~B}$ filter), in which the p-wave capture component is expected to be much suppressed with respect to that from s-wave capture.

$$
\text { 2. Decay of } \frac{172 \mathrm{Tm} \text { : The Mixing of } \mathrm{K}^{\pi}+0^{+} \text {and } 2^{+} \text {Bands in }{ }^{172} \mathrm{Yb}^{*}}{\text { (C. W. Reich, R. C. Greenwood and R. A. Lokken**) }}
$$

The level scheme of ${ }^{172} \mathrm{Yb}$ has been studied from the decay of $63.6-\mathrm{h}{ }^{172} \mathrm{Tm}$. Gamma-ray energy and intensity measurements were made using Ge(Li) spectrometers. Forty-eight $\gamma$-ray transitions, nine of them previously unreported, are observed. All of these have been incorporated into a ${ }^{172} \mathrm{Yb}$ level scheme consisting of 16 excited states as shown in Fig. B-1. The previously reported " $1119-\mathrm{keV}$ " $\gamma$ ray is shown to be a doublet, with one member de-exciting the $I, K^{\pi}=2,0^{+}$state at 1117.8 keV and the other de-exciting the $\mathrm{I}, \mathrm{K}^{\pi}=2,1^{-}$octupole-vibrational state at 1198.5 keV . This observation, together with that of the additional $\gamma$-ray transitions, provides further information on the de-excitation of the ${ }^{172} \mathrm{Yb}$ levels. Attention is focused on the properties of the excited $\mathrm{K}^{\pi}=0^{+}$bands at 1042 and 1404 keV and the $\mathrm{K}^{\pi}=2^{+}$bands at 1465 and 1608 keV . A phenomenological 5-band mixing analysis of the $\gamma$-ray branching-ratio data, involving these 4 bands and the ground-state band, has been carried out. Results of this analysis are presented for two different assumptions concerning the signs of certain of the matrix elements coupling the excited bands. Additional measurements which could help in choosing between these two alternatives are indicated. Interesting similarities in some of the properties of the two excited $2^{+}$bands are pointed out; and a qualitative explanation of these similarities is given in terms of the Nilsson level diagram relevant to ${ }^{172} \mathrm{Yb}$.

[^2]

Fig. B-1. Proposed decay scheme of ${ }^{172} \mathrm{Tm}$. The brackets at the right indicate the grouping of states into rotational bands.
3. Level Structure of ${ }^{184} \mathrm{~W}$ from the Decay of ${ }^{184 \mathrm{~g}_{\mathrm{Re}}}$ and ${ }^{184 \mathrm{~m}_{\mathrm{Re}}}$ * (McMillan ${ }^{\star k}$, Greenwood, Reich, Helmer)

The level scheme of ${ }^{184} \mathrm{~W}$ has been studied from the decay of $38-\mathrm{d}$ $184 g_{\text {Re }}$ and $165-d^{184 m_{R e}}$. Gamma-ray energy and intensity measurements were made using $\mathrm{Ge}(\mathrm{Li})$ and $\mathrm{Si}(\mathrm{Li})$ detectors; and conversion-electron measurements were made using an iron-free $\pi \sqrt{2}$ double-focusing spectrometer. From these data and extensive $\gamma-\gamma$ coincidence measurements, decay schemes for both ${ }^{184}$ Re activities have been proposed which incorporate all 42 of the observed $\gamma$-ray transitions. Unique spin and parity assignments have been made for all the energy levels observed. Detailed intensity-balance considerations for each energy level have led to improved electron-capture branching ratios and log ft values. In addition to the previously known features of the ${ }^{184} \mathrm{Re}$ decay schemes, it has been established that levels at 1424 and 1431 keV in ${ }^{184} \mathrm{~W}$ are weakly populated and that their $I^{\pi}$ assignments are $3^{+}$and $2^{+}$, respectively. The $1130-\mathrm{keV}$ level has been shown to have $I^{\pi}=2^{-}$. Also, the $4^{+} \rightarrow 2^{+}$transition within the $\gamma$-vibrational band has been observed, which enables an estimate of the relative magnitudes of the intrinsic quadrupole moments of $\gamma$-vibrational and ground-state bands to be made. Within the experimental uncertainties involved ( $\approx 10 \%$ ), these two moments are equal. A one-parameter analysis of the E2 transition probabilities between these two bands gives $z_{\gamma}=+0.0408 \pm 0.0041$. Absolute transition probabilities are obtained and discussed for the $\gamma$ rays de-exciting the $I, K^{\pi}=3,2^{-}$state at 1221 keV and the $\mathrm{I}, \mathrm{K}^{\pi}=5,5^{-}$isomeric state at 1284 keV . Evidence for mixing of $\mathrm{K}^{\pi}=2^{-}$and $3^{-}$excitations in the $5^{-}$isomeric state is presented; and a formalism for treating such admistures, of both collective and two-quasiparticle character, is developed and applied. A close similarity of the M4 $\gamma$ decay of ${ }^{184} \mathrm{~m}_{\mathrm{Re}}$ to that of the $10^{-}$isomeric state in ${ }^{182} \mathrm{Ta}$ is noted.
4. Level Structure of ${ }^{184} \mathrm{~W}$ from the ${ }^{183} \mathrm{~W}(\mathrm{n}, \gamma)$ Reaction ${ }^{\dagger}$ (R. C. Greenwood, C. W. Reich)

The level structure of ${ }^{184} \mathrm{~W}$ has been studied from the prompt $\gamma$ rays emitted following the capture of both thermal and $2-\mathrm{keV}$ neutrons by $1^{83} \mathrm{~W}$. Energies and intensities were measured for both the primary and the secondary (low-energy) prompt $\gamma$ rays. From these data, a level scheme is proposed for ${ }^{184} \mathrm{~W}$ in which all the $\mathrm{I}^{\pi}=0^{+}, 1^{+}$and $2^{+}$states below $\sim 2.0 \mathrm{MeV}$ are observed. Where possible, rotational-band assignments have

[^3]$\dagger$ To appear in Nuclear Physics A.
been made to these and other levels. In addition to the previously known features of the ${ }^{184} \mathrm{~W}$ levels, the $1130-\mathrm{keV}$ state is established as the band head of a $K^{\pi}=2-$ octupole vibration. $K^{\pi}=0^{+}$and $2^{+}$bands are established at 1322 and 1386 keV , respectively, with the $I^{\pi}=2^{+}$states (at 1431 and 1386 keV ) having a mutual admixture of $\sim 12 \%$. In the energy region above 1.5 MeV , the following bands and band-head energies are identified: $\mathrm{K}^{\pi}=1^{+}, 1613 \mathrm{keV} ; \mathrm{K}^{\pi}=0^{+}$, 1614 keV ; $\mathrm{K}^{\pi}=1^{+}, 1713 \mathrm{keV} ; \mathrm{K}^{\pi}=2^{+}, 1877 \mathrm{keV}$. The neutron binding energy in ${ }^{184} \mathrm{~W}$ has been determined to be $7411.1 \pm 0.6 \mathrm{keV}$. The band structure of the $1613-\mathrm{keV}\left(1^{+}\right)$and $1614-\mathrm{keV}$ ( $0^{+}$) bands is observed to be strongly distorted, the observed $A\left(\equiv \hbar^{2} / 2 \Im^{\prime}\right)$ values being $\sim 3.6 \mathrm{keV}$ and $\sim 32 \mathrm{keV}$, respectively. This strong distortion is shown to be explainable in terms of Coriolis coupling of reasonable strength between the two bands. A similar explanation is shown to account for the somewhat less anomalous A-values ( 22.8 keV and 14.0 keV , respectively) of the $2^{+}$band at 1386 keV and the $3^{+}$band at 1425 keV . The results of a phenomenological five-band mixing analysis involving the $\mathrm{K}^{\pi}=0^{+}$and $2^{+}$bands below $\sim 1.5 \mathrm{MeV}$ are presented and discussed. These calculations indicate, among other things, that the direct E2 matrix element connecting the $1322-\mathrm{keV}, \mathrm{K}^{\pi}=0^{+}$band and the ground-state band is quite small, possibly zero. They also indicate that a nonzero E2 matrix element exists between this excited $K^{\pi}=0^{+}$band and the $\gamma$-vibrational band and that the magnitude of this element is comparable with that between the $\gamma$-vibrational and ground-state bands. Arguments favoring and apparently refuting the interpretation of the $1322-\mathrm{keV}, 0^{+}$band as a "two-phonon $\gamma$-vibration" are presented.
5. Half-Life of $178 \mathrm{~m}_{2} \mathrm{Hf}$ and Its Neutron Capture Production* (R. G. Helmer, C. W. Reich)

The existence of a long-lived high-spin isomeric state at $>2.43 \mathrm{MeV}$ in ${ }^{178} \mathrm{Hf}$ and a study of its decay have been reported previously. ${ }^{1}$ From its observed mode of decay, this isomer was assigned $I, K^{\pi}=16,16^{+}$and was presumed to be the four-quasiparticle state built from the two lowerlying $I, K^{\pi}=8,8^{-}$states observed at 1148 and 1480 keV in ${ }^{178} \mathrm{Hf}$. The production of this isomeric state by thermal-neutron capture is itself of some interest, since its spin is 12 or more units greater than that of the capturing state. This cross section, together with those from ( $n, \gamma$ ) data for lower-spin states in ${ }^{178} \mathrm{Hf}$, should provide a good test of models used to predict cross-section ratios in ( $n, \gamma$ ) reactions.

The half-life of this isomeric state has now been measured and found to be $31 \pm 1 \mathrm{y}$. Based on this value, the cross section for the

[^4]production of this isomer in a thermal-reactor neutron spectrum has been measured to be $(2 \pm 1) \times 10^{-7} \mathrm{~b}$. The computation of this value assumes that the burn-up cross section of the isomeric state is $<20 \mathrm{~b}$, an assumption which is supported by the experimental data.
C. INTEGRAL CROSS SECTION MEASUREMENTS (Y. D. Harker)

As a part of our continuing effort to measure integral cross section values for the overall LMFBR development program, reaction rates and reactivity worths have been measured in the Coupled Fast Reactivity Measurement Facility (CFRMF) for the reactions and materials listed in Tables C-1 and C-2, respectively.

Our primary emphasis has been and remains to be reaction rate and reactivity measurements on fission product nuclides with secondary emphasis on fission rates and dosimetry related reaction rates. With regard to the latter two, we are participating in the Interlaboratory LMFBR Reaction Rate program which was established for the purpose of improving fast-reactor dosimetry methods. The CFRMF is being established as a standard neutron field in this program and the results from our integral measurements will be used to test the fission-product and dosimetry files in ENDF/B.

In an effort to accurately characterize the CFRMF neutron environment, spectrum measurements using Li-6 coated semi-conductor diodes are being implemented. These measurements will complement earlier proton-recoil spectrum measurements by providing spectrum data for the neutron energy range from . 5 MeV to 5 MeV .

In the future, cross section measurements will be completed on transplutonium nuclides as well as continued on fission-product nuclides. The priorities for the trans-plutonium work will be established by data requirements for predicting production rates of spontaneous neutron sources in fast reactor fuels.

TABLE C-1
INTEGRAL CAPTURE CROSS SECTIONS IN CFRMF

| $\frac{\text { Reaction }}{109^{2}}$ | $\frac{\bar{\sigma} \text { (barns) }}{10{ }^{8} \mathrm{Pd}(\mathrm{n}, \gamma)^{109} \mathrm{Pd}\left(\mathrm{t}_{\frac{1}{2}}=13.46 \mathrm{~h}\right)}$ |
| :---: | :--- |
| ${ }^{110} \mathrm{Pd}(\mathrm{n}, \gamma)^{111 \mathrm{~m}_{\mathrm{Pdd}}\left(\mathrm{t}_{\frac{1}{2}}=5.5 \mathrm{~h}\right)}$ | 0.143 |
| ${ }^{146} \mathrm{Nd}(\mathrm{n}, \gamma)^{147} \mathrm{Nd}\left(\mathrm{t}_{\frac{1}{2}}=10.98 \mathrm{~d}\right)$ | 0.005 |
| ${ }^{50} \mathrm{Cr}(\mathrm{n}, \gamma)^{51} \mathrm{Cr}\left(\mathrm{t}_{\frac{1}{2}}=27.7 \mathrm{~d}\right)$ | 0.070 |
| ${ }^{64} \mathrm{Ni}(\mathrm{n}, \gamma)^{65} \mathrm{Ni}\left(\mathrm{t}_{\frac{1}{2}}=2.5 \mathrm{~h}\right)$ | 0.0105 |
|  | 0.003 |

TABLE C-2
REACTIVITY WORTHS IN CFRMF

| Material | Reactivity/gram |
| :--- | ---: |
| ${ }^{143} \mathrm{Nd}_{2} \mathrm{O}_{3}$ | $-.187( \pm 5 \%)$ |
| ${ }^{144} \mathrm{Nd}_{2} \mathrm{O}_{3}$ | $-.148( \pm 5 \%)$ |
| ${ }^{145} \mathrm{Nd}_{2} \mathrm{O}_{3}$ | $-.275( \pm 5 \%)$ |
| ${ }^{148} \mathrm{Nd}_{2} \mathrm{O}_{3}$ | $-.182( \pm 5 \%)$ |
| ${ }^{150} \mathrm{Nd}_{2} \mathrm{O}_{3}$ | $-.162( \pm 5 \%)$ |
| ${ }^{109} \mathrm{Ag}$ | $-.348( \pm 3 \%)$ |

## D. DISCREPANCIES BETWEEN MEASUREMENTS OF $\bar{v}$ AND $\eta$ BY THE MANGANESE BATH METHOD (J. R. Smith)

A detailed comparison was made of the corrections used in the MTR manganese bath $n$ measurements and the corresponding quantities extracted from the Bettis Monte Carlo calculation of the ${ }^{233} \mathrm{U}$ experiment. The fast effect could not be extracted from the Monte Carlo output in a form that could be compared with the original corrections used. The other corrections agreed within $0.1 \%$ except in two cases. The Bettis calculation predicted $\sim 0.3 \%$ less absorption in the aluminum sample holder than was measured and $0.22 \%$ less loss of high-energy neutrons to oxygen and sulfur. The Bettis calculation may be more reliable in the latter case since it used more recent oxygen cross sections. However, it underpredicts the aluminum absorption since it assumed the presence of pure aluminum. The most absorptive part of the sample holder was made of 6061 aluminum. The overall effect of this comparison is to suggest that the MTR $\eta$ values could be lowered by 0.2 or $0.3 \%$. This is within the claimed accuracy of the experiment and is not enough to account for the discrepancies between the $v$ and $\eta$ values.

An experiment is being prepared to measure, as a function of manganese concentration, the ${ }^{56} \mathrm{Mn}$ activity induced in a manganese bath by a low-energy neutron beam. This experiment has three purposes. The first is to determine how straight is the curve of the reciprocal of induced activity vs. the hydrogen-to-manganese number ratio. The second is to investigate the accuracy of source measurement to be achieved by this technique. The third is to measure the ratio of the thermal absorption cross sections of hydrogen and manganese.

In the manganese bath measurements of $\bar{v}$ for ${ }^{252} \mathrm{Cf}$, neutron source strengths were determined from the intercept of a linear curve plotting the reciprocal of manganese bath activity against the hydrogen-to-manganese ratio. This method is claimed to be independent of the hydrogen-tomanganese cross-section ratio. The latter ratio can be determined from the slope of the activity curve. It is curious that, although Axton and de Volpi agree in values for $\bar{v}$ for ${ }^{252}$ Cf and claim accuracies better than $0.5 \%$ for these measurements, their values for the hydrogen-to-manganese cross-section ratio differ by $1.4 \%$. The proposed experiment will investigate the systematics of the source measurements, free from the complications of corrections applicable to higher-energy neutrons.

## ARGONNE NATIONAL LABORATORY

## A. CHARGED PARTICLE REACTIONS

1. Reactions Relevant to Controlled Thermonuclear Research
a. Measurement of Charged Particle Cross Sections for ${ }^{6} \mathrm{Li}$ and ${ }^{7} \mathrm{Li}$ (C. R. McClenahan and R. E. Segel)

The total cross sections have been measured for five reactions involving charged particles bombarding Lithium. These reactions are ${ }^{7} \mathrm{Li}(\mathrm{d}, \mathrm{p})^{8} \mathrm{Li},{ }^{6} \mathrm{Li}\left({ }^{3} \mathrm{He}, \mathrm{n}\right){ }^{8} \mathrm{~B},{ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{a}){ }^{4} \mathrm{He},{ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{p}){ }^{7} \mathrm{Li}$ and ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{n})^{7} \mathrm{Be}$; all have potential applications in controlled thermonuclear reactions. Table A-1 shows the reactions studied together with the priority assigned by J. R. McNally, the $Q$ value or threshold, the energy range requested by McNally, and the energy range we have studied. The results and a description of the experiment are given in the Argonne Report, ANL-8088.
b. The ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{n}){ }^{7}$ Be Reaction at Low Energies (A. J. Elwyn, R. E. Holland, F. J. Lynch, F. P. Mooring, and L. Meyer-Schutzmeister)

As the initial part of a program to determine absolute cross sections for charged-particle induced reactions on light nuclei, we have studied the ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{n}){ }^{7} \mathrm{Be}$ and ${ }^{6} \mathrm{Li}\left(\mathrm{d}, \mathrm{n}{ }^{3} \mathrm{He}\right){ }^{4} \mathrm{He}$ reactions at deuteron energies between 0.27 and 0.8 MeV . The pulsed and bunched beam from the Dynamitron accelerator has been utilized along with time-of-flight techniques and stilbene scintillation detectors to measure the angular distributions of the outgoing neutrons in the reactions. Thin evaporated ${ }^{6}$ LiF targets on thick Ta backings have proved to be uniform and stable over long periods of time, and could be used in the se measurements since the number of neutrons from the ${ }^{19} F(d, n)$ reaction are negligibly small at energies below 1 MeV . A technique for the determination of the target thickness by deuteron scattering from a thin layer of Au eva porated over the ${ }^{6}$ LiF has been developed, and serves furthermore to monitor the physical condition of the target during the experiment. An independent measurement of the ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{n}){ }^{7} \mathrm{Be}$ cross section based on an activation technique is also being developed.

TABLEA-1. The reactions studied and reported in the present work.

| REACTION | PRIORITY ${ }^{\text {a }}$ | Q OR THRESHOLD | ENERGY RANGE ${ }^{a}$ REQUESTED | ENERGY RANGE STUDIED |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{7} \mathrm{Li}(\mathrm{d}, \mathrm{p}){ }^{8} \mathrm{Li}$ | 4 | $\mathrm{E}_{\text {th }}=248 \mathrm{keV}$ | < 15 MeV | $280 \mathrm{keV}-3.8 \mathrm{MeV}$ |
| ${ }^{6} \mathrm{Li}\left({ }^{3} \mathrm{He}, \mathrm{n}\right){ }^{8} \mathrm{~B}$ | 3 | $\mathrm{E}_{\text {th }}=2.966 \mathrm{MeV}$ | $<8 \mathrm{MeV}$ | 2.98 MeV-7.5 MeV |
| ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{a}){ }^{4} \mathrm{He}$ | 1 | $Q=22.4 \mathrm{MeV}$ | $100 \mathrm{keV}-5 \mathrm{MeV}$ | $500 \mathrm{keV}-3.4 \mathrm{MeV}$ |
| ${ }^{6} \mathrm{Li}(\mathrm{d}, \mathrm{p})^{7} \mathrm{Li}$ | 1 | $Q=5.0 \mathrm{MeV}$ | $100 \mathrm{keV}-5 \mathrm{MeV}$ | $500 \mathrm{keV}-3.4 \mathrm{MeV}$ |
| ${ }^{6} \mathrm{Li}\left(\mathrm{~d}, \mathrm{n}_{1}\right)^{7} \mathrm{Be}{ }^{*}$ | 1 | $Q=2.9 \mathrm{MeV}$ | $100 \mathrm{keV}-5 \mathrm{MeV}$ | $500 \mathrm{keV}-3 \mathrm{MeV}$ |

[^5]The analysis of the data obtained up to the present time is in progress. Future plans include the measurements of the outgoing neutrons in the reactions at other deuteron energies, as well as the study of those $d+{ }^{6}$ Li reactions that involve outgoing charged particles.
2. Nuclear Structure Studies
a. $\frac{\text { A Study of }{ }^{249} \mathrm{Bk},{ }^{241} \text { Am, and }{ }^{231} \text { Pa with Proton }}{\text { Transfer Reactions (J. R. Erskine, G. Kyle, }}$

Proton single-particle states have been studied in the isotopes ${ }^{249} \mathrm{Bk},{ }^{241} \mathrm{Am}$, and ${ }^{231} \mathrm{~Pa}$. The reaction $(a, t)$ was utilized in the three studies. Additionally, the reaction $\left({ }^{3} \mathrm{He}, \mathrm{d}\right)$ was used in the study of levels in ${ }^{249} \mathrm{Bk}$. Many new levels were observed and some could be interpreted in terms of single-particle orbitals. Also several assignments previously made on the basis of radioactive decay studies were confirmed by the orbital signatures seen in the proton transfer spectra. Single-particle energies are extracted from the experimental data. Deformations of the nuclear central potential are deduced for ${ }^{249} \mathrm{Bk}$ and ${ }^{241} \mathrm{Am}$. Using the parameters of the central field for ${ }^{249} \mathrm{Bk}$, the $\mathrm{f}_{7 / 2}-\mathrm{f}_{5 / 2}$ splitting has been deduced for mass 250 at zero deformation and estimated for mass 300 .

> b. $\frac{\text { Levels of }{ }^{243} \mathrm{Pu} \text { as Seen in the }{ }^{242} \mathrm{Pu}(\mathrm{n}, \gamma)^{243} \mathrm{Pu},}{\left.\mathrm{L4Z} \mathrm{Pu}(\mathrm{d}, \mathrm{p})^{243} \mathrm{Pu}, \text { and }{ }^{244} \mathrm{Pu}{ }^{\prime} \mathrm{d}, \mathrm{t}\right)^{243} \mathrm{Pu} \text { Reactions }}$ (R. F. Casten, ${ }^{* *}$ J. R. Erskine, A. M. Friedman, D. S. Gale and W. R. Kane ${ }^{* *}$ )

The level scheme of ${ }^{243} \mathrm{Pu}$ has been studied in an interlaboratory collaboration using the Bragg defraction neutron monochromator facility at the Brookhaven High Flux Beam Reactor and the split-pole magnetic spectrograph at the Argonne Tandem Van de Graaff accelerator. Spectra of both high- and low-energy gamma rays, in both singles and coincidence were obtained at the $2.6-e V$ neutron resonance in ${ }^{242} \mathrm{Pu}$. High resolution ( $\mathrm{d}, \mathrm{p}$ ) and ( $\mathrm{d}, \mathrm{t}$ ) spectra were recorded at 3 angles and at a bombarding energy of 12 MeV . The

[^6]following rotational bands and base excitation energies (in keV) were observed: $7 / 2+[624], 0 ; 5 / 2+[622], 287.5 \pm 0.2 ; 1 / 2+[631]$, $381.1 \pm 0.2 ; 9 / 2-[734], 402.4 \pm 0.2 ; 1 / 2+[620], 626 \pm 1 ; 1 / 2-[750]$, $788.5 \pm 0.2 ; 3 / 2+[622], 813.7 \pm 0.2 ; 1 / 2-[501], 903.5 \pm 0.2 ;$ $3 / 2+[631], 948 \pm 2 ; 9 / 2+[615], 980 \pm 3$. Unlike the case of ${ }^{241} \mathrm{Pu}$ no mixing of the negative parity bands was observed. ${ }^{1}$

## B. FAST NEUTRON PHYSICS

1. Measured and Evaluated Fast Neutron Cross Sections of Elemental Nickel (P. T. Guenther, P. A. Moldauer, A. B. Smith, D. L. Smith and J. F. Whalen)

Fast Neutron total and scattering cross sections of elemental nickel have been measured. Differential elastic scattering cross sections were determined from incident energies of 0.3 to 4.0 MeV . Some of the measured distributions are illustrated in Fig. B-1. The cross sections for the inelastic neutron excitation of states at: $1.17 \pm 0.02,1.34 \pm 0.01,1.45 \pm 0.01,2.15 \pm 0.02,2.28 \pm 0.02$, $2.47 \pm 0.035,2.63 \pm 0.03$ and $2.73 \pm 0.03$ were measured to incident neutron energies of 4.0 MeV . The results are compared with other measured values, model calculations and evaluation in Fig. B-2. The total neutron cross section was determined from 0.1 to 5.0 MeV . The experimental results were discussed in the context of an ellipsoidal optical potential and statistical theory. It was shown that the ellipsoidal model is statistically consistent with the observed cross section fluctuations. The experimental and theoretical results, together with previously reported experimental values were used to construct a comprehensive evaluated neutron data file in the ENDF format. Thus results will soon be made available in memorandum ANL/NDM-4.
2. Evaluation of Cross Sections for Neutron Induced Reactions on Nicke1 (D. L. Smith)

An evaluation has been made of the cross sections for the ${ }^{58}{ }_{\mathrm{Ni}(\mathrm{n}, \mathrm{p})}{ }^{58} \mathrm{Co},{ }^{58} \mathrm{Ni}(\mathrm{n}, 2 \mathrm{n}){ }^{57} \mathrm{Ni},{ }^{58}{ }_{\mathrm{Ni}(\mathrm{n}, \mathrm{a})}{ }^{55} \mathrm{Fe},{ }^{58} \mathrm{Ni}(\mathrm{n}, \mathrm{d}){ }^{57} \mathrm{Co}$, ${ }^{58} \mathrm{Ni}(\mathrm{n}, \mathrm{np}+\mathrm{pn})^{57} \mathrm{Co}$, and ${ }^{58} \mathrm{Ni}(\mathrm{n}, \mathrm{natan})^{54} \mathrm{Fe}$ reactions for $\mathrm{E}_{\mathrm{n}}$ from
T. H. Braid et al., Phys. Rev. C 6, 1374 (1972).


Fig. B-1. Differential elastic scattering cross sections of nickel. Measured values are indicated by data points and a least-square-fit to the data by solid curves.


Fig. B-2. Inelastic neutron scattering cross sections of nickel. Spherical and ellipsoidal calculations and the present evaluation are indicated by curves.
threshold to 20 MeV . This work was undertaken as part of a larger program of evaluation of cross sections for all neutron interactions with nickel isotopes for $\operatorname{En}=0.1-20 \mathrm{MeV}$.
3. Gamma-Ray Production Cross Section Measurements (D. L. Smith)

The cross sections for ( $n, n^{\prime} \gamma$ ) reactions near threshold exhibit pronounced energy-dependent structure for a number of materials with engineering applications. Various reported sets of cross sections for these reactions are in considerable disagreement, possibly due to normalization problems as well as structural and resolution effects. For this reason, a program has been initiated to measure these cross sections with moderately broad energy resolution relative to the fission cross section for $U-235$ which is relatively free of structure and probably known to within $5 \%$ in the region of interest. Data has been obtained on ( $n, n^{\prime} \gamma$ ) reactions for isotopes of iron, nickel, sodium and vanadium from threshold to 2 MeV . Excitation functions were measured at a $P_{2}$ node ( $55^{\circ}$ ) in 0.05 MeV increments with $\sim 0.1 \mathrm{MeV}$ neutron energy resolution. Angular distributions will be measured at selected energies in the near future to determine the effect of $\mathrm{P}_{4}$ and higher order Legendre terms on the integrated cross sections and to provide data for comparison with the results of statistical model calculations.
4. Gamma-Ray Production Data Processing Techniques (D. L. Smith)

Gamma-ray production measurements generally involve the use of relatively large samples in order to obtain sufficient yield. The corrections for geometry, absorption and multiple scattering are significant and considerable effort is being expended to develop the computer software necessary for routine computation of the se corrections and for processing the large quantities of data which result from these measurements.
5. Neutron Yields from the $D(d, p n) D$ Reaction (J. W. Meadows and D. L. Smith)

The $D(d, n)^{3}$ He reaction is a commonly used source of monoenergetic neutrons for neutron energies above 2.5 MeV . Above a deuteron energy of 4.45 MeV the $\mathrm{D}(\mathrm{d}, \mathrm{pn}) \mathrm{D}$ reaction becomes ener-
getically possible. The cross section rises rapidly and the 0 deg. neutrons yield from this reaction is $\sim 1 / 3$ of the $0 \mathrm{deg} . D(d, n){ }^{3} \mathrm{He}$ neutron yield at 7.2 MeV deuteron energy. When the $\mathrm{D}(\mathrm{d}, \mathrm{n})$ reaction is used at deuteron energies greater than 5 MeV corrections are often needed for the lower energy neutrons from the $D(d, p n)$ reaction. With this in mind, we have made measurements of the 0 deg. yield and energy distribution of the $\mathrm{D}(\mathrm{d}, \mathrm{pn})$ neutrons at $5.3,5.8,6.3,6.7$, and 7.2 MeV deuteron energy using time-of-flight techniques. Angular distributions were measured from 0 to 30 deg . at 7.2 and 6.7 MeV . Neutrons were detected with a small plastic scintillator. The efficiency was based on calculations and a measurement of the yield of the ${ }^{7} \mathrm{Li}(p, n) \mathrm{Be}^{7}$ reaction.

## 6. Fast Neutron Capture and Activation Cross Sections of Niobium Isotopes (W. P. Poenitz)

The data evaluation of the measurements of the capture cross section of ${ }^{93} \mathrm{Nb}$ from $0.3-2.5 \mathrm{MeV}$ was completed. ${ }^{1}$ The data were normalized at 0.5 MeV to the standard capture cross section of gold. A value of 138 mb obtained in a recent evaluation was used for the latter. The experimental results are listed in Table B-1 and shown in Fig. B-3.

The capture and activation cross sections of ${ }^{93} \mathrm{Nb}$ and ${ }^{94} \mathrm{Nb}$ were calculated in terms of the statistical model. The calculation of these cross sections bases on the Hauser-Feshbach formalism. Neutron transmission cross sections were obtained from optical model calculations. Gamma transmission coefficients were calculated using the Weisskopf estimate for the $\Gamma_{Y}$ and a level density formula which included shell and pairing energy effects. The gamma transmission coefficients were then normalized with experimental values in the eVrange. The low level occupation probabilities were obtained by means of a gamma cascade model. ${ }^{2}$ The results from the calculations are shown in Figs. B-3 and B-4. The two different sets of curves for ${ }^{94} \mathrm{Nb}$ result from different assumptions for the normalization of $\Gamma_{\gamma} / D$ and indicate the uncertainty of the cross section calculation for ${ }^{94} \mathrm{Nb}$.

[^7]TABLEB-1. Experimental Results for the ${ }^{93}$ Nb Capture Cross Section

| $\mathrm{E}_{\mathrm{n}} / \mathrm{MeV}$ | $\Delta \mathrm{E}_{\mathrm{n}} / \mathrm{MeV}$ | $\sigma_{\mathrm{n}, \gamma} / \mathrm{mb}$ | $\Delta \sigma_{\mathrm{n}, \gamma} / \mathrm{mb}$ |
| :--- | :--- | :---: | :--- |
| 0.300 | 0.027 | 57.5 | 4.7 |
| 0.400 | 0.027 | 55.9 | 4.2 |
| 0.500 | 0.026 | 51.9 | 3.5 |
| 0.600 | 0.025 | 49.5 | 3.5 |
| 0.700 | 0.024 | 49.2 | 3.6 |
| 0.850 | 0.023 | 45.9 | 3.7 |
| 0.900 | 0.023 | 43.9 | 3.3 |
| 1.000 | 0.022 | 36.8 | 3.0 |
| 1.100 | 0.022 | 28.1 | 2.6 |
| 1.200 | 0.021 | 23.5 | 1.8 |
| 1.300 | 0.021 | 20.3 | 1.9 |
| 1.400 | 0.020 | 21.3 | 2.7 |
| 1.500 | 0.020 | 17.3 | 1.8 |
| 1.700 | 0.019 | 13.0 | 1.1 |
| 2.000 | 0.018 | 6.4 | 1.0 |
| 2.500 | 0.017 |  |  |



FIGURE B-3


FIGURE B-4
7. Measured and Evaluated Neutron Cross Sections of Vanadium (P. Guenther, A. Smith and J. Whalen)

Measurements of neutron total and scattering cross sections of vanadium have been completed to 5.0 MeV . The experimental values are being employed, together with information available in the literature, to construct a full evaluated file in the ENDF format.
8. Scattering From Heavy Rotationally-Deformed Nuclei
(A. Smith and P. Guenther)

The objective of this program is the understanding of neutron scattering from both even and odd heavy rotationally-deformed nuclei. The measurement program pairs similar nuclei, one being technologically measurable in considerable detail and the other difficult or impossible but of high applied importance. The two pairs under detailed study are: $\mathrm{W}^{186}-\mathrm{U}^{238}$ and $\mathrm{Ho}^{165}-\mathrm{U}^{235}$. Measurements have been made to 4.0 MeV in all four cases. Some typical results are shown in Fig. B-5. The measured values combined with theoretical extrapolation should provide improved knowledge of scattering from the important materials $\mathrm{U}^{235}, \mathrm{U}^{238}$ and $\mathrm{Pu}^{239}$.
9. Neutron Total and Scattering Cross Sections of the Isotopes of Molybdenum and Zirconium (A. Smith, P. Guenther and J. Whalen)

The total and elastic and inelastic scattering cross sections of $\mathrm{Mo}^{92}, \mathrm{Mo}^{96}, \mathrm{Mo}^{98}, \mathrm{Mo}^{100}, \mathrm{Zr}^{90}$ and $\mathrm{Zr}^{92}$ have been measured to incident neutron energies of 4-5 MeV. Data reduction is complete and physical interpretation is underway. Illustrative of the detail of the results are the elastic scattering cross sections of the molybdenum isotopes shown in Fig. B-6. The experimental results are marginally consistent with an iso-spin term in the optical potential ${ }^{1}$ but the effect is extremely small (if present) and masked by other physical uncertainties such as contributions from compound-nucleus processes and the effects of nuclear deformation.
F. Becchetti and G. Greenlees, Phys. Rev. 1821190 (1969).


Fig. B-5. Differential elastic and inelastic ( $E_{x}=0.125 \mathrm{MeV}$ ) scattering cross sections of $W^{186}$. Measured values are indicated by data points and the results of coupled-channel calculations with varying deformations.


Fig. B-6. Differential elastic scattering cross sections of even molybdenum isotopes. Measured values are indicated by data points. The curves are the result of "first pass" optical model calculations.

## C. PHOTONUCLEAR PHYSICS

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

The line shape for the 11.7 keV resonance in the reaction ${ }^{61} \mathrm{Ni}(\gamma, n)$ has been measured in order to estimate the magnitude of the nonresonant reaction amplitude (see USNDC-9). The time-of-flight spectrum in the energy region of this resonance is shown in Fig. C-1. It is evident that any interference assymmetry generated by the nonresonant amplitude is extremely weak. Our best estimate of the nonresonant ( $\gamma, n$ ) cross section at 12 keV is 0.013 mb , roughly $1 / 3$ of the potential capture cross section calculated by Lane and Lynn. ${ }^{1}$


A beam of 11.4 MeV photons, extracted from the CP-5 reactor, has been used in a high-resolution measurement of the differential cross section for photon scattering by ${ }^{238} \mathrm{U},{ }^{232} \mathrm{Th}$, and ${ }^{159} \mathrm{~Tb}$. The spectrum of scattered photons was observed in a $G e(L i)$ detector whose sensitive volume was $\sim 60 \mathrm{cc}$. Inelastic scattering which leaves the residual nucleus in a state of the ground state rotational band, i.e. Nuclear Raman Scattering, was measured relative to elastic scattering. In Table C-1 the results are compared with the predictions of the simple rotator model (SRM) of the giant dipole resonance, modified by use of resonance parameters obtained from the most recent photoabsorption data. The data for ${ }^{159} \mathrm{~Tb}$ confirm clearly the trend observed earlier in measurements at 10.8 MeV - the Raman scattering is weaker than predicted. For ${ }^{238} \mathrm{U}$ the Raman process is also weaker than predicted by the SRM. However, in contrast to ${ }^{159} \mathrm{~Tb}$ the relative strength of the Raman component for both ${ }^{238} \mathrm{U}$ and ${ }^{232} \mathrm{Th}$ agrees within $\sim 10 \%$ with results of a modified simple rotator calculation.

1
A. M. Lane and J. E. Lynn, Nucl. Phys. 17 (1960), 586.


Fig. C-1. Photoneutron time-of-flight spectrum in the region of the 11.7 keV resonance in the reaction ${ }^{61} \mathrm{Ni}(\gamma, \mathrm{n})$.

TABLE C-1. Comparison of Measured and Calculated Values of the Ratio of Raman to Elastic Scattering for 11.4 MeV Photons.

| Target nucleus | $\begin{gathered} \theta \\ \text { (Degrees) } \end{gathered}$ | Raman/elastic |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  | Measured | Calculated |  |
| ${ }^{238}{ }_{U_{92}}$ | 90 | 1.0 | 1.1 | 1.25* |
|  | 150 | 0.67 | 0.66 | 0.76 |
| ${ }^{232} \mathrm{Th}_{90}$ | 450 | 0.64 | 0.57 |  |
| ${ }^{159} \mathrm{~Tb}_{65}$ | 90 | 0.60 | 0.79 |  |
|  | $\$ 50$ | 0.46 | 0.52 |  |

[^8]
## D. FISSION PHYSICS

1. Radiochemical Investigation of Fission Fragment Mass Distributions (K. F. Flynn, J. E. Gindler and L. E. Glendenin)

Distributions of fission fragment mass after neutron emission were obtained radiochemically for ${ }^{254}$ Cf spontaneous fission ( $s f$ ) and 257 Fm thermal-neutron-induced fission ( $\mathrm{n}, \mathrm{f}$ ). The mass distribution for ${ }^{254} \mathrm{Cf}(\mathrm{sf})$ is similar to that for ${ }^{252} \mathrm{Cf}(\mathrm{sf})$ but with first moments of the light- and heavy-mass peaks at 108.6 and $141.6 \mathrm{a} . \mathrm{m} . \mathrm{u}$. respectively. The mass distribution for ${ }^{257} \mathrm{Fm}(\mathrm{n}, \mathrm{f})$ a ppears to be singlepeaked and symmetric about mass 127. This agrees with the provisional mass-yield distribution determined from kinetic energy measurements of coincident fragments. ${ }^{1}$ Thus a marked transition from asymmetric to symmetric fission occurs in the fermium isotopes: the ${ }^{256} \mathrm{Fm}(\mathrm{sf})$ mass distribution is asymmetric with a peak-to-valley ratio ( $\mathrm{P} / \mathrm{V}$ ) of $\sim 12$, the ${ }^{255} \mathrm{Fm}(\mathrm{n}, \mathrm{f})$ mass distribution has a $\mathrm{P} / \mathrm{V}$ of 2.6, and the ${ }^{257} \mathrm{Fm}(\mathrm{n}, \mathrm{f})$ mass distribution is symmetric in character.

Cross sections for the ${ }^{251} \mathrm{Cf}(\mathrm{n}, \mathrm{f})$ and ${ }^{255} \mathrm{Fm}(\mathrm{n}, \mathrm{f})$ reactions have been determined as 5300 and 3200 barns respectively. Estimated errors of $10 \%$ are placed on both values. These values are in good agreement with those of $4800 \pm 250$ b for ${ }^{251} \mathrm{Cf}(\mathrm{n}, \mathrm{f})$ and $3400 \pm 170 \mathrm{~b}$ for ${ }^{255} F m(n, f)$ reported previously. ${ }^{2}$

## 2. Fission Isomerism (K. L. Wolf and J. W. Meadows)

A study of the spontaneously fissioning isomer ${ }^{238 m_{U}\left(t_{1 / 2}\right.}=$ 295 ns ) has been completed at the Argonne Fast Neutron Generator. Delayed to prompt fission ratio measurements in the threshold region of the ${ }^{238} U\left(n, n^{\prime}\right){ }^{238 m_{U}}$ reaction are shown in Fig. D-1. A fit to the data with a statistical model calculation which uses empirical level density expressions yields a value of 2.1 MeV for the isomer excitation energy, $\mathrm{E}_{\mathrm{II}}$, relative to the ${ }^{238} \mathrm{U}$ ground state. The resonance-like

[^9]

Fig. D-1. The delayed to prompt fission ratio as a function of incident neutron energy for a high purity ${ }^{238} \mathrm{U}$ target. Neutrons were generated with the ${ }^{7} \mathrm{Li}(\mathrm{p}, \mathrm{n})$ reaction.
structure at a neutron energy of 3 MeV has been ignored in this analysis. The value of $E_{\text {II }}$ determined here is not consistent with recent measure ments for shape isomer gamma decay ${ }^{1}$ in which it is claimed that a 2.514 MeV gamma-ray is involved in the de-excitation of the ${ }^{238} \mathrm{U}$ shape isomer to the ${ }^{238} \mathrm{U}$ ground state.

## E. HALF-LIVES OF THE ACTINIDES

1. Pu Isotope Half-Lives (A. H. Jaffey, H. Diamond, K. F. Flynn, W. C. Bentley, L. Ross and D. Rokop)

A program has been started for making accurate measurements of the half-lives of the plutonium isotopes of importance in reactor technology, hopefully with a precision of $0.1 \%$ standard error. The first measurements will be made on ${ }^{239} \mathrm{Pu}$, followed by ${ }^{240} \mathrm{Pu}$ and ${ }^{238} \mathrm{Pu}$. Preparations for the ${ }^{239} \mathrm{Pu}$ measurements have started. The techniques to be used involve mass-spectrometric isotope dilution and specific activity (alpha-counting) measurements.

For the mass-spectrometry, a purified and chemically-assayed ${ }^{239} \mathrm{Pu}$ sample is allowed to sit for a defined time during which the daughter ${ }^{235} \mathrm{U}$ grows in. The plutonium sample is "spiked" with known masses of ${ }^{234} \mathrm{U}$ and ${ }^{238} \mathrm{U}$ and the ${ }^{235} \mathrm{U}$ content is determined from mass-spectrometric ratios. The concentration of each plutonium and uranium solution is determined by precision titration methods. The double internal standard in the mass spectrometry allows accurate determination of the mass discrimination bias. Aliquots from the same analyzed plutonium sample are counted with an intermediate geometry defined solid angle counter, a low geometry counter and a liquid scintillation counter. It is hoped that the discrepancies that exist between the various published results will be resolved through the crosscheck of the results of the various methods, as well as the check with results from other laboratories using other methods.

[^10]2. Specific Activity and Half-Life of ${ }^{2333} \mathrm{U}$ (A. H. Jaffey, K. F. Flynn, W. C. Bentley and J. O. Karttunen)

Samples of ${ }^{233} U$ were prepared by molecular plating and counted in an intermediate geometry alpha-proportional counter with a flat pulse height plateau. For each sample, the small amount of residual non-plated uranium was evaluated by counting in a $2 \pi$-counter. Energy analysis with a silicon-junction detector allowed accurate measurement of the small amount of activity not ascribable to ${ }^{233} \mathrm{U}$ and ${ }^{234} \mathrm{U}$. The ${ }^{234} \mathrm{U}$ activity was corrected for by calculation from the mass spectroscopically measured concentration. The specific activity was measured as $21405 \pm 20 \mathrm{~d} / \mathrm{m} / \mu \mathrm{g}{ }^{233} \mathrm{U}$, corresponding to a half-life of $(1.5911 \pm 0.0015) \times 10^{5} \mathrm{yr}$. The quoted error is statistical (standard error of the mean), based upon observed scatter of the data.

## A. NEUTRON PHYSICS

1. Fast Chopper
a) Experimental
2. Direct Neutron Capture in the 4 s Giant Resonance--Dy-164
(G. W. Cole and R. E. Chrien)

Direct neutron capture by Dy-164 at energies between thermal and 145 eV has been studied at the BNL Fast Chopper facility, as part of a continuing investigation of non-statistical effects in epithermal neutron reactions.

Figure A-1-1 shows the time-of-flight spectrum obtained with a 180 gram target of dysprosium oxide, $96 \%$ enriched in Dy-164. The resonance marked 164 is the 145 eV resonance in Dy-164; this is the lowest positive energy resonance in Dy-164. The resonance marked 162 is the 5.4 eV resonance in Dy-164; the remaining structure also comes from contaminant isotopes. Dy-164 is also known to have a bound level at -1.9 eV .1

Figure A-1-2 shows the $\gamma$-ray spectra from the 145 eV resonance, and from the region near 0.6 eV , where the bound state dominates. The strong lines at 5606 and 5557 keV populate the first two members of a $\frac{1}{2}$ [521] band known from the work of Sheline. 2 The 5109 keV level populates a level which is the head of a possible $3 / 2^{-[521]}$ band. These three states are among the most strongly populated in Sheline's ( $d, p$ ) work; we would of course hope to identify single particle effects in neutron capture with these final states which exhibit strong single particle components.

The partial cross sections for the lines of interest, as a function of neutron energy, were fitted using a multilevel formula containing Breit-Wigner resonance amplitudes and energyindependent amplitude for non-resonant capture. Partial radiative

[^11]

## DY-164 [ N.GAMMA] <br> 145.4 EV RESONANCE



widths measured in this experiment were included for the 145 eV resonance, while the partial radiative widths associated with the bound level were allowed to vary to produce the best fit. Figure A-1-3 shows such a fit for the 5606.9 keV transition; in this case the direct amplitude has been fixed to a value of zero, while the bound state contribution varied freely. Figure A-1-4 shows the same data, fitted with a freely varying direct amplitude. The dashed curve in Fig. A-1-4 is the best fit obtained when direct capture is allowed to contribute. From these figures it is clear that the effects of a bound level which is near zero energy can be distinguished from non-resonant capture, owing to the different energy dependence of the two processes. At the same time, partial radiative widths for the bound state can be deduced. Results are given in Table A-1-1.

This fit requires a direct cross section of $\approx 22 \mathrm{mb}$ at 1 eV for the 5606.9 keV transition. The 5108 keV transition gives a best fit result of $2.2 \pm 0.4 \mathrm{mb}$ at 1 eV .

We have often interpreted direct capture results in terms of the contribution of distant levels, using a result due to Lane ${ }^{3}$

$$
\sigma_{D}(\text { dist levels }) \cong \rho\left(\Gamma_{n}^{0}, \Gamma_{Y f}\right) \frac{\pi}{2} \sigma(\text { abs })<\Gamma_{\gamma f}>/ D
$$

This relation implies observable direct capture contribution from distant levels only if $\rho$, the partial width correlation coefficient, is near unity. Such cases of large statistical correlations have been rare in the 4 s giant resonance. However, the "hard-sphere" contribution to capture, which is independent of distant level contributions, is approximately given by

$$
\sigma_{\text {non-res }}(\text { hard sphere }) \approx \frac{45}{\sqrt{E_{n}}} \theta_{\mathrm{N}}^{2} \mathrm{f}\left(\mathrm{Z}, \mathrm{~A}, \mathrm{E}_{\mathrm{Y}}\right) \mathrm{mb}
$$

where $\theta_{N}^{2}$ is the reduced neutron width of the final state. This result is based on a simple calculation using a spherical WoodsSaxon potential; it seems clear that a more sophisticated calculation which takes into account the detailed nature of the final states in the deformed nucleus will allow the extraction of spectroscopic information from these results.
${ }^{3}$ A. M. Lane, Annals of Physics 63, 171 (1971).


Fig. A-1-3


Fig. A-1-4

2. Direct Neutron Capture in the 4 s Giant Resonance: A General Survey (G. W. Cole and R. E. Chrien)

In addition to the targets for which direct capture studies have been reported on in this and other USNDC contributions, namely Dy-162, Dy-164 and Sm-152, other even-even targets have been or will be included in a program to map out non-resonant capture effects across the 4 s giant resonance. Data for $\mathrm{W}-186, \mathrm{Sm}-154$ and Yb-170 are in hand, and a target of Gd-156 is presently being studied at the Fast Chopper.

Such a study offers the opportunity to examine singleparticle effects in neutron capture leading to final states whose classifications in terms of Nilsson orbitals are well known as a function of mass number. For example, the $\frac{1}{2}-[521]$ band in both Dy-162 and Dy-164 is seen to exhibit significant direct capture cross sections. We should take note of the fact that these measurements are essentially concerned with interference effects, and therefore contain information concerning the signs of the amplitudes for the single particle process. Thus, as we compare interference effects in the population of different final states from initial states whose properties are easily included in calculations (e.g. s-wave neutrons plus deformed targets), we should expect to find significant spectroscopic information. Detailed calculations are anticipated.

## 3. Fluctuation Properties of Radiative Widths in Sm-149 (F. Becvar, ${ }^{+}$R. E. Chrien and O. A. Wasson ${ }^{*}$ )

An analysis of data taken several years ago with the Fast Chopper Facility has recently been completed and is being prepared for publication. The topic concerns the study of the fluctuation properties of $\Gamma_{Y i j}$, the partial radiative widths. The nucleus chosen for this study, Sm-149, has the advantages that the low-lying states of the daughter $\mathrm{Sm}-150$ are well known from $\beta$ decay and reaction studies, and that the neutron resonances are closely spaced, but easily resolvable.

Previous analyses of width fluctuations have indicated the approximate validity of the Porter-Thomas hypothesis for several nuclei, but only in a restricted range of precision. A systematic study of width fluctuations over a broad range of nuclei is still

[^12]lacking. The present study chooses a different point of departure in order to avoid systematic errors common to previous analyses. This viewpoint is to analyze the properties of width amplitudes rather than widths. The resulting distribution, under the PorterThomas hypothesis, is "semi-Gaussian"; this hypothesis is stringently tested in the present analysis.

The present study of resonant neutron capture in Sm-149 yields the spins of 14 neutron resonances below 34 eV , and develops new information for 20 low-lying levels. The positive parity levels of $\mathrm{Sm}-150$ are assigned to bands built on the ground state and phonon excitations corresponding to $\beta, \gamma$, and $2 \beta$-vibrations. A close similarity in level structure with Gd-152 is observed.

In the range of neutron energies from 0.04 to 5.5 eV a detailed resonance-resonance interference analysis has been carried out. This yields width amplitudes corresponding to 41 primary transitions for the first three resonances and a bound level. The relative phases were observed to be randomly distributed. Figure A-1-5 shows interference plots for the observed intensities.

Both amplitude and width distributions were subjected to statistical tests. Significant departure, from the Porter-Thomas distribution is found for partial widths for E-1 transitions to states of $\mathrm{J}^{\Pi}=3,4^{+}$below 2196 keV . No significant correlations between pairs of radiative widths, nor between radiative and neutron widths are observed. It is concluded that no simple mechanism like channel or valence neutron capture plays a role in this reaction. The cumulative amplitude distribution is shown in Fig. A-1-6.

Under the hypothesis of Axel, that the photon strength function deduced from ( $n, \gamma$ ) measurements may be extrapolated from the giant dipole resonance, we can write,

$$
\left\langle\Gamma_{Y i j}(J)>/ D_{J}=k E_{Y}^{5} A^{8 / 3}\right.
$$

where $\mathrm{k}=6.1 \times 10^{-15} \mathrm{MeV}^{-5}$. Our data yields a result $\mathrm{k}=(2.2 \pm 0.4)$ $\times 10^{-15} \mathrm{MeV}^{-5}$; and thus is almost a factor of three lower than the E-1 photonuclear extrapolation.


Fig. A-1-5. Plot of the experimental photon strengths $R \equiv C\left(E_{B} / E_{\gamma}\right)^{5}\left(\sigma_{n \gamma f} / \sigma_{n \gamma T}\right)$ compared to multilevel fits. The arrows show resonance positions, and the signs show the relative phases of the amplitudes. Dashed lines indicate best fits assuming no bound level.


Fig. A-1-6. The cumulative distributions of the random variable r, related to a reduced width amplitude $\gamma_{\lambda} \gamma_{f}$ by the following: $r=2 \operatorname{erf}\left[\left|Y_{\lambda \gamma_{f}}\right| E_{\gamma}^{-5 / 2} / \mathrm{M}\right]-1$ where $M=\left(\left\langle\gamma_{\lambda Y} f^{E_{\gamma}}{ }^{-5>} \lambda_{\lambda, f}\right)^{1 / 2}\right.$. The experiment is compared to predictions of the Porter-Thomas assumption.

## 4. Nuclear Structure Studies Using the Fast Chopper

(R. E. Chrien, K. Rimawi, R. C. Greenwood* and G. W. Cole)

The Fast Chopper is a useful complement to the Tailored Beam Facility for nuclear structure studies. Where sufficiently large targets ( $\widetilde{>} 20 \mathrm{gm}$ ) are available, resonance capture spectra up to several hundred eV offer several advantages: spectra are free of isotopic contamination, proceed from a capturing state of known spin, and generally exhibit a high degree of freedom from background lines. In the past 6 -month period, resonance capture spectra have been obtained for Mo-94, Mo-96, Mo-97, Gd-154, Gd-156 and Gd-157. These targets have also been studied using the varied quasimonoenergetic beams available at the Filtered Beam facility, and the combined results are being analyzed for nuclear structure information. For the Mo isotopes the chopper results are of particular value, since the $\ell$-value of the captured neutron is known on-resonance, while average capture measurements give a mixture of $s$-wave and $p$-wave capture.

[^13]A. 2. The Tailored Beam Facility
(K. Rimawi and R. E. Chrien)
a) Equipment

In addition to the 24 keV Fe , filter a ${ }^{6} \mathrm{Li}$ filter has been installed recently. The filter is composed of 11.3 cm of ${ }^{6} \mathrm{LiCO}_{3}$ which follows a 10.5 cm Pb attenuator. The filter is designed to give a neutron flux which peaks at $\sim 1 \mathrm{keV}$.

Such a filter will allow us to compare the spectra from 1 keV neutron capture to those for capture of 24 keV neutrons, thus allowing the identification of levels that are populated following $p$-wave neutron capture.

Figure A-2-1 shows the gamma ray spectrum for a Ta-181 target obtained with the ${ }^{6}$ Li filter.
b) Experiments

Since the previous report we have obtained separated Mo isotopes which were investigated using the 24 keV beam. Spectra for $\mathrm{Nb}, \mathrm{Ce}-140,142$, $\mathrm{Gd}-154,155,156,157$, and Ho were also collected using the 24 keV neutron beam. The ${ }^{6} \mathrm{Li}$ filter was used to investigate $\mathrm{Gd}-154$, Ho and Ta . In addition, the total capture cross section was measured for Mo-98, at 24 keV .

In the following, we discuss some of these measurements:

1. Total Capture Cross Section for Mo-98

The total capture cross section was determined by measuring the intensities of the 740 and 780 keV lines following the $\beta$-decay of Mo-99 to the 920 keV level in $\mathrm{Tc}-99$. The $10_{\mathrm{B}}(\mathrm{n}, \alpha \gamma)$ cross section was used as a standard. A value of $115 \pm 10 \mathrm{mb}$ was obtained.


## 2. Valency Model Test at 24 keV

It has been observed that the single particle contribution to the primary transitions involving the decay of p-wave resonant states in Mo-92 and Mo-98 to s-wave and d-wave low lying states decreases relative to the non-single particle contribution as the resonance energy is increased. 1,2 In order to investigate this effect at higher energies, the 24 keV neutron capture was investigated for the two isotopes mentioned above together with Mo-94 and Mo-96.

The spectra showed strong transitions to some low lying states of strong single particle character for all isotopes. Figure A-2-2 shows the spectrum for capture in Mo-94 covering the gamma ray energy range from 4.7 - 7.5 MeV .

A significant correlation is observed for all isotopes between the measured intensities and those predicted from the valency model. Such a comparison is shown in Fig. A-2-3, where arbitrary units are used except for Mo-98 where partial cross sections were measured relative to $10_{\mathrm{B}}(\mathrm{n}, \alpha \gamma)$ cross section.

The contribution of non-single particle components to the capture cross section in Mo-98 may be estimated from the intercept in Fig. A-2-4. In the figure the experimental $\sigma / E_{\gamma}$ in $\mu \mathrm{b} / \mathrm{MeV}^{3}$ is plotted against the value predicted from the valency mode1.

The non-single particle component can be compared to the value derived from extrapolating the ( $\gamma, n$ ) cross section from the E-1 giant dipole resonance. Also, a comparison can be made with a value obtained from the average $E-1$ photon strength function ${ }^{3}$ for neighboring nuclei. These values are shown in Table A-2-1 for the transition to the predominantly $s 1 / 2$ ground state.
${ }^{1}$ O. A. Wasson and G. G. Slaughter, Phys. Rev. C8, 297 (1973).

2
R. E. Chrien, "Measurement of Radiative Capture Widths in Statistical Properties of Nuclei", Plenum Press, N. Y. (1972), J. B. Garg, Ed.

3
L. M. Bollinger in Proc. Intl. Conf. on Photonuclear Reaction USAEC CONF 730301 (1973).


Fig. A-2-2




Fig. A-2-3


ARBITRARY UNITS


## Table A-2-1

Partial Cross Section for Ground State Transition Following 24 keV Neutron Capture in Mo-98.

| $\sigma_{Y f}$ (measured) | $8.4 \pm 0.4 \mathrm{mb}$ |  |
| :--- | :--- | :--- |
| $\sigma_{Y f}($ valence $)$ | 1.6 | mb |
| $\sigma_{Y f}($ intercept of Fig. A-2-4) | 2.2 | mb |
| $\sigma_{Y f}($ derived from GR) | 2.0 | mb |
| $\sigma_{Y f}\left(\right.$ from $\mathrm{k}_{\mathrm{E} 1}$ estimate $)$ | 1.6 | mb |

These cross sections indicate that the valence neutron transition accounts for $\sim 20 \%$ of the total transition strength. Furthermore, neither the statistical contribution nor the extrapolation of the giant resonance is sufficient to explain the measured strength. This is similar to the enhancement of the transition to the $\mathbf{s} 1 / 2$ first excited state in Mo-92 observed by Wasson and Slaughter. 1

On the other hand, the assumption of coherent addition of the valence contribution to that of non-single particle contribution would result in the observed cross section. Such coherence suggests a collective core excitation forming a "pygmy" $\mathrm{E}-1$ resonance. In such a picture a $1^{-}$collective excitation of the Mo-92 or Mo-98 core coupled to an $s 1 / 2$ extra-core neutron would be formed by p-wave neutron capture. This is similar to the earlier suggestion of Brown ${ }^{4}$ and Clement, Lane and Rook. 5

4 G. E. Brown, Nuc1. Phys. 57, 339 (1964).

5 C. F. Clement, A. M. Lane, and J. R. Rook, Nuc I. Phys. 66, 273 (1965).
A. 3. Boron Profiling in Semiconductors Using Thermal Neutron Beams (G. W. Cole and J. F. Ziegler*)

The direct thermal neutron beam at the Tailored Beam Facility has been used for a series of measurements of the distribution of boron atoms introduced in silicon substrates by ion implantation and diffusion. This technique has been described previously. Analysis has been completed for data obtained in two runs at HFBR in April and July, 1973. The following problems were studied:
a) the range of $\mathrm{B}-10$ ions implanted at energies between 25 keV and 200 keV in $\mathrm{SiO}_{2}$ and $\mathrm{Si}_{3} \mathrm{~N}_{4}$;
b) an estimate of the diffusion constant of boron in these insulators at $1000^{\circ} \mathrm{C}$;
c) the refutation of a predicted concentration discontinuity of ion implanted boron at an $\mathrm{SiO}_{2}$-Si interface;
d) a final resolution between theoretical and experimental results for arsenic and boron interdiffused at $1000^{\circ} \mathrm{C}$;
e) a determination of the segregation of boron at an $\mathrm{SiO}_{2}-\mathrm{Si}$ interface under annealing at $1000^{\circ} \mathrm{C}$.

A total of 12.7 days of counting was required for these measurements; 47 samples were studied.
I J. F. Ziegler, G. W. Cole and J.E.E. Bag1in, J. App1. Phys. 43, 3809 (1972).
*
IBM Watson Research Center, Yorktown Heights, N. Y.

## B. NUCLEAR STRUCTURE

## 1. Study of Low Spin States in $\mathrm{Hg}-202$

(R. F. Casten, D. Breitig, W. R. Kane and G. W. Cole)

The level scheme presented previously has been refined primarily by combination of the information from our ( $n, \gamma$ ) studies with recent data from the ( $p, t$ ) reaction. ${ }^{1}$ The 1311.5 keV level is populated in ( $p, t$ ) with $40 \%$ the ground state cross section thereby assuring a natural parity. Thus the $3^{+}$spin possibility is eliminated. As a consequence the levels at 1788.5, 1861.8, 1965.5 keV can now be considered as very likely $2^{+}$states since they deexcite to the 1311.5 keV level.

The spin limitation to $3^{-}$or $4^{+}$for the 1311.5 keV level can with high confidence be further restricted to $4^{+}$on the grounds of the large ( $p, t$ ) cross section in a nucleus just below a closed shell. We have attempted to interpret the structure of this level and conclude, based on calculations of the two neutron transfer cross sectiors, that it must have a large ( $2 \mathrm{f}_{7 / 2}, 3 \mathrm{p}_{1 / 2}$ ) $v$ amplitude which is in phase with the $\left(2 f_{5 / 2}, 3 p_{3 / 2}\right) v$ amplitude.
2. The ${ }^{186} \mathrm{~W}(\mathrm{n}, \gamma)^{187} \mathrm{~W}$ Reaction at 24 keV , Hexadecapole Deformations and Fragmentation of Nilsson Strength (R. F. Casten, D. Breitig, O. A. Wasson, K. Rimawi and R. E. Chrien)

Earlier, it was reported on the basis of combined information from the ( $n, Y$ ) and ( $d, p$ ) reactions in $H f$ and $W$ that there exists considerable unexplained fragmentation for low spin states of Nilsson strength in the energy regions from $1-2.5 \mathrm{MeV}$. However, the fragmentation systematics is such that most of the predicted ( $\mathrm{d}, \mathrm{p}$ ) strength is in fact observed in Hf and in $187_{\mathrm{W}}$ but only $30-50 \%$ is identified in $183,184 \mathrm{~W}$. In an effort to identify one factor that contributes significantly to these experimental results, we have made detailed calculations of the effects of a large hexadecapole deformation. The results, summarized in the figures, show that it leads to several effects that all tend in the direction of the experimental data. The energies of the key orbitals, 1/2-[501] and 3/2-[501], are increased, pushing the cross section to higher centroid energies and possibly out of the range of measured excitation energies.

[^14]
## Figure Captions

B-1: Effects of hexadecapole deformation on properties of single particle neutron levels in the tungsten nuclei. a) single particle energies as a function of $\epsilon_{4}$ labelled by the asymptotic quantum numbers of the dominant orbitals. The upper four orbitals are those of primary interest. The others, shown for orientation, have been assigned to lower lying levels in the tungsten isotopes; they occur either near the ground state or are hole excitations at $\sim 1 \mathrm{MeV}$. b) Measure of the, $\Delta N=2$ mixing; dependence on $\varepsilon_{4}$ of $a_{3 / 2}$, the amplitude of $N=5$ in the $C_{j=3 / 2}$ coefficient for the predominantly $N=7$ orbital $3 / 2-[761]$. c) Value of the j-operator that appears in the Coriolis matrix element. The matrix elements for these three pairs of orbitals are non-zero due to the presence of $N=5$ components in the $N=7$ wave functions. For $3 / 2^{-}$states and $\varepsilon_{4}=0.16$, the $\langle 1 / 2-[770]| j-|3 / 2-[501]\rangle$ point corresponds to a full Coriolis matrix element of nearly 100 keV . The value of $<1 / 2-[501]|\mathrm{j}-|$ $3 / 2-[501]>$ is also non-zero and has the value $\sim+0.8$ more or less independently of ${ }_{12}$.

12 MeV
B-2: Calculated/(d,p) spectra for the $1 / 2^{-}, 3 / 2^{-}$states of the $1 / 2-[501]$, $3 / 2-[501], 1 / 2-[770]$ and $3 / 2-[761]$ orbitals for several values of $\varepsilon_{4}$. In each case, $\epsilon_{2}=0.22, \mu=0.42, x=0.0637$. The cross sections are at $90^{\circ}, \mathrm{Q}=+3.0 \mathrm{MeV}$. Open circles correspond to cross sections less than $50 \mu \mathrm{~b} / \mathrm{sr}$. Thus all solid bars shown represent cross sections that would becansidered strong transitions. The bottom row is identical to the one above it except for the small (<150keV) shifts in two single particle energies.


Fig. B-1

The $1 / 2-[770]$ and $3 / 2-[761]$ orbitals approach in energy the former pair and the two pairs of orbitals experience a greatly augmented $\Delta \mathrm{N}=2$ and, thereby, Corialis mixing. This tends to fragment the (d,p) strength into roughly twice as many states. Furthermore the resulting, highly admixed states, are now extremely sensitive to further perturbations (compare bottom two rows of Fig. B-2) such as interactions with phonon excitations. Finally, the total (d,p) cross section to the low $K$ intrinsic states is redistributed over spin $J$, by the change in nuclear field shape, in such a way as to decrease by about $12 \%$ the total cross section expected for $1 / 2^{-}$ $3 / 2^{-}$states. This, again, is in accord with the experimentally observed loss of strength.

A detailed explanation of the fragmentation systematics has not been obtained but it is felt that an important contributing factor may have been identified which, when incorporated with more extensive microscopic calculations, will likely modulate them in the direction of the experimental findings.

$$
\text { 3. } \frac{\text { A New Isomer of }{ }^{125} \text { Xe Formed by Resonance Neutron Capture }}{\text { (W. R. Kane, R. F. Casten, W. Gelletly, and D. R. Mackenzie) }}
$$

The isotope ${ }^{125} \mathrm{Xe}$ is particularly interesting because it lies in a mass region where nuclei probably possess stable. deformations, at least for certain excited states, and the deformation may possibly be oblate. It would thus be very useful to identify unambiguously rotational bands built on individual Nilsson orbitals in ${ }^{125}$ Xe. Unfortunately very little is known about the level structure of ${ }^{125}$ Xe since it is unstable ( $\mathrm{T}_{1 / 2}=17 \mathrm{~h}$ ) and difficult to reach in various nuclear reactions.

The use of the Bragg-diffraction neutron monochromator at the Brookhaven High Flux Beam Reactor, affords, however, the possibility of studying the excited states of ${ }^{125} \mathrm{Xe}$ in detail via neutron capture in the 5.16 eV resonance of ${ }^{124} \mathrm{Xe}$. Such studies have been performed with a target of $\sim 7 \mathrm{~cm}^{3}$ of Xe gas enriched to $64 \%$ in 124 Xe . A large number of high and low energy $\gamma$ rays attributable to the $124 \mathrm{Xe}(\mathrm{n}, \gamma)^{125} \mathrm{Xe}$ reaction were observed and $\gamma-\gamma$ coincidence measurements performed. In the course of this work delayed coincidence measurements were also carried qut. They disclosed the existence of a new isomeric state in ${ }^{125} \mathrm{Xe}$ at an energy of 295.9 keV , deexciting with a 165 nsec half life to the


Fig. B-2
first excited state at 111.74 keV . The isomeric state is the third excited state of 125 Xe and the second isomeric level to be found; the $9 / 2^{-}$second excited state at 252.5 keV decays with a half life of 55 sec . The observation of transitions populating the 295.9 keV level places new levels in ${ }^{125}$ Xe at $497.0,594.1$, and 708.0 keV excitation energy. From the intensity of the $Y$ ray deexciting the 165 nsec isomer, a lower limit of 1.5 per cent is obtained for the isomer ratio $\sigma_{m 2} / \sigma_{g . s .}$
C. NATIONAL NEUTRON CROSS SECTION CENTER

## 1. Data Libraries

Intense activity in the last year has been directed to production and distribution of a new version of the evaluated library (ENDF/B-IV). The NNCSC effort involved coordinating the ENDF/B-IV effort, hosting Task Forces on the "Big $3+2$ ", $2200 \mathrm{M} / \mathrm{Sec}$ values, fission product nuclei, standards, and CSEWG meetings dedicated to approving new evaluations. In addition NNCSC facilities were called upon to process the new evaluations for ENDF/B-IV and to extend to 20 MeV those ENDF/B-III materials being taken over directly into ENDF/B-IV. The above involved extensive checking, plotting, assembling, and editing of files.

Our staff has completed new evaluations this past year for $\mathrm{Sc}, \mathrm{Mn}$, $\mathrm{Cr}, \mathrm{Ni}, \mathrm{Co}$, Eu isotopes, the resonance region of $\mathrm{Pu}-239$ (with J. R. Smith, ANC using our facilities), and the unresolved regions of U-235 and Pu-239.

Standard ENDF programs have been upgraded to handle Version IV formats and have been distributed. Distribution of ENDF/B-Version IV Library has begun (Tapes 401-403). Additions to the ENDF/A Library this year include the libraries of Deviller (France, C.E.N.), ENDL (U.S., LLL), and U.K. (England, UKNDL).

In the last year NNCSC has taken responsibility for the USNDC Request List, prepared the Library, completed the service programs, and sent a magnetic tape to IAEA to meet WRENDA obligation.

Announcement has been made that the U. S. CINDA responsiblity will be transferred to NNCSC beginning 1 July 1974.

The compiling of new data into CSISRS continues. In addition a program of "completeness" checking with the objective of filling in "gaps" has commenced. This survey, in part, employs an interleaved CINDA-CSISRS file and is being used to upgrade both libraries.

Related to the production of BNL-325 a library of over 150,000 experimental resonance parameter values has been created.

The above efforts were demanding of NNCSC computer facilities. A batch processing capability has been implemented and allows for unattended evening and weekend operation. We have sustained as high as $90 \%$ of capacity for two-week intervals, evenings and weekends included.

Statistics for data requested from NNCSC during a 6 month period are presented in Tables I and II. Magnetic tape continues to be a favored retrieval mode. Recently, we have filled requests by transmitting via telephone line to user teletype.

## 2. Publications

BNL-325, Neutron Cross Sections, Third Edition Volume I has been published and distributed. This first volume consists of recommended resonance parameters, resonance properties, thermal cross sections, and bibliography.

A draft of a revision of ENDF-102, Formats and Procedures Manual for the Evaluated Nuclear Data File, has been written and is being circulated for comment. This has been distributed to those individuals with responsibility for ENDF/B Version IV program development.

Production of updates for ENDF-200 and 201 for ENDF/B-IV materials has begun as these evaluations become finalized.

Library preparation and prototype copy generation has begun for BNL-325 Volume II production.

## Table C-1

## Evaluation (ENDF) <br> Request Statistics <br> July 1, 1973 - December 31, 1973 (6 months)

## 1. Requests

a) Number of requests 127
2. Origin of Requests
a) Government Agencies 12
b) Educational Institutions 32
c) Industry 14
d) Foreign(includes Four-Center $\underset{\text { Members) }}{\text { a }}$
e) CSEWG Members 64
3. Mode of Requests (may be more than
one per request)
a) Magnetic Tapes 66
b) Computer Listings 49
c) Cards 2
d) Plots 25
e) Documentation 59
f) Telephone 24
Table C-2
Experimental (CSISRS)
Request Statistics
July 1, 1973 - December 31, 1973 (6 months)

1. Requests
a) Number of Requests ..... 101
2. Origin of Requests
a) Government Agencies ..... 6
b) Educational Institutions ..... 16
c) Industry (includes CSEWG members) ..... 19
d) Foreign ..... 1
e) Four-Center Members ..... 17
f) National Laboratories (includes ..... 42CSEWG members)
3. Mode of Requests (may be more than one per request)
a) Magnetic Tapes ..... 46
b) Computer Listing ..... 48
c) Cards ..... 0
d) Plots ..... 10
e) Documentation ..... 19
f) Telephone ..... 4
g) Teletype ..... 1

COLUMBIA UNIVERSITY
Division of Nuclear Science and Engineering
A. Neutron Resonance Spectroscopy 162,164 Dy (H.I. Liou, G. Hacken,

During our last run large amounts of data for the separated Dy isotopes were collected. Self indication measurements were made using the 39.57 m flight path. Transmission measurements were made using the 202.05 m flight path with 16000 detector timing channels of 40 ns width above 1280 eV , and of $2,4,8, \ldots$ times 40 ns widths at lower energies. Dysprosium, $Z=66$, has seven stable isotopes, with $A=156,158,160,161$, 162,163 , and 164. The mass numbers of Dy isotopes occur close to a relative maximum of the $s$ strength function $S_{0}$ and a relative minimum of the $p$ strength function $S_{l}$. They are therefore suitable for testing the various statistical predictions concerning fluctuations of the adjacent level spacings and the reduced neutron widths.

Our measurements were made for a range of sample thicknesses for each of the spearated isotopes, $160,161,162,163,164^{4} \mathrm{Dy}$, while ${ }^{156} \mathrm{Dy}$ and ${ }^{158}$ Dy each have $<0.05 \%$ impurity in any of these samples. The impurity of other elements is insignificantly small so all level-isotope assignments can be made without ambiguity. We have reported the results for ${ }^{163}$ Dy last year. The analysis for 162,164 Dy has now been completed. Presented herewith are their level parameters and systematics. The data for $160,{ }^{161}$ Dy are being processed, and expected to be finished soon.

Samples used have principal isotope $1 / n$ values (b/atom) of 144 , $216,652,1310$ for ${ }^{162} \mathrm{Dy}$, and $94.9,142,428,856$ for ${ }^{164} \mathrm{Dy}$. They are $92.4 \%$ enriched in ${ }^{162} \mathrm{Dy}$ and $95.7 \%$ enriched in ${ }^{164} \mathrm{Dy}$. Our conventional method of area analysis was used to yield $\Gamma_{n}$ values (and $\Gamma_{\gamma}$ in favorable cases) for each resonance. Level parameters, $E_{0}$ and $\Gamma_{n}$, are obtained to 16 keV for ${ }^{162} \mathrm{Dy}$, and to 21 keV for ${ }^{164} \mathrm{Dy}$. They are listed in Tables $\mathrm{A}-1$ and A-2. We obtain $\Gamma_{\gamma}$ for 16 levels in 162 Dy and 5 levels in ${ }^{164} \mathrm{Dy}$, which are all near their average values, 112 meV for ${ }^{162} \mathrm{Dy}$ and 114 meV for ${ }^{164} \mathrm{Dy}$.

Figures 1 a and lb give plots of the cumulative number of resonances observed for ${ }^{162,164}$ Dy. In figure $1 b$ two sets of $N$ vs $E$ are given. The upper part is for all observed ${ }^{164}$ Dy levels, while the lower is for levels considered to be $\ell=0$ through many statistical tests as described below. The indicated slopes, <D>, are visually fitted values, and do not represent our final choices since other considerations must also be included to establish best choice for <D> values for s levels. The self-indication capture data were most sensitive for detecting weak resonances, but with much lower energy resolution. They were not used for the energy region above 5 keV . This explains why the slopes of the observed $N$ vs $E$ in figures $1 a$ and $l b$ start to decrease abruptly at $\sim 5 \mathrm{keV}$.

Figures 2 a and 2 b give plots of $\Sigma \Gamma_{\mathrm{n}}{ }^{0}$ vs $E$. The stronger levels
dominate in such a plot, so the effect of observed p levels and missed weak $s$ levels is relatively unimportant. The slopes shown in the figures represent our best choices of $10^{4} S_{0}$ values, being $1.88 \pm 0.25$ for ${ }^{162} \mathrm{Dy}$, and $1.70 \pm 0.25$ for ${ }^{164} \mathrm{Dy}$. More weight is given for the lower energy region due to the better quality of the data.

The distributions of observed $\left(\Gamma_{n}{ }^{0}\right)^{1 / 2}$ values for ${ }^{162,164}$ Dy are shown in figures 3 a and 3 b . Two upper energy limits were chosen for each isotope case. The upper parts of the experimental histograms were fitted with a Porter-Thomas ( $\mathrm{P}-\mathrm{T}$ ) single-channel curve which is normalized to the experimental $S_{0}$ value. The fits for the two different upper energy limits for ${ }^{162}$ Dy or ${ }^{164}$ Dy yield essentially the same value of <D>. To consider first 1 or 2 histogram boxes it is shown that we miss many weak s levels to 10 keV for ${ }^{162} \mathrm{Dy}$, while we see even more extra p levels after compensating missed weak $s$ levels to either 5 or 10 keV for ${ }^{164} \mathrm{Dy}$.

An estimate of a threshold level strength vs energy for detection indicated that about 6 and 2 s levels would be expected to be missed for ${ }^{162} \mathrm{Dy}$ to 4.5 keV , and for ${ }^{164} \mathrm{Dy}$ to 5 keV respectively. For each of a series of choices of the $p$ strength function, a similar calculation was made of the mean number of $p$ levels which should be detected in the above energy intervals. We found that the choices of $10^{4} \mathrm{~S}_{1}=1.1$ and 1.3 correspond to a mean of 7 and 25 p levels expected to be detected in these energy intervals for ${ }^{162} \mathrm{Dy}$ and ${ }^{164} \mathrm{Dy}$. These are consistent with the P-T distribution fits in figure 3a (i.e. 71-70 = $7-6$ ), and in figure 3 b (i.e. $57-34=25-2$ ). A Bayes' theorem test was further used to single out 7 and 25 levels in these energy intervals for ${ }^{162}$ Dy and ${ }^{164} \mathrm{Dy}$, which are most likely to be p levels. They are indicated by the letter "a" before the level energy in Tables A-1 and A-2. After $p$ levels being subtracted, we added 6 and 2 extra s levels for ${ }^{162} \mathrm{Dy}$ and ${ }^{164}$ Dy respectively, at the midpoints of the largest adjacent level spacings to account for the expectation of missed weak s levels. Their level energies are 1186, 2735, 3019, 3459, 3732, and 3954 eV for ${ }^{162} \mathrm{Dy}$, and 3089 and 3935 eV for ${ }^{164} \mathrm{Dy}$.

The final s level sets were then tested using the Dyson-Mehta $\Delta$ statistic based on orthogonal ensemble (O.E.) theory. The value of $\Delta$ is the mean square deviation of the staircase plot of $N$ vs $E$ from a best fit straight line. Figures 4 a and 4 b show the fits for ${ }^{162} \mathrm{Dy}$ to 4.5 keV and for ${ }^{164} \mathrm{Dy}$ to 5 keV . One can compare $\Delta \exp =0.40$ and 0.41 with $\Delta$ theory $=0.42 \pm 0.11$ and $0.35 \pm 0.11$ for ${ }^{162} \mathrm{Dy}$ and ${ }^{164} \mathrm{Dy}$. Our final choices for <D> values were obtained from the $\Delta$ statistic fit, being
 the correlation coefficient pexp for the adjacent level spacings. They are -0.28 and -0.33 in comparison with the $0 . E$. theoretical values, $-0.27 \pm 0.11$ and $-0.27 \pm 0.16$ for ${ }^{162} \mathrm{Dy}$ and ${ }^{164}$ Dy respectively.

The comparisons of the distributions for the nearest neighbor level spacings with the Wigner formula are shown in figures $5 a$ for ${ }^{162} D y$ and 5 b for ${ }^{164} \mathrm{Dy}$. It is made both for all observed levels and for the final selected set of s levels in the indicated energy intervals. The fits for the final sets of $s$ levels are somewhat improved and fair if one considers the statistical fluctuation due to the small number of level spacings.

Figure 6 gives the integral $\left(g \Gamma_{n}\right)^{1 / 2}$ distribution for the 25 p levels selected from the Bayes' theorem test for ${ }^{164}$ Dy. The two curves show the upper parts of the P-T distribution using $10^{4} \mathrm{~S}_{1}=1.3$ and 1.4. We assume 3 times as many $p$ as $s$ levels. In the curves drawn an effective energy range of 4.8 keV is taken instead of a total 5 keV since observation of some $p$ levels would be blocked by the presence of the strong s levels. Our final choices for $10^{4} \mathrm{~S}_{1}$ are $1.1 \pm 0.4$ and $1.3 \pm 0.3$ for ${ }^{162} \mathrm{Dy}$ and ${ }^{164} \mathrm{Dy}$ respectively.
B. Neutron Resonance Spectroscopy, Calcium (U.N. Singh, H.I. Liou, J. Rainwater, G. Hacken, W. Makofske (Columbia), J.B. Garg (S.U.N.Y., Albany)

Transmission measurements on high purity metallic calcium samples were made during NVS 1970 run with a 202 m flight path. Four sample thicknesses, corresponding to $1 / \mathrm{n}=1.413,4.207,11.21$, and 33.60 $\mathrm{b} / \mathrm{atom}$ of natural calcium were used. The resolution of our system was $0.2 \mathrm{~ns} /$ meter. The main complication in the analysis related to the fact that it is more difficult for our 202 m detector to evaluate and to make proper energy and sample dependent background corrections in the energy region above about 20 keV . This process was helped by the inclusion of additional data using the "standard filter" (S.F.) technique where measurements were made with various S.F., with and without our thickest Ca sample also present. This helps to establish the Ca sample transmission at the special energies where the S.F. introduce strong resonance transmission dips in the counts vs E histogram (for Co and Cu filters) or strong transmission peaks on the low side of the strong $\ell=0$ resonances where there is a near cancellation of potential and resonance scattering (for iron S.F.). The S.F. were 3 -in. Fe or $1 / 2$ in of either Cu or Co.

The $\sigma$ vs $E$ behavior for thick sample is shown in figures 1 to 3. Below 100 keV the points shown are averaged over many channels; above 100 keV every channel is plotted. The resonance peak cross sections (where $\sigma \gg 1 / \mathrm{n}$ for thick sample) is best represented by the thin sample data. These plots show mainly the between-level cross section for natural Ca. The curves drawn serve only as a guide. The cross section data was analyzed between (1.5-550) keV, using the transmission area analysis for weak levels and R-matrix multilevel shape analysis for strong s-levels. Tables $\mathrm{B}-1$ and $\mathrm{B}-2$ show the resonance parameters obtained.

On the basis of resonance parameters $s$ - and $p$-wave strength functions for ${ }^{40} \mathrm{Ca}$ were obtained as follows:

$$
\begin{aligned}
& 10^{4} \mathrm{~S}_{0}=\left(2.97 \begin{array}{l}
+1.95 \\
-1.05
\end{array}\right) \\
& 10^{4} \mathrm{~S}_{1}=\left(\begin{array}{ll}
0.13 \\
+0.09 \\
-0.05
\end{array}\right)
\end{aligned}
$$

C. Cross Section, Resonance Parameters, and Strength Function of Cerium-140 (G. Hacken, H.I. Liou, W.J. Makofske, F. Rahn, J. Rainwater, U.N. Singh)
Transmission and self-indication data for ${ }^{140} \mathrm{CeO}_{2}$ samples ( $99.9 \%$ purity) have been analyzed for the energy range 0 to 63 keV to yield cross sections and resonance parameters for 23 levels. The levels are well resolved and analysis has determined, for each resonance, the parameters $E_{0}$ (energy) and $\Gamma_{n}{ }^{0}$ (the neutron width reduced to 1 eV by the factor $\sqrt{1 \mathrm{eV} / \mathrm{E}_{0}}$ ).

The resulting $\ell=0$ strength function, $S_{0}$, was found to be $10^{4} S_{0}=$ 1.4 $\pm 0.4$. The quoted uncertainty is statistical and is based, conservatively, on 23 levels, even though not all are necessarily s-levels. The corresponding observed level spacing is 2.47 keV . Earlier results (Duke 1959) indicated only about four. ${ }^{140} \mathrm{Ce}$ peaks below 25 keV . The present data contain 13 levels to 25 keV , starting with a level at 2.54 keV . These early results also included an estimate of $S_{0}$ for $E \leqslant 28 \mathrm{keV}$, viz. $10^{4} \mathrm{~S}_{0} \simeq 1.0$. Our present data give $10^{4} \mathrm{~S}_{0}=1.8 \pm 0.7$ for $\mathrm{E} \leqslant 28 \mathrm{keV}$ (with $10^{4} \mathrm{~S}_{0}=1.4 \pm 0.4$ for $\mathrm{E} \leqslant 63 \mathrm{keV}$ ). High resolution has allowed a determination of the optical model scattering length, $\mathrm{R}^{\prime}$, for selected resonances. The best estimate is $\mathrm{R}^{\prime}=(5.5 \pm 0.7) \mathrm{fm}$.
D. Bias in Fission Fragment Detection Using Ionization Chambers
(F. Cohensedgh, J.P. Felvinci and E. Melkonian)

In the Columbia fission cross section measurements thin ( $\leqslant 100 \mu \mathrm{~g} / \mathrm{cm}^{2}$ ) fissile targets and solid state detectors were used to obtain good pulse height distributions. These measurements have consistently demonstrated differences in pulse height distribution from resonance to resonance and yield differences in fission cross sections when compared to ionization chamber measurements. The study of such cross section variations necessitated the search for possible biases in the fission fragment detection.

By using accepted range energy relations, ion-chamber pulse height responses were calculated for varying fragment emission energy, target thickness, chamber plate spacing and gas pressure. Subsequently, the extent of fragment energy dependence of effects of a low-set alpha bias was determined as a function of chamber parameters.

It is known that when using a thick target, a low-set bias discriminates against more of the low-energy fragments than the high-energy
fragments. This preferential bias is due to two distinct effects: a) energy losses in the beginning of the track are greater for low-energy fragments than for high-energy fragments, and b) due to its shorter range, a low-energy fragment has a smaller geometric probability of surfacing into the chamber gas than a high-energy fragment. While the first effect increases rapidly with increasing target thickness, the second effect becomes important only at target thicknesses greater than $500 \mu \mathrm{~g} / \mathrm{cm}^{2}$.

Energy loss characteristics of fission fragments in different media have been extensively studied by 0 . Lassen and by Lindhart. In our analysis their results were used together with the formulations of the electrostatics of ion chamber detection to obtain pulse height response distribution of multiple-plate ionization chambers to fission fragments in the $50-110 \mathrm{MeV}$ energy range.

Figure D-1 demonstrates schematically the formulation of pulse height formation in the nongridded chamber. It is noted that the value of a pulse height is the product of the portion of fragment energy dissipated in ionizing the chamber gas and the fraction of plate-spacing distance travelled by the centroid of ionization intensity along the fragment path. Figures $D-2 a$ and $D-2 b$ show the pulse height response of a chamber having a 3 cm plate spacing to monoenergetic 50 MeV and 100 MeV fragments (range of fragments at STP argon is 1.8 cm and 2.7 cm respectively). Figures $\mathrm{D}-3 \mathrm{a}$ and $\mathrm{D}-3 \mathrm{~b}$ show the corresponding responses of a 1 cm chamber to the same fragments. The lower-energy peak in the latter is due to the fact that the plate spacing is smaller than fragment range in the chamber. Figure D-4 shows the film escape probability for different target thicknesses as a function of fragment energy. Figure D-5 shows the percentage of median high and low energy fragments discriminated against due to different bias levels as a function of target thickness. Figure D-6 shows the variation of the effect of a low-set bias on the chamber as a function of fragment emission energy and target thickness for different bias levels.

These results indicate that for those resonances which have lower than average fragment energies, the ionization chamber measurements will introduce a certain bias, thus modifying the cross section.

We have checked our calculations against published ionization chamber efficiencies for a certain configuration of target thickness, plate spacing, and gas pressure and have found very good correspondence. This gives us confidence in our program of using thin target data to correct fission cross sections measured by using thicker targets.

## E. Cross Section vs Energy with Energy Intervals Determined by Resolution (J.P. Felvinci and E. Melkonian)

In most time-of-flight measurements, the detected counts are stored at constant time width channels for preset time intervals during the burst. Starting at time zero with the basic time resolution of the system, the detected counts are stored at this resolution until such time that the time resolution is too good in comparison with other intrinsic resolution limitations of the system (usually slowing down and Doppler effect), at which time the channel width is increased by a power of two. Recording then continues until the time resolution is again too good at which time the channel collapsing process is repeated. This continues for the duration of the burst.

In recording our fission yield data, both at NEVIS and at ORELA, we have a basic time channel width of 12.5 or 20 nsec , depending on which of two systems we use. However, we record all of our data event-by-event on magnetic tape at the basic resolution without collapsing of channels, except for histograms formed for limited time intervals for monitoring purposes. Thus, all of our data exist on magnetic tape at the maximum resolution of the system. Until recently, we collapsed the channels subsequently by factors of two to get the time resolution appropriate for each neutron energy region studied.

The obvious limitation of the above procedure is that it is difficult to treat extended energy intervals without having the channel width not quite small enough at the high energy ends and too large on the low energy end.

We have recently devised a method of taking advantage of the existence of all of our data at maximum resolution to form a yield histogram in which the energy interval at each point is directly related to the intrinsic resolution at that energy. Considering only broadening by slowing down and by Doppler (the intrinsic channel width introducing only a small contribution except at the highest energies) we have chosen to take the energy interval as one fourth of the intrinsic energy resolution. Thus, a resonance narrow in natural width compared with the resolution would be outlined by four points above the half maximum height level. A larger natural width would of course have more points. This feature is true at all energies. Thus, the entire energy spectrum can be represented by one continuous histogram with the appropriate resolution at each energy point.

The initial motivation for this procedure was to find a method of putting on a common basis data taken at various times, with different flight paths and with different delay times, so that they could be combined for improved statistical accuracy. However, this method has proven to be very valuable in displaying and studying the data since one always knows the energy resolution at each point immediately and can
easily compare various sets of data before combining them. Figures F-3 and F-5 show examples of this type of histogram.

We have developed computer programs to form and plot this type of histogram, to analyze the data into the component resonance levels, and to investigate the resonances in terms of the fission fragment energy distributions. (The fission fragment pulse height is recorded in addition to the neutron time-of-flight for each event.)
F. Pulse Height Distributions in Fissile Nuclei (J.P. Felvinci and E. Melkonian)

In the past year we have performed an experiment at the ORELA facility in order to continue our investigation into the effects of fission fragment pulse height distributions on the neutron-induced fission cross sections. We have already reported on similar experiments performed at the Columbia University NEVIS synchrocyclotron (CONF710301, v.2, p.855, 1971).

Due to the great care of collimation at ORELA and also the different characteristics of the machine, the beam-associated neutron background was very low and thus we succeeded in verifying some of our earlier, partly marginal results.

The experiment consisted of measuring the time of flight (TOF) of neutrons initiating fission and the fission fragment pulse height. These were recorded event-by-event on a magnetic tape through the PDP-8 computer. The TOF unit had a basic channel width of 12.5 nsec and could accomodate four independent detectors. The fission fragment distribution was digitized by a 256 channel ADC.

The four targets used were: $\sim 20 \mu \mathrm{~g} / \mathrm{cm}^{2}{ }^{229} \mathrm{Th}$, $117 \mu \mathrm{~g} / \mathrm{cm}^{2}{ }^{233} \mathrm{U}$, $100 \mu \mathrm{~g} / \mathrm{cm}^{2}{ }^{23}{ }^{2} \mathrm{U}$, and $\sim 40 \mu \mathrm{~g} / \mathrm{cm}^{2}{ }^{239} \mathrm{Pu}$. Each of these targets was viewed by a $4 \mathrm{~cm}^{2}$ area solid state detector whose leakage current was continuously monitored to detect gain drifts due to radiation damage. The pulse height distribution was satisfactory as shown for ${ }^{233} \mathrm{U}$ in Fig. F-1.

In addition a $\mathrm{BF}_{3}$ detector and a thin ${ }^{10} \mathrm{~B}$ detector were used for the determination of the neutron flux.

The advantage of this type of measurment is that the fission fragment spectrum is not distorted. This same advantage results in a disadvantage that small, thin targets have to be used, lowering che counting rate. When the total fission cruss section is subdivided into partial cross sections the number of counts in some resonances is quite small.

In order to claim an effect we either need a large difference in the partial cross sections or we have to use sophisticated statistical analysis of the data. We developed several ways of doing this. We either treat all of the fragments and calculate average energy and
average width for the distribution for every resonance or we display the individual partial cross sections and search for correlations between them as a function of TOF. We can also use single level analysis on the partial cross sections to search for differences in the areas of the resonances.

Most of our time has been spent in developing computer programs for the analysis of the data and detailed results are going to be available soon. We can already make the following preliminary, qualitative observations:
a) The cross sections vs energy of each of the four nuclei show variations depending on the pulse height.
b) Using partial fission cross sections corresponding to different energy fragments, several small levels have been identified and some large levels have been split.
c) Shoulders of large resonances considered interference effects often show different pulse height behavior than the resonance itself. This suggests either a bona-fide level or a pulse height dependent interference effect.
d) These observations could lead to resolve the "quasi-" or mixed resonances discussed in detail by Lynn.

For ${ }^{233} \mathrm{U}$, partial fission cross sections from 1 to 15 eV and 15 to 30 eV are shown in Figures $\mathrm{F}-2$ and $\mathrm{F}-4$ respectively. These curves are for the fission fragments in the low energy peak; they are plotted for increasing fragment energies. The corresponding total fission cross sections are shown in Figures F-3 and F-5. Relevant features of these partial fission cross sections are:
a) Several small resonances are visible which show excitations in the low energy and symmetric region, fading in between. Some large resonances are shown to consist of two levels, the proportion of which changes depending on the pulse-height cuts. These levels are marked with an arrow on the plots.
b) It can be seen that the 16 eV group consists of three levels and not two as listed in BNL-325, similarly the 22 eV doublet is really a triplet.

The effects are quite large at the 29 eV group where one can see one of the resonances growing compared to the other one. It can also be seen from the figure that the 20.6 eV level is split, has two components, at 20.6 and at 20.8 eV . The 19.0 eV level has a definite shoulder and at lower pulse heights it is obvious that another level is present at around 19.3 eV . Similar effects can be seen at the 10.4 eV level and at the 13.8 eV group.
G. Capture Resonance Parameters of Thulium-169 and Rhodium-103
(J. Arbo, J. Felvinci, E. Melkonian, W. W. Havens, Jr.)

Resonance capture data for ${ }^{238} \mathrm{U},{ }^{232} \mathrm{Th},{ }^{169} \mathrm{Tm},{ }^{103} \mathrm{Rh}$, and ${ }^{197} \mathrm{Au}$ was measured in 1970 at the Nevis synchrocyclotron using an array of MoxonRae detectors ${ }^{1}$. This data set was the basis of preliminary values of $E_{n}$ and $\sigma_{0} \Gamma_{\gamma}$ reported for thulium and rhodium, normalized to gold ${ }^{2}, 3$, and was used collaterally in final reports of resonance parameters for ${ }^{238} \mathbf{U}$ and ${ }^{232} \mathrm{Th}^{4}$. However, some of the resonance yield peaks in this data set show slight anomalies in the form of "tailing" or "ghost peaks" on the lower-energy side of the resonance.

The anomalies certainly are not real, in the sense that they do not represent actual resonance properties of the sample nuclide. But attempts to associate the anomalies reliably with known detector-dependent or beam-dependent factors have been inconclusive. In order to test whether the cause of the anomalies was intrinsic to the detectors, resonance capture measurements were repeated for Tm and Au in November 1973 at the ORELA facility (through the courtesy and assistance of Dr. J.A. Harvey). This test was a satellite experiment to the fission cross-section measurement described in section $F$ of this report.

The detector array and gold samples used at ORELA in November 1973 were the same as those used at Nevis in 1970. The thulium samples were similar. The anomalies seen in the Nevis data are not seen in the data taken at ORELA. In addition, the measurements at ORELA were made at higher energy resolution ( 80 mvs 33 m ), and have somewhat improved peak/ background ratios, relative to the Nevis data. Therefore, results to be reported subsequently for thulium resonance parameters will be based on the recent ORELA data, supported by the 1970 Nevis data where there is clear agreement between the two data sets. Further reports of rhodium resonance parameters based on the 1970 Nevis data will only follow careful comparison between the Nevis and ORELA data for thulium and gold.

## References:

1. Progress Report, Div. of Nucl. Sci. \& Engr., Columbia U., 1970.
2. USNDC-7, 1973
3. USNDC-3, 1972
4. Phys.Rev.C 6, 1854 (1972)

TABLE A－1

| $\mathrm{E}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ | $\Gamma \gamma$ | $E(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ |
| :---: | :---: | :---: | :---: | :---: |
| $5.54 \pm 0.02$ | $22 \pm 3$ |  | 2526．8さ0．7 | $220 \pm 30$ |
| $71.10 \pm 0.20$ | $410 \pm 20$ | $125 \pm 15$ | $2576.2 \pm 0.7$ | $170 \pm 25$ |
| $117.22 \pm 0.11$ | $10.2 \pm 0.7$ | $120 \pm 15$ | 2673．4さ0．8 | $700 \pm 100$ |
| $207.97 \pm 0.26$ | $26 \pm 2$ | $105 \pm 15$ | 2796．8さ0．8 | $2700 \pm 400$ |
| $223.29 \pm 0.15$ | $37 \pm 3$ | $115 \pm 15$ | $2847.6 \pm 0.9$ | $790 \pm 120$ |
| $269.36 \pm 0.20$ | $650 \pm 50$ |  | 2885．9さ0．9 | $1100 \pm 160$ |
| $357.02 \pm 0.30$ | $26 \pm 2$ | $105 \pm 20$ | $2944.2 \pm 0.9$ | $150 \pm 30$ |
| $412.75 \pm 0.37$ | $150 \pm 15$ | $100 \pm 20$ | 2957．2さ0．9 | $154 \pm 30$ |
| $470.32 \pm 0.45$ | $8.0 \pm 1.0$ |  | a3028．9 ${ }^{\text {a }}$ ． 7 | $18 \pm 10$ |
| $529.83 \pm 0.27$ | $280 \pm 30$ | $120 \pm 20$ | $3080.8 \pm 4.8$ | $42 \pm 20$ |
| $632.80 \pm 0.70$ | $1550 \pm 200$ |  | $3183.4 \pm 1.0$ | $120 \pm 30$ |
| $685.96 \pm 0.40$ | $450 \pm 30$ | $110 \pm 25$ | $3243.8 \pm 1.0$ | $740 \pm 100$ |
| $716.47 \pm 0.42$ | $580 \pm 50$ | $130 \pm 25$ | a3270．9 ${ }^{\text {a }}$ ．2 | $18 \pm 12$ |
| $766.42 \pm 0.47$ | $870 \pm 80$ |  | $3327.3 \pm 1.1$ | $260 \pm 40$ |
| $866.60 \pm 0.56$ | $2500 \pm 200$ |  | $3363.9 \pm 1.1$ | $230 \pm 40$ |
| $952.08 \pm 0.33$ | $195 \pm 20$ | $110 \pm 25$ | a3513．8 $\times 5.8$ | $26 \pm 15$ |
| $1005.2 \pm 0.4$ | $51 \pm 7$ | $112 \pm 20$ | $3554.4 \pm 1.2$ | $2400 \pm 300$ |
| 1066．5 $\pm 0.4$ | $31 \pm 6$ |  | $3624.0 \pm 6.1$ | $35 \pm 25$ |
| $1110.6 \pm 0.4$ | $260 \pm 30$ | $108 \pm 25$ | $3666.0 \pm 1.2$ | $510 \pm 70$ |
| $1261.4 \pm 0.5$ | $840 \pm 90$ |  | $3798.9 \pm 1.3$ | $2900 \pm 400$ |
| $1360.2 \pm 0.3$ | $130 \pm 20$ | $110 \pm 25$ | 3894．6さ6．8 | $39 \pm 25$ |
| $\mathrm{a}_{1387.5 \pm 1.5}$ | $4.8 \pm 2.5$ |  | a3966．9 ${ }^{\text {a }}$ ．0 | $26 \pm 18$ |
| $1431.6 \pm 0.3$ | $1500 \pm 200$ |  | 4012．7士1．4 | $1400 \pm 200$ |
| $\mathrm{a}_{1483.3 \pm 1.6}$ | $7.5 \pm 4.0$ |  | $4081.8 \pm 1.5$ | $1400 \pm 300$ |
| $1526.2 \pm 0.3$ | $220 \pm 30$ | $105 \pm 25$ | $4096.1 \pm 1.5$ | $390 \pm 100$ |
| $1567.3 \pm 0.4$ | $620 \pm 70$ |  | $4114.9 \pm 1.5$ | $2600 \pm 400$ |
| $1680.7 \pm 2.0$ | $13 \pm 4$ |  | $4239.0 \pm 1.5$ | $830 \pm 120$ |
| $1724.5 \pm 0.4$ | $110 \pm 15$ | $115 \pm 30$ | $4273.3 \pm 1.6$ | $520 \pm 80$ |
| $1794.9 \pm 0.4$ | $18 \pm 6$ |  | $4393.5 \pm 1.6$ | $210 \pm 60$ |
| $1835.3 \pm 0.5$ | $220 \pm 30$ | $110 \pm 30$ | $4452.3 \pm 1.7$ | $2100 \pm 300$ |
| $1935.9 \pm 0.5$ | $930 \pm 100$ |  | $4554.9 \pm 3.4$ | $70 \pm 45$ |
| 1950．2さ2．4 | $72 \pm 18$ |  | $4657.0 \pm 8.9$ | $98 \pm 60$ |
| 2003．2 $\pm 0.5$ | $270 \pm 40$ |  | $4785.6 \pm 1.8$ | $480 \pm 80$ |
| $\mathrm{a}_{2047.6 \pm 2.6}$ | $9.2 \pm 4.6$ | － | $4844.6 \pm 9.5$ | $130 \pm 80$ |
| $2081.5 \pm 0.5$ | $180 \pm 30$ |  | $5032.2 \pm 2.0$ | $430 \pm 70$ |
| $2181.4 \pm 0.6$ | $76 \pm 15$ |  | 5084．4さ2．0 | $1200 \pm 200$ |
| $2240.9 \pm 0.6$ | $950 \pm 120$ |  | $5159.7 \pm 2.1$ | $4600 \pm 700$ |
| $2275.6 \pm 0.6$ | $790 \pm 90$ |  | $5234.6 \pm 2.1$ | $650 \pm 120$ |
| $2341.5 \pm 0.6$ | $770 \pm 90$ |  | $5375.3 \pm 2.2$ | $250 \pm 50$ |
| $2363.4 \pm 0.7$ | $420 \pm 60$ |  | $5502.7 \pm 2.3$ | $1200 \pm 250$ |
| $2492.6 \pm 3.5$ | $42 \pm 15$ |  | $5518.4 \pm 2.3$ | $970 \pm 200$ |

TABLE A－1（continued）
${ }^{162}$ Dy

| $\mathrm{E}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ | E（eV） | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ | $E(\mathrm{eV})$ | $\Gamma_{n}(\mathrm{meV})$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $5616.2 \pm 2.3$ | $6500 \pm 900$ | $7925.8 \pm 3.9$ | $620 \pm 300$ | $11258 \pm 7$ | $1700 \pm 500$ |
| 5679．0 $\pm 2.4$ | $570 \pm 170$ | $8130.6 \pm 4.0$ | $5200 \pm 900$ | $11739 \pm 7$ | $3000 \pm 900$ |
| $5733.3 \pm 2.4$ | $2000 \pm 300$ | $8236.0 \pm 4.1$ | $770 \pm 350$ | $11813 \pm 7$ | $1800 \pm 600$ |
| 5776．3土2．4 | $830 \pm 200$ | $8333.0 \pm 4.2$ | $970 \pm 400$ | 12012土7 | $2700 \pm 800$ |
| $6057.9 \pm 2.6$ | $2400 \pm 500$ | $8450.5 \pm 4.3$ | $4000 \pm 800$ | $12404 \pm 8$ | $5600 \pm 1000$ |
| $6076.0 \pm 2.6$ | $600 \pm 180$ | $8729.9 \pm 4.5$ | $1500 \pm 400$ | $12564 \pm 8$ | $8300 \pm 1800$ |
| $6099.4 \pm 2.6$ | $500 \pm 160$ | 8946．1 $\pm 4.7$ | $4000 \pm 700$ | $12626 \pm 8$ | $3200 \pm 800$ |
| $6217.2 \pm 2.7$ | $1300 \pm 200$ | 9084．3土4．8 | $1200 \pm 300$ | $12918 \pm 8$ | $3800 \pm 1000$ |
| $6353.5 \pm 2.8$ | $700 \pm 200$ | 9296．6さ4．9 | $5500 \pm 1000$ | $13163 \pm 8$ | $2900 \pm 1000$ |
| $6545.0 \pm 2.9$ | $1200 \pm 300$ | 9488．5 $\pm 5.1$ | $4900 \pm 900$ | $13196 \pm 8$ | $4000 \pm 1500$ |
| $6591.7 \pm 3.0$ | $700 \pm 200$ | $9657.8 \pm 5.2$ | $2600 \pm 500$ | $13372 \pm 9$ | $9700 \pm 2000$ |
| $6704.5 \pm 3.0$ | $730 \pm 250$ | $9720.5 \pm 5.3$ | $1100 \pm 300$ | $13726 \pm 9$ | $3700 \pm 900$ |
| $6896.4 \pm 3.2$ | $400 \pm 150$ | 9834．3 $\pm 5.4$ | $1300 \pm 400$ | $14053 \pm 9$ | $3000 \pm 800$ |
| $6964.3 \pm 3.2$ | $860 \pm 300$ | $9923.0 \pm 5.4$ | $1000 \pm 300$ | $14219 \pm 9$ | $4600 \pm 1300$ |
| $7060.8 \pm 3.3$ | $3300 \pm 500$ | $10276 \pm 6$ | $5900 \pm 1200$ | $14671 \pm 10$ | $6500 \pm 2000$ |
| $7142.7 \pm 3.3$ | $860 \pm 300$ | $10359 \pm 6$ | $1800 \pm 800$ | $14848 \pm 10$ | $6900 \pm 2000$ |
| $7460.4 \pm 3.6$ | $410 \pm 200$ | $10546 \pm 6$ | $970 \pm 600$ | $15068 \pm 10$ | $8400 \pm 2600$ |
| $7590.9 \pm 3.7$ | $5600 \pm 1000$ | $10642 \pm 6$ | $2400 \pm 1000$ | $15298 \pm 11$ | $4800 \pm 1600$ |
| 7643．7さ3．7 | $3100 \pm 600$ | $10772 \pm 6$ | $1100 \pm 600$ | $15534 \pm 11$ | $3700 \pm 1300$ |
| $7745.4 \pm 3.8$ | $2100 \pm 400$ | 10956士7 | $3100 \pm 900$ | $15814 \pm 11$ | $5400 \pm 1700$ |

TABLE A－2
${ }^{164} \mathrm{Dy}$

| $E(\mathrm{eV})$ | $\Gamma_{n}(\mathrm{meV})$ | $\Gamma_{\gamma}$ | $E(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ |
| :---: | :---: | :---: | :---: | :---: |
| $146.97 \pm 0.32$ | $830 \pm 50$ |  | a3460．5 $\pm 1.1$ | $56 \pm 12$ |
| 2227．57 ${ }^{ \pm} 0.38$ | $0.36 \pm 0.18$ |  | $3480.6 \pm 1.1$ | $1900 \pm 300$ |
| $450.41 \pm 0.42$ | $250 \pm 20$ | $110 \pm 20$ | $3520.3 \pm 1.2$ | $70 \pm 14$ |
| $\mathrm{a}_{479.39}{ }^{\text {a }}$ 0．59 | $1.6 \pm 0.5$ |  | a3621．0 ${ }^{\text {a }}$ ．1 | $17 \pm 10$ |
| $536.30 \pm 0.28$ | $115 \pm 10$ | $120 \pm 20$ | $3734.4 \pm 1.3$ | $760 \pm 100$ |
| $548.76 \pm 0.28$ | $6.9 \pm 0.8$ |  | a3911．6 $\times 6.9$ | $34 \pm 20$ |
| $2740.91 \pm 0.56$ | $3.0 \pm 1.5$ |  | a4095．8さ7．3 | $60 \pm 40$ |
| $804.24 \pm 0.50$ | $8.9 \pm 1.0$ |  | $4135.2 \pm 1.5$ | $490 \pm 80$ |
| $853.89 \pm 0.55$ | $550 \pm 50$ |  | $4231.5 \pm 1.5$ | $2200 \pm 300$ |
| a925．90 $\pm 0.80$ | $3.0 \pm 1.0$ |  | a $4348.8 \pm 8.0$ | $51 \pm 35$ |
| a940．98 $\pm 0.81$ | $5.0 \pm 2.0$ |  | $\mathrm{a}_{4389.2 \pm 8.1}$ | $29 \pm 29$ |
| $983.06 \pm 0.34$ | $118 \pm 14$ | $120 \pm 25$ | $4445.8 \pm 1.6$ | $5000 \pm 700$ |
| $1052.0 \pm 0.38$ | $230 \pm 30$ | $105 \pm 25$ | $4757.6 \pm 3.6$ | $140 \pm 60$ |
| $1207.7 \pm 0.46$ | $710 \pm 80$ |  | $4780.1 \pm 1.8$ | $1500 \pm 250$ |
| $\mathrm{a}_{1286.5} \pm 1.3$ | $4.2 \pm 2.5$ |  | $4810.1 \pm 1.9$ | $10800 \pm 1600$ |
| $1323.6 \pm 0.5$ | $920 \pm 100$ |  | a4916．0 $\pm 1.9$ | $85 \pm 30$ |
| ${ }^{2} 1405.8 \pm 1.5$ | $6.5 \pm 1.5$ |  | $4954.9 \pm 1.9$ | $170 \pm 50$ |
| $\mathrm{a} 1567.4 \pm 1.8$ | $9.8 \pm 2.3$ |  | $5169.9 \pm 2.0$ | $2050 \pm 400$ |
| $1588.1 \pm 0.4$ | $220 \pm 30$ | $115 \pm 25$ | $5211.9 \pm 2.1$ | $13000 \pm 2000$ |
| $1644.7 \pm 1.9$ | $23 \pm 4$ |  | $5592.1 \pm 2.3$ | $1600 \pm 300$ |
| $\mathrm{a}_{1} 709.0 \pm 0.4$ | $9.9 \pm 2.5$ |  | $5702.5 \pm 2.4$ | $240 \pm 70$ |
| $1896.2 \pm 0.9$ | $2000 \pm 300$ |  | $5923.2 \pm 5.0$ | $10500 \pm 2000$ |
| $1960.2 \pm 0.5$ | $1220 \pm 150$ |  | 6096．8さ2．6 | $1830 \pm 400$ |
| a2038．7 $\pm 0.5$ | $29 \pm 6$ |  | $6109.8 \pm 2.6$ | $2100 \pm 400$ |
| $2065.9 \pm 2.6$ | $46 \pm 10$ |  | $6280.7 \pm 2.7$ | $6900 \pm 1000$ |
| a2250．7 +3.0 | $8.3 \pm 4.0$ |  | $6444.7 \pm 2.9$ | $2300 \pm 350$ |
| $\mathrm{a}_{2285.1} \pm 0.6$ | $31 \pm 6$ |  | $6621.1 \pm 3.0$ | $3800 \pm 600$ |
| $2319.3 \pm 0.6$ | $1900 \pm 300$ |  | $6854.2 \pm 3.1$ | $1150 \pm 170$ |
| a $2352.6 \pm 3.2$ | $8.0 \pm 6.0$ |  | 6996．3土3．2 | $970 \pm 200$ |
| $2395.8 \pm 0.7$ | $420 \pm 60$ |  | $7432.3 \pm 3.5$ | $3900 \pm 600$ |
| $2356.6 \pm 0.7$ | $650 \pm 90$ |  | $7695.2 \pm 3.7$ | $7600 \pm 1200$ |
| $\mathrm{a}_{2723.2} \pm 4.0$ | $27 \pm 9$ |  | $7958.7 \pm 3.9$ | $930 \pm 200$ |
| a2804．4 $\pm 4.2$ | $16 \pm 6$ |  | $8090.6 \pm 4.0$ | $3100 \pm 500$ |
| 2871．9 $\pm 0.9$ | $2500 \pm 400$ |  | $8252.4 \pm 4.1$ | $4400 \pm 700$ |
| $2968.7 \pm 0.9$ | $3200 \pm 400$ |  | $8368.6 \pm 4.2$ | $370 \pm 150$ |
| a3048．2 $\pm 0.9$ | $17 \pm 8$ |  | $8763.5 \pm 4.5$ | $760 \pm 180$ |
| a3100．0 $\pm 4.8$ | $19 \pm 8$ |  | $9358.3 \pm 5.0$ | $1100 \pm 300$ |
| $3209.0 \pm 5.1$ | $53 \pm 14$ |  | $9400.5 \pm 5.0$ | $1450 \pm 300$ |
| $3281.6 \pm 1.0$ | $220 \pm 30$ |  | 9702．1 $\pm 5.2$ | $2400 \pm 400$ |
| ${ }^{2} 3416.8 \pm 5.6$ | $47 \pm 12$ |  | $10974 \pm 6$ | $6900 \pm 1000$ |

TABLE A-2 (continued)
164 Dy

| $\mathrm{E}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ | $\mathrm{E}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{meV})$ |
| :---: | :---: | :---: | :---: |
| $11530 \pm 7$ | $6800 \pm 1000$ | $15846 \pm 11$ | $2100 \pm 600$ |
| $11753 \pm 7$ | $3300 \pm 500$ | $16179 \pm 11$ | $5700 \pm 1100$ |
| $11890 \pm 7$ | $2100 \pm 400$ | $17194 \pm 13$ | $3700 \pm 900$ |
| $12411 \pm 8$ | $9400 \pm 1600$ | $17744 \pm 13$ | $1800 \pm 600$ |
| $12894 \pm 8$ | $1900 \pm 500$ | $17900 \pm 13$ | $23000 \pm 4000$ |
| $12942 \pm 8$ | $6000 \pm 1200$ | $18212 \pm 14$ | $5500 \pm 1100$ |
| $13060 \pm 8$ | $30000 \pm 5000$ | $18307 \pm 14$ | $4500 \pm 1400$ |
| $13280 \pm 9$ | $3900 \pm 800$ | $18368 \pm 14$ | $13000 \pm 3000$ |
| $13466 \pm 9$ | $2700 \pm 500$ | $18637 \pm 14$ | $6200 \pm 1800$ |
| $13762 \pm 9$ | $2600 \pm 500$ | $18685 \pm 14$ | $11000 \pm 3000$ |
| $14076 \pm 9$ | $1700 \pm 500$ | $19127 \pm 15$ | $6400 \pm 1300$ |
| $14141 \pm 9$ | $7900 \pm 1600$ | $19295 \pm 15$ | $6600 \pm 1400$ |
| $14298 \pm 9$ | $2600 \pm 600$ | $19728 \pm 15$ | $4200 \pm 1300$ |
| $14690 \pm 10$ | $8400 \pm 1600$ | $19804 \pm 15$ | $9400 \pm 2800$ |
| $14882 \pm 10$ | $4200 \pm 900$ | $20317 \pm 16$ | $6500 \pm 1800$ |
| $15335 \pm 11$ | $4300 \pm 900$ | $20573 \pm 16$ | $6300 \pm 1800$ |
| $15455 \pm 11$ | $6300 \pm 1200$ | $20917 \pm 17$ | $9100 \pm 3000$ |
| 15550 $\pm 11$ | $4300 \pm 900$ | $21151 \pm 17$ | $9400 \pm 3000$ |

Table B-1
Resonance parameters (using transmission area analysis) for levels (mainly weak) observed in neutron interaction with natural calcium below 550 keV .


Table B-2
Parameters for strong neutron levels observed in natural calcium in the energy region $100-550 \mathrm{keV}$ using R-matrix multi-level shape analysis. The values in last column are Duke group results and are given for comparison.

| $E_{0}(\mathrm{keV})$ | A | $\ell$ | J | $\Gamma_{\mathrm{n}}(\mathrm{keV})$ | $\Gamma_{\mathrm{n}} 0(\mathrm{eV})$ | Duke Group <br> $\Gamma_{\mathrm{n}}(\mathrm{keV})$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| 131.60 | 40 | 0 | $1 / 2$ | 3.174 | 8.748 | 2.540 |
| 168.57 | 40 | 0 | $1 / 2$ | 2.437 | 5.936 | 2.490 |
| 216.15 | 40 | 0 | $1 / 2$ | 7.366 | 15.84 | 7.800 |
| 241.80 | 40 | 0 | $1 / 2$ | 19.973 | 40.62 | 18.500 |
| 290.95 | 40 | 0 | $1 / 2$ | 1.798 | 3.333 | 2.400 |
| 326.35 | 40 | 0 | $1 / 2$ | 14.160 | 24.79 | 14.0 |
| 354.50 | 40 | 0 | $1 / 2$ | 1.612 | 2.708 | 2.0 |
| 435.00 | 40 | 0 | $1 / 2$ | 8.243 | 12.50 | 9.5 |
| 501.50 | 40 | 0 | $1 / 2$ | 8.113 | 11.46 | 8.0 |

TABLE C-1
Resonance Parameters for Cerium-140

| $\mathrm{E}_{0}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}(\mathrm{eV})$ | $\Gamma_{\mathrm{n}}{ }^{0}(\mathrm{meV})$ |
| :---: | :---: | :---: |
| $2543.4 \pm 0.7$ | $.56 \pm .03$ | $11.1 \pm 0.6$ |
| $6005.8 \pm 2.5$ | $.83 \pm .02$ | $10.7 \pm 0.3$ |
| $6779 \pm 3$ | $.114 \pm .010$ | $1.4 \pm 0.1$ |
| $8393 \pm 4$ | $.94 \pm .02$ | $10.3 \pm 0.2$ |
| $9574 \pm 5$ | $39 \pm 2$ | $400 \pm 20$ |
| $11235 \pm 6$ | $.47 \pm .03$ | $4.4 \pm 0.3$ |
| $11433 \pm 7$ | $13.5 \pm .5$ | $126 \pm 5$ |
| $12477 \pm 8$ | $25 \pm 5$ | $224 \pm 40$ |
| $14019 \pm 9$ | $.59 \pm .02$ | $5.0 \pm 0.1$ |
| $16142 \pm 11$ | $4.0 \pm .5$ | $31 \pm 4$ |
| $16427 \pm 12$ | $1.75 \pm .10$ | $13.7 \pm 0.8$ |
| $18168 \pm 13$ | $60 \pm 2$ | $445 \pm 15$ |
| $21626 \pm 17$ | $450 \pm 50$ | $3060 \pm 340$ |
| $24792 \pm 21$ | $70 \pm 20$ | $445 \pm 130$ |
| $28209 \pm 26$ | $55 \pm 5$ | $327 \pm 30$ |
| $30698 \pm 29$ | $11.5 \pm 1.0$ | $66 \pm 6$ |
| $38247 \pm 41$ | $85 \pm 25$ | $435 \pm 130$ |
| $41982 \pm 47$ | $260 \pm 30$ | $1270 \pm 150$ |
| $49504 \pm 60$ | $55 \pm 5$ | $247 \pm 22$ |
| $53198 \pm 67$ | $32 \pm 3$ | $140 \pm 15$ |
| $55272 \pm 71$ | $220 \pm 20$ | $936 \pm 85$ |
| $60368 \pm 81$ | $80 \pm 4$ | $326 \pm 16$ |
| $62967 \pm 87$ | $82 \pm 4$ | $327 \pm 16$ |














Figure B-1 Between level cross section for natural calcium, points shown are multichannel averages.


Figure B-2 Single channel $\sigma$ vs. E for natural calcium.


Figure B-3 Single channel $\sigma$ vs. E for natural Ca.

SCHEMATIC FORMULATION
PULSE HEIGHT FORMATION


$$
E_{\text {pulse }}=\frac{d_{\text {center }}}{D_{\text {plate }}} \int_{x_{0}}^{x_{1}}\left(\frac{d E}{d x}\right)_{\text {gas }} d x
$$

Figure D-1


Figure D-2a


Figure D-2b


Figure D-3a


Figure D-3b


Figure D-4


Figure D-5


Figure D-6


Figure F-1 Pulse height distribution of $\mathrm{U}^{233}$


Figure F-2 $\quad \mathrm{U}^{233}$ partial fission cross sections from 1 eV to 15 eV .
The curves are plotted for the low energy fission
fragments peak and are in order of increasing energies.


Figure F-3 $U^{233}$ total fission cross section from 1 eV to 15 eV .



Figure F-5 $U^{233}$ total fission cross section from 15 eV to 30 eV .

INTELCOM RAD TECH
San Diego, California
A. NEUTRON CROSS SECTIONS

1. Measurement of Gamma-Ray Production Cross Sections for Nitrogen (V. Orphan, V. Rogers, C. Hoot, and V. Verbinski)

Measurements of the gamma ray production cross sections of nitrogen, discussed in the last USNDC report, have been analyzed for the discrete gamma-ray component. Production cross sections for the 2.313, $4.913,1.632,5.106$, and 2.793 MeV gamma rays are shown in Figures $\mathrm{A}-1$ through A-3. Previous experimental values are also given in the figures. The curves shown in the figures are from a previous evaluation. 1 Table A-1 lists the preliminary values for all discrete gamma rays observed in the present measurements. Errors assigned to the cross sections are also noted in the table.

An initial analysis of the continuum-plus-discrete components obtained by unfolding the gamma-ray spectra, reveal a significant continuum component for the high incident neutron energies. Final unfolded data will be obtained subsequent to a further determination of the low gamma-ray energy background presently under investigation.
2. Measurement of Gamma-Ray Production Cross Sections for Silicon and Copper. (V. Rogers, V. Orphan, C. Hoot, V. Verbinski, and D. Costello)

Initial measurements of the gamma-ray production cross sections for silicon and copper have been performed using the Rad Tech Linac pulsed neutron source. Preliminary data have been obtained with the $\mathrm{Ge}(\mathrm{Li})$ spectrometer system for gamma rays with energies between 200 keV and 11 MeV over the neutron energy range from 0.5 to 20 MeV . Analysis of the data is still in progress.
3. Measurements of the ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha) \mathrm{T}$ and the ${ }^{10_{\mathrm{B}}(\mathrm{n}, \alpha)} 7_{\mathrm{Li}}$ Cross Sections for Neutron Energies from 1 to 1500 keV
(S. Friesenhan)

The final results of the measurements of the ${ }^{10_{B}\left(n, \alpha_{0}+\alpha_{1}\right)}{ }^{7} \mathrm{Li}$, ${ }^{10_{B}\left(n, \alpha_{1}\right)} 7_{\mathrm{Li}}{ }^{*}$ and ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha) \mathrm{T}$ cross sections from 1 to 1500 keV have been reported. 2 The final cross-section data are also available in punched card form.

1 P. G. Young and D. G. Foster, Jr. "An Evaluation of the Neutron and Gamma Ray Production Cross Sections for Nitrogen", LA-4725 (Sept. 1972).
2 S. J. Friesenhan, V. J. Orphan, A. D. Carlson, M. P. Fricke, and W. M. Lopez, "The ( $n, \alpha$ ) Cross Sections of $6_{L i}$ and $10_{B}$ Between 1 and $1500 \mathrm{keV}, "$ Intelcom Rad Tech report INTEL-RT 7011-001, Feb. 20, 1974).


Figure A-1. Gamma-ray production cross section for 2.3 .3 MeV gamma ray from nitrogen



Table A-1
NITROGEN ( $\mathrm{n}, \mathrm{x} \gamma$ ) CROSS SECTIONS FOR DISCRETE LINES (mb) g

| $\begin{gathered} \mathrm{E}_{Y} \\ (\mathrm{MeV}) \end{gathered}$ | $E_{\text {thres }}$ <br> (MeV) | $\mathrm{E}_{\mathrm{n}}(\mathrm{MeV})$ |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 2. 007 | 3.016 | 4.025 | 5.045 | 6.065 | 7. 088 | 8. 116 | 9.147 | 10.181 | 12.262 | 14.358 | 17.350 |
|  |  | 3.016 | 4. 025 | 5. 045 | 6.065 | 7. 088 | 8.116 | 9.147 | 10.181 | 12. 262 | 14.358 | 17.350 | 20.738 |
| 0.728 | 6.25 |  |  |  |  | 4.9 | 19.0 | 17.7 | 22.5 | 20. 9 | 14.7 | 17.6 | 21.5 |
| 1.632 | 4.23 |  |  | 26.1 | 43.4 | 83.4 | 79.6 | 60.4 | 46.2 | 36.4 | 31.3 | 16.5 | 17.0 |
| 2. 124 | 2. 44 | 0.9 | 1.2 | 28. 8 | 55.96 | 16.3 | 37.2 | 16.4 | 17.8 | 13.8 | 17.0 | 8.5 | 8.2 |
| 2. 313 | 2, 48 | 3.7 | 8.7 | 36.2 | 61.5 | 85.9 | 117.8 | 94.5 | 87.0 | 83.0 | 57.1 | 36.7 | 17.9 |
| 2. 500 | 6.90 |  |  |  |  |  | 1.0 | 2.8 | 2.5 | 2. 2 | 2. 0 | 1.3 | 1.3 |
| 2. 792 | 5. 48 |  |  |  | 1.8 | 4.2 | 13.2 | 11.6 | 12.4 | 12.2 | 11.8 | 11.3 | 11.8 |
| 3. 378 | 6.09 |  |  |  |  | 4. 0 | 11.4 | 12.6 | 14.7 | 13.5 | 7.5 | 14.2 | 8.7 |
| 3.684 | 9.65 |  |  |  |  |  |  |  |  | 11.5 | 29.4 | 36.8 | 27.8 |
| 3.854 | 9.83 |  |  |  |  |  |  |  |  | 5.7 | 7.8 | 20.1 | 23.7 |
| 3.894 | 6.65 |  |  |  |  |  | 2.9 | 2.8 | 4.7 | 4.0 | 3.8 | 3.6 | 4.9 |
| 4. $444^{\text {h }}$ | 4.92 |  |  |  | 0.8 | 7.0 | 40.8 | 17.2 | 13.8 | 27.4 | 34.6 | 40.0 | 39.3 |
| 4.913 | 5.25 |  |  |  | 4.8 | 12.9 | 9.0 | 8.6 | 6.8 | 5.9 | 6. 2 | 7.5 | 8.7 |
| 5.105 | 5.48 |  |  |  | 5. $4^{\text {d }}$ | $15.0{ }^{\text {c }}$ | 37.3 | 34.8 | 33.2 | 21.3 | 36.7 | 33.8 | 35.7 |
| 5.691 | 6.09 |  |  |  |  |  | 4.4 | 6.5 | 6.8 | 4.9 | 7.5 | 4.1 | 2.4 |
| 5.833 | 6.25 |  |  |  |  | 2.0 | 7.2 | 4.5 | 6.5 | 5.6 | 6.3 | 6.7 | 8.0 |
| 6.087 | 5.85 |  |  |  |  |  | 1.4 | 3.6 | 3.9 | 4.5 | 7. 8 | 6.5 | 6.1 |
| 6.198 | 6.64 |  |  |  |  |  | 1.2 | 3.2 | 1.6 | 3.1 | - | - | - |
| 6.444 | 6.90 |  |  |  |  |  | 5.8 | 15.4 | 16.7 | 12.4 | 12.0 | 11.7 | 4.7 |
| 6. 728 | 6.52 |  |  |  |  |  | 2.1 | 3.7 | 8.2 | 13.7 | 18.2 | 9.9 | 10.2 |
| 7.028 | 7. 53 |  |  |  |  |  | 2.7 | 8.7 | 18.3 | 18.5 | 24.6 | 26.6 | 22.6 |

The ${ }^{10_{B}}\left(\mathrm{n}, \alpha_{0}+\alpha_{1}\right)^{7}$ Li results are in fair agreement with the ENDF/B-III evaluation as shown in Figure A-4. The most notable disagreement is the more prominent resonance at 450 keV and the more rapid decrease of the cross section above the resonance.

In the case of the $6_{\text {Li }}$ data, the $250-\mathrm{keV}$ resonance also appears sharper than in previous measurements, and the peak cross section is significantly higher than any previous measurement. Figures A-5 and A-6 show the $6_{\text {Li }}(\mathrm{n}, \alpha) \mathrm{T}$ cross section results compared with previous determinations.

The ${ }^{10}$ B and ${ }^{6}$ Li interactions were observed simultaneously in an ion chamber designed to minimize bias efficiency and multiple-scattering corrections. This allowed a very precise ${ }^{10_{\mathrm{B}} / 6_{\mathrm{Li}}}$ cross-section ratio, shown in Figure A- $\boldsymbol{\lambda}$, to be obtained.

The present measurements were performed with a fast ion chamber at the end of a 226 -meter flight path. Thus, the energy resolution is probably superior to that of existing measurements. In addition, the cross sections were normalized at 4 keV , thus avoiding the need for detector thickness assay. The flux measurements were performed with a methane-filled proportional counter using a four-parameter computerbased data acquisition system to observe proton-recoil events. In this way the results could be based directly on the well-known hydrogen scattering cross section.

## B. INTEGRAL EXPERIMENTS

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, N. Lurie, and W. E. Gober)

A method of obtaining an accurate gamma-ray response matrix for a 2 inch x 2 inch $\mathrm{NE}-213$ detector has been developed. This response matrix is required for unfolding the secondary gamma-ray spectra obtained for a number of incident-neutron energy intervals between 1.5 to 20 MeV . A three-dimensional Monte-Carlo code was used to calculate the gamma-ray response for a series of monoenergetic gamma rays. Figures B-1 to B-3 demonstrate the excellent agreement obtained between calculated responses and measured responses for gamma rays from ${ }^{137} \mathrm{Cs}\left(662 \mathrm{keV}\right.$ ), ${ }^{22} \mathrm{Na}$ ( 511 and 1275 keV ) and $16^{\mathrm{N}}$ * ( 6128 keV ). Having demonstrated the validity of the method of calculating the NE-213 gamma response, the complete gama response matrix will be calculated and used to unfold existing secondary gamma-ray production data.



Figure A-5. ${ }^{6}$ Li $(n, \alpha) T$ cross section


Figure A-6. $6_{\text {Li }}(\mathrm{n}, \alpha) \mathrm{T}$ cross section


Figure $\mathrm{A}-7 .{ }^{6} \mathrm{Li} /{ }^{10} \mathrm{~B}$ cross-section ratio


RT-08029
Figure B-1. Comparison of calculated and measured NE-213 gamma ray response at $662 \cdot \mathrm{keV}$


Figure B-2. Comparison of calculated and measured NE-213 gamma response at 511 and 1275 MeV


RT-08030

Figure B-3. Comparison of calculated and measured
NE-213 gamma response at 6128 keV
2. Integral Concrete and Steel Shielding Experiment (L. Harris, Jr., J. C. Young, D. K. Steinman, L. Shänzler, and W. E. Gober)

The data acquisition for this integral shielding experiment was completed and much of the data has been analyzed. Fast neutron and gammaray counts have been reported as a function of time after the Linac burst. In addition, thermal neutrons and dieaway gamma rays were measured until a millisecond after the Linac burst. Vertical traverses were made along the outer face of the concrete and steel assembly with both the NE-213 fast neutron and gamma-ray detector, and the $3^{3}$ He thermal neutron detector to evaluate the influence of the concrete floor on the beam centerline measurements.
3. In Missile Radiation Experiment (L. Harris, Jr., D. K. Steinman, S. J. Friesenhan, J. C. Young, and W. E. Gober)

The silicon dosimeter has been calibrated for neutrons with energies between 1 MeV and the cadmium cut-off, and for several monoenergetic gamma rays. The neutron response below 1 MeV of a steel and polystyrene sample has been measured using the dosimeter. Calibration of the detector with neutrons in the 1 to 20 MeV range will be completed shortly; soon after, neutron induced dose in the missile autopilot and guidance system will be measured.

## C. FISSION MEASUREMENTS

1. Isomeric Gamma Rays From ${ }^{235} \mathrm{U}(\mathrm{n}, \mathrm{f})$ and ${ }^{239} \mathrm{Pu}(\mathrm{n}, \mathrm{f})$ for Times Less Than One Microsecond After Fission (V. V. Verbinski, R. E. Sund, and H. Weber)

Measurements of the isomeric gamma-ray energy spectra from the thermal-neutron fission of 235 U and ${ }^{239} \mathrm{Pu}$ were performed with a Ge (Li) detector for times between 20 nsec and $\sim 1 \mu \mathrm{sec}$ after fission. Sixtynine resolved gamma-ray peaks with different energies and half-lives were observed; 37 of these gamma-ray peaks had not been seen in previous delayed gamma-ray measurements. The fission-fragment mass numbers for many of the gamma rays were determined by comparison of the gamma-ray energies and half-lives with the results of previous ${ }^{252} \mathrm{Cf}$ measurements. Gamma rays which decay in cascade from the same isomeric state were identified on the basis of mass numbers, gamma-ray half-lives, and intensities. Isomeric gamma-ray spectra from the spontaneous fission of ${ }^{252} \mathrm{Cf}$ were also measured in the present experiment; the analysis of a number of strong, resolved gamma rays in these data indicated that the
present results are consistent with previous ${ }^{252}$ Cf results, ${ }^{1}$ within the sum of the systematic uncertainties of the two experiments. Table C-1 lists the resolved gamma-ray lines from ${ }^{235} \mathrm{U}$ and ${ }^{239} \mathrm{Pu}$, as well as corresponding lines from ${ }^{252}$ Cf measured previously. ${ }^{1}$

The total energy of the resolved peaks from this experiment, when integrated over all time, is 163 and $164 \mathrm{keV} /$ fission for 235 U and 239 Pu , respectively. Roughly $40 \%$ of the total energy of the resolved peaks is from gamma rays in the 1100 to $1340-\mathrm{keV}$ region. Isomers in ${ }_{5}^{2} 4^{\mathrm{T}} 82$ and $13 \mathrm{~K}_{2} \mathrm{Xe}_{82}$ contribute most of these high-energy gamma rays. In the 140 to $1340-\mathrm{keV}$ energy range and 20 to $958-\mathrm{nsec}$ time interval, the energy of the observed continuum of unresolved gamma rays was $220 \%$ and $\sim 24 \%$ of the total delayed gamma-ray energy for 235 U and ${ }^{239} \mathrm{Pu}$, respectively. The energy of the resolved gamma rays from this experiment for 235 U and ${ }^{239} \mathrm{Pu}$ is about twice that for the isomers from ${ }^{252}$ Cf with the same range of half-lives, as observed from previous results. Most of the difference between ${ }^{252} \mathrm{Cf}$ and 235 U or ${ }^{239} \mathrm{Pu}$ is due to seven possible gamma-ray cascades.

For convenience of the user, a rough 5-bin energy spectrum of the 235 U results is given in Table $\mathrm{C}-2$ for 235 U and in Table C-3 for ${ }^{239} \mathrm{Pu}$. These spectra are in terms of both the number of photons, and for the total energy emitted, in each of five time regions between 20 and 958 nsec after fission. The data include gamma rays for both the resolved and unresolved lines, the latter being obtained by unfolding the pulseheight spectrum after stripping off the resolved lines and associated Compton-scattering (and source-backscattering) tails.

Table C-4 lists the strongest isomeric gamma-ray lines observed from ${ }^{252}$ Cf fission as obtained from both the present experiment and the Livermore results. 1 The two sets of results agree within systematic uncertainties of $\sim \pm 10 \%$, which validates the above mentioned comparison of our complete 235 U and ${ }^{239} \mathrm{Pu}$ results with the complete ${ }^{252} \mathrm{Cf}$ data.

Table C-5 lists the gamma-ray cascades observed in all three fissionable species. These seven strong cascades account for over half of the gamma-ray energy emitted from all the observed lines in the present ${ }^{252}$ Cf measurement.

[^15]Table C-1-1
DELAYED GAMMA-RAY RESOLVED PEAKS OBSERVED IN THE PRESENT ${ }^{235}$ U AND ${ }^{239}$ Pu MEASUREMENTS For comparison the Livermore ${ }^{252}$ Cf results are shown for those gama rays which appear to correspond in energy and half life to the peaks observed from 235 U or ${ }^{239} \mathrm{Pu}$. For the present if results, a reference is given for the present 235 U and ${ }^{239} \mathrm{Pu}$ gamma-ray intensities do not include possible systematic uncertainties of $\tau \pm 10 \%$ and $\sim \pm 15 \%$, respectively, for energies above $\sim 130 \mathrm{keV}$ and somewhat larger values below 130 keV .

\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline \multicolumn{12}{|c|}{PRESENT RESULTS} \& \multicolumn{4}{|c|}{LIVERMORE RESULTS} \\
\hline \multicolumn{6}{|c|}{235 H} \& \multicolumn{6}{|c|}{\({ }^{239}{ }_{\text {pu }}\)} \& \multicolumn{4}{|c|}{\({ }^{252}\) Cf} \\
\hline \[
\begin{gathered}
E_{\gamma} \\
(\mathrm{keV}) \\
\hline
\end{gathered}
\] \& \begin{tabular}{l}
\[
\mathrm{T}_{1 / 2}
\] \\
(nsec)
\end{tabular} \& \[
\pm \Delta \mathrm{T}_{1 / 2}
\]
(\%) \& T \(1 / 2\)
Ref. \& \[
\left[\begin{array}{c}
\mathrm{I}_{\gamma} \\
\text { (photons/ } \\
\text { fission) }
\end{array}\right.
\] \& \begin{tabular}{l}
\[
\pm \Delta I_{Y}
\] \\
(\%)
\end{tabular} \& \(\mathrm{E}_{\gamma}\) (keV) \& \[
\begin{gathered}
\mathrm{T}_{1 / 2} \\
\text { (nsec) }
\end{gathered}
\] \& \begin{tabular}{l}
\[
\pm \Delta T_{1 / 2}
\] \\
(\%)
\end{tabular} \& T \({ }_{1 / 2}\)
Ref. \& ```
I
(photons/
fission)
``` \& \begin{tabular}{l}
\[
\pm \Delta I_{\gamma}
\] \\
(\%)
\end{tabular} \& \[
\begin{gathered}
E_{Y} \\
(\mathrm{keV})
\end{gathered}
\] \& \(A^{\text {a }}\) \& \[
\begin{gathered}
\mathrm{T}_{1 / 2} \\
\text { (nsec) }
\end{gathered}
\] \& \(\underset{\substack{\mathrm{b} \\ \text { (photons: } \\ \text { fission) }}}{ }\) \\
\hline 85.0 \& 15. \& 20 \& \& 0.0118 \& 50 \& 85.3 \& 15. \& 18 \& \& 0.024 \& 50 \& \(\left\{\begin{array}{l}85.6 \\ 83.7\end{array}\right.\) \& \({ }^{105}{ }_{-0}{ }^{\text {c }}\) \& 16 \& 0.0012 \\
\hline \(85.1{ }^{\text {c }}\) \& 135. \& 30 \& \& 0.0048 \& 50 \& \(85.5{ }^{\text {c }}\) \& 135. \& 27 \& \& 0.0069 \& 48 \& \& 133 \({ }_{-1}^{+0}\) \& 12 \& 0.0026 \\
\hline 91.3 \& 120. \& \& 4 \& 0.0025 \& 29 \& 91.3 \& 120. \& \& \& 0.00169 \& 26 \& \(\left\{\begin{array}{l}90.0 \\ 91.2\end{array}\right.\) \& \(108+1,-0\)
\(132 \pm 0\) \& 120
120 \& \[
\begin{aligned}
\& 0.0022 \\
\& 0.00075
\end{aligned}
\] \\
\hline 91.3 \& 15. \& \& 4 \& 0.0021 \& 35 \& 91.3 \& 15. \& \& 4 \& 0.0039 \& 35 \& \(\left\{\begin{array}{l}90.2 \\ 90.5 \\ 91.5\end{array}\right.\) \& \(108 \pm 0\)
\(142 \pm 0\)
\(101+0,-1\) \& 15
15
19 \& \[
\begin{aligned}
\& 0.0013 \\
\& 0.00089 \\
\& 0.00076
\end{aligned}
\] \\
\hline \& \& \& \& \& \& 102.8 \& 15. \& \& 4 \& 0.0038 \& 14 \& \(\left\{\begin{array}{l}102.8 \\ 103.5\end{array}\right.\) \& \(105 \pm 0\)
\(111+0,-1\) \& 15
14 \& \[
\begin{aligned}
\& 0.0038 \\
\& 0.0059
\end{aligned}
\] \\
\hline \& \& \& \& \& \& 102.8 \& 200. \& \& 4 \& 0.0099 \& 29 \& 103.2 \& \({ }^{150}+1\) \& 200 \& 0.0011 \\
\hline \& \& \& \& \& \& 106.6 \& 20. \& \& 4 \& 0.0018 \& 60 \& \(\{105.0\) \& \(146 \pm 2\) \& 20 \& 0.0023 \\
\hline \& \& \& \& \& \& \& 20. \& \& \& 0.0018 \& 60 \& 1106.0 \& \(142 \pm 2\) \& 20 \& 0.0029 \\
\hline 109.1 \& 11.9 \& 10 \& 4 \& 0.0095 \& 40 \& 109.4 \& 10.7 \& 12 \& \& 0.0079 \& 40 \& \& \& \& \\
\hline 115.3 \& 175. \& 4 \& \& 0.0103 \& 7 \& 115.3 \& 175. \& 5 \& \& 0.0089 \& 7 \& 115.0 \& \(134 \pm 0\) \& 162 \& 0.0061 \\
\hline 121.6 \& 360. \& \& 4 \& 0.0101 \& 7 \& 121.4 \& 360. \& \& 4 \& 0.0094 \& 7 \& 121.4 \& 99

-1 \& 360 \& 0.0048 <br>
\hline 121.8 \& 22. \& \& 4 \& 0.00219 \& 15 \& 121.7 \& 22. \& \& 4 \& 0.0034 \& 17 \& 122.0 \& ${ }_{99}{ }_{-0}^{+1}$ \& 22 \& 0.0025 <br>
\hline 125.0 \& 81.6 \& 14 \& \& 0.00216 \& 14 \& 125.0 \& 79.2 \& 16 \& \& 0.0033 \& 15 \& 125.1 \& $134 \pm 0^{\text {d }}$ \& 115 \& 0.00176 <br>
\hline 130.5 \& 375. \& 3 \& \& 0.0089 \& 9 \& 130.1 \& 340. \& \& 4 \& 0.0077 \& 25 \& 129.8 \& ${ }^{99}+1$ \& 340 \& 0.0029 <br>
\hline \& \& \& \& \& \& 130.5 \& 19. \& \& \& 0.0012 \& 30 \& 130.5 \& $146 \pm 0$ \& 19 \& 0.0032 <br>
\hline 141.5 \& 360. \& \& 4 \& 0.00415 \& 5 \& 141.3 \& 360. \& \& \& 0.0025 \& 11 \& 140.9 \& ${ }^{96}+1$ \& 360 \& 0.00084 <br>
\hline \& \& \& \& \& \& \& \& \& \& \& \& 140.9 \& 104 $\pm 0$ \& 62 \& 0.0016 <br>
\hline 142.3 \& 55. \& \& \& 0.0368 \& 4 \& 142.1 \& 55. \& \& \& 0.0188 \& 4 \& 142.0 \& ${ }_{91}+1$ \& 55 \& 0.0036 <br>
\hline
\end{tabular}

Table C-1-2

| PRESENT RESULTS |  |  |  |  |  |  |  |  |  |  |  | LIVERMORE RESULTS |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 235 |  |  |  |  |  | 239 $\mathrm{Pu}^{\text {c }}$ |  |  |  |  |  | ${ }^{252}$ Cf |  |  |  |
| $\mathrm{E}_{\gamma}$ $(\mathrm{keV})$ | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\pm \Delta \mathrm{T}_{1 / 2}$ $(\%)$ | $\mathrm{T}_{1 / 2}$ Ref.f. | $\begin{gathered} \mathrm{I}_{\gamma} \\ \text { (photons/ } \\ \text { fission) } \\ \hline \end{gathered}$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\mathrm{T}_{1 / 2}$ <br> Ref. | $\begin{aligned} & \mathrm{I}_{\gamma} \\ & \text { (photons/ } \\ & \text { fission) } \\ & \hline \end{aligned}$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} \mathrm{E}_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | $A^{\text {a }}$ | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\begin{gathered} \mathrm{I}_{\dot{\gamma}}^{\mathrm{b}} \\ \text { (photons } \\ \text { fission) } \end{gathered}$ |
| 162.4 | 97.1 | 4 |  | 0.0073 | 5 | 153.8 | 143. | 12 |  | 0.0021 | 11 | 153.6 $\left\{\begin{array}{l}163.0 \\ 163.5\end{array}\right.$ | $108 \pm 0$ $133+0,-1$ $152 \pm 0$ | 110 110 82 | $\begin{aligned} & 0.0077 \\ & 0.0018 \\ & 0.00011 \end{aligned}$ |
| 167.4 | 240. |  | 4 | 0.0032 | 15 | 167.1 | 240. |  | 4 | 0.00042 | 12 | 167.1 | $96_{-0}^{+1}$ | 240 | 0.0015 |
| 167.7 | 13. |  | 4 | 0.0072 | 30 | 167.7 | 13. |  | 4 | 0.0028 | 30 | 167.7 | 146-1 | 13 | 0.0073 |
| 169. | 1100. |  | 4 | 0.0027 | 21 | 170.5 | 1100. |  | 4 | 0.0039 | 19 | 170.5 | $98 \pm 0$ | 1100 | 0.0020 |
| 181.2 | 127. | 20 |  | 0.0011 | 36 | 181.0 | 127. | 20 |  | 0.0024 | 38 |  |  |  |  |
| 181.5 | 28.0 | 10 |  | 0.0013 | 30 | 181.6 | 28.0 | 10 |  | 0.0026 | 32 |  |  |  |  |
| 186.5 | 1166 | 15 |  | 0.0017 | 30 | 186.1 | 1000. | 30 |  | 0.0013 | 42 | 186.4 | $98 \pm 1^{\text {d }}$ | 650 | 0.0005 |
| 191.7 | 115. | 10 |  | 0.0023 | 25 | 191:8 | 162. | 33 |  | 0.0010 | 40 | 191.1 | ${ }^{94}{ }_{-1}^{+0}$ | 110 | 0.00029 |
| 197.3 | 3400. |  | 9 | 0.0082 | 15. | 197.3 | 3400. |  | 9 | 0.0152 | 15 | 197.3 | 136 | 2800 | $0.0060 \stackrel{\text { r }}{\sim}$ |
| 204.0 | 3000. |  | 4 | 0.0064 | 9 | 204.0 | 3000. |  | 4 | 0.0034 | 11 | 204.0 | $98 \pm 1$ | 3000 | 0.0013 |
| 204.3 | 24. |  | 4 | 0.0408 | 15 | 204.2 | 24. |  | 4 | 0.0238 | 15 | 204.3 | $95 \pm 2$ | 24 | 0.0062 |
| 217.4 | 94.4 | 10 |  | 0.0036 | 10 | 217.3 | 128. | 25 |  | 0.0015 | 25 | 217.2 | $93 \pm 0$ | 70 | 0.00044 |
| 228.8 | 16.5 | 4 |  | 0.0014 | 25 |  |  |  |  |  |  |  |  |  |  |
| 276.1 | 7.6 | 15 |  | 0.0065 | 60 | 276.0 | 7.6 |  | e | 0.0039 | 80 | 276.5 | 91 | 6 | 0.00043 |
| 283.8 | 8. |  | 4 | 0.0040 | 80 | 283.5 | 8. |  | 4 | 0.0040 | 80 | 283.9 | 147 ${ }_{-0}^{+1}$ | 8 | 0.0064 |
| 288.1 | 12.6 | 19 |  | 0.0015 | 30 | 288.2 | 12.9 | 10 |  | 0.00194 | 30 | 288.2 | $146 \pm 0$ | 17 | 0.0029 |
| 297.3 | 170. | 3 |  | 0.0297 | 5 | 297.2 | 183. | 5 |  | 0.0226 | 5 | 296.9 | $134 \pm 0$ | 162 | 0.0103 |
| 314.3 | 8.2 | 10 |  | 0.0055 | 60 | 314.1 | 8.7 | 10 |  | 0.0082 | 60 | 314.4 | 138 ${ }_{-1}^{+0}$ | 9 | 0.0039 |
| 325.3 | 555. | 5 |  | 0.0053 | 6 | 324.9 | 578. | 18 |  | 0.0031 | 19 | 324.5 | $135 \pm 0$ | 570 | 0.0031 |
|  |  |  |  |  |  | 330.8 | 26. | 30 |  | 0.028 | 33 |  |  |  |  |
|  |  |  |  |  |  | 330.8 | 168. | 70 |  | 0.00021 | 75 |  |  |  |  |
| 339.8 | 86. | 6 |  | 0.00184 | 8 | 339.5 | 79. | 14 |  | 0.00077 | 17 |  |  |  |  |
|  |  |  |  |  |  | 343.2 | 674. | 36 |  | 0.0011 | 37 |  |  |  |  |

Table C-1-3

| PRESENT RESULTS |  |  |  |  |  |  |  |  |  |  |  | LIVERMORE RESULTS |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ${ }^{235}$ U |  |  |  |  |  | ${ }^{239}{ }_{\text {Pu }}$ |  |  |  |  |  | ${ }^{252} \mathrm{Cf}$ |  |  |  |
| $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \\ \hline \end{gathered}$ | $\mathrm{T}_{1 / 2}$ <br> (nsec) | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { Ref. } \end{gathered}$ | $\begin{gathered} \mathrm{I}_{\gamma} \\ \text { (photons/ } \\ \text { fission) } \\ \hline \end{gathered}$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \\ \hline \end{gathered}$ |  | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\begin{aligned} & \mathrm{T}_{1 / 2} \\ & \text { Ref. } \end{aligned}$ | $\qquad$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | $A^{\text {a }}$ | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\begin{aligned} & \mathrm{I}_{\gamma}^{\mathrm{b}} \\ & \text { (photons } \\ & \text { fission) } \end{aligned}$ |
| 352.3 | 21.8 | 5 |  | 0.0326 | 20 | 352.1 | 22.6 | 5 |  | 0.0181 | 20 | 352.3 | $95 \pm 0$ | 21 | 0.0046 |
| 381.3 | 57. | 7 |  | 0.0012 | 19 | 381.3 | 57. | 20 |  | 0.00095 | 30 |  |  |  |  |
| 381.5 | 3400. |  | 9 | 0.0059 | 22 | 381.1 | 3400. |  | 9 | 0.0176 | 20 | 380.7 | 136 | 3400 | 0.0073 |
| 387.5 | 119. | 10 |  | 0.0010 | 30 | 387.2 | 115. | 3 |  | 0.0030 | 16 | 387.1 | $135_{-1}^{+0}$ | 110 | 0.00082 |
| 400.1 | 7.8 | 10 |  | 0.0059 | 80 | 400.1 | 8.1 | 10 |  | 0.0075 | 80 | 400.2 | $138{ }_{-1}^{+0}$ | 9 | 0.0037 |
| 412.7 | 18.3 | 6 |  | 0.0034 | 25 | 412.1 | 22.4 | 9 |  | 0.0020 | 25 |  |  |  |  |
| 415.7 | 24.5 | 6 |  | 0.0024 | 20 | 415.4 | 20.2 | 13 |  | 0.0021 | 20 | 415.6 | ${ }_{99}{ }_{-0}^{+1}$ | 16 | 0.00051 |
| 426.8 | 15.4 | 7 |  | 0.0028 | 30 | 426.4 | 15.7 | 6 |  | 0.0028 | 30 | 426.8 | $100 \pm 1$ | 16 | 0.00088 |
| 433.0 | 1960. | 48 |  | 0.0026 | 52 | 432.3 | 1450. | 55 |  | 0.0038 | 60 |  |  |  | $\stackrel{\sim}{\sim}$ |
|  |  |  |  |  |  | 444.7 | 215. | 5 |  | 0.00111 | 15 |  |  |  | $\checkmark$ |
| 444.8 | 50. | 10 |  | 0.00043 | 27 |  |  |  |  |  |  |  |  |  |  |
| 444.8 | 520. | 15 |  | 0.00099 | 29 |  |  |  |  |  |  |  |  |  |  |
| 454.2 | 19.2 | 16 |  | 0.00111 | 25 | 454.2 | 15.5 | 17 |  | 0.00125 | 25 |  |  |  |  |
| 461.2 | 161. | 14 |  | 0.00062 | 21 | 461.4 | 90. | 5 |  | 0.00075 | 15 |  |  |  |  |
| 522.4 | 382. | 11 |  | 0.00212 | 17 |  |  |  |  |  |  |  |  |  |  |
| 536.3 | 22.7 | 10 |  | 0.00178 | 16 | 535.5 | 28.9 | 10 |  | 0.00161 | 15 |  |  |  |  |
| 575.8 | 16.8 | 10 |  | 0.00226 | 30 | 576.2 | 19.8 | 16 |  | 0.00147 | 30 |  |  |  |  |
| 589.8 | 68.4 | 6 |  | 0.00183 | 12 | 590.3 | 100. | 50 |  | 0.0013 | 52 |  |  |  |  |
| 614.2 | 17.3 | 10 |  | 0.0194 | 30 | 614.2 | 17.3 | 10 |  | 0.0179 | 30 | 614.2 | $100 \pm 0$ | 20 | 0.0034 |
| 619.6 | 96. | 5 |  | 0.00187 | 10 |  |  |  |  |  |  |  |  |  |  |
| 648.7 | 165. | 17 |  | 0.00146 | 21 | 648.2 | 104. | 32 |  | 0.00076 | 34 |  |  |  |  |
| 746.7 | 132. | 37 |  | 0.00093 | 39 |  |  |  |  |  |  |  |  |  |  |
| 770.4 | 2060. | 60 |  | 0.0026 | 64 | 770.1 | 1050. | 35 |  | 0.0025 | 37 |  |  |  |  |
| 774.6 | 46.5 | 7 |  | 0.00118 | 12 | 774.8 | 49.9 | 12 |  | 0.0015 | 16 |  |  |  |  |

Table C-1-4

| PRESENT RESULTS |  |  |  |  |  |  |  |  |  |  |  | LIVERMORE RESULTS |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ${ }^{235}$ |  |  |  |  |  | $\cdots{ }^{-} \cdot{ }^{239} \mathrm{Pu}$ |  |  |  |  |  | ${ }^{252} \mathrm{Cf}$ |  |  |  |
| $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | $\mathrm{T}_{1 / 2}$ <br> (nsec) | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { Ref. } \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{I}_{\gamma} \\ \text { (photons/ } \\ \text { fission) } \\ \hline \end{gathered}$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} \mathrm{E}_{\gamma} \\ (\mathrm{keV}) \\ \hline \end{gathered}$ | $\mathrm{T}_{1 / 2}$ <br> (nsec) | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\begin{aligned} & \mathrm{T}_{1 / 2} \\ & \text { Ref. } \end{aligned}$ | $\begin{gathered} \mathrm{I}_{\gamma} \\ \text { (photons/ } \\ \text { fission) } \end{gathered}$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | $A^{\text {a }}$ | $\mathrm{T}_{1 / 2}$ <br> (nsec) | $\begin{aligned} & \mathrm{I}_{\gamma}^{\mathrm{b}} \\ & \text { (photons. } \\ & \text { fission) } \end{aligned}$ |
| 810.6 | 102. | 4 |  | 0.00134 | 16 |  |  |  |  |  |  |  |  |  |  |
| 815.4 | 15.0 | 10 |  | 0.00074 | 40 |  |  |  |  |  |  |  |  |  |  |
| 817.5 | 117. | 20 |  | 0.00070 | 35 |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  | 840.3 | 129. | 25 |  | 0.00084 | 40 |  |  |  |  |
| 968.6 | 28.2 | 14 |  | 0.00144 | 17 | 969.5 | 28.8 | 6 |  | 0.00197 | 10 |  |  |  |  |
| 974.7 | 120. | 5 |  | 0.00239 | 8 | 975.2 | 69. | 35 |  | 0.0020 | 30 |  |  |  |  |
|  |  |  |  |  |  | 975.2 | 278. | 35 |  | 0.0027 | 30 |  |  |  |  |
| 998.4 | 96. | 11 |  | 0.00092 | 35 |  |  |  |  |  |  |  |  |  |  |
| 1025.3 | 20.5 | 8 |  | 0.00211 | 20 | 1025.9 | 20.9 | 8 |  | 0.00146 | 20 |  |  |  |  |
| 1086.5 | 21.6 | 12 |  | 0.00129 | 25 | 1087.1 | 19.7 | 10 |  | 0.00145 | 25 |  |  |  |  |
| 1103.4 | 113. | 5 |  | 0.0045 | 7 | 1103.7 | 111. | 4 |  | 0.0062 | 6 |  |  |  | N |
| 1150.7 | 110. | 5 |  | 0.0041 | 5 | 1151.1 | 124. | 9 |  | 0.0061 | 9 | 1151.6 | $134^{+0}$ | 90 | 0.0021 |
| 1180.8 | 612. | 10 |  | 0.0054 | 12 | 1180.8 | 499. | 13 |  | 0.0031 | 13 | 1181.0 | $135+0$ | 670 | 0.0030 |
| 1221.5 | 31. | 50 |  | 0.0021 | 60 | 1221.4 | 15.2 | 40 |  | 0.0042 | 60 | 1221.0 | 137 ${ }_{-1}^{+2}$ | 6 | 0.0073 |
| 1279.8 | 169. | 3 |  | 0.0235 | 5 | 1279.8 | 179. | 4 |  | 0.0177 | 5 | 1279.8 | $134 \pm 0$ | 164 | 0.0126 |
| 1313.9 | 3400. |  | 9 | 0.0095 | 30 | 1313.4 | 3400. |  | 9 | 0.0156 | 35 | 1313.3 | 136 | 3000 | 0.0057 |

$a_{\text {Because of }}$ the large number of gamma rays at low energies, the assignment of the ${ }^{235} \mathrm{U}_{\mathrm{U}}$ and ${ }^{239} \mathrm{Pu}$ peaks to the A values given for the ${ }^{252}$ Cf peaks is not positive below $\sim 200 \mathrm{keV}$.
$b_{\text {See }}$ Section 4.1 for a comparison of the Livermore (Ref. 4) results for ${ }^{252} \mathrm{Cf}$ and the present results for a number of gamma rays for 252 Cf .
${ }^{C}$ This peak does not correspond to the peak with approximately the same energy and same half-life observed in the Livermore data (Ref. 4), since the Livermore peak is from A 108, and the 235 U and 239 pu fission fragment yields for this mass number are significantly lower than the observed yields.
$\mathrm{d}_{\text {Since }}$ the error bars on the ${ }^{235} \mathrm{U}$ and ${ }^{239}$ Pu half lives do not overlap the value of the ${ }^{252}$ Cf half life, the gamma rays in 235 U and 239 Pu may be from a different mass number.
$e_{\text {The half }}$ life was taken from the present ${ }^{235} U$ data.

Table C-2
GROUPED VALUES FOR 235 J ISOMERIC GAMMA RAYS
A. Number of resolved and continuum gamma rays per fission

| Energy <br> Group <br> (keV) | $20-45$ | $45-100$ | $100-215$ | $215-458$ | $458-958$ | $20-958$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |
| $140-380$ | $4.5 \times 10^{-2}$ | $4.0 \times 10^{-2}$ | $2.9 \times 10^{-2}$ | $1.85 \times 10^{-2}$ | $1.11 \times 10^{-2}$ | $1.43 \times 10^{-1}$ |
| $380-620$ | $1.63 \times 10^{-2}$ | $1.06 \times 10^{-2}$ | $5.9 \times 10^{-3}$ | $4.1 \times 10^{-3}$ | $2.7 \times 10^{-3}$ | $4.0 \times 10^{-2}$ |
| $620-860$ | $3.1 \times 10^{-3}$ | $3.0 \times 10^{-3}$ | $2.6 \times 10^{-3}$ | $1.93 \times 10^{-3}$ | $1.32 \times 10^{-3}$ | $1.19 \times 10^{-2}$ |
| $860-1100$ | $3.9 \times 10^{-3}$ | $2.7 \times 10^{-3}$ | $2.1 \times 10^{-3}$ | $1.03 \times 10^{-3}$ | $6.1 \times 10^{-4}$ | $1.04 \times 10^{-2}$ |
| $1100-1340$ | $5.4 \times 10^{-3}$ | $7.6 \times 10^{-3}$ | $1.00 \times 10^{-2}$ | $9.9 \times 10^{-3}$ | $6.0 \times 10^{-3}$ | $7.0 \times 10^{-3}$ |
| $140-1340$ | $7.4 \times 10^{-2}$ | $6.4 \times 10^{-2}$ | $4.91 \times 10^{-2}$ | $3.5 \times 10^{-2}$ | $2.2 \times 10^{-2}$ | $2.4 \times 10^{-1}$ |

B. Energy (keV) per fission for the resolved and continuum gamma rays

| $140-380$ | 10.8 | 9.2 | 6.4 | 4.4 | 2.6 | 33. |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $380-620$ | 8.5 | 5.5 | 3.0 | 2.0 | 1.26 | 20.4 |
| $620-860$ | 2.9 | 2.2 | 2.0 | 1.39 | .97 | 9.9 |
| $860-1100$ | 3.9 | 2.7 | 2.1 | 1.02 | .59 | 10.3 |
| $1100-1340$ | 6.5 | 9.3 | 12.4 | 12.2 | 7.5 | 48. |
| $140-1340$ | 33. | 28.9 | 25.9 | 21.0 | 12.9 | 121. |

C. Ratio of energy of the resolved gamma rays to the energy of the resolved and continuum gamma rays

| $140-380$ | 0.89 | 0.91 | 0.89 | 0.94 | 0.94 | 0.90 |
| ---: | :--- | :--- | :--- | :--- | :--- | :--- |
| $380-620$ | 0.73 | 0.71 | 0.54 | 0.53 | 0.70 | 0.67 |
| $620-860$ | 0.27 | 0.47 | 0.57 | 0.66 | 0.55 | 0.47 |
| $860-1100$ | 0.47 | 0.64 | 0.54 | 0.67 | 0.32 | 0.54 |
| $1100-1340$ | 0.75 | 0.90 | 0.92 | 0.95 | 0.97 | 0.91 |
| $140-1340$ | 0.71 | 0.81 | 0.81 | 0.88 | 0.89 | 0.80 |

D. Uncertainties (\%) for the number of gamma rays per fission and the energy per fission
The uncertainties do not include possible systematic uncertainties of $\sim \pm 10 \%$.

| $140-380$ | 10 | 7 | 5 | 4 | 5 |
| :---: | :---: | ---: | ---: | ---: | ---: |
| $380-620$ | 17 | 12 | 10 | 10 | 6 |
| $620-860$ | 36 | 16 | 13 | 10 | 14 |
| $860-1100$ | 24 | 11 | 16 | 13 | 40 |
| $1100-1340$ | 10 | 4 | 4 | 3 | 3 |

Table C-3
GROUPED VALUES FOR ${ }^{239} \mathrm{Pu}$ ISOMERIC GAMMA RAYS
A. Number of resolved and continuum gamma rays per fission

| Energy <br> Group <br> (keV) | $20-45$ | $45-100$ | $100-215$ | $215-458$ | $458-958$ | $20-958$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |
| $140-380$ | $3.6 \times 10^{-2}$ | $3.0 \times 10^{-2}$ | $1.96 \times 10^{-2}$ | $1.35 \times 10^{-2}$ | $1.00 \times 10^{-2}$ | $1.09 \times 10^{-1}$ |
| $380-620$ | $1.45 \times 10^{-2}$ | $9.1 \times 10^{-3}$ | $5.9 \times 10^{-3}$ | $4.9 \times 10^{-3}$ | $3.4 \times 10^{-3}$ | $3.8 \times 10^{-2}$ |
| $620-860$ | $4.0 \times 10^{-3}$ | $2.7 \times 10^{-3}$ | $2.5 \times 10^{-3}$ | $1.83 \times 10^{-3}$ | $1.72 \times 10^{-3}$ | $1.27 \times 10^{-2}$ |
| $860-1100$ | $4.1 \times 10^{-3}$ | $3.2 \times 10^{-3}$ | $2.4 \times 10^{-3}$ | $2.2 \times 10^{-3}$ | $1.40 \times 10^{-3}$ | $1.34 \times 10^{-2}$ |
| $1100-13400$ | $5.8 \times 10^{-3}$ | $7.3 \times 10^{-3}$ | $9.5 \times 10^{-3}$ | $9.3 \times 10^{-3}$ | $6.0 \times 10^{-3}$ | $3.8 \times 10^{-2}$ |
| $140-1340$ | $6.4 \times 10^{-2}$ | $5.3 \times 10^{-2}$ | $4.0 \times 10^{-2}$ | $3.2 \times 10^{-2}$ | $2.2 \times 10^{-2}$ | $2.1 \times 10^{-2}$ |

B. Energy (keV) per fission for the resolved and continuum gamma rays

| $140-380$ | 9.4 | 7.6 | 4.7 | 3.3 | 2.4 | 27.4 |
| :---: | :---: | :---: | :---: | :---: | :---: | ---: |
| $380-620$ | 7.5 | 4.6 | 2.9 | 2.2 | 1.53 | 18.7 |
| $620-860$ | 3.0 | 2.0 | 1.84 | 1.39 | 1.29 | 9.4 |
| $860-1100$ | 4.1 | 3.2 | 2.4 | 2.2 | 1.36 | 13.2 |
| $1100-1340$ | 7.1 | 8.9 | 11.5 | 11.5 | 7.5 | 46. |
| $140-1340$ | 31. | 26.3 | 23.2 | 20.5 | 14.0 | 115. |

C. Ratio of energy of the resolved gamma rays to the energy of the resolved and continuum gamma rays

| $140-380$ | 0.91 | 0.94 | 0.90 | 0.90 | 0.90 | 0.92 |
| :---: | :---: | :---: | :---: | :---: | :---: | :--- |
| $380-620$ | 0.74 | 0.73 | 0.50 | 0.49 | 0.70 | 0.67 |
| $620-860$ | 0.15 | 0.33 | 0.38 | 0.41 | 0.38 | 0.30 |
| $860-1100$ | 0.47 | 0.58 | 0.53 | 0.43 | 0.46 | 0.50 |
| $1100-1340$ | 0.74 | 0.87 | 0.89 | 0.93 | 0.93 | 0.88 |
| $140-1340$ | 0.70 | 0.79 | 0.77 | 0.79 | 0.80 | 0.76 |

D. Uncertainties (\%) for the number of gamma rays per fission and the energy per fission

The uncertainties do not include possible systematic uncertainties of $\sim \pm 15 \%$.

| $140-380$ | 9 | 5 | 7 | 4 | 3 |
| :---: | :---: | ---: | ---: | ---: | ---: |
| $380-620$ | 16 | 11 | 10 | 10 | 15 |
| $620-860$ | 42 | 21 | 19 | 18 | 19 |
| $860-1100$ | 24 | 13 | 17 | 23 | 32 |
| $1100-1340$ | 11 | 6 | 6 | 4 | 6 |

Table C-4
COMPARISON OF SELECTED ${ }^{252}$ Cf DELAYED GAMMA RAYS FROM PRESENT MEASUREMENT WITH THOSE FROM LIVERMORE MEASUREMENT ${ }^{1}$
The errors for the present results do not include systematic uncertainties of $\sim \pm 10 \%$

| PRESENT RESULTS |  |  |  |  |  | LIVERMORE RESULTS |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\begin{gathered} \mathrm{E}_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ |  | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\mathrm{T}_{1 / 2}$ Ref. | $\qquad$ | $\pm \Delta I_{\gamma}$ <br> (\%) | $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | A |  | $\begin{gathered} \mathrm{I}_{\gamma} \\ \text { (photons/ } \\ \text { fission) } \\ \hline \end{gathered}$ | $\pm \Delta I_{\gamma}$ <br> (\%) |
| 115.2 | 162. |  | 4 | 0.0058 | 9 | 115.0 | $134 \pm 0$ | 162 | 0.0061 | 7 |
| 176.3 | 89. | 5 |  | 0.0041 | 10 | 176.2 | $108{ }_{-0}^{+1}$ | 110 | 0.0031 | 7 |
| 197.4 | 3400. |  | 9 | 0.0092 | 15 | 197.3 | 136 | 2800 | 0.0060 | 8 |
| 297.3 | 168. | 3 |  | 0.0150 | 5 | 296.9 | $134 \pm 0$ | 162 | 0.0103 | 7 |
| 325.3 | 513. | 5 |  | 0.0042 | 15 | 324.5 | $135 \pm 0$ | 570 | 0.0031 | 8 |
| 352.3 | 23.1 | 5 |  | 0.0054 | 20 | 352.3 | $95 \pm 0$ | 21 | 0.0046 | 7 |
| 381.6 | 3400. |  | 9 | 0.0086 | 20 | 380.7 | 136 | 3400 | 0.0073 | 8 |
| 1150.6 | 103.1 | 6 |  | 0.0031 | 9 | 1151.6 | $134+0$ | 90 | 0.0021 | 11 |
| 1180.5 | 474. | 12 |  | 0.0029 | 10 | 1181.0 | ${ }_{135}^{+0}$ | 670 | 0.0030 | 13 |
| 1279.9 | 167. | 3 |  | 0.0114 | 5 | 1279.8 | $134 \pm 0$ | 164 | 0.0126 | 9 |
| 1313.4 | 3400. |  | 9 | 0.0086 | 35 | 1313.3 | 136 | 3000 | 0.0057 | 24 |

[^16]CASCADE DELAYED GAMMA RAYS FROM THE SAME ISOMERIC STATE
The ${ }^{235} \mathrm{U}$ and ${ }^{239} \mathrm{Pu}$ data are from the present experiment. The ${ }^{252}$ Cf data are from the Livermore experiment, 1 except the cases noted by a footnote to be from the present experiment. Systematic uncertainties in the photon intensities of $10 \%, 15 \%$, and $10 \%$ are not included in the present uncertainties in the $239^{\text {photon intensities of }} 10 \%$,

| $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | ```I (photons/ fission)``` | $\pm \Delta I_{Y}$ <br> (\%) | $\begin{gathered} E_{\gamma} \\ (\mathrm{keV}) \end{gathered}$ | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\pm \Delta \mathrm{T}_{1 / 2}$ <br> (\%) | $\begin{aligned} & \mathrm{I}_{\gamma} \\ & \text { (photons/ } \\ & \text { fission) } \end{aligned}$ | $\pm \Delta I_{Y}$ <br> (\%) | $\begin{gathered} E_{Y} \\ (\mathrm{keV}) \end{gathered}$ | A | $\begin{gathered} \mathrm{T}_{1 / 2} \\ \text { (nsec) } \end{gathered}$ | $\begin{gathered} I_{Y} \\ \text { (photons/ } \\ \text { fission) } \end{gathered}$ | $\pm \Delta I_{\gamma}$ <br> (\%) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| m-217.4 | 94. | 10 | 0.0036 | 10 | 217.3 | 128. | 25 | 0.0015 | 25 | 217.2 | $93 \pm 0$ | 70 | 0.00044 | 10 |
| :-191.7 | 115. | 10 | 0.0023 | 25 | 191.8 | 162. | 33 | 0.0010 | 40 | 191.1 | $94_{-1}^{+0}$ | 110 | 0.00029 | 13 |
| 204.3 | 24. |  | 0.0408 | 15 | 204.2 | 24. |  | 0.0238 | 15 | 204.3 | $95 \pm 2$ | 24 | 0.0062 | 12 |
| [352.3 | 21.8 | 5 | 0.0326 | 20 | 352.1 | 22.6 | 5 | 0.0181 | 20 | 352.3 | $95 \pm 0$ | 21 | 0.0046 | 7 |
| $\Gamma^{121.6}$ | 360. |  | 0.0101 | 7 | 121.4 | 360. |  | 0.0094 | 7 | 121.4 | ${ }_{99}{ }^{+1}$ | 360 | 0.0048 | 10 |
| L130.5 | 375. | 3 | 0.0089 | 9 | 130.1 | 340. |  | 0.0077 | 25 | 129.8 | ${ }_{9} 9+1$ | 340 | 0.0029 | 15 |
| ${ }^{115.3}$ | 175. | 4 | 0.0103 | 7 | 115.3 | 175. | 5 | 0.0089 | 7 | $\left\{115.2^{\text {a }}\right.$ |  | 162 | 0.0058 | 9 |
|  |  |  |  |  |  |  |  |  |  | \{115.0 | $134 \pm 0$ | 162 | 0.0061 | 7 |
| $-297.3$ | 170. | 3 | 0.0297 | 5 | 297.2 | 183. | 5 | 0.0226 | 5 | (297.3 ${ }^{\text {a }}$ |  | 168 | 0.0150 | 5 |
|  |  |  |  |  |  |  |  |  |  | 296.9 | $134 \pm 0$ | 162 | 0.0103 | 7 |
| 1279.8 | 169. | 3 | 0.0235 | 5 | 1279.8 | 179. | 4 | 0.0177 | 5 | \{1279.9 ${ }^{\text {a }}$ |  | 167 | 0.0114 | 5 |
|  |  |  |  |  |  |  |  |  |  | 1279.8 | $134 \pm 0$ | 164 | 0.0126 | 9 |
| -325.3 | 555. | 5 | 0.0053 | 6 | 324.9 | 578. | 18 | 0.0031 | 19 | 324.5 | $135 \pm 0$ | 570 | 0.0031 | 8 |
| 1180.8 | 612. | 10 | 0.0054 | 12 | 1180.8 | 499. | 13 | 0.0031 | 13 | 1181.0 | ${ }_{135}+0$ | 670 | 0.0030 | 13 |
| $\Gamma^{197.3}$ | 3400. |  | 0.0082 | 15 | 197.3 | 3400. |  | 0.0152 | 15 | $\left\{197.4^{\text {a }}\right.$ |  | 3400 | 0.0092 | 15 |
|  |  |  |  |  |  |  |  |  |  | $\{197.3$ | 136 | 2800 | 0.0060 | 8 |
| $-381.5$ | 3400. |  | 0.0059 | 22 | 381.1 | 3400. |  | 0.0176 | 20 | $\int 381.6^{\text {a }}$ |  | 3400 | 0.0086 | 20 |
|  |  |  |  |  |  |  |  |  |  | $\{380.7$ | 136 | 3400 | 0.0073 | 8 |
| 1313.9 | 3400. |  | 0.0095 | 30 | 1313.4 | 3400. |  | 0.0156 | 35 | $\left\{1313.4^{\text {a }}\right.$ |  | 3400 | 0.0086 | 35 |
|  |  |  |  |  |  |  |  |  |  | $\{1313.3$ | 136 | 3000 | 0.0057 | 24 |
| $\left[^{314.3}\right.$ | 8.2 | 10 | 0.0055 | 60 | 314.1 | 8.7 | 10 | 0.0082 | 60 | 314.4 | ${ }_{138}+0$ | 9 | 0.0039 | 8 |
| [400.1 | 7.8 | 10 | 0.0059 | 80 | 400.1 | 8.1 | 10 | 0.0075 | 80 | 400.2 | $138^{+0}$ | 9 | 0.0037 | 9 |

${ }^{\text {a }}$ Data for these gama rays are from the present experiment.
${ }^{1}$ W. John, F. W. Guy, and J. J. Wesolowski, Physe Rev. C2, 1451 (1970).

## LAWRENCE LIVERMORE LABORATORY

## A. STANDARDS

1. 235 U Fission Cross-Section Measurement. (J. B. Czirr and G. S. Sidhu)

We have completed a measurement of the relative 235 U fission cross section covering the $3-$ to $20-\mathrm{MeV}$ energy range. Data analysis is in the final stages and a complete report is scheduled by July, 1974. The statistical plus systematic errors are less than $\pm 2 \%$ from 3 to 14 MeV .

The neutron flux was measured over the full energy range with the use of a proton-recoil detector and a single $\mathrm{CH}_{2}$ radiator foil. The background was measured by replacing the $\mathrm{CH}_{2}$ with a thin graphite foil and was observed to be less than $6 \%$ at all energies.

Figure A-l is a preliminary plot of the data normalized to 1198 mb at 3.5 MeV .

## B. NEUTRON DATA APPLICATIONS

1. Integral Measurements of Gamma Spectra from Nitrogen and Oxygen Bombarded with $14-\mathrm{MeV}$ Neutrons. (L. F. Hansen, T. T. Komoto, C. M. Logan, B. A. Pohl, C. Wong and J. D. Anderson)

The gamma spectra from 0.5, 1.1, and 3.1 mean free paths (m.f.p.) of nitrogen and $0.7 \mathrm{~m} . f . \mathrm{p}$. of oxygen have been measured between 0.5 and 10 MeV using the sphere transmission and time-of-flight techniques. The experimental geometry and electronics for these measurements are identical to that described earlierl for the neutron measurements. The compton recoils in the $\mathbb{N E} 213$ scintillator were measured by time gating on the prompt $\gamma$-rays from the nitrogen and oxygen. Proton-electron discrimination was used to insure that only $\gamma$-ray recoils were being observed. The targets were dewars filled with liquid nitrogen or oxygen. The measurements were carried out at $26^{\circ}$ and $120^{\circ}$ and the detectors used at these angles were $5.08-\mathrm{cm}$ diameter by $5.08-\mathrm{cm}$ long, Pilot B and NE 213 scintillators, respectively. At $26^{\circ}$ the flight path was short ( 565 cm ), such that the number of overlap neutrons under the prompt- $\gamma$ signal is small, hence proton-electron discrimination was not needed. The absolute calibration of the scintillator system was carried out with gamma sources up to 1.84 MeV . A gamma spectrum from a pulsed carbon sphere extended
${ }^{l_{C}}$. Wong et al., Livermore Pulsed Sphere Program: Program Summary through July, 1971, UCRL-51144 (1972).

the calibration up to 4.43 MeV while the recoil spe, ra from $14-\mathrm{MeV}$ neutrons was used ${ }^{2}$ to obtain higher energy calibration points.

Calculations to reproduce the measured nitrogen and oxygen spectra are in progress. The TARTNP Code, 3 which is a coupled neutronphoton Monte Carlo Transport Code, and the ENDL Library have been used to generate the gamma spectra. The recoil electron response of the detectors as a function of gamma energy has been calculated with the Monte Carlo Photon Transport code TORTE. ${ }^{4}$ This last calculation has been able to reproduce the shape and the magnitude of the recoil electron spectra from the standard gamma sources ( $22 \mathrm{Na}, 137 \mathrm{Cs},{ }^{60} \mathrm{Co}$, and 88 y ) with an accuracy better than 10\%. Preliminary comparisons between the nitrogen measurements and the calculations indicate that the calculations are systematically lower than the measurements by $50 \%$ or more. The discrepancy seems to increase as a function of mean free path.
> 2. Comparison Between the Calculation using the ENDF/B-III, ENDF/B-IV, and the ENDL Neutron Cross Sections and the Measurements for 0.7 m.f.p. Oxygen. (L. F. Hansen, T. T. Komoto, C. M. Logan, B. A. Pohl, C. Wong and J. D. Anderson)

> The $0.7 \mathrm{~m} . f . \mathrm{p}$. measurements for oxygen ${ }^{l}$ have been compared with the predictions of the Monte Carlo Neutron Transport Code TART using the ENDF/B-III, 5 the most recent version ${ }^{6}$ ENDF/B-IV, and the revised ENDL 7 Livermore Neutron Library.

Table B-l gives the integral values of the measured and calculated spectra carried out with the above neutron libraries as a function of emitted neutron energy. From the comparison between the magnitude of the integrals with the measurements it can be concluded: a) The revised ENDL Library gives the best overall agreement with the measurements. b) As regards the III and IV versions of the ENDF/B Library, III does a better job in reproducing the magnitude of the measured integrals. c) The differences between the two versions of the ENDF/B Library are largest for the energy interval 2 to 10 MeV . Since the magnitude of the cross sections at 14 and 14.6 MeV is very similar between versions III and IV, the observed difference can only result from more substantial changes ${ }^{6}$ that were carried out in ENDF/B-IV at lower energies. Table B-2 lists the cross sections at 14 and 14.6 MeV for the above three neutron libraries.

[^17]
## Table B-1

Comparison between the measured integrals and the calculations for 0.7 m.f.p. of oxygen carried out with the different neutron libraries.

| $\begin{aligned} & \text { Time (ns) } \\ & \left(E_{n}-\mathrm{MeV}\right) \end{aligned}$ | $\begin{aligned} & \text { Experi- } \\ & \text { ment }( \pm \%) \end{aligned}$ | TART <br> ENDL | $\begin{gathered} \text { TART } \\ (\text { ENDF/B-III) } \end{gathered}$ | $\begin{gathered} \text { TART } \\ (\mathrm{ENDF} / \mathrm{B}-\mathrm{IV}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: |
| $\begin{aligned} & 142-174 \\ & (15-10) \end{aligned}$ | . 738 | . $708(-4.2 \%)$ | . $7412(+0.4 \%)$ | . $743(+0.7 \%)$ |
| $\begin{aligned} & 174-288 \\ & (10-3.6) \end{aligned}$ | . 092 | . $116(+26.0 \%)$ | .107(+16.0\%) | .122( +33.0\%) |
| $\begin{aligned} & 288-386 \\ & (3.6-2.0) \end{aligned}$ | . 047 | . $051(+8.5 \%)$ | . $063(+34.0 \%)$ | . $069(+47 \%)$ |
| TOTAL | . 877 | . $875(0.0 \%$ ) | . $911(+3.9 \%)$ | . $934(+6.5 \%)$ |

Table B-2

Point cross sections (barns) for oxygen for incident neutron energies of 14 and 14.6 MeV listed in the different Libraries.

| Energy | Neutron Library | $\sigma_{\text {total }}$ | $\sigma_{e l}$ | $\sigma_{n-e l}$ | $\sigma\left(n-n^{\prime}\right)$ | $\sigma(n, p)$ | $\underline{\sigma}\left(n_{2} n^{\prime} p\right)$ | $\underline{\sigma}(\mathrm{n}, \mathrm{d})$ | $\underline{O}(\mathrm{n}, \alpha)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 14 MeV | ENDL | 1.645 | . 960 | .685 | . 325 | .0400 | - | . 0300 | .140 |
|  | ENDF/B-III | 1.608 | . 955 | . 653 | .472 | . 0449 | - | . 153 | . 122 |
|  | ENDF/B-IV | 1.619 | .956 | .663 | .474 | . 0471 | - | . 0153 | . 126 |
| $\begin{aligned} & 14.6 \\ & \mathrm{MeV} \end{aligned}$ | ENDL | 1.731 | 1.021 | .710 | . 321 | . 0362 | . 006 | . 0320 | .176 |
|  | ENDF/B-III | 1.676 | . 991 | . 685 | . 523 | . 0365 | - | . 0136 | . 112 |
|  | ENDF/B-IV | 1.669 | . 981 | . 689 | . 520 | . 0385 | - | . 0137 | . 116 |

3. High-Energy Measurements of ${ }^{233} Z_{U},{ }^{238} U_{U}$, and ${ }^{239}$ Pu Fission Cross Sections Relative to 235U Using the Method of Threshold Cross Sections. (J.W. Behrens and G. W. Carlson)

Fission cross section measurements for a wide collection of uranium and plutonium isotopes are presently being conducted at LLL using the $100-\mathrm{MeV}$ Electron Linear Accelerator as a pulsed source for neutrons. To obtain fission cross section ratios above 1 MeV , we are using a method called the Threshold Cross Section Method. 8 This method allows us to obtain fission cross section ratios without depending on normalizations to absolute cross section measurements.

Fission cross section ratios of $\sigma_{f}(233 U): \sigma_{f}(235 U), \sigma_{f}(239 \mathrm{Pu})$ : $\sigma_{f}(235 \mathrm{U}), \sigma_{f}(238 \mathrm{U}): \sigma_{f}(235 \mathrm{U}), \sigma_{f}(238 \mathrm{U}): \sigma_{f}(233 \mathrm{U})$, and $\sigma_{f}(238 \mathrm{U}): \sigma_{f}(239 \mathrm{Pu})$ have been measured. The ratios of the fission cross sections of 238 J to $233 \mathrm{U}, 235 \mathrm{~J}$ and 239 Pu extend from $1-20 \mathrm{MeV}$ with an energy resolution of $\leq 5 \%$ and uncertainties of $<5 \%$. The ratios of 239 Pu and 233 U to 235 J range from $10 \mathrm{keV}-20 \mathrm{MeV}$ with counting uncertainties of $<3 \%$ at $5 \%$ energy resolution. Preliminary data are being documented in a UCRL report which should be available for distribution in July, 1974.

We are preparing to measure the fission cross section ratios $\sigma_{f}(234 \mathrm{U}): \sigma_{\mathrm{f}}(235 \mathrm{U})$ and $\sigma_{\mathrm{f}}(236 \mathrm{U}): \sigma_{\mathrm{f}}(235 \mathrm{U})$. Measurements of $233 \mathrm{U}, 235 \mathrm{U}$, and 239 Pu fission cross sections relative to $10_{B}(n, \alpha)$ are planned from .01 eV to 100 keV neutron energy this summer.

## C. NUCLEAR DATA FOR SAFEGUARDS

1. Photofission and Photoneutron Cross-Section Measurements for $232 \mathrm{Th}, 233 \mathrm{U}, 234 \mathrm{U}_{2} 235 \mathrm{U}, 236 \mathrm{U}_{2} 238 \mathrm{U}, 237 \mathrm{~Np}$, and 239 Pu . (R. A. Alvarez, B. I. Berman, J. T. Caldwell t, E. Dowdy ${ }^{\dagger}$, T. F. Godlove*, P. Meyer)

Using the nearly monoenergetic photons, generated by in-flight positron annihilation, at the Livermore $100-\mathrm{MeV}$ electron-positron linac, we have made simultaneous measurements of the $(\gamma, n),(\gamma, 2 n)$, and ( $\gamma, f$ ) cross sections of $232 \mathrm{Th}, 233 \mathrm{~J}, 234 \mathrm{~J}, 235 \mathrm{U}, 236 \mathrm{U}, 238 \mathrm{U}, 237 \mathrm{~Np}$, and 239 Pu over an energy range from approximately 5 to 17 MeV , with a typical energy resolution of 200 keV . The average neutron multiplicity, $\bar{v}$, for fission events was also simultaneously determined as a function of photon energy. These data tie together, in a single measurement, both the near-threshold region and the region of the giant dipole resonance.

[^18]The major portion of the data was obtained on two sets of runs. On the first set, measurements were made for $232 \mathrm{Th}, 234 \mathrm{U}, 235 \mathrm{U}, 236 \mathrm{U}$, 238 U , and 239 Pu ; on the second set, $233 \mathrm{U}, 237 \mathrm{~Np}$, and 238 U were measured with the 238 U measurements serving to internormalize the two sets of data. On each set of runs after the linac beam was tuned for a given energy measurements for each isotope of that set were made, as well as background measurements for each, before proceeding to the next sequential energy. This technique virtually eliminates any small errors in the relative cross sections which might otherwise arise because of differences in beam tuning or small drifts in detector or beam-monitor efficiency.

On another set of runs, using the same apparatus, we have also measured $\beta$, the delayed neutron yield per fission, for $232 \mathrm{Th}, 235 \mathrm{U}, 236 \mathrm{U}$, and $238_{\mathrm{U}}$, at 10,9 and 16.8 MeV ; $\beta$ has also been measured at 14.5 MeV for $232 \mathrm{Th}, 235 \mathrm{U}$, and 238 U .

A detailed analysis of these data is in progress. Preliminary analysis of the $\vec{v}$ data for $234 \mathrm{U}, 235 \mathrm{U}, 236 \mathrm{U}, 238 \mathrm{U}$, and 239 Pu shows an essentially linear increase in $\bar{v}$ with increasing energy. For ${ }^{232} \mathrm{Th}$ there appears to be a minimum in $\nabla$ at a photon energy of approximately 7.5 MeV , consistent with previously reported low-energy measurements 9 ; above 8 $\mathrm{MeV} \bar{\nabla}$ appears to increase linearly with photon energy for 232 Th also. The preliminary data analysis also indicates structure in the ( $\gamma, \mathrm{n}$ ) and/ or ( $\gamma, f$ ) cross section in the near-threshold region for several of the isotopes.

## D. BASIC SCIENCE

1. $4 \mathrm{He}(\gamma, p)-(\gamma, n)$ Ratio Measurement. (T. W. Phillips, D. D. Faul B. L. Berman, J. R. Calarco* and J. R. Hall*)

A simultaneous measurement of the ratio $d \sigma\left(\gamma,{ }^{3} \mathrm{H}\right) /\left.\mathrm{d} \sigma\left(\gamma,{ }^{\mathrm{He}}\right)\right|_{90^{\circ}}$, using a bremsstrahlung beam (end-point energy 65 MeV ) from the LLL Linac and a collimated solid-state telescope (silcon detectors 5, 17, and 500 $\mu \mathrm{m}$ thick) has been completed. A three-dimensional projection from the data obtained with 0.1-atm ${ }^{4} \mathrm{He}$ gas is shown in Figure D-1. The separation of the data into trajectories for $3 \mathrm{He}, 3 \mathrm{H}, \mathrm{l}_{\mathrm{H}}$ and noise is apparent. It was found in tests of the counter telescope at Stanford that additional collimation was required to prevent edge effects from distorting our ratio measurements. The reduction in rate made separation of the 3 H events from $\mathrm{l}_{\mathrm{H}}$ and noise impossible at energies below 40 MeV in photon energy. To obtain results at lower energy the 3H data from a run with open collimation was normalized above 40 MeV to the

[^19]

Figure D-l Three-dimensional representation of the $\gamma+{ }^{4}$ He data from a

$3_{\mathrm{H}}$ data from the tightly-collimated detector and the $3_{\mathrm{H}}$ data of the tightly-collimated detector was used to extend the ratio down to 30 MeV . These results both are shown in Figure D-2. In the region from 39 to 47 MeV where the statistical errors are small these results confirm the work of Dodge and Murphy. 10
2. Gamma Spectra from Capture of $1-105 \mathrm{eV}$ Neutrons by Ta. (M. L. Stelts and J. C. Browne)

Neutrons from the Livermore $100-\mathrm{MeV}$ linac were used to study the high-energy capture- $\gamma$-ray spectra of Ta . A $13.4-\mathrm{m}$ flight path and a $20-n s e c$ beam width were adequate to resolve most resonances below 200 eV . Resonance-averaged spectra were measured above 200 eV . The high-energy photons were detected with a three-crystal spectrometer consisting of a $17.6-\mathrm{cm}^{3} \mathrm{Ge}(\mathrm{Li})$ diode between two $12.7 \times 12.7$ - $\mathrm{cm} \mathrm{NaI}(\mathrm{Tl})$ scintillators. The system resolution was 6 keV at $6-\mathrm{MeV}$ gamma energy.

Figure D-3 shows the distribution of partial radiative widths for three of the primary transitions for 20 resolved resonances. The distribution is fit well by a chi-squared distribution with one degree of freedom consistent with the statistical model for radiative decay.

Data analysis and data acquisition of the low-energy photon spectra are continuing.
3. A Hauser-Feschbach Calculation of the Neutron Spectrum from 252Cf Spontaneous Fission. (J. C. Browne and F. S. Dietrich)

In order to investigate the origin of high-energy $\gamma$-rays that we recently observedll from ${ }^{252}$ Cf spontaneous fission, we performed a statistical calculation using the Hauser-Feschbach formalism assuming the $\gamma$-rays originate by competition with neutron emission from the highlyexcited fission fragments. A spinoff of this calculation is the energy spectrum of neutrons emitted in 252Cf spontaneous fission.

Figure D-4 represents recent measurements of the ${ }^{252}$ Cf neutron spectrum by Meadows ${ }^{12}$ and by Green et al. ${ }^{13}$ Assuming a Maxwellian distribution of the form $\sqrt{E} \exp (-E / T)$ Meadows obtained a temperature $T=1.59 \mathrm{MeV}(0.5 \mathrm{MeV} \leq \mathrm{E} \leq 10 \mathrm{MeV}$ ) while Green et al. obtained $T=1.40$ MeV ( $1 \mathrm{MeV} \leq \mathrm{E}_{\mathrm{n}} \leq 8 \mathrm{MeV}$ ). More recent measurements by Auchampaugh et al. 14

[^20]

Figure D-2 Comparison of ( $\gamma, p$ )/( $\gamma, n$ ) ratios for two different detector collimation configurations discussed in the text. The 0.25-atm data is tightly collimated.


Figure D-3 Distribution of partial radiative widths for 3 primary transitions from 20 resolved resonances. The $v=1$ (Porter-Thomas) chi-squared distribution best fits the data.

are in excellent agreement with Green et al. Our calculation yields a temperature $T=1.25 \mathrm{MeV}$ for the $2-1 \overline{3 \mathrm{MeV}}$ neutron energy range in reasonable agreement with the Green data. Details of this calculation will be presented in a forthcoming paper
4. Neutron-Capture Cross Sections for 188,190,1920s. (J. C. Browne and B. L. Berman)

We have measured the $188,190,192$ os $(n, \gamma)$ cross sections for neutron energies from 2 eV to 160 keV . Capture $\gamma$-rays were detected via a pair of C6 D6 scintillators. The $3.9-\mathrm{eV}$ "black resonance" of $165_{\mathrm{Ho}}$ was used for cross-section normalization. The shape of the neutron flux was measured with the $10_{\mathrm{B}}(\mathrm{n}, \alpha \gamma)$ reaction using a $50-\mathrm{cm} 3 \mathrm{Ge}(\mathrm{Li})$ detector to observe the $477-\mathrm{keV} \gamma$-ray. The data are currently being analyzed. Similar measurements for $186,187,1890$ s are planned for late summer of this year.
5. Neutron Total Cross Section for Tritium. (T. W. Phillips, B. L. Berman and J. D. Seagrave*)

In preparation for our upcoming measurements of the $3_{H}(n, t o t)$ cross section, we have made preliminary measurements using $1_{H}$ and $2 H$ samples in the MeV region at the pulsed-neutron facility at the Livermore linac, using a $250-\mathrm{m}$ flight path and a proton-recoil neutron detector. The gas samples, which are contained in steel cylinders l-m long at $170-\mathrm{atm}$ pressure, are cycled automatically into the beam together with an identical evacuated sample container, and all three vessels are mounted inside a rotating secondary-containment vessel. Both neutron time-of-flight and proton-recoil pulse-height data are collected for each event in a way similar to the one used for our earlier measurements on 207 Pb .15

Numberous problems in the experimental apparatus and procedures have been uncovered and/or corrected during these preliminary measurements, and the main experiment is planned to be carried out in the late summer and early fall.

[^21]
## E. CONTROLLED THERMONUCLEAR RESEARCH APPLICATIONS

1. Calculations of a Fast Fission Blanket for DT Fusion Reactors with Two Evaluated Data Libraries. (R. C. Haight and J. D. Lee)

A conceptual fusion-fission hybrid reactor blanket of Werner and Lee ${ }^{16,17}$ has been investigated with two evaluated data libraries, the ENDF/B-III and the Lawrence Livermore Laboratory Evaluated Nuclear Data Library (ENDL). These libraries are similar in their evaluations of total, fission, capture and many other cross sections for the materials in this problem ( $238 \mathrm{U}, 235 \mathrm{U}, \mathrm{Nb}, \mathrm{Ni}, \mathrm{Fe}, 7_{\mathrm{Li}}, 6_{\mathrm{Li}}$ ). The neutron emission spectra following $14-\mathrm{MeV}$ neutrons incident on $238 \mathrm{U}, 235 \mathrm{U}$, No , Ni , and Fe are however quite different in the two evaluations with the ENDL having harder emission spectra.

Calculations were made with the Monte Carlo code TART. Significant differences were found in tritium breeding, 239 Pu breeding and 238 U and 235 U fissions with the ENDL calculation being higher by 7 to $28 \%$ (Table E-I). These differences are attributed to differences in emission spectra following the first non-elastic interaction of a $14-\mathrm{MeV}$ fusion neutron. With the harder emission spectrum (ENDL) there is a greater chance for these secondary neutrons to induce fission in 238 U which has an effective threshold near 1.5 MeV . With more fissions, there are more neutrons in the system and hence more tritium and 239 Pu breeding and more ${ }^{235}$ U fissions.

Relevant differential-integral tests of the evaluated neutron emission spectra above 2 MeV exist in the $14-\mathrm{MeV}$ pulsed spheres of the lithium isotopes, 1 of iron, 1,18 and of 235 U and 238 U . 1 The sphere data for the lithium isotopes are calculated quite well by either the ENDF/B-III or the ENDL. The sphere data for iron ${ }^{18}$ and the uranium isotopes 19 on the other hand, are calculated much better with the ENDL than the ENDF/B-III, the latter library giving too few non-elastic neutrons above 2 MeV . We therefore have more confidence in the ENDL evaluations for this particular conceptual design.

[^22]Table E-1 - Reactions by Zone per Fusion

| Reaction | ENDF | ENDL | $\begin{gathered} \text { RATIO } \\ \text { (ENDF/ENDL) } \end{gathered}$ |
| :---: | :---: | :---: | :---: |
| Tritium Breeding |  |  |  |
| $\sigma_{\text {Li }(n, t)}$ | 0.94 | 1.16 | 0.81 |
| $7_{\text {Li }\left(n, n^{\prime} t\right)}$ | 0.06 | 0.07 | 0.8 |
| Total Tritium Breeding | 1.00 | 1.23 | 0.81 |
| ${ }^{239}$ Pu Breeding |  |  |  |
| ${ }^{238} 8_{U(n, \gamma)}$ | 2.13 | 2.28 | 0.93 |
| Fission |  |  |  |
| ${ }^{238} \mathrm{U}^{\text {fission }}$ | 0.60 | 0.84 | 0.72 |
| ${ }^{235}$ U fission | 0.12 | 0.13 | 0.87 |
| Total fission | 0.72 | 0.97 | 0.74 |

## LA-UR

TITLE: LASL STATUS REPORT TO THE U. S. NUCLEAR DATA COMMITTEE

AUTHOR(S): Michael S. Moore

SUBMITTED TO: Contributed Laboratory Report to the U. S. Nuclear Data Committee Meeting September 1974 at Lawrence Berkeley Laboratory, Berkeley, California

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LOS ALAMOS SCIENTIFIC LABORATORY, UNIVERSITY OF CALIFORNIA
A. STANDARDS

1. Total Cross Sections of ${ }^{3} \mathrm{He}$ and ${ }^{4} \mathrm{He}$ (Seagrave, Ha11)

In the publication of the results on ${ }^{3} \mathrm{He}$ and ${ }^{4} \mathrm{He}$ total cross sections at RPI, 1 we offered to supply spline interpolation graphs and tables on request. To provide more useful access, the results for ${ }^{3} \mathrm{He}$ are shown in Table A-1. Graphs and a table for ${ }^{4} \mathrm{He}$ (which is complicated by fitting the sharp resonance near 22 MeV ) will be given in the next status report.
2. Total Cross Section of Tritium (Seagrave; Berman, LLL)

Preparations for this experiment are sufficiently complete that a one-week run on deuterium and hydrogen has been scheduled in May, provided that final welding and tests of the high-pressure transmission cells can be carried out as scheduled.

Provisions for total containment of a tritium leak within the sample-changer barrel have eased safety considerations; elaborate welding certification procedures and testing at LLL, together with the total dry run on deuterium (handled as if it were tritium) in the operational schedule, have contributed to the confidence with which the experiment will be conducted.
3. Absolute Cross Sections for ${ }^{235} \mathrm{U}(\mathrm{n}, \mathrm{f})$ (Smith, Hansen, Barton,

Considerable time has been spent checking the accuracy of our telescope treatment against other published work, such as that of Johnson, ${ }^{2}$ by Fowler, and an unpublished report. ${ }^{3}$ These checks give considerable confidence in the efficiency of the telescope and the accuracy of the paper. Drafts of the ${ }^{235} \mathrm{U}$ and the proton recoil telescope papers are expected to be completed and available shortly.
${ }^{1}$ C. A. Goulding, P. Stoler, and J. D. Seagrave, Nucl. Phys. A215 (1973) 253-259.
${ }^{2}$ Fast Neutron Physics
${ }^{3}$ BRL Report 1657 , by Andrus Niiler and James E. Youngblood (unpublished).

Table A-1
Interpolation Table for the ${ }^{3} \mathrm{He}$ Total Cross Sections

\section*{| Energy |
| :--- |
| (MeV) |}

0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0

Sigma (mb)
2820.03
2752.92
2721.34
2720.25
2744.61
2789.40
2849.58
2919.82
2992.86
3060.70
3115.56
3154.47
3179.01
3190.91
3191.92
3183.79
3147.07
3094.68
3036.50
2974.87
2911.33
2847.38
2784.54
2723.72
2664.92
2608.08
2553.13
2500.00
2448.61
2398.90
2350.79
2237.07
2131.84
2034.00
1942.61
1857.28
1777.69
1703.55
1634.54
1570.35
1510.70


Sigma (mb)
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
22.0
22.5
23.0
23.5
24.0
24.5
25.0
25.5
26.0
26.5
27.0
27.5
28.0
28.5
29.0
29.5
30.0
1455.26
1403.73
1355.80
1311.18
1269.55
1230.60
1194.04
1159.55
1126.84
1095.70
1066.07
1037.87
1011.05
985.53
961.24
938.12
916.09
895.10
875.07
855.94
837.63
820.09
803.24
787.01
771.34
756.16
741.41
727.01
712.89
699.00
685.25
671.59
657.95
644.25
630.44
616.44
602.18
587.60
572.64
557.21

## B. NEUTRON DATA APPLICATIONS

1. Weak Gamma Transitions from ${ }^{9} \mathrm{Be}(\mathrm{n}, \gamma){ }^{10} \mathrm{Be}$ and Radiative

The prompt gamma-ray spectrum from thermal neutron capture in natural beryllium ${ }^{1,2}$ has recently been remeasured with the internaltarget, thermal-capture-gamma-ray facility at the LASL Omega West Reactor. $\mathrm{A} G e(\mathrm{Li})$ detector, surrounded by an optically divided NaI annulus, was operated in the anticoincidence mode to observe the spectrum up to 3 MeV and in the double-escape mode to cover the 2 to 7 MeV energy range. The amount of target material viewed by the detector was approximately 0.6 mol. Cross-section normalization to hydrogen capture was made by recording the spectrum from the beryllium target combined with a $140 \mathrm{mg} / \mathrm{cm}^{2}$ target of $\mathrm{CH}_{2}$.

The gamma rays observed in this experiment are listed in Table B-1. The five weaker of these transitions have not been reported previously; the intensity of the weakest gamma ( 219 keV ) corresponds to a partial capture cross section of about $4 \mu \mathrm{~b}$. The transitions in Table B-1 are all consistent with known levels in ${ }^{10} \mathrm{Be}$, as shown in Fig. B-1.

The ( $n, \gamma$ ) cross section of ${ }^{9} \mathrm{Be}$, calculated by taking an energy-weighted sum of the observed gamma rays, is $7.6 \pm 0.8 \mathrm{mb}$. The value of $9.2 \pm 1.0 \mathrm{mb}$, given in BNL-325, ${ }^{3}$ is based on a variety of measurements that include gross absorption techniques (pile oscillator, diffusion) that are susceptible to trace amounts of chemical impurities in the sample used. The beryllium used in the measurement reported here was an exceptionally pure one, obtained from Kawecki Berylco Company. Its major impurities were determined for a separate application by observing the "impurity" capture gamma-ray spectrum.

[^23]

Fig. B-1. Decay of ${ }^{10} \mathrm{Be}$ following thermal neutron capture by ${ }^{9}$ Be. Intensities are in photons for 100 n captured; transition and level energies are in keV.
2. R-Matrix Analysis of the Compound System ( $\mathrm{n}+{ }^{12} \mathrm{C}$ ) from 1.6 to 8.3 MeV ) (Auchampaugh, Ragan)

The least-squares search routines MULTI ${ }^{1}$ and EDA ${ }^{2}$ are being used to fit the recent high-resolution total cross-section data ${ }^{3}$ and the differential data ${ }^{4}, 5$ on ${ }^{12} \mathrm{C}$ in an attempt to determine the spins and parities of all known resonances in the ${ }^{13} \mathrm{C}$ system up to $12.6-\mathrm{MeV}$ excitation energy. MULTI has been used to obtain a preliminary set of parameters for the resonances using just the $\sigma_{T}$ data. These parameters will be used as starting values in the code EDA, which simultaneously handles both $\sigma_{\mathrm{T}}$ and d $\sigma$ to obtain a final set of parameters.
3. Gamma-Ray Angular Distribution from the Radiative Capture of $14-\mathrm{MeV}$ Neutrons (Arthur, Drake; Halpern, VSM, University of Washington)

We are continuing the measurements of gamma-ray angular distributions from the radiative capture of $14-\mathrm{MeV}$ neutrons. Whereas we made previous measurements of capture on light nuclei ( ${ }^{10} \mathrm{~B},{ }^{12} \mathrm{C},{ }^{29} \mathrm{Si}$, and ${ }^{40} \mathrm{Ca}$ ), we have now obtained data for radiative capture on ${ }^{89} \mathrm{Y},{ }^{90} \mathrm{Zr}$, ${ }^{165} \mathrm{Ho},{ }^{207} \mathrm{~Pb}$, and ${ }^{238} \mathrm{U}$. We observed some forward-backward asymmetry in the angular distributions obtained from capture on the heavier nuclei, in contrast to the symmetric distributions observed in radiative capture of light nuclei. The anisotropy observed in these gamma ray angular distributions may result from collective quadrupole excitations in the target nucleus; although, to confirm this, we plan a systematic study of radiative neutron capture on medium-to-heavyweight nuclei. A Letter that describes the results of the previous angular distribution measurements on ${ }^{10} \mathrm{~B},{ }^{12} \mathrm{C},{ }^{29} \mathrm{Si}$, and ${ }^{40} \mathrm{Ca}$ has been written, and results from capture of ${ }^{89} \mathrm{Y},{ }^{96} \mathrm{Zr},{ }^{165} \mathrm{Ho}$, and ${ }^{238} \mathrm{U}$ were presented at the Washington APS meeting.

[^24]Table B-1. Energies and Intensities of Gamma Rays from ${ }^{9} \mathrm{Be}(\mathrm{n}, \gamma)^{10} \mathrm{Be}$.

| Gamma Ray <br> Energy <br> $(\mathrm{keV})$ | Transition <br> Energy <br> $(\mathrm{keV})^{\mathrm{a}}$ | 219.30 | $\mathrm{I}_{\gamma}$ <br> $(\mathrm{mb})$ |
| :---: | :---: | :---: | :---: |
| $219.30 \pm 0.2$ | 547.42 | $0.004 \pm 0.001$ | $\mathrm{I}_{\gamma}$ <br> $(\gamma / 100 \mathrm{n})$ |
| $547.41 \pm 0.15$ | 631.85 | $0.012 \pm 0.002$ | 0.05 |
| $631.83 \pm 0.15$ | 853.57 | $0.018 \pm 0.003$ | 0.16 |
| $853.53 \pm 0.2$ | 2590.51 | $2.0 \pm 0.2$ | 0.24 |
| $2590.15 \pm 0.1$ | 2812.2 | $1.7 \pm 0.2$ | 26.4 |
| $2811.8 \pm 0.3$ | 2896.9 | $0.010 \pm 0.002$ | 22.4 |
| $2896.4 \pm 0.3$ | 3368.2 | $0.011 \pm 0.002$ | 0.13 |
| $3367.6 \pm 0.2$ | 3444.1 | $2.5 \pm 0.2$ | 0.15 |
| $3443.5 \pm 0.2$ | 5958.6 | $0.86 \pm 0.08$ | 33.0 |
| $5956.7 \pm 0.3$ | 6811.9 | $0.11 \pm 0.02$ | 11.3 |
| $6809.4 \pm 0.3$ |  | $4.9 \pm 0.5$ | 1.5 |
|  |  |  |  |

$\overline{{ }^{\text {Gamma-ray energy corrected }} \text { for nuclear recoil. }}$
4. Cross-Section Evaluations
a. ${ }^{6}$ Li (Hale, Dodder, Young, Stewart)

A multichannel, multilevel R-matrix analysis of the system ( $n-{ }^{6} \mathrm{Li} ; \alpha-\mathrm{T}$ ) has been used to provide evaluated ${ }^{6} \mathrm{Li}(\mathrm{n}, \mathrm{n}),{ }^{6} \mathrm{Li}(\mathrm{n}, \alpha)$ and total cross sections up to neutron energies of $\sim 1.7 \mathrm{MeV}$. Input data have included differential cross sections and polarizations, as well as total and integrated cross sections. Because of apparent discrepancies among different data sets, which cannot be resolved at the present time, the analysis was heavily weighted in favor of the Harwell and ORNL total cross sections and the shapes of the integrated ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha)$ cross sections.
b. ${ }^{7} \mathrm{Li}$ (Foster, Young)

The total cross section has been reevaluated above 500 keV to take advantage of recent measurements and the entire data file has been extended to an incident neutron energy of 20 MeV in order to meet the requirements of ENDF/B-IV.

## C. BASIC PHYSICS DATA

1. ${ }^{33} \mathrm{~S}(\mathrm{n}, \alpha)$ (Auchampaugh, Howard)

The ${ }^{33} \mathrm{~S}(\mathrm{n}, \alpha)$ cross section has been measured from 10 to 666 keV using a thin lithium target ( $\sim 50 \mathrm{keV}$ ) for the data above 200 keV and a thick lithium target and conventional time-of-flight techniques for the data below 200 keV . The data are presented in Fig. C-1. A foil of ${ }^{235} U$ was used to measure the flux. The amount of material on the $S$ foils was determined by using a thermal beam and the known ${ }_{\text {th }}(n, \alpha)$ of $140 \pm 30 \mathrm{mb}$. These data will be combined with a measurement of the $\sigma(n, \gamma)$ cross section currently underway at ORELA to determine the $\Gamma_{\alpha} / \Gamma_{\gamma}$ branching ratio for this nucleus, which is of importance in the nucleosynthesis of the rare isotope ${ }^{36} \mathrm{~S}$.
2. Direct Reaction Fission Studies (Britt, Gavron, Weber, Wilhelmy)

Preliminary runs have been performed to investigate two aspects of the fission process. First, we have looked at the dependence of $\Gamma_{\mathrm{f}} / \Gamma_{\mathrm{n}}$ on the excitation energy above the fission barrier, using ( ${ }^{3} \mathrm{He}, \mathrm{d}$ ) and ( ${ }^{3} \mathrm{He}, \mathrm{t}$ ) reactions. Various microscopic models predict dips in this ratio a few MeV above the barrier, and we will attempt to determine if they exist experimentally. The second series of experiments involves determination of the mass and kinetic energy distribution of fission fragments as a function of the excitation energy in various direct reactions. In particular, we wish to determine whether these distributions vary when the fissioning nucleus goes through a vibrational (subbarrier) resonance and whether different components of the mass spectrum have different fission barriers.

Preliminary runs have been performed for each of these experiments, and the experimental equipment is operating satisfactorily. We plan to schedule runs for serious data taking in the near future.


Fig. C-1. Cross section of ${ }^{33} \mathrm{~S}(\mathrm{n}, \alpha)$ from 10 to 666 keV .

## D. NUCLEAR DATA FOR SAFEGUARDS

Spectrum of Delayed Neutrons from Fast Fission of ${ }^{235} \mathrm{U}$
(Evans, East)
A ${ }^{3} \mathrm{He}$ neutron spectrometer of the type developed by Shalev ${ }^{1,2}$ has been used to measure the energy spectrum of delayed neutrons from subMeV fission of ${ }^{235} \mathrm{~J}$. Delayed-neutron spectra have been measured for thermal fission, ${ }^{3-5}$ and for fission induced by $14-\mathrm{MeV}$ neutrons. ${ }^{6}$

The LASL Group A-1 Van de Graaff was used to accelerate $25 \mu \mathrm{~A}$ of $2.15-\mathrm{MeV}$ protons onto a $1.9-\mathrm{mg} / \mathrm{cm}^{2}$-thick lithium target, producing neutrons of energies between 80 and 420 keV at an approximate level of 1.25 $\mathrm{x} 10^{9} \mathrm{n} / \mathrm{sr}-\mathrm{sec}$ in the forward direction. A $75-\mathrm{mm}$ - by $75-\mathrm{mm}$ - by $1-\mathrm{mm}-$ thick plate of uranium enriched to $97 \%{ }^{235} \mathrm{U}$ was placed directly in front of the target. The Shalev spectrometer was positioned with its axis 190 mm in front of the uranium plate. A $50-\mathrm{mm}$-thick lead shield was placed between the sample and the spectrometer to suppress gamma pileup. To suppress the thermal and epithermal neutron response of the system, the spectrometer was enclosed in a $6.35-\mathrm{mm}$-thick Boral box lined with 0.75 mm of cadmium.

The energy response of the spectrometer was measured with monoenergetic neutrons produced by bombarding a $0.1-\mathrm{mg} / \mathrm{cm}^{2}$-thick lithium target with protons to produce neutrons of energies between 0.15 and 1.50 MeV . The calibration runs were normalized to the response of a modified ${ }^{3} \mathrm{He}$ long counter known to have an energy-independent response in the interval from 0.25 to 4.0 MeV . The "long counter" was located 2 m from the target and $7.5^{\circ}$ off the beam line. Pulse-shape discrimination was used to suppress gamma radiation and ${ }^{3} \mathrm{He}$ recoils from the response of the detector system.

[^25]Delayed-neutron spectra were accumulated using the modulated-source technique ${ }^{8}$ as modified for small-sample assay. ${ }^{9}$ The uranium sample was bombarded with $35-\mathrm{msec}$ pulses of neutrons at a rate of 10 pulses $/ \mathrm{sec}$. Delayed neutrons were detected during $40-\mathrm{msec}$ counting gates starting 15 msec after termination of the beam pulses. With this duty cycle, the spectrum measured is a true equilibrium delayed-neutron spectrum as would be found in a steady-state reactor.

The delayed-neutron spectrum shown in Fig. D-1 has been corrected for detector response (i.e., detector efficiency vs energy) derived as above; however, no attempt has been made to correct for the continuum of pulses for neutrons of energy less than about 250 keV . Thus, the lower energy region of the spectrum in Fig. D-1 is overestimated in intensity.

The delayed-neutron spectrum is seen to have a complex line structure, as observed by Shalev ${ }^{4}$ and by Sloan and Woodruff. 10 Table D-1 1ists the neutron energy peaks observed in ${ }^{235} \mathrm{U}$ neutron-induced fission and in spontaneous fission of ${ }^{252} \mathrm{Cf}$ (the latter was obtained using a time-offlight technique by Chulick et al.17. The corroboration is obvious.

Fig. D-2 is a log plot of the neutron spectrum showing the magnitude of the high-energy "tail." The measurements of Sloan et al. 12 indicate that about $2 \%$ of the observed spectrum is caused by prompt neutrons from fission produced by multiplication in the sample. This would indicate that the energy end point of the delayed-neutron spectrum as observed in this work is about 2 MeV , in rough agreement with Sloan.

[^26]Table D-1
Comparison of Measured Delayed-Neutron Energy Peaks in ${ }^{235} \mathrm{U}$
Neutron-Induced Fission and ${ }^{252} \mathrm{Cf}$ Spontaneous Fission


## U-235 FAST-FISSION DELAYED NEUTRONS



Fig. D-1. Spectrum of delayed neutrons from sub-MeV fission of ${ }^{235} \mathrm{U}$.

U-235 FAST-FISSION DELAYED NEUTRONS


Fig. D-2. Logarithmic plot of the delayed-neutron spectrum from neutroninduced fission of ${ }^{235} \mathrm{U}$.

## E. CHARGED PARTICLE REACTIONS

 R. Poore, J. Sunier, R. Hardekopf, L. Morrison, and G. Sal zman)

A long run in January allowed the completion of the planned measurements at 7 MeV . We have tentatively decided to publish this information and defer the $14-\mathrm{MeV}$ measurements to a later date. The $\mathrm{K}_{\mathrm{Z}}^{2}{ }^{1}$ data, in particular, do not agree with the predictions provided by Dodder and Hale (based on the mirror system) and, hence, are proving valuable for straightening out the phenomenology of the five-nucleon system. A paper on this subject was presented at the Washington APS meeting, as follows:
"The six polarization transfer coefficients $K^{X^{\prime}}(\theta), K_{Z}^{z '}(\theta)$, $K^{Z}{ }^{\prime}(\theta), K_{X}^{X^{\prime}}(\theta), K_{y}^{y}{ }^{\prime}(\theta)$, and $K_{y}^{y_{y}^{\prime}}(\theta)$ for the reaction $T(d, n)$ ${ }^{4}$ He have been measured at a laboratory deuteron energy of 7.0 MeV . The angular range $\theta=0^{\circ}$ to $\theta=105^{\circ}$ was covered. The outgoing neutron polarization was measured with the aid of either a dipole or a solenoid spin-precession magnet and a liquid helium polarimeter. The relation $\mathrm{K}_{2}^{2}\left(0^{\circ}\right)=$ $\frac{2}{3}\left[1 \div \frac{1}{2} \mathrm{~A}_{\mathrm{zz}}\left(0^{\circ}\right)\right]$ holds for reactions with the present spin structure $\left(1+\frac{1}{2} \rightarrow \frac{1}{2}+0\right)$. The practical utility of this relation for producing a beam of neutrons with known polarization will be discussed."
2. Polarization Transfer in $\mathrm{p}^{-{ }^{3} \mathrm{He} \text { Elastic Scattering at } 16 \mathrm{MeV}, ~}$ (R. Hardekopf and D. Armstrong)

The data analysis for this experiment has been completed, and G. Hale (LASL Group T-2) is incorporating the results in his calculations on the $\mathrm{p}-{ }^{3} \mathrm{He}$ system. The abstract of a paper that was presented at the Washington APS meeting is as follows:
"Angular distributions of the polarization transfer coefficients $K_{X}^{X^{\prime}}, K_{Z}^{X^{\prime}}$, and $K_{Y}^{Y^{\prime}}$ (Wolfenstein parameters $R, A$, and D) were measured at 16.2 MeV for ${ }^{3} \mathrm{He}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{p}})$ elastic scattering. The angular range covered was $30^{\circ}$ to $90^{\circ}$ (lab) in $10^{\circ}$ steps. The experiment used a polarized proton beam of 150 to 200 nA , a liquid-nitrogen cooled ${ }^{3} \mathrm{He}$ gas target, and a ${ }^{4} \mathrm{He}$-filled proton polarimeter. Predictions of the transfer coefficients from the R-matrix parameters of Hale et al. ${ }^{1}$ are in good agreement with the data."

[^27]3. R-Matrix Analysis of the $\mathrm{d}+{ }^{4} \mathrm{He}$ System (D. Dodder, K. Crosthwaite, and G. Oh1sen)

A paper was presented at the Washington APS meeting on this work. The fit remains at $\sim \chi^{2}=3$ per point, but examination of the fits convinces us that the problem lies in the data. The abstract is as follows:
"An R-matrix analysis of ${ }^{4} \mathrm{He}(\mathrm{d}, \mathrm{d}){ }^{4} \mathrm{He}$ cross section, analyzing power, and polarization transfer measurements in the energy range $0-12 \mathrm{MeV}$ has been made. All inelasticity is presumed to arise from the ${ }^{4} \mathrm{He}(\mathrm{d}, \mathrm{p})^{5} \mathrm{He}$ * and ${ }^{4} \mathrm{He}(\mathrm{d}, \mathrm{n}){ }^{5} \mathrm{Li}$ * reactions. The general behavior of the phase shifts found by Schmelzbach et al. ${ }^{1}$ are confirmed. Many new data ${ }^{2}, 3$ are included in the analysis. At several points there is sufficient information to uniquely determine all of the elements of the $M$ matrix. Our ability to fit the data in these cases gives us confidence that our solution is qualitatively correct."

[^28]
## THE UNIVERSITYY OF MICHIGAN

## A. INTRODUCTION

The Cross Section Project at The University of Michigan has continued to emphasis those measurements for which our facilities are best suited, that is, the absolute measurement of neutron-induced reaction rates in nearly monoenergetic neutron fluxes produced by photoneutron sources. The facilities described in the prior progress report have been augmented with the addition of handling and monitoring equipment to permit the routine use of plutonium and californium foils. Fission measurement plans for the next year will make use of these new facilities to supplement earlier work completed on uranium foils. Work has also begun on the use of a californium fission spectrum source to augment the point energy measurements afforded by the photoneutron sources.
B. ABSOLUTE DETERMINATION OF THE ${ }^{235} \mathrm{U}$ FISSION CROSS SECTION AT 964 keV
(D. M. Gilliam, G. F. Knoll)

The results reported earlier for this measurement have been extended by an additional fission rate measurement using a larger foil-to-source spacing. This additional data has allowed us to better calculate the room return component of the neutron flux in which the measurements are made, and also provide a check on values obtained from earlier measurements using two independent smaller spacings. The additional data is in excellent agreement with that obtained earlier and result in a cross section value essentially unchanged from that reported earlier ( 1.20 barns). The additional counting statistics, however, allow a reduction in the estimated uncertainty of the measurement from $2.3 \%$ to $2.0 \%$. Work on this measurement is now essentially completed except for a possible check on target foil masses through alpha essay. While we do not feel that the weighings used in our present determination of the target masses are subject to significant error, an independent determination through alpha counting would be desirable and is now planned to be carried out in cooperation with the National Bureau of Standards.
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,

Experimental work is now near completion on a measurement of the 235 fission cross section using a Na-D photoneutron source. Primarily due to the increased influence of reaction kinematics, the spectrum calculated by Monte Carlo for this source shows a substantially broader distribution than the spectrum for the $\mathrm{Na}-\mathrm{Be}$ source. We calculate a FWHM of 70 keV about a median energy of 261 keV .

Procedures identical to those used in the higher energy measurement were employed with the same uranium oxide target foils. Data from track etch counters are now being accumulated and various correction factors evaluated.
D. THE ${ }^{6_{L i}}(\mathrm{n}, \alpha)$ CROSS SECTION AT 964 keV (W. P. Stephany, G. F. Knoll)

Methods used in the measurement of this cross section were described in the last progress report and the experimental data have been completed for some time. The principal uncertainty lies in the extraction of the fraction of reaction products lying below the low-amplitude pile up tail due to intense gamma ray flux in which the measurements are made. Recent efforts have dealt with a more accurate modeling of the corrections required for target foil self absorption and are now near completion. A paper is now in preparation which describes details of this measurement for presentation at the Philadelphia Meeting of the American Nuclear Society in June.

E. THE ${ }^{239}$ Pu FISSION CROSS SECTION AT 964 keV (G. F. Knoll, M. C. Davis, J. C. Engdahl)

The plutonium handling facilities mentioned earlier have been put to initial use in a measurement of the ${ }^{239} \mathrm{Pu}$ fission cross section using a pair of $\mathrm{PuO}_{2}$ foils. Some difficulties have been experienced in loss of material from the bare target foils. As a result we have suspended further measurements for the time required to overlay the foils with a suitable containment cover to facilitate the close handling required in our measurement techniques. We expect to be able to resume these measurements shortly.

## F. FISSION MEASUREMENTS USING A CALIFORNIUM FISSION SPECTRUM

In the interest of providing a useful and reproducable integral measurement, we have begun to evaluate the feasibility of conducting fission measurements in the neutron spectrum provided by the spontaneous fission of ${ }^{252}$ Cf. We have acquired a suitable low-mass californium source and are now adapting our experimental procedures to accomodate that source. We intend to again calibrate source intensity through the use of our manganese bath facility, and use restricted solid angle fission fragment counting for registration of fission events in a separate measurement.
G. NU-BAR DETERMINATION FOR ${ }^{252}$ Cf

We are also studying the feasibility of using our manganese bath facility in the measurement of nu-bar (average number of neutrons per fission) for the spontaneous fission of ${ }^{252}$ Cf. Our initial plan is to measure the neutron emission rate against NBS-II with the bath, and the fission rate with restricted solid-angle counting. A .05 microgram foil has been obtained for initial studies of fragment distributions and detection efficiency. Long-term goals include an absolute calibration of the bath to remove dependence on NBS-II calibrations.

## 1. NATIONAL BUREAU OF STANDARDS

## A. NEUTRON PHYSICS

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

A paper entitled "Total Neutron Cross Section of Carbon from 1 keV to $1.4 \mathrm{MeV}^{12}$ was given at the Washington Meeting of The American Physical Society. The abstract follows:
"We have measured the total neutron cross section of high purity carbon to an accuracy of $1 \%$ over the energy range 1 keV to 1.4 MeV using the 40 m TOF facility at the NBS linac. The measurements were made with a detector consisting of approximately 1 kg of $1 \mathrm{O}_{\mathrm{B}}$ viewed by 4 NaI crystals. The hydrogen cross section was measured at the same time as a check on the accuracy of the system with the result that the agreement between the measured hydrogen cross section and the results of the effective range value using the Davis and Barschall* parameters was within 0.6\%. As a further check on the carbon cross section, a measurement of it using an Li glass scintillator was made from 1 to 250 keV . The results from these two detectors agree on the average to within $0.7 \%$. Finally, the carbon results agree in the energy region of overlap with our previous results in the MeV region using a proton recoil spectrometer. A polynomial fit to the data was made with

$$
\begin{aligned}
\sigma & =4.757-3.419 E+1.548 E^{2}-.328 E^{3} b(.001 \leq E \leq 1.4) \\
\text { where } E & =\text { neutron energy in MeV." }
\end{aligned}
$$

2. ${ }^{10_{\mathrm{B}}(\mathrm{n}, \alpha)^{7}}$ Li Branching Ratio (G. P. Lamaze, A. D. Carlson, and M. M. Meier)

Measurements of the branching ratio to the ground and first excited states of 7 Li have been completed. A technical note on this work is being submitted to Nuclear Science and Engineering. The abstract of that work follows:

[^29]> "In order to resolve a discrepancy in determinations of the ${ }^{10_{B}(n, \alpha)}$ Li branching ratio, a new measurement has been been made at the Nationai Bureau of Standards. The measurement was made with a $10^{10} F_{3}$ gas proportional counter and monoenergetic 790 keV neutrons obtained at the NBS 3-MV Van de Graaff laboratory. A branching ratio of $0.66 \pm 0.03$ was obtained. This determination agrees with $\overline{\text { the }}$ measurements of Petree et al.and Davis et al."
3. Fissionable Deposits for Absolute Fission Rate Measurements (J. A. Grund)

A set of fissionable deposits at the National Bureau of Standards includes five major isotopes, ${ }^{239} \mathrm{Pu},{ }^{235} \mathrm{U},{ }^{238} \mathrm{U},{ }^{237} \mathrm{~Np},{ }^{233} \mathrm{U}$, from more than a dozen batches of fissionable materials. The deposits, all 12.7 mm in diameter on 19 mm diameter backings of platinum or quartz, were fabricated at three different laboratories. The largest number comes from the Los Alamos Scientific Laboratory where techniques of vacuum evaporation with double rotation have provided uniform deposits for many years; important supplementary groups of fissionable deposits -- with mass assay in some cases -- have come from the Geel Target Preparation Center in Belgium and from the Oak Ridge Isotope Target Laboratory. Isotopic masses for the deposits are based on the determination of absolute alpha emission rates complemented by fission comparison counting in Maxwellian and monoenergetic thermal neutron beams.

## 4. Calculations for Intermediate Energy Standard Neutron Field Facility (ISNF) (C. M. Eisenhauer)

We have investigated the effect on the ISNF spectrum of adding materials necessary for the fabrication of the boron shell. The addition of $.02 \mathrm{at} /(\mathrm{b}-\mathrm{cm})$ of copper to the $.05 \mathrm{at} /(\mathrm{b}-\mathrm{cm})$ of boron decreases the flux in the energy region from $1-30 \mathrm{keV}$ by up to $20 \%$. Much of this decrease is due to scattering resonances in copper. However, addition of $.02 \mathrm{at} /(\mathrm{b}-\mathrm{cm})$ of aluminum to the boron decreases the flux in this region by less than $2 \%$. Suprisingly enough, the addition of a similar amount of carbon decreases the flux by as much as $8 \%$. Responses for various types of detectors have been calculated for the ISNF spectrum and for the cavity spectrum with no boron.

## 5. Calculation of Detector Responses in Fast Reactor Fluxes (C. M. Eisenhauer)

We have modified existing computer codes to calculate the response of an arbitrary type of thin detector foil in an arbitrary spectrum of neutrons. The main modification was to permit the neutron spectrum to be specified in an arbitrary group structure. The code replaces the flux in each group by a linear function of lethargy in an attempt to better approximate the shape of the physical spectrum This spectrum is then folded with a fine set of detector cross sections to calculate the detector response. For cross section data we are using the 620-group SAND II library which includes sets based on ENDF/B III data.

## 6. Neutron Radiography Using a Linac Neutron Source (J. Menke, R. A. Schrack, and C. D. Bowman)

An investigation has begun on the use of energy dependent neutron radiography with a linac neutron source. Samples are inspected by transmission measurements which are made with a spatial resolution of $1 / 4$ inch for samples as large as 8 inches by 8 inches. A lithium glass neutron detector located 8 m from a moderated tungsten neutron source is employed to determine neutron energies from their time-of-flight. This detector is interfaced to an SDS-920 computer. A computer program has been written for which four neutron time-of-flight windows may be selected which correspond to energies of characteristic neutron cross section structures in the materials to be investigated. Thus, four computer pictures are produced for each object investigated. The computer program permits automatic scanning of the 8 -inch by 8 -inch area to a preselectable statistical accuracy per mesh point. Preliminary runs with this system indicate that a good contrast picture can be obtained in less than one day with a beam power of 10 kW . This technique, although it is slow, has shown the capability of energy dependent linac neutron radiography measurements. A considerable improvement in spatial resolution and time required should be possible with position sensitive detectors.
7. Investigation of Properties of NE-110 (G. P. Lamaze)

This investigation is now completed and a letter to the editor is being prepared for submission to Nuclear Instruments and Methods. The experiment involved a comparison of responses of NE-110 and NE-102 to monoenergetic neutrons. The comparisons were made using the same RCA 8850 photomultiplier tube for both scintillators. Figure 1 shows the relative efficiencies of these two scintillators as a function of neutron energy. The basic conclusion is that the responses of both scintillators are essentially the same above the 150 keV and that the NE-110 is more efficient below that energy. To obtain maximum benefit of this higher efficiency, high quality photomultiplier tubes are recommended.

8. Search for $\gamma$-Ray Decays in the Second Well of $U^{239}$ (C. D. Bowman, 0. A. Wasson, and A. D. Carlson)

We performed a preliminary search for $\gamma$ ray transitions in the second minimum of the double humped potential barrier in $\mathrm{U}^{239}$. In particular we concentrated on the region of the 720 eV resonance where the RPI Group * has observed subthreshold fission which is associated with the second well. Since the second well is placed about 2.2 MeV above the first well and the neutron binding energy is 4.8 MeV , the maximum energy for $\gamma$ ray transitions in the second well is about 2.6 MeV . We thus searched for enhanced $\gamma$ ray strength for $\gamma$ ray energies less than 2.6 MeV. The experiment was carried out at the 5 meter flight path of the newly installed Above-Ground Neutron Time-of-Flight Facility. We observed $\gamma$ ray spectra with a $\mathrm{Ge}(\mathrm{Li})$ detector for neutron capture in individual resonances of $U^{238}$. We observed no enhancement in the $\gamma$ ray spectrum for neutron energies near 720 eV and have suspended operations until a more intense electron gun is available on the linac.

## B. ELECTRONUCLEAR PHYSICS

1. Measurement of Nuclear Shapes by Electron Scattering (S. Penner, J. W. Lightbody, Jr., and S. P. Fivozinsky)

We have been measuring the inelastic electron scattering cross sections of low-lying collective states in medium to heavy nuclei. The NBS facility is well suited to this work because our good energy resolution allows us to extract the cross sections for the often closely-spaced levels. The transition charge density between each level observed and the ground state is determined by the momentum transfer dependence of the cross section. In the case of a nucleus which is permanently deformed in its ground state, the transition charge densities of the states comprising the ground state rotational band, together with the spherical-average ground state charge distribution determined by elastic scattering, defines the three-dimensional charge density of the nucleus.

Experjpents of this type haye been performed to date on the rare earth nuclei ${ }^{152} \mathrm{Sm},{ }^{154} \mathrm{Sm},{ }^{166} \mathrm{Er},{ }^{167} \mathrm{Er},{ }^{175 \mathrm{Yb}}$, and on ${ }^{232} \mathrm{Th}$ and ${ }^{238} \mathrm{U}$, in collaboration with a group from MIT. Assuming these nuclei to be rigid rotors, we have deduced their ground state charge distributions including the quadrapole and hexadecapole ( $2^{4}$-pole) components. Examples of these charge distributions are shown in Figure 2. An appropriate integral over these charge distributions gives the electric hexadecapole moment of the nucleus, which is the quantity measured by, for example coulomb excitation

[^30]${ }^{238} U$

experiments using heavy charge particle probes. In all cases, our agreement with published values of the hexadecapole moment (or the $B(E 4)$ value, which is closely related) is good. We emphasize that, because of the momentum transfer variable which can be adjusted at will in electron scattering work, our data provides a measure of the details of the charge distribution which is not accessible to conventional coulomb-excitation experiments.

## C. DATA COMPILATION

1. X-Ray Attenuation Coefficient Information Center (J. H. Hubbell)

The coherent and incoherent bound-electron scattering data tabulations discussed in the last USNDC status report have been extended to include molecular as well as atomic hydrogen. Computational tasks have been completed, including numerical integrations to obtain total scattering cross sections as described in the following abstract of a manuscript in progress for the Journal of Physical and Chemical Reference Data:
"Tables of the Atomic Form Factor and Incoherent Scattering Function for $0.005 \leq \sin (\theta / 2) / \lambda \leq 10^{9} \AA^{-1}$, and Photon Coherent and Incoherent Scattering Cross Sections for $0.1 \mathrm{keV} \leq \mathrm{E}_{\gamma} \leq 100 \mathrm{MeV}$, for $1 \leq \mathrm{Z} \leq 100$
J. H. Hubbell, National Bureau of Standards, Washington, D. C. 20234;
W. J. Veigele and E. Briggs, Kaman Sciences Corp.,

Colorado Springs, Colorado 80907;
and R. T. Brown and D. T. Cromer, Los Alamos Scientific Lab., Los Alamos, New Mexico 87544.

Tabulations are presented of the atomic form factor, $F(q, Z)$, and the incoherent scaţtering function, $S(q, Z)$, for values of $q=(\sin (\theta / 2) / \lambda)$ from 0.005 to $10^{9} \AA^{-1}$, for all elements $Z=1$ to 100 . These tables are constructed from available state-of-the-art theoretical data, including the Pirenne formulas for $Z=1$, configuration-interaction results by Brown using Brown-Fontana and Weiss correlated wave functions for $Z=7$ to 100, and a relativistic K-shell analytic expression for $F(q, Z)$ by Bethe and Levinger for $q>10 \AA-1$ for all elements $Z=2$ to 100. These tabulated values are graphically compared with available photon scattering angular distribution measurements. Tables of coherent (Rayleigh) and incoherent (Compton) total scattering cross sections, obtained by numerical integration over combinations of $\mathrm{F}^{2}(\mathrm{q}, \mathrm{Z})$ with the Thomson formula and $\mathrm{S}(\mathrm{q}, \mathrm{Z})$ with the Klein-Nishina formula, respectively, are presented for all elements $Z=1$ to 100 , for photon energies $100 \mathrm{eV}(\lambda=124 \AA)$ to $100 \mathrm{MeV}(0.000124 \AA)$. The incoherent scattering cross sections also include the radiative and double-Compton corrections as given by Mork.

A table of $F\left(q, \frac{1}{2} H_{2}\right)$ values is also given interpolated and extrapolated from the values calculated by Stewart el al using a modified form of the Kolos-Roothaan $\mathrm{H}_{2}$ wavefunction, as well as $\mathrm{S}\left(\mathrm{q}, \frac{1}{2} \mathrm{H}_{2}\right)$ and the integrated coherent and incoherent scattering cross sections derived therefrom."
2. Photonuclear Data Center (E. G. Fuller, H. M. Gerstenberg, and H. Vander Molen)

With considerable help from Harold Vander Molen, the Nuclear Information Research Associate sponsored by the NAS ad hoc Panel on Nuclear Data Compilation, progress is being made on the development of a comprehensive annotated compilation of photonuclear-reaction cross section data. Sample evaluated data summaries have been prepared for several nuclides. These are being circulated to a number of both basic and applied users of photonuclear reaction data for comment and criticism before a final format for data presentation is frozen. They are also being discussed with possible publishers of the final compilation. At the present time, it appears that the compilation will be first published in a series of three sections, each covering a section of the periodic table.
D. FACILITIES

1. Above-Ground Neutron Time-of-Flight Facility (C. D. Bowman, A. D. Carlson, 0. A. Wasson, J. Menke, R. A. Schrack, and
H. T. Heaton, II)

The construction of the above-ground facility has been completed. Diagnostic runs in preparation for a measurement of the 235 U fission cross section in the MeV region are now being performed at the 60 meter station. The neutron flux determination for this measurement will be obtained by counting proton recoils from a thin hydrogenous film with a Si(Li) detector. The 235 U fission events will be detected in a parallel plate ionization chamber. At the 200 meter station, techniques are being developed for accurate measurements of the neutron flux from 1 keV to 2 MeV . The present effort is being concentrated on proton recoil gas proportional counters and black ${ }^{10} 0_{\mathrm{B}}$ and $\mathrm{NE}-110$ detectors. When this capability has been achieved, measurements of standard neutron cross sections will be made in the keV energy region.

The software and hardware for the Datacraft $6024 / 5$ on-line computer are nearly completed. A disc based multiparameter data acquisition system will be a central element in this system.

Considerably larger currents at short pulse widths will soon be available from the linac when a new high current injector and a tapered velocity buncher are installed.

2. 3 MeV Van de Graaff Facility (M. M. Meier, G. P. Lamaze, and A. D. Carlson)

The associated particle apparatus for keV neutron flux normalization is assembled and has now been in operation for about three months. This device, similar to the one described by Liskien and Paulsen, monitors neutron flux from the $T(p, n)^{3}$ He reaction by detecting the associated 3 He nuclei. In order to operate in the neutron energy range below 1 MeV the 3 He nuclei must be detected at small angles. The presence of a large flux of elastic and inelastic protons and other reaction products from Al, Ti and T in the solid target presents a formidable background problem, illustrated in Figure 3. The curve labeled "ungated, undeflected" is a pulse height spectrum from a surface barrier detector (SBD) at a lab angle of $10^{\circ}$, showing the dominant elastic peak and continuum of charged particles which have been multiply scattered in the target chamber. For the "ungated, electrostatic deflection" curve the surface barrier detector has been displaced from the 100 collimation axis and an electrostatic field sufficient to steer the $3 H^{++}$beam into the SBD has been applied. The counting rate is drastically reduced, contaminant reactions still dominate the spectrum. Finally, by using pulsed beam time-of-flight techniques a gate can be generated for the appropriate flight time of a ${ }^{3}$ He nucleus from target to SBD. Applying this gate to the SBD pulse height spectrum strongly suppresses the contaminating background and allows the 3 He peak to stand out as seen in the last curve of the figure. The instrument presently has the following characteristics for a neutron energy of 200 keV :

1. Count rate: 20-30 neutrons/second in the associated cone.
2. Neutron profile: The neutron cone has a full width at $1 / 10$ maximum of $\sim 140$.
3. Background in the ${ }^{3} \mathrm{He}$ peak: $1.5-3 \%$

There are many promising avenues open for improvement of the above figures and they should therefore be regarded as truly preliminary.

The 3 MeV Van de Graaff accelerator has been operating satisfactorily with most down time due to source replacement. Planned beam transport modifications include an after pulse to reduce dark current and a quadrupole for a threefold increase in analyzed, pulsed beam.


Figure 3
Pulse Height Distributions in Surface Barrier Detector of Associated Particle Apparatus

Interfacing at the Datacraft $6024 / 5$ to CAMAC is in its final phase and on-line acquisition is anticipated in late summer. In the meantime, the recent extension of memory to a total of 16 K has made possible the off-line use of the machine for detector design computations. An executive for data acquisition and various manipulations has been written and debugged and operates in conjunction with the vendor supplied tape operating system.
3. Beam Filters (R. B. Schwartz and I. G. Schroder)

The scandium filter has been installed, and an approximate measurement of the beam characteristics has been made. The 2 keV neutron flux is approximately $5 \times 10^{5}$ neutrons $\mathrm{cm}^{2} / \mathrm{sec}$, using the full 110 cm of scandium. The higher energy neutron flux, due to other windows in the scandium amounts to approximately $2 \%$ of the 2 keV flux. The addition of 1 cm of titanium cuts the higher energy flux by approximately a factor of two, but also removes approximately $25 \%$ of the 2 keV flux. The gamma ray background in the beam is approximately $2 \mathrm{mR} / \mathrm{hr}$ above the room background. Additional measurements will be made to characterize the beam more accurately. An additional in-pile collimator has been designed which will further reduce the gamma ray background in the beam, and additional shielding is being built to lower the general room background.

The silicon filters are expected to arrive from Oak Ridge this month, and will be installed by this summer.

## 4. The Photon Activation Analysis Bremsstrahlung Facility

 (W. R. Dodge)The photon activation bremsstrahlung facility has recently been used over a much larger energy range and with larger incident electron beam currents than in the past. Current users of this facility (NBS photoactivation group and the Nuclear Atmospherics group at the University of Maryland) have needed more accurate photon beam position and intensity monitoring. A new electron beam viewing screen, water-cooled collimator, and ferrite beam current monitor have been installed in order to monitor the position and intensity of the incident electron beam. Emissions from coal burning power plants and from sludge burning disposal plants in this area have been analyzed for F and Pb content using this facility.

## NAVAL RESEARCH LABORATORY

## A. NEUTRON PHYSICS

1. Spins of Resonances in $\mathrm{Lu}^{175}$ (A. I. Namenson, A. Stolovy and G. L. Smith)

The ratios of low energy gamma rays were measured to determine the spins. The NRL Linac was used as a pulsed neutron source, and an $80 \mathrm{cc} \mathrm{Ge}(\mathrm{Li})$ detector was used to detect the gamma rays. Data were accumulated as two parameter information - time-of-flight by gamma ray energy. Flight paths of 22 m and 10 m were used. The Lu ${ }^{175}$ sample was $99.9 \%$ pure. The very high density of low energy gamma rays in $\mathrm{Lu}^{175}$ made it difficult to resolve many of the lines from nearby ones. However, nine lines were of sufficient intensity that they would not be significantly perturbed by the presence of nearby ones. The energies of these lines together with the spins and parities of the levels from which they originate are listed in Table A-1 below. All energies are in keV.

Table A-1

| Line | Leve1 | Line | Leve1 | Line | Leve 1 |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
|  |  |  |  |  |  |  |
| 183 | $3092^{-}$ | 201 | $4415^{-}$ | 284 | 661 | $\left(5^{+}\right)$ |
| 187 | $4915^{+}$ | 225 | $6623^{-}$ | 310 | 437 | $2^{-}$ |
| 192 | $3901^{-}$ | 262 | $3901^{-}$ | 335 | 639 | $\left(4^{+}\right)$ |

The intensities of the $201,284,192$, and 262 keV lines showed a significant dependence on the spin of the resonance. Since the 192 and 262 keV lines originate from the same level, their intensities were added together and they were treated as a single line. Some correlation was also noticed between the intensities of the 201 and 284 keV lines, even after the dependence on spin was removed. The intensities of these lines were, therefore, also combined. However, the dependence of the. intensity on the spin of the resonance was different for the two different lines, so instead of simple addition, an optimum linear combination was taken. This combination was such as to maximize the dependence on spin as compared to the fluctuations due to experimental uncertainties and Porter-Thomas fluctuations. This leaves two sets of independent ratios from which the spin determinations were made. For illustration purposes, another optimum linear combination of these two independent ratios is shown in Figure $A-1$. In the left portion of this figure, the combined ratio for each resonance is plotted as a function of neutron energy. The error bars on the points represent experimental uncertainties only. The spins of resonances indicated by triangles have


Figure A-1
been determined with better than $90 \%$ probability. The two solid horizontal lines represent the average ratio for each spin, and the pair of dashed lines surrounding each solid line represents an estimate of the fluctuations due to Porter-Thomas statistics. We can see that there are very few ambiguous cases. The histogram on the right is the result of dividing the vertical scale into forty equal intervals and counting the average number of resonances in each zone. Noting that the error bars represent a Gaussian probability distribution for the location of the resonances, an expectation value for the number of resonances in each zone was calculated.

Table A-2 shows our spin assignments together with the probabilities of their being correct. ${ }^{1}$ From these assignments we can study the possible spin-dependence of the distribution of the number of resonances, the average reduced neutron width, and the strength function. A Wald-Wolfowitz calculation showed that the spin 3 and spin 4 resonances are interlaced in a random manner.

Table A-3 shows some of the results of these calculations. The errors quoted in the first two lines for the spin 4 and spin 3 populations are not completely independent. However, the third line shows a comparison of the two different groups with appropriate errors. All quoted uncertainties include uncertainties due to the finite number of resonances as well as uncertainties due to an incomplete knowledge of all the spins. It should be noted that the last two calculations are based on only sixteen resonances. In view of the considerably larger number of spins now known it would be interesting if more neutron widths were determined.
2. Resonances in $0 s^{187}$ (A. I. Namenson, A. Stolovy and G. L. Smith)

The apparatus and method of data collection is the same as in section 1 except that data were accumulated using only a ten meter flight path. Data collection was difficult since only 0.3 gm of $0 \mathrm{~s}^{187}$ was available. Because the $\mathrm{Os}^{187}$ sample was enriched to only $46 \%$ there was considerable interference from other Os isotopes - chiefly from Os ${ }^{189}$. Nevertheless, from our two-dimensional data we generated time-of-flight spectra corresponding to the 155 keV line in $0 \mathrm{~s}^{287}$ and to the background regions on either side of this line. By suitable subtraction of spectra we obtained a "background corrected" time-of-flight spectrum for the 155 keV line. In this spectrum the interference of other isotopes was reduced to zero.

[^31]Table A-2

| $\begin{aligned} & \text { Neutron Energy } \\ & \text { (ev) } \end{aligned}$ | Spins of Neutron Resonances in $\mathrm{Lu}^{175}$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Spin | $\begin{gathered} \text { Probability } \\ (\%) \end{gathered}$ | $\begin{aligned} & \text { Neutron Energy } \\ & (\mathrm{eV}) \end{aligned}$ | Spin | $\begin{gathered} \text { Probability } \\ (\%) \end{gathered}$ |
| 2.6 | 4 | 100 | 127.4 | 3 | 100 |
| 4.7 | 4 | 100 | 129.4 | 4 | 99 |
| 5.2 | 3 | 100 | 137.8 | 3 | 86 |
| 11.2 | 3 | 100 | 143.0 | 3 | 98 |
| 14.0 | 3 | 96 | 146.2 | 3 | 99 |
| 15.3 | 4 | 100 | 148.8 | (4) | 63 |
| 20.5 | 3 | 100 | 150.9 | 4 | 98 |
| 23.5 | 3 | 100 | 155.4 | 4 | 99 |
| 28.1 | 4 | 100 | 158.7 | 3 | 100 |
| 30.2 | 4 | 100 | 164.0 | 3 | 99 |
| 31.1 | 3 | 100 | 169.2 | 4 | 98 |
| 36.5 | 3 | 97 | 171.5 | 3 | 94 |
| 40.7 | 3 | 100 | 175.8 | 3 | 97 |
| 49.2 | 3 | 99 | 180.9 | 4 | 99 |
| 50.2 | 4 | 99 | 185.4 | 3 | 99 |
| 53.5 | 4 | 99 | 193.3 | 3 | 99 |
| 56.7 | 3 | 93 | 196.8 | 4 | 94 |
| 60.9 | 4 | 99 | 202.6 | (3) | 51 |
| 69.6 | 4 | 98 | 204.4 | 4 | 81 |
| 85.3 | 4 | 99 | 217.6 | 4 | 94 |
| 88.1 | (3) | 70 | 223.9 | 3 | 94 |
| 96.3 | 4 | 100 | 227.9 | 4 | 98 |
| 99.7 | 3 | 99 | 229.6 | 4 | 99 |
| 100.9 | 4 | 82 | 236.9 | (4) | 55 |
| 102.8 | 4 | 100 | 244.5 | 3 | 97 |
| 107.3 | 4 | 99 | 251.5 | (4) | 69 |
| 112.7 | 3 | 99 | 256.4 | 3 | 99 |
| 115.1 | 3 | 100 | 274.0 | 4 | 99 |
| 118.6 | 3 | 99 |  |  |  |

Table A-3
Average Properties of the Resonances

## Relative Populations

Expected
Relative Populations from 2J+1 Rule

| Spin 4 | $.476 \pm .070$ | .5625 | $0.68 \pm .39$ |
| :--- | ---: | ---: | ---: |
| Spin 3 | $.524 \pm .070$ | .4375 | $1.63 \pm .73$ |
| Difference | $-.048 \pm .140$ | .1250 | $-0.95 \pm .83$ |

$$
\begin{aligned}
& <2 \mathrm{~g} \Gamma_{\mathrm{n}}^{\mathrm{O}}> \\
& \text { ( In MeV- } \\
& \text { based only } \\
& \text { on resonances } \\
& \text { up to } 57 \mathrm{eV} \text { ) }
\end{aligned}
$$

The energies of resonances (in eV ) observed in $0 \mathrm{~s}^{187}$ are: 9.48, $12.6,19.9,39,40,43,48,49.8,50.3,62,63.5,65,71.3,78,83.5$, $90,92.5,99,105,109,123,124,127,138,141,145,155,164,168$, $176,178,189,201,207,214,224,227,236,258$, and 290.

The spins of resonances at the following energies were identified with $85 \%$ confidence or better:

$$
\begin{aligned}
& \text { Spin 1: } 9.48,12.6,19.9,43,109,138,177,215 \\
& \text { Spin 0: } 48,49.8
\end{aligned}
$$

## B. NEUTRON DATA APPLICATIONS

1. Fast Neutron Spectrum Measurements with ${ }^{10}{ }_{B}$ (A. Stolovy, A. I. Namenson, G. L. Smith, and D. H. Walker)

A time-of-flight technique has been used to determine the fast neutron spectrum from a neutron generator at the NRL Linac. This generator is being used to study the susceptibility of semi-conductor devices to fast neutron damage. The neutrons are produced when a 22 MeV electron beam strikes a water-cooled Ta target, which is surrounded by 4 inches of lead. The time-of-flight was observed for a 25 meter evacuated flight path, using 20 nsec beam pulses, a repetition rate of 360 pulses per sec., and channel widths of 10 nsec .

The detector must have an efficiency which is reasonable over a very wide range of neutron energies, and it must recover rapidly ( $<1 \mu$ sec.$)$ from the linac gamma-ray flash. The spectrum from 0.1 MeV to 6 MeV was observed with the following system: A target containing 514 gm of ${ }^{10} \mathrm{~B}$ was placed in the neutron beam at 25 meters from the neutron generator. The 478 keV gamma-ray from the ${ }^{10} \mathrm{~B}(\mathrm{n}, \alpha \gamma)^{7} \mathrm{Li}$ reaction was observed with a 2 inch diameter by 2 inch thick NaI detector at a back angle and about 5 inches from the boron. With $1 / 8$ inch of lead in front of the detector, recovery from the flash in less than $1 \mu \mathrm{sec}$ was obtained. Two parameter data (time-of-flight and gamma-ray energy) were taken, processed by an on-line computer, and stored on magnetic tape. The time-of-flight spectrum corresponding to the region of the gamma-ray spectrum at 478 keV is thus the desired result.

After accounting for the energy dependence of the ${ }^{10} B$ capture cross section, ${ }^{2}$ the detector efficiency, geometrical factors, the absorption of 478 keV gamma-rays by various materials, and converting

[^32]time-of-flight into energy, the desired spectrum shown in Figure $B-1$ is obtained. The many transmission dips observed are due to resonances in the lead blanket which surrounds the neutron generator target. These resonances serve as a convenient way to calibrate the time-of-flight to energy conversion.
2. Thin Film Measurements with Neutron Resonances (A. Stolovy and A. I. Namenson)

Many materials have slow neutron resonances with very high peak cross sections. This suggests that time-of-flight spectroscopy could be used as a non-destructive technique for detecting the presence of small amounts of such materials.

To test this idea, the transmission of timed slow neutrons has been observed through thin films of gold deposited on a glass substrate of the following thicknesses in angstrom units: 1630, 1040, 880 and 570. In addition, data were taken with a "thick" ( 0.001 inch) gold foil. The detector was a ${ }^{6}$ Li glass scintillator located 10 meters from the moderated pulsed neutron source at the linac. The areas above the transmission dips for the different sample thicknesses corresponding to the large resonance at 4.91 eV were measured. Unfortunately, a one-half inch thick lead beam filter was later found to contain about $1 \%$ silver by weight. The silver resonance at 5.19 eV overlaps with the gold resonance. It was necessary to subtract the effect of the silver resonance from the data. After this is done, the areas above the transmission dips were normalized to the total number of counts in each case, and plotted vs. thickness, as shown in Figure B-2. The straight line through the origin is based solely upon the data for the 0.001 inch sample, corrected for sample thickness and Doppler broadening. The other points are seen to fit this line very well. It seems reasonable to say that this technique could be used to measure considerably thinner films, perhaps down to $100 \AA^{\circ}$.


Figure B-1


Figure B-2
A. NEUTRON DATA APPLICATIONS SUBCOMMITTEE
A.1. Gamma-Ray Production Measurements

1. $\frac{{ }^{28} \mathrm{Si}\left(\mathrm{n}, \mathrm{n}^{\prime} \gamma\right) \text { Photon Production Cross Sections for } \mathrm{E}_{\gamma}=}{\frac{1.78 \mathrm{MeV}, 5.0 \leq \mathrm{E}_{\mathrm{n}} \leq 9.5 \mathrm{MeV} *}{\text { G. L. Morgan) }} \text { (J. K. Dickens and }}$

The excitation function for the production of the $1.78-\mathrm{MeV}$ gamma ray due to neutron interactions with ${ }^{28}$ Si has been measured for incident neutron energies between 5 and 9.5 MeV with neutron energy resolution $\sim 35 \mathrm{keV}$ for $\mathrm{E}_{\mathrm{n}}=5 \mathrm{MeV}$ to $\sim 80 \mathrm{keV}$ for $\mathrm{E}_{\mathrm{n}}=9.5 \mathrm{MeV}$. These data are compared with previously reported values and with the current ENDF/B evaluation.

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    To be published in Physical Review C.
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2. Gamma-Ray Production Due to Neutron Interactions with Tin for Incident Neutron Energies Between 0.75 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 tin have been obtained for neutron energies between 0.75 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 ${ }^{Y}$. These data consist of neutron and 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 $\mathrm{E}_{\mathrm{\gamma}} \leq 1 \mathrm{MeV}$ td $\overline{1} 60 \mathrm{keV}$ for $\mathrm{E}_{\gamma} \sim 9 \mathrm{MeV}$. Neutron energy intervals varied from $\gamma . \overline{25} \mathrm{MeV}$ for $E_{n}=0.75$ to 2 MeV to 3 MeV for $\mathrm{E}_{\mathrm{n}}=14$ to 20 MeV .
*Abstract of ORNL-TM-4406
3. Gamma-Ray Production Due to Neutron Interactions with Zinc for Incident Neutron Energies Between 0.85 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 zinc have been obtained for neutron


energies between 0.85 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 are presented as gamma-ray production group groeswsection values of $\mathrm{d}^{2} \sigma / \mathrm{d} \omega \mathrm{d} \mathrm{E}$ for 0.7 < $\mathrm{E}_{\gamma} \leq 10.5 \mathrm{MeV}$, with gamma-ray intervals ranging from 20 keV for $\mathrm{E}_{\gamma}<1 \mathrm{MeV}$ to $\overline{1} 60 \mathrm{keV}$ for $\mathrm{E}_{\gamma} \sim 9 \mathrm{MeV}$. Neutron energy intervals varied from $0 . \overline{1} 5 \mathrm{MeV}$ for $E_{n}=0.85$ to $\gamma_{1 ~ M e V ~ t o ~} 3 \mathrm{MeV}$ for $E_{n}=14$ to 20 MeV .

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Abstract of ORNL-TM-4464.
**
Relevant to request No. 216.
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4. Gamma-Ray Production Due to Neutron Interactions with Fluorine and Lithium for Incident Neutron Energies Between 0.55 and $20 \mathrm{MeV}:$ 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 lithium fluoride have been obtained for neutron energies between 0.55 and 20 MeV for $\theta_{\gamma}=125 \mathrm{deg}$. The cross-section values were obtained using a NaI photon spectrometer and the Oak Ridge Electron Linear Accelerator as the neutron source. The data for neutron interactions with fluorine are presented as gamma-ray production group corss-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 $\mathrm{E}_{\gamma} \leq 1 \mathrm{Me} \overline{\mathrm{V}}$ to $\overline{1} 60 \mathrm{keV}$ for $\mathrm{E}_{\chi} \sim 9 \mathrm{MeV}$; for these data neutron. energy intervals varied from 0.25 MeV for $1.25 \leq \mathrm{E}_{\gamma} \leq 2 \mathrm{MeV}$ to 3 MeV for $14 \leq \mathrm{E}_{\mathrm{n}} \leq 20 \mathrm{MeV}$. The data for neutron interactions with lithium are presented ${ }^{\mathrm{n}}$ as gamma-ray production cross-section values of $\mathrm{d} \sigma / \mathrm{d} \omega$ for the 0.478 MeV gamma ray; for the data the neutron energy intervals varied between 10 keV at threshold and 1 MeV for $\mathrm{E}_{\mathrm{n}} \geq 14 \mathrm{MeV}$.

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    Abstract of ORNL-TM-4538.
**
    Relevant to request No. 11.
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5. Gamma-Ray Production Due to Neutron Interactions with Magnesium for Incident Neutron Energies Between 0.8 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 magnesium have been obtained for neutron energies between 0.76 and 20 MeV . The cross-section values were obtained using a NaI spectrometer. These data consist of (a) the production of gamma rays by neutron reactions with 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 $\sim 0.25 \mathrm{MeV}$ for $\mathrm{E}=0.76$ to 1.5 MeV to 3 MeV for $\mathrm{E}_{\mathrm{n}}=14$ to 20 MeV ; and (b) values of $\mathrm{d} \sigma \mathrm{\eta} \mathrm{~d} \omega$ for $\mathrm{E}=1.37 \mathrm{MeV}$ for $\theta_{\gamma}=125^{\mathrm{n}} \mathrm{deg}$ and for

$\mathrm{E}_{\mathrm{n}}$ between threshold and 6.0 MeV and for $\mathrm{E}_{\gamma}=1.81 \mathrm{MeV}$ for $\theta_{\gamma}=125 \mathrm{deg}$
and for $\mathrm{E}_{\mathrm{n}}$ between threshold and 3.2 MeV. *
Abstract of ORNL-TM-4544.
6. $\frac{\text { Gamma-Ray Production Due to Neutron Interactions with Zinc }}{\frac{\text { Tabulated Differential Cross Sections for } 31 \text { Gamma Rays for }}{\text { Incident Neutron Energies Between } 0.9 \text { and } 6 \text { MeV*.** (G. G. }}}$

Numerical values of differential cross section for gamma rays produced by neutron interactions with zinc have been measured for neutron energies between 0.9 and 6 MeV for $\sigma_{\gamma}=120 \mathrm{deg}$. The $\mathrm{d} \sigma / \mathrm{d} \omega$ data were obtained using a $35 \mathrm{~cm}^{3} \mathrm{Ge}(\mathrm{Li})$ detector. The data consist of cross section values for 31 gamma rays having $E_{\gamma}$ between 300 and 2780 keV . Neutron energy intervals varied between a minimufh of $\sim 50 \mathrm{keV}$ at $\mathrm{E}_{\mathrm{n}} \sim 900 \mathrm{keV}$ and a maximum of $\sim 1.5 \mathrm{MeV}$ for $\mathrm{E}_{\mathrm{n}} \sim 5.8 \mathrm{MeV}$.
*Abstract of ORNL-TM-4523
**Relevant to request No. 216.
7. Direct-Interaction Interpretation for ${ }^{40} \mathrm{Ca}(\mathrm{n}, \mathrm{np} \mathrm{y}){ }^{39} \mathrm{~K}$ Reactions at $\mathrm{E}_{\mathrm{n}}=17-20 \mathrm{MeV}$ * (J. K. Dickens)

Gamma-ray production cross sections measured for the ${ }^{40} \mathrm{Ca}(\mathrm{n}, \mathrm{np}){ }^{39} \mathrm{~K}$ reactions are interpreted using a model based upon the 2-particle-2-hole configuration mixing in the ground-state wave function of ${ }^{40} \mathrm{Ca}$ and a direct knock-out reaction mechanism.

[^33]
## A.2. Neutron Scattering

1. $\frac{{ }^{206} \mathrm{~Pb},{ }^{207} \mathrm{~Pb} \text { and }{ }^{208} \mathrm{~Pb} \text { Neutron Elastic- and Inelastic- }}{\frac{\text { Scattering Cross Sections from } 5.50 \text { to } 8.50 \mathrm{MeV}^{*}}{\text { (W. E. Kinney and F. G. Perey) }}}$

Measured neutron ${ }^{208} \mathrm{~Pb}$ differential elastic scattering cross sections at $5.50,7.00$, and 8.50 MeV are given and compared with previous results. Measured ${ }^{206} \mathrm{~Pb},{ }^{207} \mathrm{~Pb}$, and ${ }^{208} \mathrm{~Pb}$ neutron inelastic-scattering cross sections are given at roughly 0.5 MeV intervals from 5.50 to 8.50 MeV and also compared with previous results. ENDF/B III Mat 1136 elastic angular distributions, angle integrated elastic-and inelastic-scattering cross sections, and nuclear temperatures are in generally good agreement with experiment over this energy range.

[^34]
## A.3. Neutron Total Cross Sections

1. The Total Neutron Cross Sections of the Isotopes of Zr

Measurements have been completed on the total cross sections of the isotopes of Zr . The results for ${ }^{9}{ }^{0} \mathrm{Zr}$, obtained for a metallic sample, were presented earlier. Fig. 4 is a representation of the results for ${ }^{92,94,96} \mathrm{Zr}$ in which the earlier results for ${ }^{90} \mathrm{Zr}$ are given for comparison. The measurements were performed using both the ${ }^{6} \mathrm{Li}$ glass and the NE-110 plastic detectors at 80 meters, but only the results with the ${ }^{6} \mathrm{Li}$ glass detector are shown here. The ${ }^{96} \mathrm{Zr}$ was only $58-42$ percent enriched; Table I below summarizes the isotopic computation of the ${ }^{92,94,96} \mathrm{Zr}$ targets.

Table I

|  | Composition |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Target | 90 | 91 | 92 | 94 | 96 |  |
|  |  |  |  |  |  |  |
| 92 | 1.65 | 0.98 | 96.68 | 0.70 | $<0.10$ |  |
| 94 | 1.95 | 0.576 | 0.878 | 96.35 | 0.258 |  |
| 96 | 22.70 | 4.33 | 6.42 | 8.20 | 58.42 |  |


2. The Neutron Total Cross Section of ${ }^{243} \mathrm{Am}^{*}$, ** (0. D. Simpson, ${ }^{\dagger}$ $\bar{F}$. B. Simpson, $\dagger$ J. A. Harvey, G. G. Slaughter, R. W. Benjamin, $\dagger \dagger$ and C. E. Ahlfeld + )

Neutron transmission measurements have been made on two highpurity samples of ${ }^{243} \mathrm{Am}$, having inverse thicknesses of 1288.2 and $279.3 \mathrm{~b} / \mathrm{a}$, respectively. Data were collected from $0.5-1000 \mathrm{eV}$ using the Oak Ridge Electron Linear Accelerator. High resolution data were taken using $10-\mathrm{nsec}$ and $30-\mathrm{nsec}$ bursts of $140-\mathrm{MeV}$ electrons, $10-\mathrm{nsec}$ channel widths, and a flight path of 18.576 meters. An average value of $\Gamma_{\gamma}$ of $39 \pm 1 \mathrm{MeV}$ was determined from shape analysis of 24 resonances below 18 eV. Single level Breit-Wigner resonance parameters were obtained from area analysis up to 250 eV . The average level spacing between resonances was found to be $0.68 \pm 0.06 \mathrm{eV}$. An s-wave neutron strength function of ( $0.96 \pm 0.10$ ) $\times 10^{-4}$ was determined from the resonance parameters. The resonance-absorption integral for neutrons with energies above 0.625 eV was determined to be $1810 \pm 70 \mathrm{~b}$ from the resonance.

[^35]3. Neutron Total Cross Section of ${ }^{248} \mathrm{Cm*}$ (R. W. Benjamin, $\dagger$ C. E. Ahlfeld, $\dagger$ J. A. Harvey and N. W. Hill)

The neutron total cross section for ${ }^{248} \mathrm{Cm}$ has been measured from 0.5 to 3000 eV using the Oak Ridge LINAC, ORELA, as a pulsed neutron source. The small diameter ( 1.6 to 4.0 mm ) cylindrical samples contained up to 13 mg of $97 \%{ }^{248} \mathrm{Cm}$ and $3 \%{ }^{246} \mathrm{Cm}$ in the oxide form. Samples were cooled with liquid nitrogen to reduce Doppler broadening. The thickest sample had an inverse-thickness for curium isotopes of 625 barns/atom which made possible the identification of forty-seven resonances attributable to ${ }^{248} \mathrm{Cm}$ and five resonances attributable to ${ }^{246} \mathrm{Cm}$. The cross-section data have been analyzed to obtain single-level, Breit-Wigner resonance parameters for all observed resonances. An average level spacing $40 \pm 5 \mathrm{eV}$ and an
average s-wave neutron strength function of $(1.2 \pm 0.2) \times 10^{-4}$ were determined for ${ }^{248} \mathrm{~cm}$. The resonance contributions to the thermal capture cross sections and the resonance integrals determined from the resonance parameters are: ${ }^{248} \mathrm{Cm}-\sigma^{2000}=2.51 \pm 0.26 \mathrm{~b}, \mathrm{I}_{\mathrm{ny}}=259 \pm 12 \mathrm{~b} ;{ }^{246} \mathrm{Cm}-\sigma_{000}^{2000}=1.2 \pm 0.4 \mathrm{~b}$, $I_{n \gamma}=101^{n} \underline{\underline{n}} 11 \mathrm{~b}$. These values compare well with the results of integral measurements.

[^36]4. Neutron Total Cross Section of ${ }^{6} \mathrm{Li}$ from 100 eV to 1 MeV (J. A. Harvey and N. W. Hill)

${ }^{6}$ (i 7 Transmission measurements were made upon two samples of ${ }^{6} \mathrm{Li}$ (98.75\%) with inverse thicknesses of 11.84 and 2.585 barns/atom. Data were obtained with a Li glass scintillator and an NE-110 proton recoil detector 78.203 meters from the neutron target at ORELA. The neutron energy resolution $\Delta E / E$ was $\sim 0.1 \%$ or 0.2 keV at 247 keV . Since no fine structure was observed, the data with the thin sample using the NE-110 detector shown in Figure 5 have been averaged to give $\sim 2-\mathrm{keV}$ resolution. The statistical accuracy on these averaged points is 20.05 barns. The backgrounds (room and $2.23-\mathrm{MeV}$ gamma rays from neutron capture in the water of the moderator) were < $1 \%$ in this energy region. Other systematic errors arising from uncertainties in the neutron monitor are estimated to produce << 0.1 barn uncertainty. The observed peak cross section is $11.0 \pm 0.1$ barns in good agreement with values reported in references 1 and 2. The data obtained with the thin sample and the ${ }^{6}$ Li glass detector are in excellent agreement (within 0.1 barns and 0.5 keV ) with the data shown in Figure 5. The energy scale is accurate to § $0.1 \%$. The resonance energy obtained by the method of diameters is $246 \pm 1 \mathrm{keV}$, in good agreement with the time of flight measurements of Uttley ${ }^{1}$ ( 247 keV ). Energy values from Van de Graaff measurements on this nuclide are $\sim 5 \mathrm{keV}$ too high. In the energy region from 300 to 10000 eV the data from the thin sample are in excellent agreement (within 20.05 barns or ${ }^{2} 1 \%$ ) with the formula proposed by Uttley ${ }^{1}$ namely $\sigma_{T}=0.70+$ $149.5 / \sqrt{E}$.

[^37]

## A.4. Neutron Capture

1. $\frac{\text { Comments on the Doorway State in }{ }^{206} \mathrm{~Pb} *}{\text { R. L. Macklin, C. Y. Fu and R. R. Winters }}+{ }^{\text {( }}$ (B. J. Allen, ${ }^{\dagger}$

The neutron capture cross section of ${ }^{206} \mathrm{~Pb}(\mathrm{n}, \gamma)$ has been measured with high resolution at the Oak Ridge Electron Linear Accelerator. The capture results show that the reported $s_{1 / 2}$ doorway in ${ }^{206} \mathrm{~Pb}$ is not observed in the photon channel.

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* Phys. Rev. C, 7, No. 6 (1973) p. 2598.
\daggerPresent address: Australian Atomic Energy Commission, Lucas Heights,
    Australia.
\dagger\dagger
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2. Neutron Capture Gamma-Ray Yields in Iron* (J. E. White
Gamma-ray yields as a function of neutron energy from thermal
to 1 MeV for iron have been generated with a combined experimental and theoretical approach. The theoretical part is to a large extent statistical; however, parameters are introduced to compensate for the nonstatistical behavior. Experimental information used to evaluate these parameters are the branching ratios among discrete levels and the gamma-ray primary transitions from thermal and available resonance capture. A discussion of the implications of additional resonance capture yield data, which was made available after the completion of the calculation, is included. The results have been compared with integral experiments, and the agreement is favorable. Considerable variations in the capture gamma-ray yields as a function of incident neutron energy are noticed.
*Nuc1. Sci. Eng. 51, 496-508 (1973).
3. Gold Neutron Capture Cross Section from 3 to 550 keV *

A careful remeasurement of this standard cross section at ORELA using the pulse height weighting technique in small scintillators has been completed. The 4.9 eV resonance was used for calibration and the ${ }^{6} \mathrm{Li}(\mathrm{n}, \alpha)$ cross section for flux shape. Estimated errors range from $1.4 \%$ near 30 keV to $3.3 \%$ at 550 keV . Individual resonance parameters
were deduced in the $2.6-4.9 \mathrm{keV}$ range and the fluctuations over tens of resonances were analyzed below 90 keV . The fluctuations are larger than expected, limiting the precision attainable with monoenergetic sources using this standard. The fluctuation intensity appears to indicate intermediate resonance structure in the compound nucleus with 10 keV width and 50 keV spacing.

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*Submitted to Physical Review C.
\({ }^{\dagger}\) Present address: Denison University, Granville, Ohio.
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\text { 4. } \frac{\text { A Study of }{ }^{205} \mathrm{Tl}(\mathrm{n}, \gamma)^{206} \mathrm{Tl} \text { Resonance Parameters* }}{\text { (E. D. Earle, } \dagger \text { R. R. Winters, } \dagger \dagger \text { and R. L. Macklin) }}
$$

We have repeated with improved resolution and statistics a ${ }^{205} \mathrm{~T} \ell(\mathrm{n}, \gamma)^{206} \mathrm{Tl}$ cross-section measurement ${ }^{1}$ for $\mathrm{E}_{\mathrm{p}}<400 \mathrm{keV}$ using the total energy gamma-ray detector at the ORELA 40 m station. ${ }^{2}$ The energy resolution was $0.2 \%$ and, since the level spacing is about 1 keV , most resonances below 250 keV were resolved. The relative magnitude of the 5.5 MeV gammaray anomaly ${ }^{1}$ for each resonance is determined and where possible values of the resonance parameters $\Gamma_{\mathrm{n}}$ and $\mathrm{g} \Gamma_{\gamma}$ are deduced from the measured widths
and capture areas. and capture areas.
${ }^{7}$ Presented at the APS Meeting, Washington, D. C., April 23-26, 1974; published in the Bulletin of American Physical Society 19, 574 (April 1974). $\dagger_{\text {Present }}$ address: Chalk River Nuclear Laboratories, AECL, Chalk River, Ont., Canada.
$\dagger$ Present address: Denison University, Granville, Ohio.
${ }^{1}$ E. D. Earle, M. A. Lone, G. A. Bartholomew, B. J. Allen, G. G. Slaughter and J. A. Harvey, "Statistical Properties of Nuclei" (J. B. Garg, Ed.) Plenum Press, New York (1972) p. 263.
${ }^{2}$ R. L. Macklin and B. J. Allen, Nuc1. Instr. Meth. 91 (1971) 565.
5. The ${ }^{57} \mathrm{Fe}(\mathrm{n}, \gamma)^{58} \mathrm{Fe}$ Reaction and Shell Model Calculations of ${ }^{58} \mathrm{Fe}$ Levels (G. G. Slaughter, S. Raman, W. M. Good, J. A. Harvey, J. B. McGrory and D. Larson)

We have studied 14 neutron resonances below 30 keV in the
${ }^{57} \mathrm{Fe}+\mathrm{n}$ system via both transmission and capture gamma-ray studies. A level scheme for ${ }^{58} \mathrm{Fe}$ was constructed with 23 excited states below 5.3 MeV . We have collected together all available information on ${ }^{58} \mathrm{Fe}$ levels
in order to make a rigorous comparison with the results of a shell model calculation. The calculated energy levels correlate very well with observed ones. The agreement is less satisfactory in the case of gamma-ray branchings, partly due to the uncertainty concerning the effective Ml operator.
*Presented at the APS Meeting, Washington, D. C., April 22-25, 1974; published in the Bulletin of American Physical Society 19, 430 (April 1974).

6. The ${ }^{143} \mathrm{Nd}(\mathrm{n}, \gamma)$ Reaction*,** (D. A. McClure, $\dagger$ S. Raman, G. G. Slaughter, J. A. Harvey, J. C. Wells, Jr., †† Jung Lin, $\dagger$ t and E. T. Jurney, $\dagger+\dagger$ )

Continuing our investigations of levels in ${ }^{144} \mathrm{Nd}$ (Ref. 1), we have carried out $\mathrm{Ge}(\mathrm{Li})-\mathrm{Ge}(\mathrm{Li})$ coincidence measurements with a natural Nd target bombarded with thermal neutrons. The two-parameter ( $4096 \times 4096$ channe1) measurements involved $\approx 16 \times 10^{6}$ coincidence events collected in 120 h . The level scheme now contains $\approx 60$ levels (a third of these confirmed by coincidence measurements) below 3.5 MeV and incorporates $\approx 225$ gamma rays (half of the total observed). The coincidence measurements were invaluable in avoiding (and in some cases confirming) multiple placements of gamma rays.
*Presented at the APS Meeting, Washington, D. C., April 22-25, 1974;
${ }_{* *}$ published in the Bulletin of American Physical Society 19, 500 (April 1974).
Relevant to request No. 318.
$\dagger_{\text {Present }}$ address: Georgia Institute of Technology, Atlanta, GA.
${ }^{\dagger}$ Present address: Tennessee Technological University, Cookeville, TN.
$\dagger+\dagger$ Present address: Los Alamos Scientific Laboratory, Los Alamos, NM.

## A.5. Charged Particle Induced Reactions

1. Differential Cross Sections for the Production of Neutrons from the Bombardment of ${ }^{12} \mathrm{C},{ }^{27} \mathrm{~A} 1,{ }^{54} \mathrm{Fe}$, and ${ }^{208} \mathrm{~Pb}$ by $40-\mathrm{MeV}$ Protons*, ** (J. W. Wachter, R. T. Santoro, T. A. Love and W. Zobe1 $\dagger$ )

Differential cross sections in energy and angle have been obtained using time-of-flight spectroscopy for secondary neutrons produced in the reactions of 39.3 - and $40.8-\mathrm{MeV}$ protons with ${ }^{12} \mathrm{C},{ }^{27} \mathrm{Al},{ }^{54} \mathrm{Fe}_{\text {, }}$ and ${ }^{20}{ }^{8} \mathrm{~Pb}$. Neutron energy spectra are given for laboratory angles of $0^{\mathrm{d}}, 20^{\circ}$, $45^{\circ}, 60^{\circ}, 90^{\circ}$, and $135^{\circ}$ for energies $\geq 6 \mathrm{MeV}$. The NE-213 efficiency was calculated using the 05S Monte Car1o code. Comparisons with the predictions of the intranuclear-cascade model of Bertini show good agreement at
medium angles. As with the earlier $63-\mathrm{MeV}$ measurements, the data do not show the predicted quasifree scattering peak at small angles. The calculated cross sections at $135^{\circ}$ are low by factors of 3 to 6 .
*Presented at the 1973 Winter APS Meeting, Berkeley, CA, December 27-29, 1973. ** Relevant to request No. 630.
$\dagger_{\text {Present }}$ address: Tennessee Valley Authority, Knoxville, TN.

> 2. $\frac{\text { Coulomb Excitation of Vibrational-Like States in the }}{\text { Even-A Actinide Nuclei* }}$ (F. K. McGowan, C. E. Bemis, Jr., W. T. Milner, J. L. C. Ford, Jr., R. L. Robinson and P. H. Stelson)

Coulomb excitation of vibrational-like states in the even-A actinide nuclei ( $230 \leq \mathrm{A} \leq 248$ ) was measured using ${ }^{4} \mathrm{He}$ ions in order to test nuclear models describing these states. In particular, the one-phonon octupole vibrational interpretation of the low-lying negative parity states provides an interesting theoretical framework with which to compare the experimental information. The excitation probabilities were determined relative to the elastic scattering by the observation of elastically and inelastically scattered ${ }^{4} \mathrm{He}$ ions using a split-pole magnetic spectrometer equipped with a position-sensitive proportional detector. The values of $B(E \lambda, O \rightarrow J=\lambda)$ range from 0.5 to 4 single-particle units for $\lambda=2$ and from 10 to 30 single-particle units for $\lambda=3$. For those cases, where the K , $\mathrm{J} \pi$ assignments are known, the agreement between the experimental results and the microscopic calculations by Neegard and Vogel of the $B(E 3,0 \rightarrow 3)$ for the $3^{-}$members of the one-phonon octupole quadruplet is good when the Coriolis coupling between the states with $K$ and $K \pm 1$ is taken into account. The magnitudes of the reduced EO nuclear matrix element, $\rho\left(E O, 2^{\prime} \rightarrow 2\right)$, extracted from the EO transition probabilities $T\left(E O, 2^{\prime} \rightarrow 2\right.$ ) for decay of the $\beta$-vibrational-like $2^{\prime+}$ state are $0.37 \pm 0.06$ and $0.43 \pm 0.06$ for ${ }^{232} \mathrm{Th}$ and ${ }^{238} \mathrm{U}$, respectively. Several $2^{+}$states observed in this Coulomb excitation reaction survey are presumed to be $2^{+}$members of rotational bands based on $0^{+}$excited states which are strongly populated in the ( $p, t$ ) reaction.

[^38]
## A.6. Benchmark Measurements

1. Final Report on a Benchmark Experiment for Neutron Transport in Thick Sodium* (R. E. Maerker, F. J. Muckenthaler, R. L. Childs and M. L. Gritzner ${ }^{\dagger}$ )

An experiment concerning deep neutron penetration in sodium is described, and experimental results are presented which provide a basis for verification of the accuracy of sodium cross sections to be used in transport calculations. The experiment was performed at the Tower Shielding Facility of ORNL and included measurements of both the neutron fluence and neutron spectra through a large diameter sample of sodium up to 15 ft thick. Calculated results for the experiment are presented for comparison with the experimental measurements. These results were obtained using the multigroup Monte Carlo code, MORSE, and a two-dimensional discrete ordinates code, DOT III. One-hundred group data sets were developed from both a preliminary and the final version of the ENDF/III set (MAT=1156) for sodium for use in the calculations. Comparisons of the calculations with experiment indicate that the preliminary version is slightly superior to the final version and that using the preliminary set the total neutron leakage above thermal energies penetrating up through 15 ft of sodium can be calculated to within $\sim 15 \%$ and the absolute spectra penetrating up through 12.5 ft of sodium can be calculated to within $20 \%$. Using the final set, the corresponding comparisons are $30 \%$ and $60 \%$.

[^39]
## 2. Final Report on a Benchmark Experiment for Neutron Transport Through Iron and Stainless Steel* (R. E. Maerker and F. J. Muckenthaler)

An experiment concerning neutron penetration in iron and stainless steel is described, and experimental results are presented which provide a basis for verification of the accuracy of iron cross sections to be used in transport calculations. , he experiment was performed at the Tower Shielding Facility of ORNL and included measurements of both the neutron fluence and neutron spectra through samples of iron up to 3 ft thick and of stainless steel up to 18 in. thick. Calculations of the experiment were performed with a special version of the MORSE multigroup Monte Carlo code which uses point total cross sections. Comparison of the calculations with experiment indicates that the recently evaluated MAT 4180-Mod. 1 iron crosssection set is superior to the older MAT 1101 and MAT 1124 sets. Calculations using this newest set result in total neutron leakages above thermal energies penetrating up to 3 ft of iron or 18 in . of stainless steel that agree with experiment to within about $20 \%$. The calculated leakage spectra above 90 keV arising from scattering through up to 1 ft of iron or 18 in .
of stainless steel also agree with experiment to within about $20 \%$. Using any of the three sets, the calculated unscattered component through 1 ft of iron or stainless steel above 1 MeV is only accurate to within about $40 \%$.
*Abstract of ORNL-4892.
A.7. Cross-Section Sensitivity Work

1. Estimated Uncertainties in Evaluated Data* (F. G. Perey)

During the last decade large efforts have gone into preparing microscopic neutron cross section data files, called evaluated data files, to serve as basic input data for various neutron transport applications. A prime example of such evaluated microscopic cross sections is the ENDF/B set, a cooperative effort of the Cross Section Evaluation Working Group (CSEWG). The ENDF/B cross-section reference set is updated periodically to provide increased coverage of nuclides, energy range, reaction types, ...etc., and generally to upgrade the data files to reflect our improved knowledge of the cross sections due to new measurements or theoretical calculations and also to remove deficiencies discovered in the analysis of integral experiments (Phase II data testing). The data files are intended to represent as accurately as possible our knowledge of the microscopic cross sections and, therefore, should be application independent. However, because this evaluation work has been funded almost exclusively out of various applied programs, invariably the content of the ENDF/B set has been influenced by the applications for which the different evaluations were needed. The most efficient use of limited financial resources devoted to this aspect of nuclear technologies, the different stages of development of these technologies with respect to nuclear data needs, and the varying importance of the nuclei of the set in different applications have caused the 'intrinsic quality' of the data in the files to vary widely as a function of nuclei, reaction types and energy ranges. The fact that an evaluated file exists for a nuclei in the official CSEWG reference set at a given time is not a proof of its adequacy for any specific application, but only represents the collective judgement of the CSEWG members that it was the best overall evaluation available in this format at that time and it meets a minimum of procedural requirements (Phase I review).

At the moment possibly only one evaluation, the one for hydrogen, is generally thought to exceed the accuracy requirements in the microscopic data for most present, or contemplated, applied uses. For most important neutron transport applications, it is generally conceded that many of the neutron cross sections will not be known, for a long time, to such a high degree of accuracy that uncertainties in the basic microscopic data can be ignored. Several studies have been made, for a few applications, of the cost and design penalties associated with nuclear data uncertainties and yielded what we could call 'target accuracies' in the various microscopic data as acceptable for these applications. These studies have had to
assume what were acceptable design parameter uncertainties and on the basis of the then known cross sections make assumptions on what would be the 'correlations on the uncertainties' in the final acceptable data set. At present it is thought that for some applications a few of the very important partial cross sections may be known to within a factor of two of the 'target accuracies' of these studies. There is, however, no consensus on the question of whether the present estimated uncertainties are sufficiently uncorrelated or not.

In order to answer in a credible manner most of the questions regarding the adequacy of nuclear data for different applications, we require a knowledge of the estimated uncertainties, and their correlations, in the evaluated data. This information at the present time is sometimes to be found in the documentation of the evaluations, is very incomplete, difficult to extract and sufficiently ill-defined as to the nature of the correlations in the data so as to prevent very credible quantitative statements to be made regarding the adequacy of the data. With ENDF/B-IV a start has been made toward the implementation of the complete description of the estimated covariances of the microscopic data on the tape. We will present the concepts and major features of the ENDF/B-IV format for representing the covariance matrices of the pointwise microscopic cross sections as a function of energies, of different partial cross sections for a given nuclei and of cross sections for different nuclei. We will show how the method of representation chosen allows the computation of covariance matrices of group cross sections as a straightforward additional step to most present group cross-section processing codes. The problems of representing these covariances and their handling by processing codes for the resolved and unresolved resonance regions are under active investigation and will be alluded to.

[^40]
## 2. The Formalism for Data Covariance Representation in ENDF/B* (F. G. Perey)

In many transport calculations a significant fraction of the uncertainties in the calculated results comes from the uncertainties in the basic cross-section data used as input. The implications of such uncertainties for the design of reactors and their significant economic impacts have been discussed by Greebler, Bane, Usachev, and others. Evaluated microscopic neutron cross-section files used to generate the input data for such calculations have not in the past attempted to represent in the files the estimated covariances of the microscopic cross sections for the purpose of propagating these estimated uncertainties to the final results of transport calculations. CSEWG decided for ENDF/B-IV to adopt formats to allow a precise representation of estimated covariances in some of the microscopic data.

It is the purpose of this paper to present in some detail how estimated uncertainties and correlations in the evaluated data, the covariances
of the cross sections, can be represented in the ENDF/B files. The basic concept used in the formalism is the expansion of the covariances of the energy dependent cross sections into elements which are fully correlated over a stated energy range.

[^41]$$
\text { 3. } \frac{\text { Radiation Transport Cross-Section Sensitivity Analysis }- \text { A }}{\text { General Approach Illustrated for a Thermonuclear Source in }}
$$

A general approach to radiation transport cross-section sensitivity analysis is introduced and its applicability demonstrated for a problem involving neutron and gamma-ray transport in air. The basis for the method is generalized perturbation theory using flux solutions to the transport equation and its adjoint. Both an analytical aspect of the technique, designed for surveying the sensitivity of a result to the entire crosssection data field, and a predictive aspect, designed for predicting the effect of changes in the data field, are presented. The analytic procedure is demonstrated by results that include a determination of important energy regions in the total, partial, and gamma-ray-production cross sections of nitrogen and oxygen for deep-penetration calculations of tissue dose in air. The predictive capability is illustrated for specific cross-section perturbations in the system and the effects of truncating the Legendre expansion of the scattering kernel. In addition, the applicability of the method for predicting variances in a calculated result arising from cross-section data uncertainties is demonstrated. In the sample case, the variance in the total neutron-gamma tissue dose is estimated from preliminary cross-section error files given in the evaluations of the nitrogen and oxygen cross sections.
*Abstract of ORNL-TM-4335.
4. Effects of Highly Anisotropic Scattering on Monoenergetic Neutron Transport at Deep Penetrations* (E. Oblow, K. Kin, $\dagger$ H. Goldstein, ${ }^{4}$ and J. J. Wagshal ${ }^{\text {ff }}$ )

The sensitivity of the flux in deep-penetration problems to anisotropic scattering was studied within the framework of monoenergetic transport theory. Several parameterized, anisotropic scattering kernels were used to represent a general class of anisotropies. The representation of these kernels in Legendre polynomial series of various orders was explored to determine their effect on calculated discrete eigenspectra and infinite medium fluxes. Eigenspectra for several kernels are presented as a function of the kernel parameter. Conclusions were drawn about the
order of the Legendre expansion of the kerne1s required for accurate deeppenetration calculations, and the possible existence of multiple diffusion decay modes in realistic problems. In general, rather low order Legendre expansion was found to be adequate for problems in which the scalar flux was the primary quantity of interest.

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    * Abstract of ORNL-TM-4408.
    \daggerPresent address: Columbia University, New York, NY.
\dagger Present address: Columbia University, New York, NY.
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## 5. Effects of Air-Density Perturbations on the Transport of Gamma Rays Produced by Point Gamma-Ray Sources* (B. J. McGregor ${ }^{\dagger}$ and F. R. Mynatt)

A series of MORSE Monte Carlo calculations have been performed to determine the effect that changes in the air density produced by one weapon detonation would have on the transport of gamma-ray radiation produced by a second weapon detonated about one second later. The response of interest was the ionization that would be induced in silicon by gamma rays in the vicinity of and beyond the first burst. A gamma-ray emission spectrum was used for the second weapon and four burst separation distances were considered. The medium was assumed to be infinite air, and spherical geometry was employed with the origin at the center of the second detonation. The changes in density about the first detonation were handled with a pseudocollision technique. Boundary-crossing estimators were used at two radii from the second detonation and within nine solid angles measured from an axis passing through both detonations. Total, uncollided, and time-dependent gamma-ray ionization responses were calculated at each detector position. Total responses calculated for a position in the perturbed air immediately beyond the first burst were about $50 \%$ higher than those obtained in air; an even greater increase was calculated for the uncollided response, which is a significant portion of the total response at detector positions between 1000 and 1500 m from the source.

The changes in the total ionization due to the perturbations were very similar to the changes in the neutron displacement calculated for a $14-\mathrm{MeV}$ neutron source in a previous study. Changes in the peak ionization rate followed changes in the total ionization for large separation distances but were less for small separations.

[^42]6. Cross-Section Sensitivity of Breeding Ratio in a FusionReactor Blanket ${ }^{*}$ (D. E. Bartine, R. G. Alsmiller, Jr., E. M. Oblow, and F. R. Mynatt)

For a particular fusion-reactor-blanket configuration, the changes in the tritium breeding ratio, i.e., in the number of tritium nuclei produced in the blanket per incident neutron, due to changes in nuclear cross-section data are calculated on the basis of linear perturbation theory. Results are presented for the changes in the breeding ratio due to changes in specific energy ranges of various partial cross sections of ${ }^{6} \mathrm{Li},{ }^{7} \mathrm{Li}, \mathrm{Nb}$, and C . The breeding ratio is found to be most sensitive to changes in the ${ }^{7} \mathrm{Li}\left(\mathrm{n}, \mathrm{n}^{\prime}\right) \alpha, t$ cross section, but the sensitivity to changes in this cross section is not large.
*Nucl. Sci. Eng. 53, 304-318 (1974).

## 7. Reactor Cross-Section Sensitivity Studies Using Transport Theory* (E. M. Oblow)

An approach to making reactor sensitivity studies and reactor parameter uncertainty analysis using transport theory is developed. Sensitivity functions based on variational principles are reviewed and compared with an alternate approach using generalized perturbation theory. The computational implementation of the method using transport codes is also discussed. Finally, the use of cross-section error files in conjunction with sensitivity coefficients in estimating uncertainties in reactor parameters is described.

[^43]8. Generalized Reactor Sensitivity Analysis Program at ORNL ${ }^{*}$ (E. G. Silver, E. M. Oblow, J. M. Kallfelz,† C. R. Weisbin, D. E. Bartine, G. F. Flanagan and F. R. Mynatt)

The shielding sensitivity analysis program at ORNL based on one-dimensional transport calculations is currently being expanded to include core physics sensitivity analysis capability. Major development items associated with this task lie in the areas of applying generalized perturbation theory to transport calculations of reactor core problems and generating and utilizing correlated cross-section uncertainty data in estimating uncertainties in reactor design parameters. The problems associated with applying generalized perturbations theory are numerical in nature and particular to the use of finite-difference methods in solving the transport equation; they do not occur in using the diffusion approximation. As a result, restrictions are placed on the type of reactor models which can be analyzed with transport methods. Estimation of uncertainties in reactor
paremeters presents major problems in the areas of evaluating the uncertainties in the cross-section data used in a reactor calculation with particular attention to correlations between the data. Computer formats suitable for storing the correlated uncertainty data and codes for processing such data into multigroup data files must be developed. The effort at ORNL is directed towards automating in a single computer code system the procedure for solving generaled perturbation theory equations to generate sensitivity coefficients and linking this data with processed cross-section uncertainty files to generate and analyze reactor design parameter uncertainties.

[^44]
## A.8. Theoretical Analysis

## 1. Compilation of Phenomenological Optical-Model Parameters 1969-1972* (C. M. Perey and F. G. Perey)

A little over a year ago, we published a pilot compilation of phenomenological optical-model parameters obtained by fitting elasticscattering data. This compilation covered only two years of publication 1969 and 1970, but we have been led to believe that it is more widely used than we had anticipated. Encouraged by this result, we continued collecting optical-model parameters and have now added the years 1971 and 1972 to our compilation.

* To be published in Nuclear Data Tables.

2. Calculated Secondary-Particle Spectra from Alpha-Particle and Carbon-Induced Nuclear Reactions* (T. A. Gabriel, R. T. Santoro, N. W. Bertini, and N. M. Larson)

A newly developed calculational model for nucleus-nucleus collisions has been applied to obtain secondary-neutron spectra from 100$\mathrm{MeV} / \mathrm{nucleon}$ alpha particles incident on C and from $100-\mathrm{MeV} / \mathrm{nuc}$ eon C incident on $C$. These data can be used in estimating shielding requirements for medium-energy heavy-ion machines. Also included is a comparison between a previous model used only for calculating secondary-particle spectra from alpha-particle nuclear reactions and the new, more general nucleus-nucleus collision model.

[^45]3. $\frac{\text { Treatment of Large Perturbations of the Hamiltonian and the }}{\text { Foundary Conditions of a Quantum Mechanical System as an }}$

On the basis of an integrodifferential equation satisfied by the transition T-matrix, together with its associated initial conditions, we have developed a general formalism to treat large perturbations in both the Hamiltonian and the boundary conditions of a quantum mechanical system. As a result of this formalism, a set of first order differential equations, in terms of any of the physical parameters of the system, is given for the widths and poles of the collision U-matrix.

The technique is illustrated by the coversion of a set of $R$-matrix resonance parameters into its equivalent set of U-matrix widths and poles, which corresponds to the passage from the R-matrix boundary conditions to the complex, momentum-dependent boundary conditions associated with the Kapur-Peierls reaction formalism.

The case of large perturbations of the Hamiltonian is illustrated by the calculation of the elastic- and inelastic-scattering cross sections in a strongly coupled two-channel system which was proposed by Tobocman and has been widely used as testing grounds for reaction theorites.

[^46]OHIO UNIVERSITY ACCELERATOR LABORATORY

## A. TANDEM ACCELERATOR PROGRAM

1. Performance of a high-pressure, high-beam-current gas target* (J.D. Carlson)

A low mass, small-volume gas target which utilizes 0 -rings for mounting the entrance window is described. The target is intended as a neutron source using the $D(d, n)^{4} \mathrm{He}$ and $T(p, n)^{4} \mathrm{He}$ and $T(p, n)^{3} \mathrm{He}$ reactions. The performance of the gas target with respect to gas pressure and beam intensities is discussed.

* Work published Nuc. Inst. and Methods $\underline{113}$ (1973) 541.

2. Optical Model Analysis of quasielastic ( $\mathrm{p}, \mathrm{n}$ ) reactions at 22.8 MeV* (J.D. Carlson, C.D. Zafiratos** and D.A. Lind**)

Quasielastic ( $\mathrm{p}, \mathrm{n}$ ) differential cross sections have been measured for 29 nuclei ranging from ${ }^{9} \mathrm{Be}$ to ${ }^{208} \mathrm{~Pb}$ at an energy of 22.8 Mev in approximately $7.5^{\circ}$ steps from $10^{\circ}$ to $152^{\circ}$. The results have been analyzed with a distorted-wave Born-approximation in terms of the generalized optical model due to A.M. Lane. Starting with a complex isospin interaction form factor, $\mathrm{U}_{1}$, deduced from the Becchetti-Greenlees global set of proton optical parameters, the shape of the surface-peaked, imaginary part of $\mathrm{U}_{1}$ was varied until good fits to the data were obtained. The shape of the real part of $U_{1}$ and the ratio of the real to imaginary well depths were kept fixed at the Becchetti-Greenlees values. The resulting best-fit form factors had overall strengths $20-30 \%$ less than the BecchettiGreenlees value. Further, the resulting imaginary part of $U_{1}$ was found to peak at a decreasing radius relative to the real part of $U_{1}$ with an increasing width as A increases. A smoothed parameterization of the best-fit $\mathrm{U}_{1}$ is given for all nuclei with $\mathrm{A}>40$. The individual best-fit $\mathrm{U}_{1}$ are used to generate self-consistent neutron optical potentials from the Becchetti-Greenlees proton optical potentials as prescribed by the Lane model. Neutron elastic scattering angular distributions and reaction cross section predicted by these self-consistent potentials are in good agreement with observed neutron scattering data

[^47]3. Elastic Scattering of 11 MeV Neutrons (J.D. Car1son, J. Ferrer, J. Rapaport and J.F. Lemming)

Angular distribution measurements of elastically scattered 11 MeV neutrons with a resolution of 200 keV have been completed. Scattered neutrons produced by the $D(d, n)^{3} \mathrm{He}$ reaction were detected simultaneously by five liquid organic scintillators employing time of flight method. A total of 21 target nuclei ranging from Mg to Bi were used including enriched samples of $92,96,98,100 \mathrm{Mo},{ }^{120} \mathrm{Sn}$ and ${ }^{206} \mathrm{~Pb}$. Analysis of the data that takes into account multiple scattering, sample attenuation and angular spread corrections is presently in progress.
4. Measurements of differential neutron elastic cross section for $\overline{\mathrm{Al}, \mathrm{Fe}, \mathrm{Nb},{ }^{120} \mathrm{Sn}, \mathrm{Bi}, \mathrm{Pb} \text { at } 26.0 \mathrm{MeV} \text {. (J.D. Carlson and J. }}$ Rapaport)

Angular distributions of $26-\mathrm{MeV}$ neutrons scattered from $\mathrm{A} 1, \mathrm{Fe}, \mathrm{Nb}$, ${ }^{120} \mathrm{Sn}, \mathrm{Bi}, \mathrm{Pb}$ have been measured between $25^{\circ}$ and $155^{\circ}$ in $5^{\circ}$ steps. A relative uncertainty of approximately $2 \%$, based only on counting statistics was obtained. Five ( $8^{\prime \prime}$ diameter, and $2^{\prime \prime}$ thick NE224) neutron detectors were used simultaneously at a flight path of 6.5 meters. A beam of 5-7 $\mu \mathrm{A}$ of $1.2-1.5 \mathrm{nsec}$. pulsed 9 MeV deuterons ( 5 mcs rep rate) was used in conjunction with a gas cell filled with 1100 TORR of tritium gas, to provide the 26 MeV neutrons.

The data is at present being corrected for multiple scattering and finite geometry corrections.
5. Structure Studies of Light Nuclei with Neutrons
a. Study of Level Structure of ${ }^{11} \mathrm{~B}$ from the Scattering of Neutrons from ${ }^{10}$ B. (S.L. Hausladen, R.O. Lane, J.M. Cox, C.E. Nelson, H.D. Knox and R.W. Fin1ay)

The following are abstracts of two papers recently published: "Evidence for Assignment of 14.0 MeV State in ${ }^{11} \mathrm{~B}$ from ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{n}){ }^{10} \mathrm{~B}^{\prime \prime *}$ (J.M. Cox, H.D. Knox, R.O. Lane and R.W. Finlay)
''The differential cross section and polarization for neutrons scattered from ${ }^{10} \mathrm{~B}$ have been measured at $\mathrm{E}_{\mathrm{n}}=2.63 \mathrm{MeV}$ ( $\mathrm{E}_{\mathrm{x}}=13.85 \mathrm{MeV}$ ). The results of this experiment and other available neutron scattering data in the range $1<\mathrm{E}_{\mathrm{n}}<4 \mathrm{MeV}$ are interpreted through a single-level R-matrix calculation over the region $12<\mathrm{E}_{\mathrm{X}}<15 \mathrm{MeV}$. Based on this analysis the most probable $J^{\pi}$ assignment for the 14.0 MeV level in ${ }^{11} \mathrm{~B}$ is $\frac{11+}{2}$. The anomaly near $\mathrm{E}_{\mathrm{X}}=13.1 \mathrm{MeV}$ can only be explained in terms of two overlapping levels having assignments of (5/2,7/2) ${ }^{-}$and (3/2,5/2,7/2) ${ }^{+}$."
"Structure Study of ${ }^{11} \mathrm{~B}$ from the Scattering of Neutrons from ${ }^{10} \mathrm{~B}^{1 * * *}$ (S.L. Hausladen, C.E. Nelson and R.O. Lane)
'Differential cross sections for neutrons scattered from ${ }^{10} \mathrm{~B}$ have been measured for $1.5 \mathrm{MeV}<\mathrm{E}_{\mathrm{n}}<4.4 \mathrm{MeV}$. These results and elastic scattering and polarization data at lower energies together with data from thr reactions ${ }^{10} \mathrm{~B}\left(\mathrm{n}, \alpha_{0}\right)^{7} \mathrm{Li}$ and ${ }^{10} \mathrm{~B}\left(\mathrm{n}, \alpha_{1}\right)^{7} \mathrm{Li}(0.48 \mathrm{MeV})$ have been simultaneously fitted using a two-level, four-channel R-matrix formalism with a non-diagonal background $\mathrm{R}^{0}$ matrix. The level parameters obtained from the R-matrix fitting of these data for states in ${ }^{11} \mathrm{~B}$ with excitaiton energies $11.5 \mathrm{MeV}<\mathrm{E}_{\mathrm{X}}<15.5 \mathrm{MeV}$ are consistent with other reactions such as ${ }^{10} \mathrm{~B}\left(\mathrm{n}, \mathrm{n}^{\prime} \gamma\right){ }^{10} \mathrm{~B}(0.717),{ }^{7} \mathrm{Li}\left(\alpha, \mathrm{n}_{0}\right){ }^{10} \mathrm{~B}$ and ${ }^{7} \mathrm{Li}\left(\alpha, \mathrm{n}_{1}\right){ }^{10} \mathrm{~B}(0.717)$ which lead to states in ${ }^{11}$ B."

Very recent calculations by the Los Alamos evaluation group (G. Hale, private comm.) with their large R-matrix search program have confirmed our results for assignments of states in ${ }^{11} \mathrm{~B}$. Their fitting includes more extensive data on ${ }^{7} \mathrm{Li}(\alpha, \alpha){ }^{7} \mathrm{Li},{ }^{7} \mathrm{Li}\left(\alpha, \alpha{ }^{1}\right){ }^{7} \mathrm{Li} *,{ }^{7} \mathrm{Li}\left(\alpha, \mathrm{n}_{0}\right){ }^{10} \mathrm{~B}$ and ${ }^{7} \mathrm{Li}\left(\alpha, \mathrm{n}_{1}\right)^{10} \mathrm{~B}^{*}$ and has so far been 1imited to $\mathrm{E}_{\mathrm{n}} \approx 1 \mathrm{MeV}$. The leve1 structure in this nucleus is quite complex above $\mathrm{E}_{\mathrm{X}}^{\mathrm{n}} \sim 10 \mathrm{MeV}$ and consideration is being given to various additional measurements including neutron polarization that might reduce the uncertainty in assignments at the higher energies.

[^48]b. Structure Study of ${ }^{12}$ B from the Elastic Scattering of Neutrons from ${ }^{11}$ B.* (C.E. Nelson, S.L. Hausladen and R.O. Lane)

The following is and abstract of a paper recently published on this topic:
'Differential cross sections for neturons scattered from ${ }^{11} B$ have been measured for $2.2 \mathrm{MeV}<\mathrm{E}_{\mathrm{n}}<4.5 \mathrm{MeV}$. The differential cross section $\sigma(\theta)$ is fitted reasonably well by ${ }_{+}$R-matrix parameters for broad states in ${ }^{12} \mathrm{~B}$ with assignments 1 and (1) ${ }^{+}$at excitation energies $\mathrm{E}_{\mathrm{x}}=5.8$ and 6.8 MeV respectively. The broad $1^{-}$state has not been previously observed and is believed to be the $1^{-}$member of the $1 p_{5 / 2^{-1}} d_{5 / 2}$ particlehole multiplet predicted to exist by earlier shell model calculations. Its existence completes the identification of all of the levels of this multiplet ( $3^{-}, 2^{-}, 4^{-}, 1^{-}$). The broad (1) level at $\mathrm{E}_{\mathrm{x}}=6.8 \mathrm{MeV}$ has not been previously observed. States at excitation energie's $\mathrm{X}_{\mathrm{x}}=5.61,5.73$ and 6.6 MeV have been assigned spins and parities of $3^{+,} 3^{-}$and (1) ${ }^{+}$respectively. these states had previously been assigned spins of 2,3 and $\geqq 1$ respectively. Work on $\mathrm{T}=1$ states in ${ }^{12} \mathrm{C}^{*}$ has been compared with the present work."

Neutron scattering from ${ }^{11}$ B offers a paricularly good opportunity to compare experiment and shell model structure calculations because of the low excitation energies available in ${ }^{12} \mathrm{~B}$ and the relatively simple
particle-hole structure. To this end, further investigations are being made into the comparisons of our results with model predictions in the $A=12$ system such as those of Rowe $\&$ Wong 1 . Because neutron interactions with ${ }^{11} \mathrm{~B}$ at these energies lead only to pure $\mathrm{T}=1$ states in ${ }^{12} \mathrm{~B}$ a more direct comparison with theory can be made than for states in ${ }^{12} \mathrm{C}$ because theory predicts ${ }^{1}$ states of pure-T whereas the observed mixing of $\mathrm{T}=0$ and $\mathrm{T}=1$ in ${ }^{12} \mathrm{C}$ presents difficulties in separating out the two in experimental data for ${ }^{12} \mathrm{C}$. Very recent calculations by J. Birkholz and V. Heil ${ }^{2}$ use continuum shell model calculations for neutron scattering from ${ }^{11} \mathrm{~B}$ to derive states in ${ }^{12} \mathrm{~B}$ and from these predict differential scattering cross sections and polarizations. These are shown by Birkholz and Heil to agree fairly well with the experimental results of the present authors. However, there are differences in some regions, and these are being investigated to see if further experimental work is indicated.

[^49]1. D.J. Rowe and S.S.M. Wong, Nuc1. Phys. Al53, 561 (1970).
2. J. Birkholz and V. Heil, Report I KDA 7 $7 / 11$, Institut für Kernphysik, Technische Hochschule Darmstadt, (Nucl. Phys. In press).
c. Structure Study of ${ }^{13} \mathrm{C}$ from the Scattering of Neutrons from ${ }^{12} \mathrm{C}$.

The following is an abstract of a paper recently published on this topic:
"Differential Cross Section and Polarization for 2.63 MeV Neutrons
Scattered from ${ }^{12}$ C. '"* (H.D. Knox, J.M. Cox, R.W. Finlay and R.O. Lane)
"The differential cross section and polarization of 2.63 MeV neutrons scattered from ${ }^{12} \mathrm{C}$ have been measured at eight angles between $17^{\circ}$ and $118^{\circ}$ in the laboratory system. By simultaneously fitting the cross section and polarization data, a set of scattering phase shifts was obtained. The values of the resulting d-wave phase shifts were larger than those of other existing sets of phase shifts in the energy region. A subsequent $R$-function analysis, reflecting these larger d-wave phase shifts, gave excellent fits to other experimental data below 3 MeV neutron energy region. The influence of narrow states at 7.50 and 7.55 MeV excitation energy in ${ }^{13} \mathrm{C}$ is discussed."

[^50]d. Structure Studies of Light Nuclei with Neutrons (R.O. Lane)

An invited paper on this topic has been published in the Proceedings of the International Conference on Nuclear Structure Study with Neutrons, held in Budapest, Hungary, July 31-August 4, 1972; Publishing House of the Hungarian Academy of Sciences, pages 31-64.
e. Performance of Polarization System for Elastic Neutron Scattering with $1-n s e c$. Pulsed-Beam TOF Technique. (C.E. Nelson and R.O. Lane)

The capability for definitive structure studies in the light nuclei by neutron scattering can be considerably enhanced by polarization measurements made simultaneously with that of the differential scattering cross section. Because excited-state groups or break-up neutrons from source reactions and inelastic groups from scattering samples cause dificulties at all but the lowest energies, some method of separation of these undesired neutrons must be employed. The properties of the Ohio University Tandem Accelerator were exploited to develop a time-of-flight system of at least 5 large ( 8 -inch dia.) scintillators in shielded collimators which observe polarized beams of neutrons scattered from various cylindrical scatterers over a scatterer-to-detector flight path of ~1.5-2.0 meters. The source reaction produces polarized beams of neutrons at $\sim 50^{\circ}$ from the incident charged particle beam. The polarized beam of neutrons passes through the transverse field of a spin precession magnet (formerly used by the Argonne group) before striking the scatterer. The source-to-scatterer distance is approximately 75 cm . Both ${ }^{7} \mathrm{Li}(\mathrm{p}, \mathrm{n})^{7} \mathrm{Be}$ and ${ }^{9} \mathrm{Be}(\mathrm{p}, \mathrm{n}){ }^{9} \mathrm{~B}$ have been used as polarized source reactions in preliminary measurements and others such as $T(p, n){ }^{3} \mathrm{He}$ are also under consideration. The calibration of the precession magnet has been rechecked and gave good agreement with the previous one at Argonne for energies used in that earlier work.

This method of TOF separation with a pulsed beam of discrete energy has certain advantages over the use of continuum spectra used in other techniques, and we are just beginning to develop the full potential of this on our high-intensity tandem at Ohio University. Because neutron polarization work is difficult by any method, it is important to make determinations of the same nuclear parameters by two independent and quite different methods in order to have high confidence in assignments for theory comparisons. Thus the discrete and continuum methods may be considered as complimentary to each other.

As a check on this fairly novel application of tandem pulsed beams, the polarization of neutrons scattered from ${ }^{12} \mathrm{C}$ at $\mathrm{E}_{\mathrm{n}}=1.8 \mathrm{MeV}$ was measured and compared to previous measurements made at Argonne with a d.c. beam, different detectors but the same precession magnet. The results are shown in Fig. A-1 and indicate excellent agreement with good statistical accuracy. Of course, simultaneously along with the polari-
zation data come the corresponding differential scattering cross section data determined from calibrated detector efficiencies. These naturally have much higher statistical accuracy. A very important point here is that fitting or comparisons of nuclear model or even R-matrix calculations with data is much more meaningful when using results from a simultaneous self-consistent measurement of polarization and differential cross section data rather than fragments from unrelated experiments.

With a figure of merit thus established for this configuration of equipment, investigations into some of the light nuclei will be pursued.

Figure A-1

f. ${ }^{11}$ C Production by a Tandem Van de Graaff for Medical Uses. (A.G. Perris, R.O. Lane, J.D. Matthews and J.Y. Tong)

The Following is an abstract of a paper published on this topic:
"The Production of Carbon-11 for Medical Uses by a Tandem Van de Graaff Accelerator by the Reaction ${ }^{11} \mathrm{~B}(\mathrm{p}, \mathrm{n})^{11} \mathrm{C}^{1 *} *$
(A.G. Perris, R.O. Lane, J.Y. Tong and J.D. Matthews) Carbon-11 for medical uses was produced by the ${ }^{11} B(p, n)^{11} C$
reaction on the Ohio University Tandem Accelerator. The proton energy was 6 MeV with a beam current of $3 \mu \mathrm{~A}$. Boron trioxide was used as a target with helium as a carrier gas. A Havar window separated the pressure in the target cell from the accelerator vacuum. Liquid nitrogen and chemical traps were used to collect the active material which was recovered in the forms of ${ }^{11} \mathrm{CO}_{2}$ and ${ }^{11} \mathrm{CO}$. Activities of approximately 50 mCi were recovered for runs of 100 min . The ratio of ${ }^{11} \mathrm{CO}_{2} /{ }^{11} \mathrm{CO}$ was found to be $3 \cdot 5$. The effect of the flow rate of the carrier gas on the recovered total activity is presented. The significant advantages of the ${ }^{11} \mathrm{~B}(\mathrm{p}, \mathrm{n})^{1 \mathrm{I}} \mathrm{C}$ reaction over the extensively used ${ }^{10} \mathrm{~B}(\mathrm{~d}, \mathrm{n})^{11} \mathrm{C}$ reaction are discussed. The feasibility of the production of useful amounts of ${ }^{11} \mathrm{C}$ by Van de Graaff accelerators is also discussed.

[^51]6. Decay of ${ }^{51} \mathrm{Mn}^{*}$ (J.C. Ferrer, J. Rapaport, S. Raman**)

We have investigated the $\gamma$-rays from the decay of $46-\mathrm{min}{ }^{51} \mathrm{Mn}$ produced by the ${ }^{50} \mathrm{Cr}(\mathrm{d}, \mathrm{n})$ reaction. Twelve $\gamma$-rays were observed. These $\gamma$-rays have been incorporated into a level scheme of ${ }^{51} \mathrm{Cr}$ with levels at $0,749.1,1164.4,1353.3,1557.4,1899.4,2001.4,2312.5$ and 2829.7 keV . Branching ratios, $\log \mathrm{ft}$ values, and $\mathrm{J}^{\pi}$ assignments are discussed for these levels. The lifetime of the 749.1 keV level was measured to be $\mathrm{T}_{1}=7.60 \pm 0.3$ ns by utilizing the ${ }^{5 l} \mathrm{~V}(\mathrm{p}, \mathrm{n} \gamma)^{5 \mathrm{l}} \mathrm{Cr}$ reaction produced by a 3.8 MeV pulsed proton beam. The 749 keV , E2 transition is hindered by a factor of 34 compared to the Weisskopf estimate.

[^52]** Nuclear Data Group, Oak Ridge National Lab.
7. Anomalies in the ${ }^{72} \mathrm{Ge}(\alpha, \mathrm{n})^{75} \mathrm{Ge}$ Reaction near Isobaric Analog Resonances in ${ }^{76} \mathrm{Se}^{*}$ (A.J. Elwyn**, J.E. Monahan**, J.F. Lemming, J. Rapaport and M. Sample)

Anomalies in the excitation function of the reaction ${ }^{7}{ }^{2} \mathrm{Ge}(\alpha, \mathrm{n})^{7} \mathrm{~S}_{\mathrm{S}}$ are compared with isobaric analog resonances observed in the ${ }^{75} \mathrm{As}(\mathrm{p}, \mathrm{n})^{75} \mathrm{Se}$ reactions. The results are consistent with the interpretation that the same analog resonance is populated in both reactions. Since the ( $\alpha, \mathrm{n}$ ) reaction through isobaric analog states is isospin forbidden in both entrance and exit channels, these results imply some isospin-breaking mechanism for the excitation of analog resonances via alpha and/or neutron channels.

[^53]8. The ${ }^{75} \mathrm{As}(\mathrm{d}, \mathrm{p})^{76} \mathrm{As}$ reaction* (J.F. Lemming, J. Rapaport, and A.J. Elwyn**)

The low lying level structure of ${ }^{76}$ As has been studied by the ${ }^{75} \mathrm{As}(\mathrm{d}, \mathrm{p}){ }^{76} \mathrm{As}$ reactions with 12.0 MeV incident deuterons using the ANL split-pole spectrograph. Experimental angular distributions are compared with distorted-wave Born approximation calculations. Angular momentum values are determined for the observed transitions up to approximately 2.0 MeV excitation energy. Spectroscopic strengths are deduced from the data of the thirty one levels up to 1.03 MeV ; nine have pure $\ell_{n}$ values while all the others showed some degree of admixture. Possible ${ }^{n}$ spin and parity values are assigned for some of the levels based on the present results and $(\mathrm{n}, \gamma)(\mathrm{p}, \mathrm{n})$ and $(\mathrm{p}, \mathrm{n} \gamma)$ studies.

* Work submitted for publication to Nuclear Physics.
** Physics Division, Argonne National Lab.

9. Low lying states of ${ }^{96} \mathrm{Tc}$ * (G. Doukellis, C. McKenna, R. Fin1ay, J. Rapaport, H.J. Kim**)

The ${ }^{96} \mathrm{Mo}(\mathrm{p}, \mathrm{n})$ and ${ }^{96} \mathrm{Mo}(\mathrm{p}, \mathrm{n} \gamma)$ reactions have been studied for proton energies between 3.8 and 5.5 MeV . Energy levels in ${ }^{96} \mathrm{Tc}$ up to 632 keV excitation energy have been determined. Possible spin and parity assignments are given for several levels based on the neutron enhancement and angular distributions observed on and off resonance of the $5 / 2^{\dagger}$ isobaric analog state in ${ }^{97} \mathrm{Tc}$, as well as the observed gamma yields. The first excited state reported at 34 keV was found to be a close doublet only 0.8 keV apart. The observation of this doublet in the ( $p, \mathrm{n}$ ) reaction was used to determine the ground state $Q$ value $Q=-3.760 \pm 0.010 \mathrm{MeV}$.

* Work accepted for publication in Nuclear Physics.
** Physics Division, Oak Ridge National Lab.

10. Masses of Technetium Isotopes (J.R. Comfort, R.W. Finlay, C.M. McKenna, P.T. Debevec*)

The masses of $97,98 \mathrm{Tc}$ were determined by investigations of ( $p, n$ ) and ( ${ }^{3} \mathrm{He}, \mathrm{d}$ ) reactions on molybdenum targets. The ( $\mathrm{p}, \mathrm{n}$ ) measurements were performed by using time-of-flight techniques at the Ohio University Tandem Laboratory. The $Q$ value for the ${ }^{97} \mathrm{Mo}(\mathrm{p}, \mathrm{n})^{97} \mathrm{Tc}$ reaction was calibrated against the ${ }^{55} \mathrm{Mn}(\mathrm{p}, \mathrm{n}){ }^{55} \mathrm{Fe}$ reaction, while that ${ }^{98} \mathrm{Mo}(\mathrm{p}, \mathrm{n}){ }^{98} \mathrm{Tc}$ reaction was calibrated against the ${ }^{65} \mathrm{Cu}(\mathrm{p}, \mathrm{n})^{65} \mathrm{Zn}$ reaction. The $\left({ }^{3} \mathrm{He}, \mathrm{d}\right)$ measurements were made with magnetic spectrographs at the tandem laboratories of Argonne National Laboratory and the University of Pittsburgh. The new values have a precision better than 10 keV and are listed in Table A-2. The $Q$ value measured in this laboratory for ${ }^{96} \mathrm{Tc}$ agrees well with the value in Ref. 1. For ${ }^{97} \mathrm{Tc}$, the $Q$ value for the ( $\mathrm{p}, \mathrm{n}$ ) reaction is shifted by +28 keV from the value in the 1971 Atomic Mass Evaluation. ${ }^{2}$ The measurement for ${ }^{98} \mathrm{Tc}$ represent new values since the previous measurements had an error of 200 keV .

Table A-2. The Q values for ( $p, n$ ) and ( ${ }^{3} \mathrm{He}, \mathrm{d}$ ) reactions leading to technetium isotopes, and the mass excesses for the residual nuclei. The mass excesses are revised from the 1971 atomic-mass compilation (Ref. 2)

| Reaction | Q Value (MeV) | $\begin{gathered} \text { Mass Excess } \\ (\mathrm{MeV}) \end{gathered}$ |
| :---: | :---: | :---: |
| ${ }^{96} \mathrm{Mo}(\mathrm{p}, \mathrm{n})^{96} \mathrm{Tc}$ | $-3.760(10)^{\text {a }}$ | -85.820 (10) |
| ${ }^{96} \mathrm{Mo}(\mathrm{p}, \mathrm{n}){ }^{96} \mathrm{Tc}$ | $-3.755(6)^{\text {b }}$ | -85.825 (6) |
| ${ }^{97} \mathrm{Mo}(\mathrm{p}, \mathrm{n}){ }^{97} \mathrm{Tc}$ | -1.102 (6) | -87.221 (6) |
| ${ }^{96} \mathrm{Mo}\left({ }^{3} \mathrm{He}, \mathrm{d}\right){ }^{97} \mathrm{Tc}$ | 0.229 (8) ${ }^{\text {c }}$ | -87.230 (8) |
|  | $0.220(8)^{\text {d }}$ | -87.221 (8) |
| ${ }^{98} \mathrm{Mo}(\mathrm{p}, \mathrm{n}){ }^{98} \mathrm{Tc}$ | -2.458 (10) | -86.432 (10) |
| ${ }^{97} \mathrm{Mo}\left({ }^{3} \mathrm{He}, \mathrm{d}\right){ }^{98} \mathrm{Tc}$ | 0.680 (8) | -86.420 (8) |
| ${ }^{\text {a }}$ See previous abstract |  |  |
| ${ }^{\mathrm{b}}$ Ref. 1 |  |  |
| C Argonne data |  |  |
| ${ }^{\text {d }}$ Pittsburgh dat |  |  |

* Physics Division, Argonne National Laboratory.

1. R.G. Kruzek et al., Bull. Am Phys. Soc. 17, 514 (1972); but see also Nuc1. Data $\overline{B 8}, \overline{615}$ (1972)
2. A.H. Wapstra and N.B. Gove, Nuc1. Data A9, 265 (1971).

## B. NUCLEAR THEORY

1. The Odd-A ${ }^{59-65} \mathrm{Ni}$ Isotopes in the Core-coupling Model* (P. Hoffman-Pinther and Jerry L. Adams)

The low-lying spectra of th odd-A $59-60 \mathrm{Ni}$ isotopes and transitions in these isotopes have been described in terms of the Core-coupling model of Thankappan and True ${ }^{1}$ ) modified by taking quasiparticles into account. In the present case one quasiparticle is coupled to the core. The core states are the $0^{+}$ground state and the $2^{+}$first excited state of the appropriate neighboring even-even Ni isotope. The $\mathrm{Of}_{5 / 2}, 1 p_{3 / 2}$, and $1 \mathrm{p}_{1 / 2}$ orbits are open to the last neutron. The energies of the core states and the occupation probabilities for the last neutron are taken from experimental data. The quasiparticle energies and the strength parameters of the quasiparticle-core interaction have been varied to fit both the experimental energy level spectra and the spectroscopic factors for several levels seen in ( $\mathrm{d}, \mathrm{p}$ ) reactions. This procedure establishes close correspondence between a number of calculated and experimental states. The wavefunctions of the corresponding calculated states have been used to calculate M1 and E2 transition rates and magnetic dipole and electric quadrupole moments.

The calculation reproduces well the overall pattern of low-lying spectra for ${ }^{59-65} \mathrm{Ni}$. Th energies of the lower lying calculated states are in good agreement with the corresponding experimental energies while the calculated spectroscopic factors are in qualitiative agreement with the experimental values. In addition, the calculated transition rates reproduce many of the branching ratios, $B(E 2)$ values, and lifetimes of $59-63 \mathrm{Ni}$.

[^54]1. V.K. Thankappan and W.W. True, Phys. Rev. 137B, 793 (1965).
C. A-CHAIN COMPILATIONS (J.F. Lenming* and J. Rapaport)
2. Nuclear Data Sheets for $A=142^{* *}$ (J.F. Lemming and S. Raman ${ }^{\dagger}$ )

Level schemes and decay characteristics are presented for all nuclei with mass number 142. Experimental data, adopted values, comparisons with theory and arguments for spin and parity assignments are given. The adopted level scheme and decay properties are based on data received before March 1, 1973.

[^55]2. Nuclear Data Sheets for $A=143^{*}$ (J.F. Lemming)

Level schemes and decay characteristics are presented for all nuclei with mass 143. Experimental data, adopted values, comparisons with theory and arguments for spin and parity assignments are given.

The adopted level schemes and decay properties are based on data received before Jan. 1, 1974.

* To be published.

3. Nuclear Data Sheets for $A=81^{*}$ (J.F. Lenming)

The 1966 version of the Nuclear Data Sheets has been revised on the basis of data received before March 1, 1974. New level schemes and decay properties were adapted.

* The manuscript is now being typed.

4. Nuclear Data Sheets for $A=82$ (J.F. Lerming and S. Raman*)

The work is almost $80 \%$ completed on the revision of mass 82 Nuclear Data Sheets. Approximately 50 new references have been reviewed.

* Nuclear Data Group, Oak Ridge National Lab.


## RENSSELAER POLYTECHNIC INSTITUTE

## A. CROSS SECTION MEASUREMENTS


(H. D. Knox ${ }^{+}$
R. W. Hockenbury, N. N. Kaushal and R. C. Block)

The capture analysis has been checked from raw data to relative capture yields. Multiple scattering corrections have been made to some low energy resonances using a Monte Carlo code. These calculations are still in progress. 151
A comparison of our Eu capture results in the keV region to those of Czirr ${ }^{1}$ shows good agreement with the exception of the region near 4 keV where our data are lower.

* Req. Nos. 377, 339, 305
+ Now at Texas A. \& M. University, College Station, Texas 77843

$$
242
$$

2. KeV Neutron Capture Cross Section of ${ }^{242} \mathrm{Pu}^{*}$
(A. J. Sanislo, N. N. Kaushal and R. W. Hockenbury)

The high-low bias data (used to separate the capture and fission contributions) have been corrected for deadtime and background effects. The blank sample data are being normalized to the foreground data in order to remove the effects of the relatively small amount of capture in the sample container

The relative flux data has been processed through the usual deadtime, background, path compression, airpath attenuation, and relative efficiency codes.

The next step will be to obtain an absolute normalization of the capture and fission data.
*Req. No. 539
$\overline{1 \text { J. B. Czirr, UCRL-50804. }}$
3. Capture and Total Cross-Section Measurements on $54,58 \mathrm{Fe}$ and ${ }^{61} \mathrm{Ni}^{*}$
(M. Pandey, N. N. Kaushal, R. Garg, H. D. Knox, R. C. Block and R. W. Hockenbury)

High resolution transmission measurements were made on ${ }^{54} \mathrm{Fe}$ and $61_{\mathrm{Ni}}$ from about 15 keV to 100 keV . A channel width of 8 ns and a linac pulse width of 11 ns were used; with a $10 \mathrm{~B}-\mathrm{NaI}$ detector at 28 m . The transmission of a 58 Fe sample was measured with a time channel of 31.25 ns since the level spacing is such that the higher resolution was unnecessary.

The capture and transmission data are being processed for deadtime and background corrections. Net counts vs energy are shown in Fig. 1.
*Req. Nos. 169, 173, 187, 200


## TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

## A. NEUTRON AND FISSION PHYSICS

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

The initial phase of installation and instrumentation of the CycloGraaff Neutron Time-of-Flight (TOF) Facility has been completed. Hopefully, efforts will soon be resumed on the complementary $n-\gamma$ spectrometer.

Experimental studies were made of the time-correlated and uncorrelated background associated with the primary neutron source reaction $D(d, n)^{3} \mathrm{He}$ at deuteron energies of 6,8 , and 10 MeV . The neutron TOF spectra were practically devoid of neutrons produced by deuteron reactions on beam line contaminants such as carbon, oxygen, silicon, etc. For $E_{d}=10 \mathrm{MeV}$, the intensity in the unstructured background between the quasi-monoenergetic $D(d, n)^{3} \mathrm{He}$ neutron group and the break-up continuum due to $D(d, n p) D$ appear to be superior to that shown in recently published TOF spectra for the $T(p, n)^{3} \mathrm{He}$ reaction at comparable neutron energies and detector biases. This very clean source spectrum is a result of (1) excellent vacuum obtained in an all metal beam line pumped by a turbo-molecular pump with $\mathrm{LN}_{2}$ trapping; (2) beam optics which minimize the interactions of the deuteron beam with the beam line components; and (3) optimum design of the massive neutron collimator and detector-shield system.

Experimental studies were also performed to determine the extent of the time correlated and uncorrelated background associated with elastic and inelastic scattering of neutrons by $C$ at a number of angles and incident neutron energies. Present background levels are reduced by a factor of 1.4 as compared to an earlier version of the TOF spectrometer-goniometer system. The lower background is aided by improved laboratory shielding and superior electronic pulse shape discrimination of $\gamma$-rays.

Elastic and inelastic differential scattering experiments were performed on natural carbon (USNDC-6, Request No. 56) at 28 angles between $25-160^{\circ}$ for $\mathrm{E}_{\mathrm{n}}=9$ and 10 MeV . The data at 9 MeV overlap previous data from the Aerospace

[^56]Research Laboratories while the 10 MeV data has not been previously measured. The conversion of the yields to absolute cross sections is performed using measured detector relative efficiencies, and an auxiliary $n, p$ scattering experiment performed on a cylindrical polyethylene sample. The relative efficiency for the NE21858DVP detector system has been determined over the neutron energy range 2-13 MeV using the absolute differential cross sections for the production of neutrons of known energy via the $D(d, n)^{3} \mathrm{He}$ reaction. The auxiliary $n, p$ scattering experiment was also used to determine the beam zero to within $\pm 0.1^{\circ}$ from the relative positions of the elastic and inelastic neutron groups in the TOF spectra.

A number of on- and off-line data-reduction programs are in use in order to extract background and dead-time corrected yields, convert to absolute cross sections, and correct the data for attenuation of the incident and scattered neutron flux density, angular resolution, finite size and anisotropy of the primary neutron source, and multiple scattering in the sample.

The plan is to extend the carbon scattering measurements on up to 15 MeV neutrons.
2. Resolved Neutron Total Cross Sections and Intermediate Structure (J. Clement, B.-H. Choi, W. F. E. Pineo, M. Divadeenam, H. W. Newson)

A paper entitled "Intermediate Structure: ${ }^{28} \mathrm{Si}$ " is ready for submission to Annals of Physics. The abstract follows.
"A Multi-level R-Matrix analysis of Si neutron cross section data measured at NBS has been performed up to about 4.5 MeV neutron energy. Both p - and f -wave resonance structure around I MeV and 1.7 MeV , respectively, is interpreted in terms of the doorway state effects. Besides the well known 180 keV strong $1 / 2^{+}$resonance, the s-wave resonance structure is of moderate strength, while the d-wave assignments are not unambiguous. A spherical shell-model $2 p-1 \mathrm{~h}$ doorway interpretation is attempted both for $s$ - and $p$-waves. In addition the intermediate coupling model of Lane, Thomas and Wigner is applied to the $p$ - and $f$-wave structure. Only a small fraction of the p-wave s.p. strength is observed while the identified $f$-wave strength is located around 1.7 MeV neutron energy. Making use of a complex potential model a rough estimate of the $p$ - and $f$-wave spreading width for the corresponding intermediate structure is made. These
widths are of the order of $0.5-1.0 \mathrm{MeV}$. Finally possible correlation between neutron and gamma decay channels and the connection between the states observed in $(n, n),(d, p)$, $(n, \gamma)$ and $(\gamma, n)$ channels is discussed."

The role of $1 f_{5 / 2}$ single-particle state in the theoretical doorway description of the $5 / 2$ resonances in ${ }^{29} \mathrm{Si}$ compound nucleus is investigated--the details are given in Al2.

An R-Matrix interpretation of ${ }^{32} S$ neutron cross section data measured by Farrell et. al ${ }^{1}$ in this laboratory a few years ago has been completed. The $s$ - and p-wave doorway effects are not as pronounced as in the case of ${ }^{28} \mathrm{Si} \mathrm{i}$ n resonances. The analysis reveals a 1.2 keV wide f -wave resonance at 585 keV neutron energy. This resonance has a large reduced width $\gamma^{2}=1270 \mathrm{keV}$ which is about $70 \%$ of the single-particle limit. This is in agreement with the shell-model picture, in that the $1 f_{5 / 2}$ state should occur at low neutron energies. A similar pronounced $f$-wave structure was observed in ${ }^{28} \mathrm{Si}$ neutron cross section data at about 1.7 MeV (see above and section A12). The f-wave assignment for two resonances around 1.7 MeV in ${ }^{28} \mathrm{Si}$ is more definite than in the case of ${ }^{32} \mathrm{~S}$. A d-wave assignment for ${ }^{32} \mathrm{~S}+\mathrm{n}$ 585 keV resonance is not ruled out, however the optical model and shell model arguments favor $f$-wave description for this resonance. The onset of $d$-wave resonances occurs above 600 keV neutron energy. A paper ${ }^{2}$ discussing the details of analysis and comparison to spherical shell model $2 \mathrm{p}-1 \mathrm{~h}$ doorway calculations will be presented at the Spring Washington American Physical Society meeting in April, 1974.

Pending the analysis of ${ }^{58} \mathrm{Ni}$ neutron cross sections extracted from the natural sample data, ${ }^{3}$ the publication of the ${ }^{60} \mathrm{Ni}$ neutron cross section analysis results is withheld.

Preparation of a paper on $\mathrm{Sr}+\mathrm{n}$ cross section data is in its final stages.
A paper on the neutron cross section data of Pb isotopes is in progress.
3. Averaged Cross Sections, Strength Functions, and Intermediate Strucfure (W. F. E. Pineo, M. Divadeenam, E. G. Bilpuch, H. W. Newson)

Part Il of the series on Strength Functions and Average Cross Sections

[^57]is scheduled to appear in Annals of Physics, Volume 84 (1974).
Part III of the series is in preparation. The abstract follows.
> "Neutron cross sections measurements on the separated isotopes ${ }^{92}, 94,95,96,98,{ }^{100}$ Mo and remeasurements on natural Ru , $\mathrm{Rh}, \mathrm{La}, \mathrm{Hf}, \mathrm{Ta}, \mathrm{W}, \mathrm{Ir}, \mathrm{Os}, \mathrm{TI}, \mathrm{Bi}, \mathrm{Th}$, 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-, 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 $A=60$ and 160."
4. Charged Particle Fission (F. O. Purser, J. R. Boyce, D. E. Epperson, H. W. Newson, E. G. Bilpuch, H. W. Schmitt*)
a. Analysis of Fission Cross-Section Measurements

This analysis is continuing with a view toward using the results to aid in the reduction of multi-chance mass yield data. Current efforts are being directed toward resolving the ambiguities introduced by use of optical model results for total reaction cross sections and for the inverse neutron cross sections required by the fission decay model.

## b. Mass And Kinetic Energy Measurements

A systematic study of the fission fragment mass and kinetic energy distributions produced in proton induced fission of the uranium isotopes has been resumed. Results thus far obtained include measurements for ${ }^{235} \mathrm{U}$ and ${ }^{236} \mathrm{U}$ for proton energies from 6.0 to 13.0 MeV . A major part of the work has been to obtain accurate measurements for incident proton energies below the thresholds for second

[^58]chance fission in these isotopes. Preliminary results from these measurements including the effect of the onset of second chance fission will be reported at the Spring meeting of the American Physical Society. The eventual goal of the program is to obtain mass and kinetic energy data for highly excited fissioning nuclei from which the effect of higher chance fission events has been removed.
c. Cross Section Measurements

The analysis of the fission fragment angular distribution data is continuing.

## 5. A Selectively Excited And Distorted (SEXD) Liquid Drop Model (H. W. Newson)

This model includes both liquid-like and Fermi gas-like phenomena in such a way that shell effects via the $2 p-1$ hechanism (see Rule 3 , Table 1) impose selection rules on the conventional LDM. One can now understand the fragment properties without abandoning the latter model.

The selection rules have been formulated so that they can be justified without reference to fission data. They are then used to account for the deviations from the LDM not only in yields but also in neutron emission and fine structure effects. The Rules are discussed briefly in the Table. A paper which develops the consequences of these rules and compares them with experiment is being prepared.
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)

A publication summarizing the results of these measurements is being prepared. However, some new DWBA calculations for the ${ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He}, \mathrm{n}\right)$ may be required if the results of the coupled-channel study concerning the ${ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He},{ }^{3} \mathrm{He}\right){ }^{13} \mathrm{C}$ scattering (see Section B. 23) show that significant changes in the optical model parameters are called for.

[^59]It has been frequently pointed out by Nix that the LDM predicts a very short time interval between last barrier and scission. Since 2 plh promotion out of closed structures is known to be slow,* the kinematics of the LDM accounts for their surprising stability (even at very high $E_{x}$ ) and consequently for asymmetric fission.

TABLE 1

RULES (In Order of Priority)

1. OPTIMUM PENETRATION OF LAST BARRIER REQUIRES MAXIMUM ENERGY RELEASE (Qmax) DUE TO LDM EFFECTS, AND

## Remarks

It can be shown that $Q^{\max }$ is at asymmetric division when: $82+82=164>$ $\mathrm{N}_{0}>132=: 82+50 . \mathrm{N}_{0} \equiv$ number of neutrons in compound nucleus.
2. ALSO AS MANY OF THE MORE EF- Other shells are much less effective, forFECTIVE CLOSED SHELLS AS POSSIBLE: bidden by Rule 1, or (eg. 56N) redundant. $82 \mathrm{~N}, 50 \mathrm{Z}$ OR $50 \mathrm{~N}, 28 \mathrm{Z}, 40 \mathrm{Z}, \mathrm{IN}$ Relative effectiveness is assigned by comBOTH FRAGMENTS TOGETHER ( $=$ ALLOWED MODE). paring the excitation energy $E_{x}$ of the first $2^{+}$states of singly magic nuclei.
3. CONSISTENT WITH FRAGMENT $E_{x}$, The probability of promotion (via the AND KINEMATICS, STATISTICS, $2 p 1 h$ mechanism) decreases with fragment FISSION CONSERVES FAVORED CLOSED STRUCTURES: 28Z, 50Ñ OR $50 \mathrm{Z}, 82 \mathrm{~N}, 40 \mathrm{Z}, \mathrm{HIGH} \mathrm{j}^{\pi}$ SUBSHELLS.
4. AT HIGHER COMPOUND NUCLEUS The observed effects of unfavored modes $\left(E_{x}\right)_{0}$ FORBIDDEN AND UNFAVORED MODES BECOME MORE IMPORTANT THAN FOR SPONTANEOUS FISSION.
excitation energy $H\left(E_{X}\right)_{L}$, with size of energy gap above closed shell, and with pairing energy. Promotion is emphasized more in heavy than in light fragments by LDM effects which favor symmetry. are usually the same, but eg., $\operatorname{Fm}\left(n_{\text {f }} \mathrm{f}\right)$ has a strong symmetric mode which cannot be due to promotion out of one allowed by Rule 2; $\mathrm{Fm}(\mathrm{Sf})$ behaves as expected.
7. Polarization Produced in The ( $\mathrm{d}, \mathrm{n}$ ) Reactions on ${ }^{9} \mathrm{Be}$ and ${ }^{11} \mathrm{~B}$ (J. Taylor,* * G. Spalek, ${ }^{+}$Th. Stammbach, ${ }^{++}$R. L. Walter)

This project has been inactive and publication of the data will be withheld until further ( $\mathrm{d}, \mathrm{n}$ ) reaction studies with polarized deuteron beams are initiated for these targets.

[^60]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)

Polarization transfer coefficients $K Y^{\prime}$ have been deduced from measurements of the neutron polarization produced by the breakup of pure vectorpolarized deuterons on $\mathrm{D}_{2}$ and ${ }^{4} \mathrm{He}$. Although the data must be additionally corrected for multiple scattering and average analyzing power variations as a function of the continuum neutron energy, the results verify that the polarization transfer coefficient is approximately 0.90 of its maximum value.
9. Transfer Polarizations Studies of ${ }^{12} \mathrm{C}(\overrightarrow{\mathrm{d}}, \overrightarrow{\mathrm{n}})$ and ${ }^{28} \mathrm{Si}(\vec{d}, \vec{n})$ at A Reaction Angle of $0^{\circ}$ (P. W. Lisowski, G. Mack, T. B. Clegg, R. L. Walter)

The polarization produced in the ${ }^{12} \mathrm{C}(\vec{d}, \vec{n})$ and ${ }^{28} \mathrm{Si}(\vec{d}, \vec{n})$ reactions has been measured for several deuteron energies from 7 to 12 MeV . Beams of from 25 to 75 nA of typically $70 \%$ pure vector polarized deuterons were used. The outgoing neutron polarizations were measured by scattering from a high-pressure ${ }^{4} \mathrm{He}$ gas scintillator. Statistical uncertainties in the calculated values of the transfer polarization coefficient $K y^{\prime}$ are about 0.04 . Data were obtained for both the $n_{0}$ and $\mathrm{n}_{1}$ neutron groups for ${ }^{12} \mathrm{C}(\mathrm{d}, \mathrm{n})$. Although geometry, multiple scattering and average analyzing power corrections need to be applied before final values are obtained, preliminary analysis shows that the transfer coefficients are very large, positive and have little energy dependence.
10. 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. $\quad{ }^{3} \mathrm{He}(\overrightarrow{\mathrm{n}}, \overrightarrow{\mathrm{n}})^{3} \mathrm{He}$

The previously obtained angular distributions at 8, 12, and 17 MeV and the phase-shift analysis of the $n+{ }^{3} \mathrm{He}$ system have been put in final form. Work is in progress on preparing a report for publication.
b. $\quad{ }^{4} \mathrm{He}(\overrightarrow{\mathrm{n}}, \overrightarrow{\mathrm{n}})^{4} \mathrm{He}$

Recent experiments were conducted at TUNL to test the precision of the Quench-ratio method for determining beam polarizations. These experiments have yielded precision angular distributions of ${ }^{4} \mathrm{He}(p, p)^{4} \mathrm{He}$ asymmetries at $4.8,6.3$, and 12.3 MeV . These data are being incorporated in the data set used in an Rmatrix analysis of the $n-{ }^{4} \mathrm{He}$ and $p-{ }^{4} \mathrm{He}$ systems. It is expected that these proton asymmetry data along with the accurate neutron asymmetry data which have been
reported before at 14 and 17 MeV will stabilize the R -matrix parameterization. This comprehensive analysis should provide a substantially better comparison of $n-{ }^{4} \mathrm{He}$ and $\mathrm{p}-{ }^{4} \mathrm{He}$ phase shifts and a better test of the differences in these mirror systems.

11. Transfer Polarization Studies in ( $\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}}$ ) Reactions (P. W. Lisowski, G. Mack, R. Byrd, T. B. Clegg, R. L. Walter)

Previously reported polarizations produced at a reaction angle of $0^{\circ}$ for ( $\vec{p}, \vec{n}$ ) reactions on several light nuclei have been used to deduce polarization transfer coefficients. A major effort was spent on developing a computer code to resolve the effects of three-body breakup neutrons from monoenergetic neutron groups. The statistical uncertainty of the transfer coefficients varies from about 0.03 to 0.10 . Data for the following reactions will be reported at the Washington meeting of the American Physical Society:
a. $D(\vec{p}, \vec{n}) p p$
b. $\quad{ }^{11} \mathrm{~B}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}})$
c. $\quad{ }^{13} \mathrm{C}(\overrightarrow{\mathrm{p}}, \vec{n})$
d. $\quad{ }^{9} \mathrm{Be}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{n}})$
e. $\quad \operatorname{Cu}(\vec{p}, \vec{n})$
12. Polarization Transfer at $0^{\circ}$ in the $\mathrm{D}(\mathrm{d}, \mathrm{n})$ Reaction (P. W. Lisowski, C. E. Busch, T. B. Clegg, R. L. Walter)

The polarization transfer coefficient $K Y^{\prime}$ and the analyzing power $A_{z z}$ have been measured at a reaction angle of $0^{\circ}$ for the $D(d, n)$ reaction. Since the last report, the determinations of $\mathrm{A}_{\mathbf{z z}}$ below 3 MeV and some of the measurements for $K^{\prime} Y^{\prime}$ have been rechecked and verify a departure from the constant values for these coefficients which are exhibited for energies above 3 MeV . The resulting data provide a comprehensive set of transfer coefficients and analyzing powers which may be used to calculate neutron polarizations produced by using the $D(\vec{d}, \vec{n})$ reaction for a source of polarized neutrons. The earlier data were reported at the American Physical Society Indiana meeting and are being prepared for final publication.

## 13. 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

${ }^{28} \mathrm{Si}+\mathrm{n}$ : A paper incorporating the $2 \mathrm{p}-\mathrm{lh}$ doorway calculations is ready for submission to Annals of Physics (see section A2 for the abstract). An abstract ${ }^{1}$ entitled "The Role of $\mathrm{If}_{5 / 2}$ s.p. State in ${ }^{28} \mathrm{Si}+\mathrm{n}$ f-wave Resonances" has been submitted to the Washington Spring American Physical Society meeting. A comparison of theory with $5 / 2^{-}$neutron resonance widths will be presented. ${ }^{209},{ }^{207} \mathrm{~Pb}$ are still in progress.
${ }^{208} \mathrm{~Pb}+\mathrm{n}$ and ${ }^{206} \mathrm{~Pb}+\mathrm{n}: ~ 2 p-1$ shell model calculations in
${ }^{40} \mathrm{Ca}+\mathrm{n}$ and ${ }^{48} \mathrm{Ca}+\mathrm{n}$ : A paper ${ }^{2}$ giving the details of theoretical $2 p-1$ doorway calculations and comparison to experimental neutron resonance results was presented at the recent Bloomington Nuclear Physics Division meeting. A paper incorporating these results is planned for the near future.

## (2) Odd-Odd Compound Nuclei


#### Abstract

${ }^{89} Y+n$ : The shell model code which had been previously used by Ramavataram et al, ${ }^{-3}$ has been recently generalized to handle mociel space for any $J^{\pi}$. A mixing of $1 p n>, l p,\left(n n^{\prime} n^{-1}\right)>$ and $1\left(p p^{\prime} p^{-1}\right), n>$ configurations is allowed in the program. Diagonalization for $J \pi=0^{+}, 1^{+}$and $2^{+}$levels corresponding to p -wave resonances is performed in the compound nucleus ${ }^{90} \mathrm{Y}$. These preliminary calculations indicate that most of the $p$-wave resonance strength located in the region of 450 keV agrees well with the observations ${ }^{4}$ of Divadeenam, Beres and Newson. It is planned to submit a short report on these calculations as a contributed paper to the International Conference on Nuclear Structure and Spectroscopy, September 9-13, 1974, in Amsterdam.


[^61]${ }^{207} \mathrm{~Pb}+\mathrm{n}$ : No progress has been made since the last report on calculating the ${ }^{208} \mathrm{~Pb} \mathrm{l}_{\mathrm{p}}$-1h state neutron escape widths to compare with experimental ${ }^{207} \mathrm{~Pb}$ neutron resonance results.
b. Particle-Vibration Model
(1) Even-Odd Compound Nuclei
${ }^{40} \mathrm{Ca}+\mathrm{n}$ and ${ }^{48} \mathrm{Ca}+\mathrm{n}$ : The predicted particle-vibration doorway escape widths were combined with the $2 p-1$ h doorway model calculations to compare with experimental data. (See above, Part a.)
${ }^{208} \mathrm{~Pb}+\mathrm{n}$ and ${ }^{206} \mathrm{~Pb}+\mathrm{n}$ : The particle-vibration doorway width calculations have been extended to $\mathrm{p}-\mathrm{d}$-, and f -wave resonances in compound nuclei ${ }^{209} \mathrm{~Pb}$ and ${ }^{207} \mathrm{~Pb}$. These predictions will form a part of the paper on Pb isotopes (see Part A2).

The marked difference between the spreading widths of the ${ }^{209} \mathrm{~Pb}$ and ${ }^{207} \mathrm{~Pb} 500 \mathrm{keV} \mathrm{1/2+}$ doorway was explained in terms of the nuclear spreading of the particle-vibration doorway into particle-2 vibrations (hallway) states. Similar model calculations will be extended to other suitable cases.

An abstract ${ }^{2}$ entitled "Non-Local Energy Dependent Imaginary Optical Potential For ${ }^{208} \mathrm{~Pb}$ " has been submitted to the Washington American Physical Society meeting. In addition a paper entitled "Complex Non-Local Optical Potential for Neutron Scattering From ${ }^{208} \mathrm{~Pb}$ " has been submitted to Physical Review. Amos Lev and William P. Beres are co-authors for this paper. The abstract follows.

"A non-local energy dependent imaginary optical potential is calculated for neutron scattering from ${ }^{208} \mathrm{~Pb}$ in the intermediate structure model with weak particle-vibration coupling. The energy range studied is $0-12 \mathrm{MeV}$ and the partial waves considered are $\ell=0-4$. The corresponding contribution to the real potential has also been obtained and is relatively small; this potential is presented for s-waves. The imaginary potenrial

[^62]is used to calculate the absorption cross section in this energy range for each partial wave. Both compound nucleus and inelastic contributions to the potential and the absorption cross section are included. Below 5 MeV compound nucleus contributions are dominant. Above this energy inelastic excitations based on single particle resonances and compound nucleus states based on giant resonances contribute, with the former being more significant. A comparison of the calculated absorption to experiment for $\mathrm{s}-, \mathrm{p}-\mathrm{d}$-, and f -waves is made below the inelastic threshold of 2.6 MeV . The agreement, except for $p$-waves, is quite good in terms of the number of resonances and other significant details of the cross section. The calculated absorption cross sections up to 12 MeV are compared to the results from a phenomenological, local, surface peaked imaginary potential. The non-local potential is also surface peaked and the details of its radial behavior for an arbitrary energy are given in a contour plot."
(2) Even Mass Compound Nuclei

No progress has been made since the last report.

## c. Particle-Rotation Model

${ }^{28} \mathrm{Si}+\mathrm{n}$ : A short paper entitled "Rotator Particle P-wave Neutron Resonances in the Compound Nucleus ${ }^{29} \mathrm{Si}^{\prime \prime}$ has been accepted for publication (in December 1973) in Lettere al Nuovo Cimento. 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 spin-
orbit term is used for the continuum neutron."
Similar calculations will be extended to the ${ }^{24} \mathrm{Mg}^{+} \mathrm{n}$ case.

## 14. Shell-Model Investigation of Doorway State Properties for Compound Nuclei in the s-d Shell Region (S. Maripuu, M. Divadeenam)

The effect of mixing the single particle, $2 p-1 h$ states and more complicated configurations ( $3 p-2 h$, etc., ) is being investigated for compound nuclei ${ }^{29} \mathrm{Si}\left({ }^{28} \mathrm{Si}+n\right)$ and ${ }^{33} \mathrm{~S}\left({ }^{32} \mathrm{~S}+\mathrm{n}\right)$. A realistic interaction derived from the Sussex relativeoscillator matrix elements and corrected for $3 p-1 h, 4 p-2 h$ and $2 h$ space truncation effects is being used. In addition phenomenological two-body matrix elements are being employed. The present study mainly aims at interpreting the distribution of the single particle strength among $2 p-1 h$ doorway states and possibly the spreading of $2 p-1 h$ doorway states among the $3 p-2 h$ states. A paper based on these findings will be presented at the forthcoming American Physical Society Spring me eting in Washington.' The predictions will be compared to experimental neutron resonance structure. Similar calculations are being extended to other compound nuclei in this mass region.
15. Theoretical Investigation of Neutron and Gamma Decay of A (Common) Doorway (M. Divadeenam, A. Lev, W. P. Beres)

In recent years the concept of common doorways has been emphasized by Lane and others. Experimentally strong channel correlation between neutron and $\gamma$-decay channels has been observed. In order to investigate this phenomenon theoretically, the $2 p-1$ h doorway model will be employed to calculate neutron doorway $\gamma$-decay widths to the compound nuclear ground state. In addition, these observed calculations will be directed to understand the occurance of El pigmy giant resonance in both photo-induced (and neutron capture) reactions and MI giant resonances observed in nuclei around ${ }^{208} \mathrm{~Pb}$.
16. Computer Programs
a. MODSNOOP: No improvements made since the last report.
b. ROTORP: This program calculates both the continuum and bound states for even-odd compound nuclei. The even-even target is assumed to be

[^63]a symmetric rotor and the compound nuclear states are generated in the Nilsson scheme. Band mixing is taken into account with the help of the coriolis coupling term. Feshbach's doorway state formalism is employed to calculate the level shifts and neutron escape widths. Calculation of El transition strengths from the $p$-wave resonances is planned.
c. SEEK and INEL: The former program is being used continuously to fit total neutron cross section data to extract resonance energies and widths.
d. LAVAL: This shell model program has been developed in collaboration with S. Ramavataram of Universite Laval, Quebec. Compound nuclear states in an odd-odd nuclei are generated within the framework of the spherical shell model. $2 p$ and $3 p-1 h$ states in the odd-odd compound nucleus are mixed via an effective interaction to obtain doorway states both in the bound and continuum regions. Target nucleus ${ }^{89} \mathrm{Y}$ is being considered as a test case. The case of ${ }^{31} \mathrm{P}+\mathrm{n}$ will be considered next.

## B. CHARGED PARTICLE REACTIONS

1. Fine Structure of Isobaric Analogue States--Charged Particle Scattering (E. G. Bilpuch, G. E. Mitchell, H. W. Newson, D. Flynn, D. Outlaw, W. M. Wilson, J. D. Moses)
a. The Iron Isotopes

Work has continued on the development of a high resolution system for the 4 MV accelerator laboratory. Most of the recent efforts have been towards improving the target chamber--vacuum. Past experience has shown that a good vacuum is essential for high resolution studies. Remeasurements of the ${ }^{54} \mathrm{Fe}(p, p)$ and ${ }^{54} \mathrm{Fe}\left(p, p\right.$ ) reactions from $E_{p}=3.36$ to 3.48 MeV yielded improved data with an overall resolution less than 500 eV . Analysis of these data suggests that satisfactory fits to the resonance structure may be obtained at these energies with the present analysis codes.

## b. The Titanium Isotopes

A paper on ${ }^{50} \mathrm{Ti}$ has been published: "High Resolution Proton
Scattering on ${ }^{50} \mathrm{Ti}, "$ N. H. Prochnow, H. W. Newson, E. G. Bilpuch and G. E. Mitchell, Nuclear Physics A213, 134 (1973). Results on ${ }^{46} \mathrm{Ti}$ and ${ }^{48} \mathrm{Ti}$ have been published previously.

Future plans include a study of inelastic scattering from ${ }^{48} \mathrm{Ti}$ to obtain more information on the channel spin mixing ratios.
c. The Calcium Isotopes

A paper entitled "Thomas-Ehrman Shifts in ${ }^{41} \mathrm{Ca}^{41} \mathrm{Sc}^{4}$ has been submitted for publication. The following is the abstract for that paper:
"Differential cross sections were measured for
${ }^{40} \mathrm{Ca}(\mathrm{p}, \mathrm{p})$ at four angles from $\mathrm{E}_{\mathrm{p}}=1.80$ to 2.90 MeV with an overall energy resolution about 400 eV . Spins, parities, proton widths, and reduced widths were extracted for the five observed levels. The ambiguities in several of the spin assignments determined from a previous experiment have been removed in the present work. The Thomas-Ehrman "boundary condition level displacement" was calculated for each of the five levels in the mirror system. These calculations are in qualitative agreement with the observed displacements. There is evidence that the $3 / 2^{-}$level at $E_{x}=3.772 \mathrm{MeV}$ in ${ }^{41} \mathrm{Sc}$ is the analogue of the second member of the recently resolved 3.61 MeV doublet in ${ }^{41} \mathrm{Ca} .{ }^{\prime \prime}$

A talk will also be presented at the Washington meeting on this topic. Other papers are in preparation.
d. $\quad{ }^{30} \mathrm{Si}$

Analysis of these data is nearing completion. A talk on the ${ }^{30}$ Si results will be presented at the Washington American Physical Society meeting in April. The following is the abstract for that talk:
"Differential cross sections for the ${ }^{30} \mathrm{Si}(\mathrm{p}, \mathrm{p})^{30} \mathrm{Si}$ reaction were measured at four angles ( $160^{\circ}, 135^{\circ}, 105^{\circ}$ and $90^{\circ}$ ) over the proton energy range 1.1 to 3.0 MeV . The targets were $1-2 \mu \mathrm{~g} / \mathrm{cm}^{2}$ of ${ }^{30}$ Si enriched to $95 \%$ and deposited on thin carbon backings. With the high resolution electrostatic analyzer-homogenizer system on the TUNL 3 MV Van de Graaff accelerator, an overall energy resolution of $350-450 \mathrm{eV}$ was achieved. Approximately 60 resonances were observed and analyzed with a multi-level R-matrix formalism. Resonance
energies, spins, parities and proton widths were extracted for each resonance. Several analogue states have been tentatively identified and spectroscopic factors and Coulomb energies determined for these analogues. The importance of the present results for the $p^{1 / 2}$ and $p^{3 / 2}$ strength functions will be emphasized."
e. $\quad{ }^{34} S$

Processing and analysis of the ${ }^{34} \mathrm{~S}(\mathrm{p}, \mathrm{p})$ data is now in progress. The proton spectra are analyzed to determine concentrations of ${ }^{28} \mathrm{Si}$ (and other contaminants) and the appropriate background subtraction performed. The thickness of the Cadmium Sulfide target is a slowly varying function of time, due to boil-off of sulfur. The data fitting procedure has been modified to permit a slowly varying normalization of the off-resonance data to the Rutherford cross section. This correction is at most $5 \%$ at the ends of a fitting region. With these modifications quite satisfactory fits to the data are obtained. R-matrix analysis of these data to obtain resonance energies, spins, parities and reduced widths is nearing completion.

$$
\text { f. } \quad{ }^{92} \mathrm{Mo}
$$

A paper has been accepted for publication in Physical Review: "A High Resolution Study of The $1 / 2^{+}$Analogue State in ${ }^{93} \mathrm{Tc}$ ". The following is the abstract of that paper:
"The ${ }^{92} \mathrm{Mo}(\mathrm{p}, \mathrm{p})$ excitation function was measured with high energy resolution over the $1 / 2^{+}$analogue state at 5.3 MeV . A total of 125 individual $\mathrm{s}, / 2$ resonances were resolved and analyzed. Results of the analysis of the analog state fine structure distribution are presented."

Further studies of the fine structure of analogue states in this mass region are under consideration.

- 2. Fine Structure of Analogue States--The Capture Reaction (G. E. Mitchell, E. G. Bilpuch, K. Wells, J. F. Wimpey)
a. General

Further capture studies have been delayed while developmental work on both the acquisition and analysis of capture data is carried out. A modification of the present data acquisition program for $\mathrm{Ge}(\mathrm{Li})$ spectra incorporates gain
stabilization. Two pulses from a precision pulser are used to correct gains periodically.

An automatic peak location and area determination computer program is being developed for analysis of $\mathrm{Ge}(\mathrm{Li})$ spectra. The basic program was obtained from Nyman (B. Nyman, Nuclear Instruments and Methods 108, 237 (1973). At this stage of modification of the program, peak locations are found in a reliable manner, but difficulties still exist with the area analysis.

Future plans are to search for higher multipole transitions in the ${ }^{58} \mathrm{Fe}(\mathrm{p}, \gamma)$ reaction.
b. $\quad{ }^{44} \mathrm{Ca}$ and ${ }^{62} \mathrm{Ni}$

A dissertation entitled "Electromagnetic Decay of Fragmented Analogue States in ${ }^{45} \mathrm{Sc}$ and ${ }^{63} \mathrm{Cu}$ ", by J. F. Wimpey has been completed. The following is the abstract of that dissertation:
"Capture excitation functions were measured for ${ }^{44} \mathrm{Ca}(\mathrm{p}, \gamma)^{45} \mathrm{Sc}$ from 1.56 to 2.28 MeV and for ${ }^{62} \mathrm{Ni}(p, \gamma){ }^{63} \mathrm{Cu}$ from 2.30 to 2.70 MeV . Detailed study of the electromagnetic decay of 57 resonances in ${ }^{45} \mathrm{Sc}$ and 35 resonances in ${ }^{63} \mathrm{Cu}$ was performed using an $80 \mathrm{~cm}^{3} \mathrm{Ge}(\mathrm{Li})$ detector. The experiments were performed with the TUNL 3 MV Van de Graaff accelerator and associated electrostatic analyzer-homogenizer system. The overall energy resolution of the proton beam was about 350 eV .

For the 92 resonances studied in detail, absolute, partial and total gamma-ray widths and inelastic widths were determined. Three fragmented analogues were studied in ${ }^{45}$ Sc. These states had spin and parity $3 / 2^{-}$, $1 / 2^{-}$and $1 / 2^{+}$, and were the analogues of the sixth, eighth, and tenth excited states of ${ }^{45} \mathrm{Ca}$, respectively. One analogue state was studied in ${ }^{63} \mathrm{Cu}$, the analogue of the $3 / 2^{-}$second excited state of ${ }^{63} \mathrm{Ni}$. The decay of a number of non-analogue (or background) resonances were also studied in both ${ }^{45} \mathrm{Sc}$ and ${ }^{63} \mathrm{Cu}$.

Emphasis was placed on correlations between partial widths in different channels. Statistically significant correlations were measured between the elastic
and inelastic widths on the $1 / 2^{-}$analogue in ${ }^{45} \mathrm{Sc}$ and the $3 / 2^{-}$analogue in ${ }^{63} \mathrm{Cu}$. The correlations between elastic and total capture widths are statistically significant on each of the analogue states. There are also statistically significant correlations between the elastic widths and the gamma-ray widths to particular final states. The correlations between the elastic widths and gamma-ray widths of the background $1 / 2^{+}$ resonances in ${ }^{63} \mathrm{Cu}$ and the background $1 / 2^{-}$resonances in ${ }^{45} \mathrm{Sc}$ are consistent with purely statistical behavior.

The strengths of the MI decay of the $3 / 2^{-}$analogues are as expected for this mass region. Surprisingly the MI strength for the $1 / 2^{-}$analogue in ${ }^{45} \mathrm{Sc}$ is about the same as for the $3 / 2^{-}$analogue in the same nucleus.

In addition to information concerning analogue states, decay of the background states yielded a number of statistical results such as the effective number of degrees of freedom. The combined results for both analogue and background states yielded several hundred transitions strengths of known multipolarity.

Inelastic spectroscopic factors were calculated for the $1 / 2^{-}$and the $1 / 2^{+}$analogue states in ${ }^{45} \mathrm{Sc}$ and the $3 / 2^{-}$analogue state in ${ }^{63} \mathrm{Cu}$. These results indicate that the inelastic spectroscopic factors are oftem comparable to the elastic spectroscopic factors."
3. High Resolution Inelastic Scattering (G. E. Mitchell, E. G. Bilpuch, T. Dittrich, C. R. Gould)

A program of measurements of $\gamma$-ray angular distributions following inelastic scattering of protons from even-even targets in the mass 50 region is currently being undertaken in order to extend and check the results of earlier high resolution elastic scattering and capture studies. If the inelastically scattered protons are not observed, the angular distribution of the resulting $2^{+} \rightarrow 0^{+} \gamma$-rays is of the form

$$
W(\theta)=\sum_{k} a_{k} P_{k}(\cos \theta)
$$

where, for an isolated resonance of spin $J, k$ is even and < $2 J$. The coefficients
$\mathrm{a}_{\mathrm{k}}$ are quadratic in the channel spin mixing ratio, $X$, which can be defined (in analogy with the $\gamma$-ray multipole mixing ratio) by

$$
x=\Gamma_{5} / 2 / \Gamma_{3 / 2} \quad-\infty<x<\infty
$$

Here $\Gamma_{5} / 2$ is the width for emission of a proton in the inelastic channel with channel $\operatorname{spin} 5 / 2$.

A measurement of the angular distribution of the $\gamma$-rays allows, in principle, a determination of the spin of the resonance and also a determination of both the sign and magnitude of $X$. In contrast, a measurement of the angular distribution of the outgoing inelastically scattered protons yields only a value for the absolute magnitude of the channel spin mixing ratio.

A specially designed target chamber has been constructed which allows for $\mathrm{NaI}(\mathrm{TI})$ detectors to be placed simultaneously at angles of $30,45,60$ and $90^{\circ}$ around a target at a distance of $\sim 4 "$. By careful collimation and focussing of the beam and extensive use of lead shielding, $\gamma$-ray backgrounds have been kept to a minimum. The four $\mathrm{NaI}(\mathrm{TI})$ spectra are stored in the DDP-224 computer and can be analyzed on-line to provide an immediate remote display of the angular distribution of the $\gamma$-rays following a run. Preliminary investigations of the performance of the system indicate typical run times are of the order of $10-20$ minutes for $p$-wave resonances in ${ }^{50} \mathrm{Cr}$. A detailed search for possible $1 / 2^{-}, 3 / 2^{-}$measurements of $p-$ wave resonances in ${ }^{44} \mathrm{Ca}$ is planned.

$$
\text { 4. } \quad \frac{\text { Statistical Properties of Nuclei from Proton Resonance Reactions }}{\text { Bilpuch, G. E. Mitchell, H. W. Newson, W. M. Wilson, J. D. Moses) }}
$$

Statistical tests were applied to the sequence of $1 / 2^{-}$levels in -
${ }^{44} \mathrm{Ca}(p, p)$ from $E_{p}=1.5$ to 3.0 MeV and to the sequence of $1 / 2^{+}$levels in ${ }^{48} \mathrm{Ti}(p, p)$ from 2.1 to 3.0 MeV . Since the theories from which the statistics are derived assume constant level density, the first step in the analysis was to "correct" for the energy dependence of the density observed in both sets of data. The procedure used was the following: the cumulative number of observed levels vs. proton energy was fit, in the least squares sense, to the integral of a theoretical density. (In the previous method reported by our group, a "local average spacing" was calculated from the data at intervals of 100 keV or so, and these numbers were fit to the theoretical average spacing $\langle D\rangle=\rho^{-1}$, where $\rho$ is the density. The present technique is preferred. A new set of spacings (having constant density, i.e., constant spacing) was generated by dividing the data by the fit; that is, if $\rho(E)$ is the functional form of the density determined in the fitting procedure, the new set of spacings is calculated from

$$
D_{i}^{\prime}=D_{i} \rho\left(E_{i}\right)\langle D\rangle,
$$

where $D_{i}$ is the measured spacing and <D> is the (arbitrary) constant average spacing. The data were fit to two theoretical densities: $\rho \sim \exp (-E / T)$, where $T$ is the nuclear temperature; and $\rho \sim \exp (2 \sqrt{a E})$, where $a$ is a constant. New sets of spacings were generated from each fit and used for the statistical tests. The results were essentially the same for the two sets, indicating that the density unfolding technique is not strongly dependent on the theoretical model.

The tests included calculating the $\mathrm{k}^{\text {th }}$ nearest neighbor spacing distribution (up to $k=10$; where $k=0$ corresponds to the Wigner distribution), the Dyson-Mehta $\Delta_{3}$ statistic (which measures long range correlations between levels); the covariance $\operatorname{cov}\left(D_{i} ; D_{i+1}\right)$ (which measures short range correlations between levels); and the Dyson F-statistic, which is sensitive to missing and spurious levels.

The results for the calcium data indicate missing or spurious levels in the sequence. The spurious levels are most likely misassigned $3 / 2^{-}$levels since the $\ell$-value of the resonance is usually well determined from the line shape of the $90^{\circ}$ differential cross section. For $p$-wave resonances with widths greater than $15-20 \mathrm{eV}$ the spin is usually determined unambiguously from the line shape of the $135^{\circ}$ differential cross section. Therefore the spurious levels in the sequence of $1 / 2^{-}$levels are most likely those with small widths. In the future we plan to measure the angular distribution of the gamma decay of these small resonances, thereby enabling us to eliminate the spurious $3 / 2^{-}$levels in the sequence. Anomalies in the statistical tests for the revised sequence then would be entirely due to missing levels.

The titanium data apparently has few missing or spurious levels. The results of the statistical tests are in agreement with G.O.E. theory: $\Delta_{3}^{\exp }=0.51$, $\Delta_{3}^{\text {theo }}=0.42 ; \operatorname{cov}\left(D_{i} ; D_{i+1}\right)^{\exp }=-0.21, \operatorname{cov}\left(D_{i} ; D_{i+1}\right)^{\text {theo }}=-0.27$. As reported previously, the nearest neighbor spacing distribution is in remarkable agreement with the Wigner distribution.

> 5. Studies of The Gamma Decay of Excited Levels of ${ }^{51} \mathrm{Ti}$ (G. P. Lamaze,* C. R. Gould, N. R. Roberson, D. R. Tilley)
> Preparation of a paper on this subject, based on the Ph.D. dissertation of G. P. Lamaze, is in progress.

[^64]6. $\frac{\text { Mean Lifetimes of Excited States in }{ }^{38} \mathrm{Ca}}{\text { son, D. R. Tilley) }}$ (E. C. Hagen, N. R. Rober-

The Doppler shift attenuation method (DSAM) has been used to determine the mean lifetimes of low-lying excited states of ${ }^{38} \mathrm{Ca}$. The levels were populated by the ${ }^{36} \mathrm{Ar}\left({ }^{3} \mathrm{He}, n \gamma\right)^{38} \mathrm{Ca}$ reaction at ${ }^{3} \mathrm{He}$ bombarding energies of $9.0,10.0$, and 10.5 MeV . Both enriched ( $99.6 \%$ ) and solid targets were employed. The solid target was a tantalum foil with ${ }^{36} \mathrm{Ar}$ imbedded in it. Precise energies for the first six levels have been determined. A doublet at 3.7 MeV was resolved as a $\mathrm{J} \mathrm{\pi}=3^{-}$ state at 3.703 MeV , and a $\mathrm{J}^{\pi}=2^{+}$state at 3.684 MeV . The lifetimes determined in this study are $98 \pm 42 \mathrm{fs}, 30 \pm 14 \mathrm{ps},<8 \mathrm{fs}, 225 \pm 95 \mathrm{fs}$ and $35 \pm 17 \mathrm{fs}$, for the levels at $2.213,3.084,3.684,3.703$ and 4.384 MeV , respectively. The mean lifetime of the level at 4.193 MeV was not determined. The level scheme is compared with other $A=38$ nuclei and with a calculation performed with the Oak Ridge-Rochester shell model code.

This work is being prepared for publication and was reported at the Spring meeting of the American Physical Society (Bull. Am. Phys. Soc. 19 (1974) 571). The work comprises the Ph.D. dissertation of E. C. Hagen. The abstract follows:
> "The Doppler shift attenuation method (DSAM) has been used to measure the mean lifetimes of low-lying excited states of ${ }^{38} \mathrm{Ca}$. The levels were populated by the ${ }^{36} \mathrm{Ar}\left({ }^{3} \mathrm{He}, \mathrm{n} \mathrm{\gamma}\right){ }^{38} \mathrm{Ca}$ reaction at ${ }^{3} \mathrm{He}$ bombarding energies of $9.0,10.0$ and 10.5 MeV . Both enriched ( $99.6 \%$ ) ${ }^{36} \mathrm{Ar}$ gas and solid targets were used. The solid target was a tantalum foil with ${ }^{36}$ Ar embedded in it. Precise energies for the first six levels have been determined. A doublet at 3.7 MeV was resolved as a $\mathrm{J}^{\pi}=3^{-}$state at 3.703 MeV and a $\mathrm{J} \mathrm{\pi}=2^{+}$state at 3.684 MeV . The lifetimes determined in this study are $98 \pm{ }_{40}^{44} \mathrm{fs}, 27 \pm{ }_{11}^{17} \mathrm{ps},<8 \mathrm{fs}$, $225 \pm{ }_{85}^{100} \mathrm{fs}$ and $35 \pm 17 \mathrm{fs}$ for the levels at 2.213, 3.084, $3.684,3.703$ and 4.384 MeV . The lifetime of the level at 4.193 MeV was not determined.

> The experimental level scheme is compared with other $A=38$ nuclei and with a calculation performed with the Oak Ridge-Rochester shell model code. The model used $\left(s_{1 / 2}\right)^{j}\left(d_{3 / 2}\right)^{k}\left(f_{7 / 2}\right)^{i}\left(p_{3 / 2}\right)^{m}$ configurations with $1+m \leq 2$, $j \geq 2$ and $k \geq 4$.
7. Further Study of Excited States in ${ }^{39} \mathrm{Ca}$ and ${ }^{39} \mathrm{~K}$ (W. Kessel, R. Bass, E. C. Hagen, N. R. Roberson, C. R. Gould, D. R. Tilley)

A paper has been submitted to Nuclear Physics. The abstract is given
below.

> "Excited states in ${ }^{39} \mathrm{Ca}$ up to 4 MeV have been studied with the ${ }^{36} \mathrm{Ar}(\alpha, \mathrm{n} \gamma)^{39} \mathrm{Ca}$ reaction. The outgoing gamma-rays were measured in coincidence with either neutrons or gammarays detected at $0^{\circ}$ with respect to the beam axis. The excitation energies for levels in ${ }^{39} \mathrm{Ca}$ have been measured; near 3.88 and 3.95 two doublets have been found. Mean lifetimes of excited states have been determined by the Doppler-shift attenuation method. The results are $90 \pm 15 \mathrm{ps}, 24 \pm 11 \mathrm{ps}$, and $30 \pm 20 \mathrm{ps}$ for the levels at $2796 \mathrm{keV}, 3640 \mathrm{keV}$, and 3951 keV in ${ }^{39} \mathrm{Ca}$, respectively. Upper limits on the mean lifetimes of several other states were determined. With the $\gamma-\gamma$ coincidence condition, the mean lifetime of the state at 5164 keV in ${ }^{39 \mathrm{~K} \text { was determined to be } 18 \pm 5 \text { ps. The re- }}$ sults are compared with existing data and theoretical predictions."
8. Measurements With a Tensor-Polarized Deuteron Beam of (d, pr) Angular Correlations (C. P. Cameron, T. B. Clegg, C. R. Gould, J. D. Hutton, R. D. Ledford, R. O. Nelson, N. R. Roberson, D. R. Tilley, J. R. Williams)
a. ${ }^{33} \mathrm{~S}$ and ${ }^{35} \mathrm{~S}$

This work has been completed and is being prepared for publication. A talk will be given on this work at the American Physical Society Washington meeting, 22-25 April 1974.

This work comprises the Ph.D. dissertation of J. D. Hutton. The abstract follows:

> "The properties of $\gamma$-ray decays of low-lying levels in ${ }^{33} \mathrm{~S}$ and ${ }^{35} \mathrm{~S}$ have been studied via the ${ }^{32,34 \mathrm{~S}(\mathrm{~d}, \mathrm{p} \gamma)^{33,35} \mathrm{~S}}$ reactions. Multipole mixing ratios have been measured for $\gamma$-ray transitions between bound levels with particle$\gamma$-ray angular correlations and Method II of Litherland and Ferguson. This is one of the first uses of a very po-
werful polarized beam technique developed and first used at TUNL (68) which allows the extraction of information not previously possible with the ( $d, p \gamma$ ) reaction. A tensor polarized deuteron beam from the TUNL Lamb-shift polarized ion source accelerated to 4.72 MeV with the TUNL FN Tandem accelerator was used to bombard $80 \mu \mathrm{~g} / \mathrm{cm}^{2}$ natural sulfur and enriched ( $90 \%)^{34}$ S targets prepared by evaporating sulfur onto a gold foil then evaporating gold on top. Four $7.6 \times 7.6 \mathrm{~cm}$ $\mathrm{NaI}(\mathrm{TI})$ scintillation detectors situated at angles between $30^{\circ}$ and $90^{\circ}$ to the beam detected $\gamma$-rays in coincidence with protons detected at $180^{\circ}$ in a 2 mm thick annular surface barrier detector. Results for ${ }^{33} \mathrm{~S}$ are compared with previous results (5) with which they agree well, and with current shell-model theory. Mixing ratios have been measured for many levels in ${ }^{35} \mathrm{~S}$ as follows ( $\left.E_{x}: J \pi: \delta\right):\left(1991: 7 / 2^{-}: 0.042\right),\left(2348: 3 / 2^{-}: 0.044\right)$, (2718: $\left.\left(3 / 2^{+}\right): 0.065,-5.4\right),\left(2718:\left(5 / 2^{+}\right):-0.36,-7.1\right)$, (2935: (3/2) : 0.34), (2935: (5/2) : 0.086), (3802:3/2-: 0.18, -8)."
b. ${ }^{41} \mathrm{Ca}$

This project is inactive for the present.

## c. ${ }^{49} \mathrm{Ti}$

Analysis of data observed earlier on 16 levels below 4.3 MeV excitation energy has indicated better statistics will be required for meaningful interpretation.
9. Linear Polarization Measurements in ${ }^{29}$ AI (J. R. Williams, C. R. Gould, R. O. Nelson, D. R. Tilley)

Linear polarization measurements for the $\gamma$-rays from the low lying levels of ${ }^{29} \mathrm{Al}$ have been made with a 5 -crystal NaI polarimeter (see Sec. C-8). The measurements were made for the $\gamma$-rays in coincidence with protons in the ${ }^{26} \mathrm{Mg}(\alpha, \mathrm{pr})^{29} \mathrm{Al}$ reaction with $\mathrm{E}_{\alpha}=11.26 \mathrm{MeV}$. The results indicate a $\mathrm{J} \mathrm{\pi}$ assignment of $3 / 2^{+}$for the 2.23 MeV level and are consistent only with $7 / 2^{+}$or $3 / 2^{+}$ for the level at 1.76 MeV . This assignment is in agreement with recent collective model calculations which assume ${ }^{29} \mathrm{Al}$ to have a prolate deformation.
10. Angular Correlation and Lifetime Studies in ${ }^{61} \mathrm{Ni}$ (J. R. Williams, R.O. Nelson, C. R. Gould, D. R. Tilley, D. G. Rickel, N. R. Roberson)

The ${ }^{58} \mathrm{Fe}\left({ }^{4} \mathrm{He}, \mathrm{n}\right){ }^{61} \mathrm{Ni}^{*}$ reaction, at incident beam energy $\mathrm{E}=8.0 \mathrm{MeV}$, has been used to populate the levels in ${ }^{61} \mathrm{Ni}$ below 2.5 MeV in excitation energy. Gamma rays for both angular correlation and lifetime studies were observed with a GeLi detector in coincidence with neutrons detected at $0^{\circ}$. Particle-gamma ray coincidence measurements were also performed with the ${ }^{60} \mathrm{Ni}(\mathrm{d}, \mathrm{p})^{61} \mathrm{Ni}$ * reaction in order to clarify the decay scheme of the excited states in ${ }^{61} \mathrm{Ni}$. Preliminary analysis yields mean lifetimes of $450 \pm 220 \mathrm{fs}, 400 \pm 150 \mathrm{fs}$, and $88 \pm 12 \mathrm{fs}$ for the states at 909, 1132 , and 1730 keV , respectively. Lifetimes or limits for approximately ten other levels in ${ }^{61} \mathrm{Ni}$ have been determined.
11. The Decay Properties of Low Lying Levels of ${ }^{53} \mathrm{Fe}$ (R. O. Nelson, N.R. Roberson, C. R. Gould, D. R. Tilley)

This work has been published in Nuclear Physics A215 (1973) 541.
12. Lifetimes of Levels in ${ }^{55} \mathrm{Co}$ (R. O. Nelson, J. R. Williams, D. R. Tilley, D. G. Rickel, N. R. Roberson)

Lifetimes of levels in ${ }^{55} \mathrm{Co}$ up to 4.8 MeV have been studied with the Doppler-shift attenuation method. Levels were populated with the ${ }^{54} \mathrm{Fe}\left({ }^{3} \mathrm{He}, \mathrm{d} \gamma\right){ }^{55} \mathrm{Co}$ reaction with $12 \mathrm{MeV}^{3} \mathrm{He}^{++}$beams. Scattered particles were detected in two $\mathrm{E}-\Delta \mathrm{E}$ telescopes located at $\theta \gamma=90^{\circ}$ and $130^{\circ}$. The approximately unshifted $\gamma$-ray spectra with $\theta_{d}=-55^{\circ}$ and $\theta_{\gamma}=130^{\circ}$ lend support for a proposed doublet ${ }^{1}$ at 2166 keV , and in addition, indicate a probable doublet at 2566 keV . Preliminary mean lifetime measurements include ( keV , fs) : 2924(>280), 2939 (280 $\pm 110$ ), $3303(73 \pm 19), 3323(59 \pm 19), 3643\left(4700_{-210}^{+1180}\right), 3944(>150), 4164(47+11)$, $4181(<33), 4722(<35)$ and $4749(<61)$.
13. The Polarization of ${ }^{3} \mathrm{He}$ Particles Scattered from ${ }^{27} \mathrm{Al}$ and ${ }^{28} \mathrm{Si}$ (E. J. Ludwig, T. B. Clegg, R. L. Walter)

A paper describing this work has been published in Nuclear Physics A211 (1973) 559.

[^65]
## 14. The ${ }^{28} \mathrm{Si}(\overrightarrow{\mathrm{d}}, \alpha)^{26} \mathrm{Al}$ and ${ }^{14} \mathrm{~N}(\overrightarrow{\mathrm{~d}}, \alpha)^{12} \mathrm{C}$ Reactions at 15 MeV (W. Jacobs, E. J. Ludwig, T. B. Clegg)

The angular distribution and vector analyzing power of a particles produced in the ${ }^{14} \mathrm{~N}(\vec{d}, \alpha)^{12} \mathrm{C}$ reaction using 15 MeV vector polarized deuterons has been measured from $25^{\circ}-100^{\circ}$. Distributions of these quantities have also been obtained for the ${ }^{28} \mathrm{Si}(\vec{d}, a)^{26} \mathrm{Al}$ reaction in the angular range from $25^{\circ}-50^{\circ}$. Both analyzing power distributions show large oscillations and have magnitudes approaching 0.7. These data will be used to attempt an evaluation of the probability of deuteron pick-up and to study the j -dependence of vector analyzing powers.

15. Lifetimes of Levelsin ${ }^{59} \mathrm{Cu}$ (R. O. Nelson, C. R. Gould, D. R. Tilley, N. R. Roberson)

This work has been accepted for publication in the Physical Review. The abstract is given below:
"The mean lifetimes of levels in ${ }^{59} \mathrm{Cu}$ below 3.6 MeV have been investigated with the Doppler-shift attenuation method and the ${ }^{58} \mathrm{Ni}\left({ }^{3} \mathrm{He}, \mathrm{d}\right){ }^{59} \mathrm{Cu}$ reaction at 11.6 MeV . Scattered particles were detected in two E- $\triangle E$ telescopes at $\pm 55^{\circ}$ with respect to the beam axis, in coincidence with $\gamma$-rays observed at $90^{\circ}$ in a $50-\mathrm{cm}^{3} \mathrm{Ge}(\mathrm{Li})$ detector. New Levels were observed at 3114 and 3614 keV . Mean lifetimes are reported for the following levels (energy in keV , lifetime in fsec$): 491(830 \pm 300), 914(>1600)$, $1399(570 \pm 240), 2266(310 \pm 140), 2324(36 \pm 5)$, $3043(1150 \pm 500), 3114(20 \pm 11), 3130(10 \pm 4)$, $3511(<15), 3580(240 \pm 1400)$ and $3615(<35)$. The experimental results are compared with the predictions of a core-particle coupling calculation."
16. Inelastic Deuteron Scattering from ${ }^{28} \mathrm{Si}$ and ${ }^{30} \mathrm{Si}$ (R. A. Hilko, R. O. Nelson, T. G. Dzubay, N. R. Roberson)

Extensive coupled-channel analysis has been carried out. The ${ }^{28} \mathrm{Si}$ data suggest a rotator-vibrator with $\beta_{2}=-0.46$ and $\beta_{0}=-0.32$. The ${ }^{30} \mathrm{Si}$ data has been fit with the rotational model with $\beta_{2}=0.32$. Some of these results will be used in a Ph.D. dissertation (RAH) presently being written.
17. $\frac{\text { The }(d, t) \text { and }\left(d,{ }^{3} \mathrm{He}\right) \text { Reaction on }{ }^{28} \mathrm{Si} \text { and }{ }^{30} \mathrm{Si}}{\text { Nelson, C. R. Gould, N. R. Roberson) }}$ (R. A. Hilko, R. O.

Coupled-Channel Born Approximation (CCBA) calculations with the shell-model and deformed Woods-Saxon band mixing model amplitudes have been performed. $B(E 2)$ and $B(M 1)$ transition rates have been calculated to support the band mixing calculation and have unified the results. The ${ }^{30} \mathrm{Si}\left(\mathrm{d},{ }^{3} \mathrm{He}\right)$ and ${ }^{30} \mathrm{Si}(\mathrm{d}, \mathrm{t})$ is currently the subject of a Ph.D. thesis (RAH).
18. A Study of The Proton Partial Widths for The Lowest $T=3 / 2$ States in ${ }^{41}$ Sc and Other $4 n+1$ Nuclei (T. A. Trainor, T. B. Clegg, W. J. Thompson, E. J. Ludwig, P. G. Ikossi)
a. $\quad{ }^{41} \mathrm{Sc} v \mathrm{via}^{40} \mathrm{Ca}+\mathrm{p}$

Work has continued on re-analyzing the experimental conclusions discussed in the last report. It is clear that the isospin mixing which causes the non-zero proton partial width can arise because of $\mathrm{T}=1$ mixing in the ${ }^{40} \mathrm{C}$ ground state and because of $T=1 / 2$ mixing in the $T=3 / 2$ state of ${ }^{41} \mathrm{~S} C$. Both types of mixing are likely to be present and contributing simultaneously, perhaps with large amplitudes which interfere destructively to obtain small proton partial width. In an attempt to try to determine whether one of these types of mixing dominates over the other, we have extracted the $Z$-dependence of the proton reduced widths $\gamma_{p}^{2}$ for the lowest $T=3 / 2$ states in $A=4 n+1$ nuclei. These $\gamma^{2}$ values increase at least as fast as $Z^{2}$. This evidence alone seems to imply that mixing with $T=1 / 2$ states such as the antianalog state is not important. It cannot prove, however, that one particular type of mixing is dominant.
b. $\quad{ }^{25} \mathrm{Al}$ via ${ }^{24} \mathrm{Mg}+\mathrm{p}$

The lower two $\mathrm{T}=3 / 2$ states in ${ }^{25} \mathrm{Al}$ have been observed through the isospin forbidden reactions ${ }^{24} \mathrm{Mg}\left(p, p_{0}\right)$ and ${ }^{24} \mathrm{Mg}\left(p, p_{1}\right)$. Excitation function differential cross section and analyzing power data at 3 angles in 10 keV steps or less have been taken in the energy region between 5.6 and 6.3 MeV with a 5 keV thick target.

In search for the isospin forbidden resonances data were taken in 1 keV steps with targets $\lesssim 2 \mathrm{keV}$ thick at 4 angles.

Angular distributions were taken at energies 10 keV above and below each isospin forbidden resonance to establish optical model parameters. The analysis of these data is in progress.

We intend to extend the study of the $T=3 / 2$ isospin forbidden resonances with the reactions ${ }^{32} S(p, p)$ and ${ }^{28} \mathrm{Si}(p, p)$ in order to establish the $Z$ dependence of the resonance reduced widths.
19. ${ }^{208} \mathrm{~Pb}\left(p, \mathrm{p}^{\prime}\right),{ }^{208} \mathrm{~Pb}(\mathrm{p}, \mathrm{d})$ and ${ }^{208} \mathrm{~Pb}(\mathrm{p}, \mathrm{t})$ Reactions from 16.7 to 27.3 MeV (E. J. Ludwig, P. Nettles, C. Bush, M. Divadeenam)

Weak-coupling particle-vibration model is employed to describe the parent states in ${ }^{209} \mathrm{~Pb}$ to study the inelastic decay of their analogs in ${ }^{209} \mathrm{Bi}$. The ${ }^{208} \mathrm{~Pb}$ core excited states $3^{-}, 5_{1}^{-}, 5_{2}^{-}, 2^{+}, 4^{+}, 6^{+}, 8^{+}$, and $10^{+}$are assumed to be one phonon states. The spreading of the single particle states into the particlevibration doorways in ${ }^{209} \mathrm{~Pb}$ is being calculated. The analogs of these parent states in ${ }^{209} \mathrm{Bi}$ range from 18.7 to 25.7 MeV . Proton elastic and inelastic decay widths of the ${ }^{209} \mathrm{Bi}$ analogs will be estimated to calculate the excitation function for the ${ }^{208} \mathrm{~Pb}\left(p, p^{\prime}\right)$ reaction populating the various excited states of the target states referred to above. The predictions will be compared to the experimental data.

Any possible connection between the particle-vibration model and the transfer reaction yields will be investigated.
20. Isobaric Analog Resonances in ${ }^{71} \mathrm{Ga}$ (P. G. Ikossi, C. E. Busch, T. B. Clegg, E. J. Ludwig, W. J. Thompson)

A paper describing this work has been submitted to Nuclear Physics.
21. Study of Isospin-Dependence in ( $\vec{d}, t)$ and $\left(\vec{d},{ }^{3} \mathrm{He}\right)$ Transfer Reactions and Investigation of The WBP Model as Applied to Elastic Scattering and (d, t) and ( $\mathrm{d},{ }^{3} \mathrm{He}$ ) Reactions (S. Datta, C. E. Busch, E. J. Ludwig, T. B. Clegg, W. J. Thompson)

This work, involving the bombardment of targets of ${ }^{10} \mathrm{~B},{ }^{12} \mathrm{C},{ }^{13} \mathrm{C},{ }^{14} \mathrm{~N}$, ${ }^{16} \mathrm{O},{ }^{28} \mathrm{Si},{ }^{30} \mathrm{Si}$ and ${ }^{32} \mathrm{~S}$ with 15 MeV vector-polarized deuterons and measuring vector analyzing powers for elastic scattering and the ( $d, t$ ) and ( $d,{ }^{3} \mathrm{He}$ ) reactions, has been divided into three studies.
a. Elastic Deuteron Scattering from ${ }^{10} \mathrm{~B},{ }^{12} \mathrm{C},{ }^{13} \mathrm{C},{ }^{14} \mathrm{~N}$ and ${ }^{16} \mathrm{O}$

A paper describing this work has been accepted for publication
in Nuclear Physics.
b. $\quad(\vec{d}, t)$ and $\left(\vec{d},{ }^{3} \mathrm{He}\right)$ Reactions in Ip Shell Nuclei

A paper describing this work is ready to be submitted to Nuclear
Physics.
c. Comparison of Vector Analyzing-Power Distributions for (d, d) Scattering and ( $d, t$ ) or ( $d,{ }^{3} \mathrm{He}$ ) Reactions for $\ell=0$ Transfers

A paper describing this work has been published in Physical Review Letters 31 (1973) 949.
22. Compound Nuclear Scattering Studies with Polarized Deuterons Incident on 4n Nuclei (R. J. Eastgate, R. F. Haglund, Jr., W. J. Thomp- , son, T. B. Clegg, R. Henneck)
a. Thick Target Studies

Further studies of ${ }^{28} \mathrm{Si}\left(\mathrm{d}, \mathrm{d}_{0}\right)^{28} \mathrm{Si}$ using a thick natural-silicon wafer ( $5.9 \mathrm{mg} / \mathrm{cm}^{2}$ ) target have been carried out over an angular range of $110^{\circ}$ $165^{\circ}$ at three contiguous energies to give an effective averaging interval of $\sim 1.3 \mathrm{MeV}$ centered at 7.0 MeV (Lab). Composite energy-averaged angular distributions of $T_{20}, T_{21}, T_{22}, i T_{11}$ and $d \sigma / d \Omega$ have now been obtained over the above angular range. The corresponding $\left(\vec{d}, d_{1}\right)$ and $\left(\vec{d}, p_{0}\right)$ data have been taken where feasible. Forward hemisphere angular distributions will be taken with thinner targets so that a thorough optical model plus modified Hauser-Feshbach analysis may be done. Preliminary optical model calculations are encouraging.

## b. Thin Target Studies

Beams of $\sim 40 \mathrm{nA}$ of vector-polarized deuterons and $\sim 20 \mathrm{keV}$ thick targets of ${ }^{28} \mathrm{Si}$ have been used to measure the cross-section and vector-analyzing power for ${ }^{28} \mathrm{Si}+\mathrm{d}$ scattering. Data have been collected in 20 keV steps at $\theta_{\text {Lab }}=130^{\circ}$ for $E_{d}=7.5-10.4 \mathrm{MeV}$ and at $\theta_{\text {Lab }}=150^{\circ}$ for $E_{d}=6.0-10.4$ MeV for elastically scattered deuterons and the first inelastic group. The ground state and six excited-state proton groups resulting from ${ }^{28} \mathrm{Si}(\mathrm{d}, \mathrm{p})$ reactions were observed. Strong Ericson-type fluctuations are present in the data for both crosssection and vector analyzing power. A new method of testing the Random Phase Approximation for compound nucleus amplitudes was developed for the fluctuations in the vector analyzing power of all exit channels. In addition an Ericson Fluctuation Analysis is being applied to the cross-section fluctuations. Both ways of analysis will give statistical information about the reaction mechanism and will be used to test the Random Phase Approximation for compound nucleus amplitudes.

An abstract has been submitted to the American Physical Society Washington meeting (April 22-25, 1974).
23. $\frac{\text { Cross-Section and Polarization Studies for }{ }^{13} \mathrm{C}\left({ }^{3} \mathrm{He},{ }^{3} \mathrm{He}\right){ }^{13} \mathrm{C} \text { Elastic }}{\text { Scattering (T. C. Rhea, R. L. Walter, E. J. Ludwig) }}$

The lack of agreement (discussed in the last report) between optical model predictions and the $P(\theta)$ and $\sigma(\theta)$ data may be associated with the large inelastic scattering cross section to low lying states and tests of the polarization sensitivity to such are being looked into by way of existing coupled-channel codes.
24. The Tensor Analyzing Power $\mathrm{A}_{\mathbf{z z}}$ at $\theta=0^{\circ}$ for the ${ }^{3} \mathrm{He}(\overrightarrow{\mathrm{d}}, \mathrm{p})^{4} \mathrm{He}$ Reaction (T. A. Trainor, P. W. Lisowski, T. B. Clegg)

A paper describing this work has been accepted for publication in Nuclear Physics.
25. Angular Correlation, Linear Polarization, and Lifetime Measurements for Excited States in ${ }^{30} \mathrm{~V}$ (D. Rickel, R. O. Nelson, J. R. Williams, D. R. Tilley, N. R. Roberson)

In the last report we described work which was underway for measuring lifetimes and $\gamma$-ray angular distributions of the low-lying levels in ${ }^{50}$. These measurements have now been completed and the data analyzed. In addition to these data, linear polarization measurements of the $\gamma$-ray emissions from ${ }^{50} \mathrm{~V}$ were also obtained. These latter measurements utilized the laboratory's two $-\mathrm{Ge}(\mathrm{Li})$-crystal symmetric Compton polarimeter. As a result of the above work, spin and parity assignments for all ${ }^{50} \mathrm{~V}$ levels from 836 keV to 1560 keV have been made plus the lifetime measurements of these levels.

A manuscript is now being prepared for submission to Nuclear Physics reporting this work. The table below summarizes our results:
Level

836
910
1301
1331
1400


Lifetime (fs)
$110 \pm 40$
$110 \pm 12$
$60 \pm 10$
$24 \pm 8$
No observed shift

Section B. 25 table continued

| Level | $J \pi$ | Lifetime (fs) |
| :---: | :---: | :---: |
| 1493 | $1^{+}$ | $74 \pm 10$ |
| 1517 | $2^{+}$ | $270 \pm 50$ |
| 1560 | $2^{+}$ | $\tau>550$ |
| 1677 | $(2)^{+}$ | $\tau>500$ |

26. Linear Polarization Studies of $\gamma$-ray Decays from ${ }^{61} \mathrm{Ni}$ (D. G. Rickel, J. R. Williams, C. R. Gould, D. R. Tilley, N. R. Roberson)

Studies of the $\gamma$-ray decay properties of ${ }^{61} \mathrm{Ni}$ have been underway for about a year at this laboratory (see B-10 above). One problem encountered is that the $\gamma$-ray angular correlation measurements do not lead to unique spin assignments for any of the levels studied. In many instances it is felt that unique assignments can be made knowing the linear polarization of $\gamma$-ray emissions from these levels. For this reason we have measured the linear polarization and $\gamma$-ray angular distributions in singles via the ( $\alpha, n$ ) reaction for ${ }^{61} \mathrm{Ni}$ levels up to 2122 keV . Partial analysis of these data shows that we have good substate alignment resulting in strong angular correlations for most levels. As of yet the linear polarization data have not been analyzed. It is hoped that when analysis is complete unique spin and parity assignments can be made to the 8 levels below 2200 keV which are either unassigned or have tentative assignments.

$$
\text { 27. } \frac{\text { The GDR of }{ }^{15} \mathrm{~N} \text { from }{ }^{14} \mathrm{C}(\vec{p}, \overrightarrow{\mathrm{p}})^{14} \mathrm{C} \text { Measurements }}{\text { Rickel, N. R. Roberson, D. R. Tilley) }} \text { (H. R. Weller, D. G. }
$$

We have measured the elastic proton polarization for the ${ }^{14} \mathrm{C}(\overrightarrow{\mathrm{p}}, \overrightarrow{\mathrm{p}})^{14} \mathrm{C}$ reaction in an attempt to see if effects of the giant dipole resonance can be detected in such data. Data were taken at sixteen angles and fourteen energies in the range of $E_{p}=7.5$ to 13.25 MeV . This region covers the giant dipole resonance region (GDR) of ${ }^{15} \mathrm{~N}$. A preliminary optical model analysis of these data (combined with cross section data) indicates that $V_{\text {so }}$ varies over this energy region in a manner which suggests that the effect is due to the GDR. When the equivalent phase shifts are calculated from these optical potentials, it appears as though the $d_{3} / 2$ partial wave shows resonance behavior in this region. This would be consistent with the fact that the GDR at $10-11 \mathrm{MeV}$ is $\mathrm{J} \mathrm{\pi}=3 / 2^{+}$. A detailed analysis in terms of background phase shifts plus resonances is being performed. It is hoped that this technique will provide another means for studying the GDR phenomenon.
28. X-Ray Studies (A. B. Baskin,* G. A. Bissinger,** C. E. Busch, ${ }^{+}$P. H. Nettles, ${ }^{+}$J. T. May, A. W. Waltner, S. M. Shafroth, B. Doyle, R. White, D. Sircar, K. Hill, J. W. Cooper ${ }^{++}$R. S. Deslattes, ${ }^{++}$W. W. Jacobs)
a. $\quad \mathrm{Ag} \mathrm{K}$ and L and Au L x-rays Produced by $12-50 \mathrm{MeV}{ }^{16} \mathrm{O}$ Bombardment

The manuscript for this paper is now complete and as soon as the figures are drawn it will be submitted for publication, probably to Phys. Rev. A.
b. High Resolution Study of Ag L x-rays Produced by $0.5-3.5 \mathrm{MeV}$ Proton, 18-24 MeV ${ }^{16} \mathrm{O}$ Ion Bombardment and Photon Excitation

This work has been extended to include $\mathrm{He}^{++}, \mathrm{Li}^{+++}$and $\mathrm{C}^{5+}$ projectiles of energies from 0.5 to $5 \mathrm{MeV} / \mathrm{AMU}$. We have also done measurements for protons with a semi thick target $5.8 \mathrm{mg} / \mathrm{cm}^{2}$ ) in order to check the effect of target thickness on the spectra and to check the thick target correction program. M hole production probabilities per electron, Pm , were deduced. They are in rough agreement with $\mathrm{Pm} \sim \mathrm{Z}^{2}$ where Z is the projectile nuclear charge. For $\mathrm{He}^{++}$projectiles $\operatorname{Pm}$ varies from $0.2=0.1$ when $\mathrm{E} \alpha$ varies from $12-21 \mathrm{MeV}$.
c. $\quad \mathrm{Bi}$ and PoKx-rays Arising from Proton Bombardment of Bi $E p=3-13 \mathrm{MeV}$

Mr. D. Sircar has been preparing a manuscript for publication on this work. Absolute $K$ x-ray cross sections have been extracted. They agree well with relativistic BEA and are about 5 X the value given by PWBA theory. The cross sections for production of Po K x-rays are about a factor of 10 less than for Bi K $x$-rays above $\mathrm{Ep}=12 \mathrm{MeV}$. We are attempting to estimate the amount of zero impact parameter coulomb excitation vs. nuclear $K$ electron ejection excitation due to processes like internal conversion etc. The harmonic oscillator model of Mr. K. Hill will be used for this work. Should this be successful we would have a new method of predicting $[\sigma(p, n)+\sigma(p, 2 n)+\sigma(p, \gamma)]$.

[^66]\[

$$
\begin{aligned}
& \text { The ratios, } \frac{\sigma\left(K_{\beta_{1}}+K_{\beta_{3}}\right)}{\sigma\left(K_{\beta_{2}}\right)}=\frac{\Gamma_{\mathrm{mIII}}+\Gamma_{\mathrm{mII}}}{\Gamma_{\mathrm{NII}, \mathrm{III}}} \text {, } \\
& \frac{\sigma\left(K_{\alpha 2}\right)}{\sigma\left(K_{\alpha 1}\right)}=\frac{\Gamma_{L_{I I}}}{\Gamma_{L_{I I I}}} \\
& \text { and } \quad \frac{\sigma\left(K_{\alpha 1}\right)}{\sigma\left(K_{\beta_{2}}\right)}=\frac{\Gamma_{L_{I I I}}}{\Gamma_{N_{\text {II, III }}}}
\end{aligned}
$$
\]

were obtained as a function of $E_{p}$ and compared with theoretical calculations of Scofield. Rough agreement was found but an interesting effect was observed. Specifically the effect was that these ratios depended on bombarding energy and that transitions from weakly bound levels such as NII, III became relatively stronger as $\mathrm{E}_{\mathrm{p}}$ increased. This is probably due to the fact that simultaneous KL vacancy productions increase by $E_{p}$ faster than simultaneous $K N$ vacancy production, and so the effect is attributed to a reduction in $\mathrm{K}_{\alpha}$ radiation relative to $\mathrm{K}_{\beta 2}$ radiation as $E_{p}$ increases. The reduction is due to missing $L$ shell electrons then. An attempt to fit the data qualitatively using harmonic oscillator were functions and zero impact parameter calculations of K . Hill is underway.
d. U and Np K x-ray Production Arising from 2-15 MeV Proton Bombardment of $U$

Professor A. Waltner is preparing this work for publication. He has extracted absolute $K, L$ and $M$ cross sections over the entire energy range. Also at $E_{p}=15 \mathrm{MeV}$ the Np K x-ray cross section can be obtained from the data. It is hoped that this aspect of the work can be analyzed using Mr. K. Hill's method so that $[\sigma(p, n)+\sigma(p, 2 n)+\sigma(p, \gamma)]$ can be determined. Ratios of cross sections for the $L$ x-rays have permitted the extraction of primary vacancy distribution information which can be directly compared with PWBA, BEA, SCA calculations. The $M \times$-ray spectrum has considerable structure also but little thought has yet been given to its significance. The most intense line seen when a $\mathrm{KeVex} \mathrm{Si}(\mathrm{Li})$ detector is used is $M_{\alpha, \beta}$.

The semiconductor detector data should be understandable in the light of a Bragg Spectrometer $M$ x-ray spectrum taken at $E_{x}=3 \mathrm{MeV}$ on a thick $U$ target. $M \times$-rays excited by 5.95 keV x-rays from an ${ }^{55} \mathrm{Fe}$ source have provided comparison spectra where the $M$ holes are not dependent of filling of deeper holes $(\mathrm{K}+\mathrm{L})$ as in the proton data.
e. Au K x-rays Excited by Protons (2-14 MeV) and ${ }^{16} \mathrm{O}^{\text {n+ }}$ Ions ( $18-42 \mathrm{MeV}$ )

No further work has been done since the last report.
f. $\quad \mathrm{L}$ and M x-rays of Bi and $U$ Arising from $0.5-15 \mathrm{MeV}$ and 2-15 MeV Proton Bombardment of Bi and U

No progress has been made since the last report on Bi . The UL $x$-rays are discussed in " d " above.
g. PbL and Mx -rays

A paper entitled " Pb and Bi L -Subshell Ionization Cross Section Ratios Versus Proton Bombarding Energy from 0.5 to $4 \mathrm{MeV}^{\prime \prime}$ has been published in Phys. Rev. A9, 675 (1974).
h. High Resolution Study of $\mathrm{Zr} \mathrm{L} x$-rays Excited by Photons, p, $\mathrm{He}^{++}, \mathrm{Li}^{+++}, \mathrm{O}^{++}$lon Beams

The Zr spectra have been fit with binomial distributions for $p$, He and Li projectile excitation. In the case of proton excitation the $L_{\alpha}$ peak and the two satellite peaks (approximated by Gaussians) are distinguishable. After extracting areas for these peaks the data are fit to a binomial distribution of the form $\left(\begin{array}{l}18\end{array}\right) \mathrm{P}_{\mathrm{m}}\left(\mathrm{I}-\mathrm{P}_{\mathrm{m}}\right)^{18-n}$. In the case of $\mathrm{He}^{++}$excitation the diagram line and 3 satellites are distinguishable. Further a range of bombarding energies from 4 to 12 MeV in 2 MeV steps was taken and the values of $\mathrm{P}_{\mathrm{m}}$ decrease linearly with increasing projectile energy with a slope

$$
\frac{\Delta \mathrm{P}}{\Delta \mathrm{E}}=\frac{2.2 \times 10^{-3}}{\mathrm{MeV}}
$$

Also in the case of $\mathrm{Li}^{+++}$projectiles the diagram line $\left(\mathrm{L}_{\alpha}\right)$ and three satellites were analyzed. A plot of $P_{m}$ vs $Z^{2}$ (projectile) at the same velocity for the three projectiles increases linearly with a slope

$$
\frac{\Delta P}{\Delta Z^{2}}=5.9 \times 10^{-3}
$$

The oxygen on Zr data has the problem that the $L^{\prime}{ }^{\prime}$ peak interferes with the $L_{\alpha}$ satellites so no analysis has been done yet. However it seems that the diagram line is too strong to fit a binomial distribution pattern--a fact which we have been puzzling over. L x-ray spectra have been taken for 27 and/or $32 \mathrm{MeV} \mathrm{O}^{\mathrm{n}^{+}}$on Sr , $Y, \ln , \mathrm{Sn}$ and Mo to study the diagram line to satellite ratio. Ta $M_{\alpha}, \beta x$-rays were excited with $33 \mathrm{MeV} \mathrm{On+}$.
i. High Resolution Study of $\mathrm{Zr} L \times$-rays Arising from $\mathrm{p}, \mathrm{a},{ }^{7} \mathrm{Li}^{\mathrm{n}+}$, ${ }^{16} \mathrm{O}^{\text {n+ }}$ Ion Bombardment And Photon Irradiation

A short paper entitled "Energy Shifts vs. Projectile Z for Ti Ka X-rays And Satellites*" by D. H. Madison, K. W. Hill, B. L. Doyle and S. M. Shafroth has been submitted for publication to Physics Letters. The abstract follows:
"A high resolution study of $\mathrm{Ti} \mathrm{K} \alpha$ x-ray spectra vs. projectile $Z$ has been performed. Energy shifts and width changes were observed in both the diagram and satellite lines. These effects are explained as multiple ionization of the $M$ shell."

A paper, being prepared for publication by Mr. K. W. Hill, which documents this work in more detail and includes a comparison of theory and experiment for the ratios of various satellite peaks to total $\mathrm{K} \times$-ray yield, is nearing completion. The harmonic oscillator wave function, semi classical, zero impact parameter calculations of Mr . K. Hill are capable of describing the trend of these ratios with projectile energy better than any other calculations we know of. Mr . B. Doyle has done fits of the $\mathrm{Ti} \mathrm{K}_{\alpha}$ x-ray spectra to binomial distribution functions and extracted $P_{L}$ for each spectrum. These increase linearly with $Z^{2}$ (projectile) (at the same velocity) and decrease linearly with increasing projectile energy. Since the last report we have excited the $\mathrm{Ti}_{\mathrm{K}} \mathrm{x}$-rays with $\mathrm{C}^{+}+$ions of 21,27, $36,39.3$ and 45 MeV and $\mathrm{Li}^{3+}$ ions of $10.5,16.4,21$ and 27.75 MeV .

## j. Development Progress

In order to obtain improved data with the NBS Flat Crystal XRay Spectrometer, Mr. B. Doyle wrote a data-taking program for the TUNL DDP224 on-line computer. This program uses the memory of the DDP-224 and an ADC to store proportional counter spectra and sum the counts in the peak of interest. The $x$-ray spectrum (counts vs. $\sin \theta$ ) is stored and displayed as the spectrum is acquired. Control of the stepping motor is still done using the NBS system. However, this system is about to be returned. We are in the process of duplicating the x-ray tube and have ordered an ARL curved crystal spectrometer so that high resolution work can continue. The ARL spectrometer will be computer controlled.
29. Tests of The Suitability of a 3 MeV Proton Beam for Trace Element Studies (R. L. Walter, R. D. Willis, W. Gutknecht, J. M. Joyce)

A review paper on our preliminary studies will appear in the June issue of Analytical Chemistry. The spectrum fitting code TRACE written for our off-line
computer and which requires some interactive input is nearly completed. In its current status, spectrum analysis for about 18 elements is achieved in about 80 seconds. A report on the versatility and suitability of this code for $x$-ray spectral analysis will be submitted for publication when the last modifications are included. A brief report on our enzyme studies appeared in Analytical Biochemistry 57 (1974) 618. A more complete description of the analysis of ion-exchange membranes appeared in Analytical Chemistry in March, 1974. The final report for the EPA contract will be postponed so that a thorough evaluation of the sensitivities for elemental analysis in environmental specimens can be supplied. Also included will be a review of the merits of using this method for analyses compared to other techniques.
30. $\frac{{ }^{6} \mathrm{Li}\left(\mathrm{p},{ }^{3} \mathrm{He}\right)^{4} \mathrm{He} \text { Reaction from } 3 \text { to } 12 \mathrm{MeV}}{\mathrm{J} . \text { R. Williams) }}$ (C. R. Gould, J. R. Boyce,

The experimental phase of this work has been completed and the results are being prepared for publication. Our data for this reaction indicate the total cross section to be monoatomically decreasing from $\sim 150 \mathrm{mb}$ at 3 MeV down to $\sim 40 \mathrm{mb}$ at 12 MeV with little indication of resonance structure. These results agree well with those of Hooton and Ivanovich' at 3 MeV and support their contention that the cross section in this region is much higher than had previously been supposed. Additional measurements of proton elastic and inelastic scattering from ${ }^{6} \mathrm{Li}$ made in the region 4 to 8 MeV imply cross sections for these reactions are also higher than earlier results. ${ }^{2}$ This work was reported at the Chicago meeting of the American Physical Society. Investigations are planned for other absolute cross section measurements of interest to thermonuclear reactor studies, in particular those involving light mass nuclei.

## C. DEVELOPMENT

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

The chopper-buncher system for the production of pulsed beams is now in routine operation. Deuteron burst lengths less than 1.5 nanoseconds with beam currents in excess of $2.0 \mu \mathrm{~A}$ have been utilized in target room 5. Protons,

[^67]deuterons and ${ }^{3} \mathrm{He}$ can be bunched with the present system. A new buncher cylinder with a sufficiently large aperture to permit pulsed beam operation with the polarized source output is under construction.

A slight modification of the extraction aperture of the direct extraction source now permits dc operation with beams in the order of $50 \mu \mathrm{~A}$ of deuterons and $60 \mu \mathrm{~A}$ of protons with little apparent loss in emittance properties.
b. Injector Cyclotron

The injector cyclotron has been placed back in operation following repairs. Circulating beam currents and extracted beams are virtually unchanged from their former values. The magnetic extraction channel now has the capability of being remotely positioned thus adding a slight degree of flexibility which facilitates extraction with primary magnetic field settings optimized for high resolution operation.
2. Pulsed Beams (F. O. Purser, H. W. Newson, N. R. Roberson, T. B. Clegg, D. W. Glasgow, D. E. Epperson, J. R. Boyce, J. Clement, G. Mack,* K. Setlzer**)
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

The main neutron time-of-flight system is now in routine operation. Pulsed deuteron beams of over $2.0 \mu \mathrm{~A}$ with burst lengths less than 1.5 ns are produced in the neutron target room. All electronics and equipment are working satisfactorily.

A second elevated track has been installed to support a massive gamma ray shield which can be used in ( $n, \gamma$ ) cross section measurements or ( $n, \gamma$ ) correlations. The main shield and radial carriage are designed to fit either on its own angular carriage, with angular range from $-30^{\circ}$ to $+150^{\circ}$, or to be installed on the angular carriage of the main neutron collimator. The copper, tungsten, and lead $\gamma$-ray shield is designed for use with either $\mathrm{Ge}(\mathrm{Li})$ detectors or with a $5^{\prime \prime} \times 5^{\prime \prime}$

[^68]$\mathrm{NaI}(\mathrm{TI})$ crystal. When installed in front of the main neutron collimator the shield is designed to act as a second double Langsdorf cone collimator for the neutron detector. The added shielding should prove most beneficial for neutron measurements at higher energies. Design and shop drawings have been completed. Fabrication will begin in our machine shop around the first of April.

3. Polarized Source Operation (T. B. Clegg, P. W. Lisowski, R. Henneck, W. W. Jacobs)

The polarized source has continued to be used extensively for experiments since the last report--usually for an average of $10-15$ days/month. Accelerated beams are down somewhat from those last reported and are typically $80-$ $120 \mu \mathrm{~A}$ for both protons and deuterons. The operation of the source has been accomplished with a minimum of maintenance--usually several hours work before each accelerator run of 4-8 days. No major modifications in the ion source have been made since the last report.
4. Hardware and Software for Tensor Polarization Experiments (R. F. Haglund, Jr., R. J. Eastgate, T. B. Clegg)

The automatic chamber rotation system is being rebuilt as a result of two problems which arose after bench-testing: repeated failures of the optical limit switches, and false-switching due to transients associated with switching the gear-motor from forward to reverse. The new circuitry will, it is hoped, solve both problems, by replacing the optical limit switches with microswitches and isolating the logic system from the motor control circuit to a greater degree than before.

The data-taking program DMASS for the 16K upper memory of the DDP-224 $\beta$-computer has been modified to do particle identification for four particle telescopes, with two particle types identified in each telescope. This contrasts with the three particle groups for two telescopes available in the previous version. The quench ratio calculation has been changed to allow for the storage of quench ratios throughout a sequence of measurements--thus giving a more accurate determination of the average beam polarization. This is particularly important for tensor polarization measurements, where a single point may require several "sub-measurements" extending over an hour and a half or more. The program also can now handle a variety of schemes for measurement of tensor polarization.
5. Beam Accelerator Optics for The Low-Energy End of The Tandem Accelerator (T. B. Clegg, E. Edney)

The new einzel lens installed in the low energy beam handling system for the tandem accelerator prior to the last progress report has been shown to yield significantly improved beam transmission through the accelerator at all terminal voltages above $\sim 3 \mathrm{MV}$. It is now possible to obtain polarized beam transmissions higher than $60 \%$ from the low-energy to high-energy ends of the tandem accelerator with the best transmission of $\sim 85 \%$ coming for a terminal voltage of approximately 3.5 MV. There is an average improvement of $\sim 20 \%$ in the transmission area performance before this einzel lens was installed.
6. High Resolution on The Tandem Accelerator (E. G. Bilpuch, F. O. Purser, J. D. Moses, H. W. Newson, G. E. Mitchell, D. A. Outlaw)

High resolution measurements on the tandem have been greatly improved with the addition of the direct extraction source. A paper describing these improved results has been published: Nuclear Instruments and Methods 113, 603 (1974).
D. THEORY

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

Inactive.
2. Excited-State-Threshold Resonance Effects in ${ }^{9} \mathrm{Be}(\mathrm{p}, \mathrm{p})^{9} \mathrm{Be}$ and
${ }^{9} \mathrm{Be}(\mathrm{p}, \mathrm{n})^{9}$ B (H. J. Votava, W. J. Thompson)
Inactive.
3. Proton Optical-Model Potential Near The Coulomb Barrier (J. S. Eck (Kansas State University)), W. J. Thompson)

Inactive.

[^69]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 ${ }^{24} \mathrm{Mg}\left(\alpha_{1} \alpha^{\prime} \gamma\right)^{24} \mathrm{Mg}$ (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. Shell Model Calculations in The $A=55-65$ Region (R. J. Eastgate, S. Maripuu)

Energy spectra have been calculated for Ni and Cu isotopes with a "realistic" two-body force derived from the Sussex interaction and with the singleparticle binding energies taken from the ${ }^{57} \mathrm{Ni}$ experimental spectrum. The valence nucleons are assumed to be in $p_{3} / 2, f_{5 / 2}$ and $p_{1 / 2}$ orbits with ${ }^{56} \mathrm{Ni}$ regarded as a closed core. Another calculation which allows excitations of up to two particles from the $f_{7} / 2$-shell has also been performed. The single particle energies are as above and the two-body interaction is "realistic" and renormalized for the case of ${ }^{40} \mathrm{Ca}$ as a core. The aim of this study is to compare excitation energies and transition strengths and in this way to find the importance of excitations from the $\mathrm{f}_{7} / 2$ shell for nuclei with a few nucleons outside ${ }^{56} \mathrm{Ni}$.

A paper with the above title has been submitted to the Washington
meeting: Bull. Am. Phys. Soc. 19, 527 (1974).

## 9. Structure of ${ }^{38} \mathrm{Ca}$ (and ${ }^{38} \mathrm{Ar}$ ) (E. C. Hagen, S. Maripuu)

Recent experimental results' on excitation energies and lifetimes of ${ }^{38} \mathrm{Ca}$ have inspired this shell model study of the $T=1$ levels for $A=38$. An inert ${ }^{28} \mathrm{Si}$ core is assumed with the valence nucleons distributed among (a) $\mathrm{s}_{1} / 2$ and $\mathrm{d}_{3} / 2$ shells and (b) up to two nucleons excited into the $f_{7} / 2$ and $p_{3} / 2$ shells. The modified surface-delta interaction (MSDI) has been used as the two-body force. The observables and the results of the two calculations are displayed in Fig. 1. The agreement between experiment and theory is found to be good. It is noteworthy that the first excited $\mathrm{O}^{+}$state can only be explained with the extended configuration space calculation. It is indeed found that more than $90 \%$ of its components are ( fp$)^{2}$ excitations. The calculation $B(M 1)$ and $B(E 2)$ values is in progress.


TE. C. Hagen, Ph.D. dissertation.
10. Shell Model Study of Zr Isotopes (G. Grube, S. Maripuu)

The neutron spectra of Zr isotopes with mass numbers 92 to 96 are studied assuming an inert $\mathrm{Zr}^{90}$ core and the valence neutrons distributed among the $2 d_{5} / 2,3 s_{1 / 2}$ and $2 d_{3 / 2}$ shells. In order to study the importance of proton excitations another calculation will be performed with $\mathrm{Sr}^{88}$ as inert core. The two-body forces used are of the modified surface delta and Gaussian type.
11. Proton $2 p-1$ and Particle-Vibration Doorways (M. Divadeenam, W. P. Beres, A. Lev, H. R. Weller, E. G. Bilpuch, H. W. Newson, K. Ramavataram)

40+p: Calculations are in progress.
${ }^{208} \mathrm{~Pb}+\mathrm{p}:$ The latter model has been applied to the ${ }^{208} \mathrm{~Pb}$-plus-proton case to calculate the spreading widths. The abstract of a paper ${ }^{1}$ which appeared in Physics Letters follows:
"The nuclear spreading width of the $2 g_{9} / 2$ antianalog state in ${ }^{209} \mathrm{Bi}$ is calculated within the particle-vibration intermediate structure scheme. The width is several MeV only in three distinct energy regions. The distribution of the $2 g_{g} / 2$ strength is also studied."

An attempt is being made to calculate the inelastic proton yields to various excited states of the target ${ }^{208} \mathrm{~Pb}$ (see Section A-14).
${ }^{28} \mathrm{~S}_{\mathrm{i}+\mathrm{p}}:$ No progress has been made since the last report.
${ }^{14} \mathrm{C}+\mathrm{p}$ : The compound nucleus ${ }^{15} \mathrm{~N}$ has been considered to predict $2 \mathrm{p}-1 \mathrm{~h}$ doorway energies for $J^{\pi}=1 / 2^{+}, 3 / 2^{+}, 5 / 2^{+}, 1 / 2^{-}$and $3 / 2^{-}$. Elastic proton escape widths for $1 / 2^{+}, 3 / 2^{+}$and $5 / 2^{+}$analogs and for $1 / 2^{-}$and $3 / 2^{-}$resonances are calculated. Preliminary results were presented ${ }^{2}$ at the recent Bloomington American Physical Society Nuclear Division meeting.

A paper entitled "The $2 \mathrm{p}-1 \mathrm{~h}$ Structure of ${ }^{15} \mathrm{~N}$ from ${ }^{14} \mathrm{C}(\mathrm{p}, \mathrm{p}){ }^{14} \mathrm{C}$ cross Section and Polarization Measurements" has been submitted to Physical Review. The abstract follows.

[^70]
#### Abstract

"The cross-section for the ${ }^{14} \mathrm{C}(p, p){ }^{14} \mathrm{C}$ reaction has been measured for proton energies from 4 to 11.5 MeV . The elastic proton polarization has been measured for proton energies from 3.2 to 5.7 MeV . The region between 3.2 and 7.5 MeV has been fitted using complex background phase shifts and 13 resonances. The data suggest several new candidates for $T=3 / 2$ states in ${ }^{15} \mathrm{~N}$. A $2 p-1$ doorway state calculation shows reasonable agreement with most of the experimental results."


12. A Core-Plus-Particle Model and Shell Model Investigation of Ni Isotopes (M. Divadeenam, C. R. Gould and K. Ramavataram)

No progress has been made since the last report.
13. 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 zero-range repulsive and density dependent form plus a finite range non-renormalized part is used in an averaged localdensity 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."
14. Computer Codes for High Accuracy Single Particle States (R. Y. Cusson, E. G. Bilpuch, H. P. Trivedi, D. Kolb)

A Ph.D. dissertation has been completed by H. P. Trivedi: "Brueckner-Hartree-Fock Calculations in Two Nuclear Models for Closed Shell And Superheavy ( $A=298, Z=114$ ) Nuclei Using Effective K-Matrix". The abstract follows:
"We motivate from the Brueckner K-matrix formalism a method for introducing a realistic effective single particle
hamiltonian in nuclear matter. A transition to finite nuclei is then made using a modified energy density functional method. Various finite nuclei corrections are then introduced, justified, and their effects discussed. Brueckner-Hartree-Fock calculations for several closed shell nuclei are performed and their binding energies, radii, density distributions and single particle spectra determined with two models. While both models are found to account for the properties of the nuclei under investigation satisfactorily, model II seems to give better results than model I in just about every respect. Model I is simpler and it is based on Meldner's work while model II is more complex and is derived from Bethe's arguments. Model II reproduces the observed level density near the Fermi surface in finite nuclei significantly better than model I and also all other self-consistent calculations to date.

Calculations for the superheavy nucleus ( $A=298$, $Z=114$ ) are also performed with both models and compared with predictions of other authors. Briueckner rearrangement energies and the resulting distinction between the self-consistent single particle energy and the removal (for separation) energy as well as the ambiguities in the definition of the latter are discussed.

The method used for solving the resulting nonlocal density dependent Schrodinger equation is described in detail."

## 15. Single-Particle Wavefunctions and Energies for Stripping and Pickup Reactions (R. Y. Cusson, G. R. Satchler ((ORNL)), H. P. Trivedi)

The reported sensitivity of one-particle transfer reactions to the precise value of the sp energy has been taken into account for 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 near the nuclear surface. The equivalent local potential is being constructed and recoil corrections are being performed.
16. Realistic Single Particle Hamiltonian for Fission Calculation (D. Kolb

A paper has appeared in Nuclear Physics A215 (1973) 1.
17. Asymmetric Fission of ${ }^{236} U$ in A Realistic K-Matrix Model (R. Y.

A paper has been submitted to Physical Review. The abstract follows:
"The phenomenological single-particle Hamiltonian of Meldner is rederived as a renormalized single-particle Kmatrix and is used to calculate the properties of ${ }^{236} \mathrm{U}$ on the fission path from the ground state to scission into asymmetric fragments. Substantial radial density fluctions or "bubble configurations" are observed as well as a displacement of the neutron center of mass relative to that of the protons. It is also found that the presence of a broad third minimum and saddle near scission can be observed for one of the parameter sets of the interaction. These parameters of our deformation and atomic number independent model were obtained by fitting to the experimental properties of ${ }^{16} \mathrm{O},{ }^{40} \mathrm{Ca},{ }^{48} \mathrm{Ca}$, and ${ }^{208} \mathrm{~Pb}$ and nuclear matter. The present results are used to illustrate the essential importance of using a non-orthogonal twooscillator basis as well as taking into account the properties of nuclear matter."
18. Coriol is Anti-Stretching in ${ }^{20} \mathrm{Ne}$ and a Widths (H. C. Lee and R. Y. Cusson)

Inactive.
19. Applications of Group Theory to Rotational Vibrational Bands on Nuclei (R. Y. Cusson, L. C. Biedenharn, O. L. Weaver (Kansas State $\overline{U n i v e r s i t y))}$

In a recent study we used the group $T_{5} \oplus S U(2)$ to describe rotational bands in nuclei (Annals of Physics 77 (1973) 250) and we suggested to use the group $C M(3)=T_{6}$ © $S L(3, R)$ to include vibrational excitations. This work has been carried out and a class of rotational-vibrational bands has been discovered. Each rotational-vibrational band is characterized by a fixed quantized vorticity, $v$. The $v=0$ bands are the well-known SO(5) Bohr-Hottelsen bands. The new $v \rightarrow$ O bands play the role of particle-rotational couplings, without the need to introduce explicitly the degrees of freedom of the decoupled particles. Applications to back bending roational bands are envisaged. A paper on those results is being written.
20. Do Protons and Neutrons Have Internal Rotational Vibrational Excitations? (S. Brown, R. Y. Cusson)

One model of a relativistically covariant nucleus with rotator-like internal degrees of freedom consists in assuming that the ten Porncare generators are realized on some internal space. A paper entitled "A Solvable Model of Internal Interactions Having Positive Energy" has been submitted to Nuovo Cimento on this question. The abstract follows.
"We present a model of a particle of mass $m$ having some internal structure. Introducing an internal interaction, we find that the mass splits covariantly according to

$$
-p^{2}=\left[ \pm m+\alpha\left(25+1 \pm \frac{1}{25+1}\right)\right]^{2}
$$

where $\alpha$, a real number, is the interaction strength and $S$ is the total spin of the particle. We also find certain values of $a$ for which only positive energy solutions exist. For spin $1 / 2$ particles the $g$-factor is 2 only in the presence of the aforementioned interaction."

## U. S. ARMY ABERDEEN RESEARCH AND DEVELOPMENT CENTER Radiation Laboratory

## A. NEUTRONS PHYSICS

1. Small-Angle Elastic Scattering Cross Sections for Pb (W. Bucher, C.E. Hollandsworth, and J. Youngblood)

The absolute cross section for the small-angle scattering of neutrons from Pb has been measured to an accuracy of 3 percent over the 7-14 MeV energy range. The results are shown in Table I. The last column is a least squares representation of the data by the function $f(E, \theta)=\exp \left[A(E)+B(E) \theta+C(E) \theta^{2}\right]$, where $B$ and $C$ are quadratic in $E$.
2. Small-Angle Scattering from $\mathrm{Be}, \mathrm{C}, \mathrm{Al}, \mathrm{Fe}, \mathrm{Cu}, \mathrm{Ni}, \mathrm{Sn}, \mathrm{W}, \mathrm{Bi}$, and U (W. Bucher, C.E. Hollandsworth, and J. Youngblood)

Measurements have been made of the small-angle scattering of $7.55,11.0$, and 14.0 MeV neutrons from $\mathrm{Be}, \mathrm{C}, \mathrm{Al}, \mathrm{Fe}, \mathrm{Cu}, \mathrm{Ni}, \mathrm{Sn}, \mathrm{W}$, Bi , and U . The data are currently being processed.
B. SINGLE PARTICLE PROTON STATES POPULATED WITH THE ( $\mathrm{d}, \mathrm{n}$ ) REACTION (J. Horton, C.E. Hollandsworth, and W. Bucher)

The ( $\mathrm{d}, \mathrm{n}$ ) reaction has been used to populate single particle proton states in various $\mathrm{Y}, \mathrm{N}$, and Al isotopes. Angular distributions of the reaction neutrons have been measured from $10^{\circ}-55^{\circ}$ in $5^{\circ}$ steps at a beam energy of 12 MeV . Spectroscopic factors will be determined using distorted wave Born approximation techniques. These results will be compared to previously reported results of analogous ( ${ }^{3} \mathrm{He}, \mathrm{a}$ ) studies for which absolute normalization factors are not as well known.

## C. ERODED GUN BORE SURFACE DIAGNOSTICS (A. Niiler, S. Caldwell, J.E. Youngblood, and T.J. Rock)

Gun barrel erosion and the resulting wear limited lifetime for most high performance gun barrels has been a long-standing problem for the Army. Most of the high-performance propellants in use today burn at temperatures where the iron oxides are formed in preference to the nitrides and carbides of iron. A method by which the presence of oxygen in the surface can be detected would lead to a better understanding of the burning propellant, bore surface interaction. Use of the $\left(d, \alpha_{0}\right),\left(d, p_{0}\right)$ and ( $d, p$ ) reactions on ${ }^{16} 0$ have been investigated in order to measure the depth concentration profile of oxygen under the surface to a depth of $5-10 \mu \mathrm{~m}$. We have shown that at a deuteron beam energy of about 3 MeV , the depth profiles of oxygen can be obtained
with better than $.02 \mu \mathrm{~m}$ resolution using high resolution silicon surface barrier detectors. Depth profiling of Nitrogen has been shown to be feasible also using the ( $\alpha, \alpha_{0}$ ) and ( $d, \alpha$ ) reaction on ${ }^{14} N$.

Preliminary data on steel surfaces which have been exposed to the erosive environments of burning propellants have been encouraging. Oxygen concentrations of less than $10^{16}$ at/ $\mathrm{cm}^{2}$ have been detected and it is hoped that this limit can be lowered by a factor of 10 by use of better electronics. Plans have been made to measure the ( $\alpha, \alpha_{0}$ ), and ( $d, p$ ) cross sections for ${ }^{16} 0$ in the .3 to 1.0 MeV range so that the diagnostic technique can be applied at deuteron energies at this lower energy region.

TABLE I

| CORRECTIONS ${ }^{\text {a }}$ |  |  |  |  |  | $\Delta \sigma / \sigma^{\text {b }}$ | $\begin{aligned} & \sigma_{\mathrm{c} . \mathrm{m} .} \\ & \mathrm{b} / \mathrm{sr} . \end{aligned}$ | $\begin{aligned} & \mathrm{f}(\theta, \mathrm{E})^{\mathrm{d}} \\ & \mathrm{~b} / \mathrm{sr} . \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $E_{1 a b}$ <br> MeV | $\begin{aligned} & \theta_{\mathrm{c} . \mathrm{m} .} \\ & \mathrm{deg} . \end{aligned}$ | Finite Geom. \% | Air Scat. \% | Mult. Scat. \% | $\Delta R / R$ $\pm \%$ |  |  |  |
| 7.00 | 3.44 | 0.3 | 2.7 | -3.0 | 3.1 | 3.5 | 7.115 | 7.094 |
|  | 6.87 | 0.3 | 1.3 | -3.2 | 1.1 | 1.9 | 6.403 | 6.522 |
|  | 10.75 | 0.6 | 0.7 | -4.0 | 0.7 | 1.7 | 5.542 | 5.527 |
|  | 14.64 | 0.4 | 0.6 | -4.4 | 0.7 | 1.7 | 4.340 | 4.322 |
|  | 19.87 | 0.2 | 0.4 | -5.8 | 0.5 | 1.8 | 2.679 | 2.704 |
| 7.55 | 3.48 | 0.3 | 3.3 | -2.8 | 2.6 | 3.1 | .7.017 | 6.987 |
|  | 6.97 | 0.3 | 1.6 | -3.0 | 1.5 | 2.4 | 6.342 | 6.320 |
|  | 10.90 | 0.7 | 1.0 | -3.8 | 1.4 | 2.1 | 5.091 | 5.190 |
|  | 14.85 | 0.4 | 0.9 | -4.2 | 1.1 | 1.9 | 3.858 | 3.868 |
| 8.00 | 3.45 | 0.4 | 2.8 | -2.6 | 2.5 | 3.0 | 7.150 | 6.990 |
|  | 6.89 | 0.3 | 1.5 | -2.8 | 1.1 | 1.9 | 6.188 | 6.275 |
|  | 10.77 | 0.7 | 0.8 | -3.6 | 0.8 | 1.7 | 5.164 | 5.076 |
|  | 14.68 | 0.4 | 0.7 | -4.0 | 0.9 | 1.8 | 3.745 | 3.693 |
|  | 19.89 | 0.2 | 0.4 | -6.3 | 0.5 | 1.8 | 2.038 | 2.015 |
| 8.55 | 3.45 | 0.4 | 2.8 | -2.5 | 1.7 | 2.3 | 6.917 | 7.076 |
|  | 6.89 | 0.4 | 1.4 | -2.6 | 1.0 | 1.8 | 6.402 | 6.282 |
|  | 10.77 | 0.7 | 0.9 | -3.4 | 0.8 | 1.7 | 4.876 | 4.966 |
|  | 14.68 | 0.3 | 0.7 | -3.8 | 0.7 | 1.7 | 3.489 | 3.486 |
| 9.00 | 3.45 | 0.4 | 2.6 | -2.4 | 1.6 | 2.3 | 7.335 | 7.211 |
|  | 6.89 | 0.4 | 1.4 | -2.5 | 1.1 | 1.8 | 6.334 | 6.348 |
|  | 10.77 | 0.8 | 0.8 | -3.2 | 0.9 | 1.7 | 4.991 | 4.933 |
|  | 14.68 | 0.3 | 0.7 | -3.6 | 1.0 | 1.8 | 3.337 | 3.367 |
| 9.55 | 3.48 | 0.5 | 2.6 | -2.2 | 1.8 | 2.4 | 7.468 | 7.418 |
|  | 6.97 | 0.4 | 1.4 | -2.3 | 2.3 | 2.8 | 6.481 | 6.453 |
|  | 10.90 | 0.8 | 0.8 | -3.1 | 1.3 | 2.0 | 4.854 | 4.891 |
|  | 14.85 | 0.3 | 0.8 | -3.4 | 1.9 | 2.4 | 3.222 | 3.210 |
| 11.0 | 3.44 | 0.5 | 2.6 | -2.1 | 2.2 | 2.7 | 8.441 | 8.425 |
|  | 6.87 | 0.5 | 1.2 | -2.2 | 0.9 | 1.8 | 7.281 | 7.214 |
|  | 10.75 | 0.9 | 0.8 | -3.0 | 0.7 | 1.6 | 5.302 | 5.270 |
|  | 14.64 | 0.2 | 0.7 | -4.0 | 0.7 | 1.7 | 3.151 | 3.244 |
| 12.5 | 3.44 | 0.6 | 2.7 | -2.3 | 1.9 | 2.5 | 10.15 | 9.914 |
|  | 6.87 | 0.5 | 1.3 | -2.4 | 0.9 | 1.8 | 8.420 | 8.386 |
|  | 10.75 | 0.9 | 1.2 | -3.2 | 0.6 | 1.6 | 6.036 | 5.939 |
|  | 14.64 | 0 | 0.5 | -4.2 | 0.8 | 1.7 | 3.452 | 3.435 |
| 14.0 | 3.44 | 0.6 | 2.4 | -2.5 | 2.5 | 3.0 | 11.82 | 11.85 |
|  | 6.87 | 0.5 | 1.2 | -2.8 | 0.6 | 1.6 | 9.951 | 9.978 |
|  | 10.75 | 0.9 | 0.9 | -3.5 | 0.8 | 1.7 | 6.830 | 6.943 |
|  | 14.64 | -0.1 | 0.8 | -5.0 | 1.1 | 1.9 | 3.863 | 3.830 |
|  | 19.87 | -4.0 | 1.0 | -13.0 | 0.7 | 3.4 | 1.043 | 1.044 |

## TABLE I (continued)

## NOTES:

${ }^{\text {a }}$ Not listed above is attenuator bar-ring interference correction, which is $-0.5 \%$ for all 3.5 degree data points.
b
Uncertainty includes, besides counting statistics, the following: $1 \%$ in each the transmission and yield-efficiency product; $15 \%$ uncertainty in each of the multiple scattering and air scattering corrections; and $50 \%$ in the finite geometry correction at $20^{\circ}$ and 14.0 MeV .
c Mott-Schwinger scattering not included.

## 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 $n-{ }^{6} \mathrm{Li}$ Scattering

The analyzing power of ${ }^{6} \mathrm{Li}$ for neutron scattering has been measured throughout the energy range 2 to 5 MeV and at four angles between $40^{\circ}$ and $150^{\circ}$. The polarization of the neutron beam was absolutely determined using a neutron double scattering method. The analyzing power of ${ }^{6} \mathrm{Li}$ was found to be remarkably constant in energy for all measured angles. A multi-level R-matrix analysis, which also includes the ${ }^{6} \mathrm{Li}(\mathrm{n}, a)^{3} \mathrm{H}$ channel, was performed of the analyzing power measurements.
2. Polarization of Neutrons in $n-{ }^{4} \mathrm{He}$ Scattering

Measurements of the asymmetry of elastically scattered polarized neutrons from a liquid He target have been completed at four angles and at energies between 2 and ? MeV . The experiment used the absolutely calibrated source of polarized neutrons from the ${ }^{12} C(n, \vec{n})^{12} C$ reaction. An analysis of the results is now underway.
3. Polarization of Neutrons in $n-{ }^{9}$ Be Scattering

A detailed analysis of the measured differential polarization of neutrons elastically scattered from ${ }^{9} \mathrm{Be}$ at energies up to 5 MeV is now being carried out using a general nuclear reaction formalism.

## B. POLARIZATION OF PHOTONEUTRONS

1. Differential Polarization of Photoneutrons from the Reactions ${ }^{12} \mathrm{C}\left(\gamma, \overrightarrow{\mathrm{n}}_{0}\right)^{1{ }^{12}} \mathrm{C}$ and ${ }^{16} 0\left(\gamma, \mathrm{n}_{0}\right)^{15} \mathrm{O}$ (R. Nath, F.W.K. Firk)

The differential polarization of photoneutrons from the reactions ${ }^{12} \mathrm{C}\left(\gamma, \vec{n}_{0}\right)^{12} \mathrm{C}$ and ${ }^{16} 0\left(\gamma, \vec{n}_{0}\right)^{15} 0$ has been
measured with good resolution throughout the energy regions of the giant dipole states using the ${ }^{12} C(\vec{n}, \vec{n})^{2 / 2} C$ reaction as an analyzer. Measurements were made at angles between $30^{\circ}$ and $135^{\circ}$ using the recently installed electron beam bending magnet. The results are being analyzed in conjunction with recent differential cross section results obtained by Syme and Crawford at Glasgow University.
2. Differential Polarization of Photoneutrons from Liquid Deuterium (L. Drooks, F.W.K. Firk, R.J. Holt and H.L. Schultz)

The liquid deuterium target is complete and has been tested and installed. A new electron beam bending magnet has been constructed and tested: this will provide a wide range of reaction angles $\left(30^{\circ}<\theta 1 \mathrm{ab}<150^{\circ}\right)$. Preliminary measurements of the polarization of photoneutrons at $150^{\circ}$ are now being made using a ${ }^{12} \mathrm{C}$ cylinder of known analyzing power as a means of measuring the polarization. This technique is well-suited to precise studiec in the photon energy range $5<\mathrm{E}_{\gamma}<15 \mathrm{MeV}$.


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