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INFORMAL REPORT
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REPORTS TO THE DOE NUCLEAR DATA COMMITTEE

Compiled by the
NATIONAL NUCLEAR DATA CENTER
U.S. Department of Energy
Nuclear Data Committee

May 1992

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

National Nuclear Data Center

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PREFACE

The reports in this document were submitted to the Department of Energy Nuclear Data Committee (DOE–NDC) in April, 1992. The reporting laboratories are those with a substantial program for the measurement of neutron and nuclear cross sections of relevance to the U.S. applied nuclear energy program.

The authors of the Status Report contributions are responsible for collecting and editing individual contributions from their laboratory and are not necessarily the sole authors of the contributions. The scientists responsible for the work described in each individual contribution are listed at the beginning of the contribution.

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 α–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 data in progress at the submitting laboratory.

This compilation has been produced almost completely from master copies prepared by the individual contributors listed in the Table of Contents, and reports are reproduced *without change* from these master copies.

DOE STATUS REPORTS

1992

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ARGONNE NATIONAL LABORATORY

A. NEUTRON TOTAL AND SCATTERING CROSS-SECTION MEASUREMENTS

1. Fast-neutron Total and Scattering Cross Sections of ^{58}Ni and Nuclear Models. (A.B. Smith, P.T. Guenther, J.F. Whalen and S. Chiba†)

A manuscript describing this work has been accepted for publication in J. Phys. G.

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† Visiting Scientist, Physics Division, JAERI, Tokai, Japan.

2. Differential Neutron Scattering from ^{40}Ca. (A.B. Smith, S. Chiba†, P.T. Guenther and R. D. Lawson)

The measurement aspects of this program, which have provided very detailed information from ≈ 1-10 MeV, are complete. These data, combined with those available in the literature to ≈ 40 MeV, are being interpreted. That interpretation is proving very difficult as there is clearly anomalous behavior of the compound-elastic scattering, which is a factor up to ≈ 10 MeV. The conventional width-fluctuation corrections do not apply. The problem has not been recognized in previous similar studies (or it has been ignored). There is a strong impact upon the dispersion integral.

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† Visiting Scientist, Physics Division, JAERI, Tokai, Japan.

3. Fast-neutron Interaction with Elemental Zirconium and the Dispersive Optical Model. (S. Chiba†, P.T. Guenther, A.B. Smith and R.D. Lawson)

A paper describing this work in detail has been accepted for publication in Phys. Rev. C.

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† Visiting Scientist, Physics Division, JAERI, Tokai, Japan.

4. Elastic Neutron Scattering from ^{238}U and ^{232}Th. (P.T. Guenther, A.B. Smith and S. Chiba†)

The measurement aspects of this work are complete, as reported previously. The interpretation continues in an effort to determine the

elastic and non-elastic cross sections to better than 3%.

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† Visiting Scientist, Physics Division, JAERI, Tokai, Japan.

5. Neutron Scattering from Iron from 4-10 MeV. (A.B. Smith and P.T. Guenther)

This work, which has been in progress for some time, is now providing a unique definition of the fast-neutron scattering process in this energy range. High-resolution inelastic-scattering measurements using flight paths of 18+ m are planned for the near future. Upon their completion, the physical interpretation will be initiated.

6. Neutron Scattering from Chromium from 4-10 MeV. (A.B. Smith and P.T. Guenther)

This work is similar to that of Topic A.5, and it is being carried out in parallel with the former.

7. Neutron Scattering from Titanium from 4-10 MeV. (A.B. Smith and P.T. Guenther)

Again, this work is similar to that of Topic A.5, and it is being carried out in parallel with the former.

8. A Comprehensive Study of Fast-neutron Scattering from Cd, Sn, Pd and Sb over the 4-10 MeV Energy Range. (A.B. Smith and P.T. Guenther)

A very comprehensive experimental study has been initiated for this mass and energy region. Many of the elastic-scattering measurements are already completed, and high-resolution inelastic-scattering measurements have started. The objective is to obtain greatly improved knowledge of neutron interactions with fission products, particularly those scattering processes for which the available cross-section information is very uncertain or non-existent in the respective evaluated files.

B. CONTINUUM NEUTRON EMISSION STUDIES

1. Double-differential Inelastic Neutron Emission Measurements. (P.T. Guenther and A.B. Smith)

Those steps undertaken during the previous year to improve experimental technique and efficiency have been successfully concluded.

Measurements were resumed in December 1991, and these are currently in progress. Aside from confirming previously obtained results on mono-isotopic elements, materials of applied interest, such as Cu and Re, are now being investigated.

C. STANDARDS MEASUREMENTS

1. International Comparison of the Dosimetry Cross Section Standards $^{58}Ni(n,p)^{58}Co$ and $^{93}Nb(n,2n)^{92m}Nb$. (D.L. Smith, J.W. Meadows, R.C. Haight†, W. Mannhart‡, H. Vonach§, G. Winkler§ and M. Wagner§)

The data analysis was completed and a joint conference paper was prepared for the 1991 Juelich Conference. This exercise showed that very good overall agreement could be obtained by different laboratories using various modern techniques for measurement and data analysis, so long as they agreed on the reference standards.

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† Physics Division, Los Alamos National Laboratory.
‡ Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
§ Institut fuer Radiumforschung und Kernphysik, Vienna, Austria.

D. ACTIVATION REACTION CROSS-SECTION MEASUREMENTS

1. A Search for Neutron-induced Long-lived Activities in Silver, Hafnium, Europium and Terbium. (J.W. Meadows, D.L. Smith, L.R. Greenwood†, R.C. Haight‡, Y. Ikeda§ and C. Konno§)

Cross-section values were derived from the measured experimental data. These results were reported at a research coordination meeting (held in Vienna, Austria, in November 1991) which was sponsored by the International Atomic Energy Agency.

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† Battelle Pacific Northwest Laboratories, Richland, Washington.
‡ Physics Division, Los Alamos National Laboratory.
§ Reactor Engineering Division, JAERI, Tokai, Japan.

2. Measurement of the $^{89}Y(n,p)^{89}Sr$ Cross Section. (G.J. Piccard†, D.L. Smith and J.W. Meadows)

All data analysis was completed and the results were used by GJP in preparing a thesis for his Masters degree in Nuclear Engineering at the University of Michigan, Ann Arbor. Reasonably good agreement was obtained between the experimental integral and differential results. It appears that

the differential cross section is considerably larger at energies below 10 MeV than was previously expected.

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† Department of Nuclear Engineering, University of Michigan, Ann Arbor.

3. Measurements of Neutron Cross Sections for $^{54}Fe(n,p)^{54}Mn$ and $^{54}Fe(n,\alpha)^{51}Cr$ Between 5.3 and 14.6 MeV. (D.L. Smith, J.W. Meadows, L.P. Geraldo†, W. Mannhart‡, G. Boerker‡, G. Mueller‡ and L.R. Greenwood§)

Final cross section values have been obtained from this experimental investigation. The results were reported at the 1991 Juelich Conference.

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† IPEN, Sao Paulo, Brazil.
‡ Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
§ Battelle Pacific Northwest Laboratories, Richland, Washington.

E. NEUTRON-SPECTRUM STUDIES

1. Investigation of the Neutron Spectra from Bombardment of Thick Be-Metal Targets with Protons and Deuterons. (J.W. Meadows)

Zero-degree spectra and total yields for neutron emission by thick beryllium targets bombarded with MeV protons and deuterons have been measured, relative to ^{235}U and ^{238}U neutron-fission cross sections, for incident particle energies from 2.6-7.0 MeV in 0.4-MeV intervals. The results will be reported in an Argonne National Laboratory report during 1992 (ANL/NDM-124).

F. NUCLEAR DATA EVALUATION AND RELATED ACTIVITIES

1. Comprehensive Evaluated Neutronic-data File for Zirconium. (A.B. Smith, D.L. Smith, J.W. Meadows, P.T. Guenther, R.D. Lawson and R.J. Howerton†)

With the completion of the associated experimental program (Topic A.3), this evaluation will proceed. Minor reactions remain to be completed.

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† Physics Division, Lawrence Livermore National Laboratory.

2. Evaluated Total and Elastic- and Inelastic-Scattering Cross Sections of ^{238}U and ^{232}Th. (S. Chiba†, P.T. Guenther and A.B. Smith)

This work will be completed when the physical interpretation for Topic A.4, is finished. This effort is a part of an international evaluation task force.

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† Visiting Scientist, Physics Division, JAERI, Tokai, Japan.

3. Evaluated Fast-neutron Cross Sections of ^{58}Ni. (A.B. Smith)

Work on this partial evaluation has been restarted with publication of the measurements and interpretations, as outlined in Topic A.1.

4. A Review of Nuclear Data Needs for Fusion. (D.L. Smith and E.T. Cheng†)

A survey has been made of nuclear-data needs for fusion, and the status of these data have been reviewed. The results of this study were reported at the 1991 Juelich Conference and are now being documented in greater detail in an Argonne National Laboratory Report for issue in 1992 (ANL/NDM-123).

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† TSI Research, Inc., Solana Beach, California.

G. NUCLEAR THEORY, MODELS AND CODES

1. Implementation of the Nuclear-reaction Code GNASH. (J.W. Meadows)

A copy of code GNASH for statistical and pre-equilibrium nuclear reaction calculations has been obtained. This code originated in the Theory Division, Los Alamos National Laboratory. The code is being adapted to run on a DEC MicroVax computer.

2. PC Version of ABAREX. (P.T. Guenther and R.D. Lawson)

ABAREX is a spherical optical-model code used to describe the scattering of neutrons from spherical nuclei. A version of this program has now been made that can be used on either a 286- or 386-based PC. The source coding is consistent with Microsoft Fortran 5.0. This PC version and a DEC MicroVax version, together with documentation and examples, have been sent to the code center at Oak Ridge National Laboratory. They are available for general distribution from this source.

3. Lecture Notes on ABAREX. (R.D. Lawson)

A "how to" set of lecture notes is being prepared to illustrate the use of the code ABAREX in describing the properties of spherical nuclei. These lectures will be presented at the "Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety" to be held in Trieste, Italy, on February 10 to March 13, 1992.

4. Inelastic-neutron Excitation of Yrast 2^+ Levels. (A.B. Smith, P.T. Guenther and R.D. Lawson)

Measurements of the elastic and inelastic scattering to the yrast 2^+ levels have been carried out in this laboratory for cadmium, palladium, tin and the antimony isotopes, thereby providing an extensive data base for theoretical analysis. For the first two of these isotopes, extensive electromagnetic data are known (up to and, in some cases, above the so-called three-phonon states). The value of beta obtained from these E2 electromagnetic studies has been used to predict the neutron excitation of the yrast 2^+ levels in Cd and Pd, with good success. This study illustrates the potential usefulness of the electromagnetic matrix elements for calculating inelastic cross sections where neutron data are not available.

H. ANALYTICAL METHODS DEVELOPMENT

1. Fast-neutron Scattering Program Support Software. (P.T. Guenther)

Development of a code package for the analysis of discrete- and continuum-neutron scattering data has been completed, and it is now being used routinely for the analysis of new data acquired in this laboratory.

2. Probability, Statistics and Data Uncertainties in Nuclear Science and Technology. (D.L. Smith)

This monograph project was completed during 1991 and the resulting book has been published by the American Nuclear Society.

3. Resolution of "Peelle's Pertinent Puzzle". (S. Chiba† and D.L. Smith).

This study of an important phenomenon in nuclear-data evaluation by the method of least-squares has been completed. The results will be presented in an Argonne National Laboratory report to be issued in 1992 (ANL/NDM-121).

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† Visiting Scientist, Physics Division, JAERI, Tokai, Japan.

I. INSTRUMENTATION DEVELOPMENT AND RELATED TOPICS

1. Design of a Gridless, High-current, Low-activation Gas Target System for Reaction-cross-section and Applied-technology Studies. (D. Feautrier† and D.L. Smith)

A new, gridless gas target system has been developed for high-current irradiations using deuterium filler gas. The materials employed in this target assembly have been selected for their activation characteristics as well for as their physical properties. An attempt has been made to incorporate mainly those materials which develop only short-lived activities or very modest long-lived activities during routine use. The target components were fabricated in 1991 and the assembled target will be tested during 1992.

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† Student, Ecole Normal Superior de Cachan, France.

2. Upgrade of the Time-of-flight System at the FNG Laboratory. (A.B. Smith and P.T. Guenther)

Larger scintillators have been incorporated in the ten-angle neutron scattering spectrometer, leading to a factor-of-three increase in overall detector efficiency, with no apparent degradation of timing resolution. Scattering data with this spectrometer are now being recorded exclusively with a 386 PC computer-data-acquisition system.

3. FNG Accelerator General Facility Hardware and Procedures Improvements. (R.R. Whitman, A.B. Smith, J.W. Meadows, P.T. Guenther and D.L. Smith)

A great many modifications have been made to the facility and corresponding operating procedures in order to gain compliance with contemporary environmental, health, and safety requirements. This comprehensive and time-consuming effort has been carried out under the guidance of Argonne ES&H personnel and in accordance with DOE orders. Extensive documentation dealing with facility systems and procedures has been prepared.

1. BROOKHAVEN NATIONAL LABORATORY

A. LINEAR BEHAVIOR OF $E(2^+_1)$ VERSUS P

It was shown in previous years that the systematics of different nuclear observables plotted against the valence product N_pN_n were extremely smooth, with all values for a given region typically falling on a single curve. The same is true in plots against the P factor ($P = N_pN_n/(N_p+N_n)$). In studying such phenomenology during the last year a remarkable fact was noted, namely that while P plots of $E(2^+_1)$ for a given region yield the typical smooth hyperbolic shaped curve, P plots for a given *isotopic series* almost invariably fall on straight lines. In isotopic series that undergo a phase transition to a deformed shape, the data usually fall on two linear segments with a kink at the phase transitional point. This phenomenon, now studied and mapped from Z = 40 to the actinides, is so universal that it points to a simple explanation in terms of general features of shell structure and residual interactions. A two-pronged effort is underway to try to understand this phenomenon. One is in terms of a traditional collective model viewpoint with emphasis on the interplay of deformation and pairing effects, while the second approach is more microscopic in terms of model interactions in a single-j-shell valence space. It is worth stressing that there are two points that need explanation. One is the linearity for individual isotopic chains while the other is the systematic behavior of the *slopes* as a function of N,Z. The latter, while not completely regular, seem to have a parabolic-type behavior throughout a shell, being largest near closed shells and smallest near mid-shell. While this seems plausible in terms of the more rapid changes in 2^+ energies in near-magic regions, a quantitative explanation is still elusive as is a physical understanding of the linearity of the plots themselves.

B. ANALYTIC FORMULAS FOR B(E2) VALUES IN EVEN-EVEN NUCLEI

As part of our continuing effort to extend the analytic applicability of the IBA, and as a step towards our goal of using B(E2) values to extract complete sets of effective charges for all medium and heavy nuclei (see another paragraph in this report), a rather general analytic formula for $B(E2:0^+_1\rightarrow 2^+_1)$ values was developed during this period. Inspired by similar formulas for regions of dynamical symmetries of the IBA, this formula attempts to provide an approximate relation valid for the entire symmetry triangle of the IBA. Naturally, it is more complicated and involves some parameters from the IBA Hamiltonian. Yet, with microscopic guidance, it was possible to establish a universal formula which is now parameter-free and provides simple estimates of B(E2) values in any region from $A \cong 60$ to the actinides. The formula successfully reproduces the empirical results to 15% or better with few exceptions. As such, it serves two purposes. First, since its form is identical to analytic expressions for other regions, it can be used in the same way as they can to extract effective charges, e_ν and e_π (see above). Secondly, it can provide guidance to expected B(E2) values

in unknown regions far from stability or, for example, in unknown nuclei that will become accessible with RNB facilities later in this decade.

C. STUDIES OF OLD IRRADIATED SAMPLES

During the 1950's ~70 elements were irradiated with thermal neutrons in the BNL Graphite Reactor with the aim of later searching for new radioactivities. These samples were allowed to cool for several decades in order to enhance weak but long-lived activities. The samples are now being measured with a well-shielded Ge(Li) γ-ray detector, each for at least 24 hours. The analysis remains to be done.

D. PRECISION ENERGY MEASUREMENT OF ^{166M}Ho γ Rays

Precision energy measurements using ^{110m}Ag, ^{182}Ta, and ^{192}Ir standards were completed on ^{166m}Ho γ rays. The energies of 23 γ rays, with uncertainties in the range 1.1-8 eV, were determined, and the source is recommended as an energy calibration standard.

E. NATIONAL NUCLEAR DATA CENTER

1. Cross Section Evaluation Working Group (CSEWG)

CSEWG held one meeting in 1991, its 25th year of activity. The release of the ENDF/B-VI data file has been completed. The decay data, the fission product yields and the charged particle sublibraries were released. The Summary Documentation for ENDF/B-VI has been published.

Revision 1 of the neutron reaction sublibrary was released containing mostly corrections. Revision 2 will be released in the Fall of 1992. It will consist of several new or revised evaluations.

The NEANSC Working Party on Evaluation Cooperation has completed three years of work. A total of 11 projects were undertaken during that time. Two have been completed and several more will be finished by Fall 1992.

The Symposium on Nuclear Evaluation Methodology will be held in October 1992. The sessions and their chairmen have been selected. Final paper selection will occur in June 1992.

2. Nuclear Data Sheets

The NNDC has been producing the Nuclear Data Sheets at the rate of about an issue a month. Of these, nine issues a year are devoted to nuclear structure evaluation and the remaining three to the publication of Recent References. In 1991, 29 a-chains were published in the Nuclear Data Sheets.

The Center evaluated A=46, 48, 57, 94, 96, 212 and A=50, 66 (in the continuous mode) in 1991 and A=70, 71 in 1992 and submitted them for publication. A=65, 95, 97,99 and 140 are being evaluated.

The program RADLST which calculates the atomic and nuclear radiations from radioactivity decay data from ENSDF and their associated doses is gaining wide acceptance within the applied user communities, in particular Nuclear Medicine. It has been successfully installed on VAX, SUN, Cray and MacIntosh computers. Work is under way to enhance the program and produce an IBM-PC version.

Data extracted from the ENSDF and the Wallet Cards will be published in the following publications:

1. CRC Handbook of Nuclear Decay Modes, CRC Publication, Edited by Dorin N. Poenaru.

2. Prompt Gamma Neutron Activation Analysis, CRC Publication, Edited by Z. B. Alfassi and Prof. Chung.

3. Handbook on Nuclear Data for Geophysics Applications, Edited by N. Kocherov.

The U.S. is a part of an international network of evaluators contributing recommended values of nuclear structure information to the Evaluated nuclear Structure Data file (ENSDF). Publication of the Nuclear Data sheets proceeds directly from this computerized file. In addition to the U.S., evaluations have been received or are anticipated from the USSR, France, Japan, Belgium, Kuwait, Sweden, the People's Republic of China, Canada and Taiwan.

Use of the concise format for the published A-chains in the Nuclear Data sheets is functioning smoothly. This format reduces the size of the publication without omitting essential information and improves its readability.

3. On-line Services

For approximately 5½ years, the NNDC has offered on-line access to several of its nuclear data bases. This service is available on the NNDC's VAX-11/780 and 8820 computers via ESNET, INTERNET or over telephone lines. Approximately one-half of the queries have been to the NSR data base (see Table 1). The complete on-line service software was installed on the new Micro VAX II computer for the IAEA's Nuclear Data Section.

No new data bases have been added to the service. Efforts have concentrated on improving the capabilities and user interfaces of the existing data base retrieval programs. Several new features were developed including FAX transmissions of tables and graphic files, recording of problems and suggestions by users and on-line look-up of additional new system features. A self sign-up capability has been added at logout from a "GUEST" user. Most new users now use this method when gaining access for the first time.

Table 1
On-line Access Statistics 1986-1991 at the NNDC

Year	Runs	Retrievals	NSR	ENSDF	NUDAT	CINDA	CSISRS	ENDF
1986	648	1621	814	142	536	129	--	--
1987	1275	4263	2521	863	815	60	--	--
1988	2264	8748	5022	1303	1492	285	459	187
1989	3374	8406	3253	850	1841	522	1649	150
1990	5436	12067	5613	1256	2204	187	1623	1019
1991	10142	22183	11517	2807	4021	371	1384	1525

COLORADO SCHOOL OF MINES

During the past year, we have continued our investigation of deuteron induced nuclear reactions on light nuclei at low energies. We have concentrated on two areas of this class of reactions, preliminary results of which were presented in last year's report to the DOE Nuclear Data Committee. These areas are (1) the radiative capture of deuterons by 2H, 6Li, and 10B, and (2) the investigation of the Oppenheimer-Phillips effect in which (d,p) reactions at low energies may be enhanced relatiove to other nuclear reactions at low energies by virtue of the electric polarization of the projectile deuteron in the Coulomb field of the target.

1. Radiative capture of deuterons by 2H, 6Li and 10B. We measured the gamma ray to charged particle branching ratios for the D-D, D-6Li and D-10B reactions between lab energies of 40 and 170 keV. The techniques used in these measurements are described in some of our earlier branching ratio measurements [1]. The charged particle spectra are shown in Fig.1.

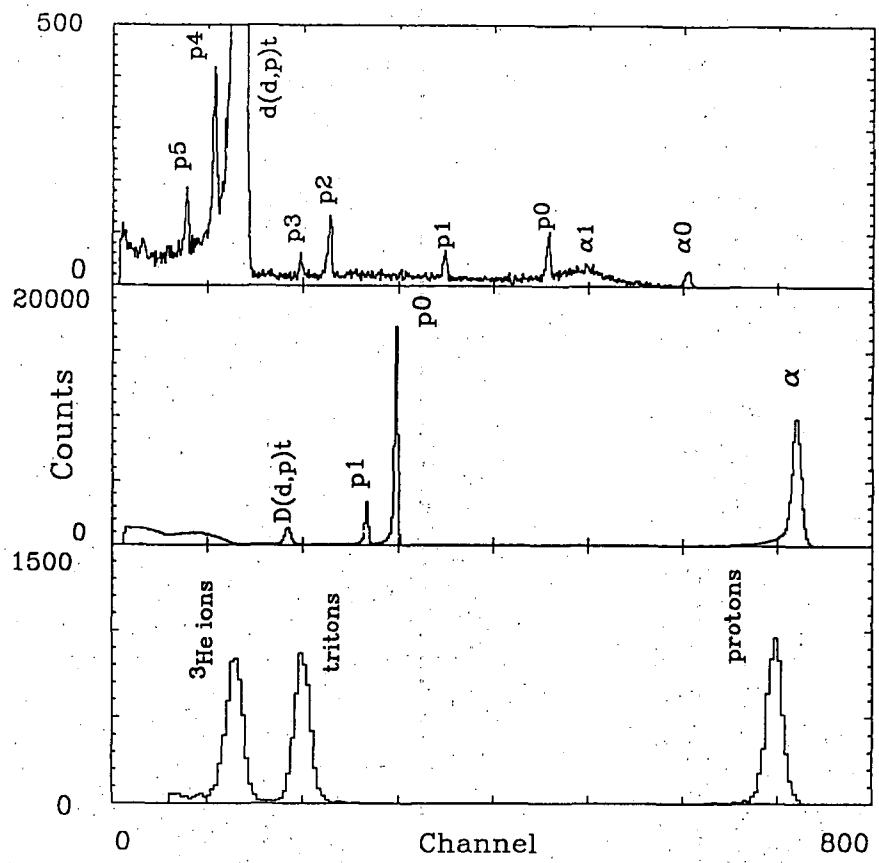

Fig. 1. Spectra of charged particle measured during deuteron bombardment of 2H (bottom), 6Li (middle) and 10B. The laboratory, excitation energy, and relative yield of the particle groups observed during the bombardment of 6Li and 10B are given in Table 1.

TABLE 1

Observed levels during deuteron bombardment of 6Li and 10B

Target	Group	Final nucl.	Ex. energy	Lab energy	Rel. yield
^{6}Li	α0	^{4}He	0.0 MeV	11.19 MeV	.43
^{6}Li	p0	^{7}Li	0.0	4.39	.44
^{6}Li	p1	^{7}Li	0.478	3.91	.13
^{10}B	α0	^{8}Be	0.0	11.94	.040
^{10}B	α1	^{8}Be	3.04	8.90	.485
^{10}B	p0	^{11}B	0.0	8.46	.078
^{10}B	p1	^{11}B	2.12	6.34	.040
^{10}B	p2	^{11}B	4.44	4.02	.099
^{10}B	p3	^{11}B	5.02	3.44	.007
^{10}B	p4	^{11}B	6.74	1.72	.191
^{10}B	p5	^{11}B	7.28	1.18	.060

The concurrently measured gamma ray spectra with our NaI(Tl) gamma ray spectrometer is shown shown in Fig 2.

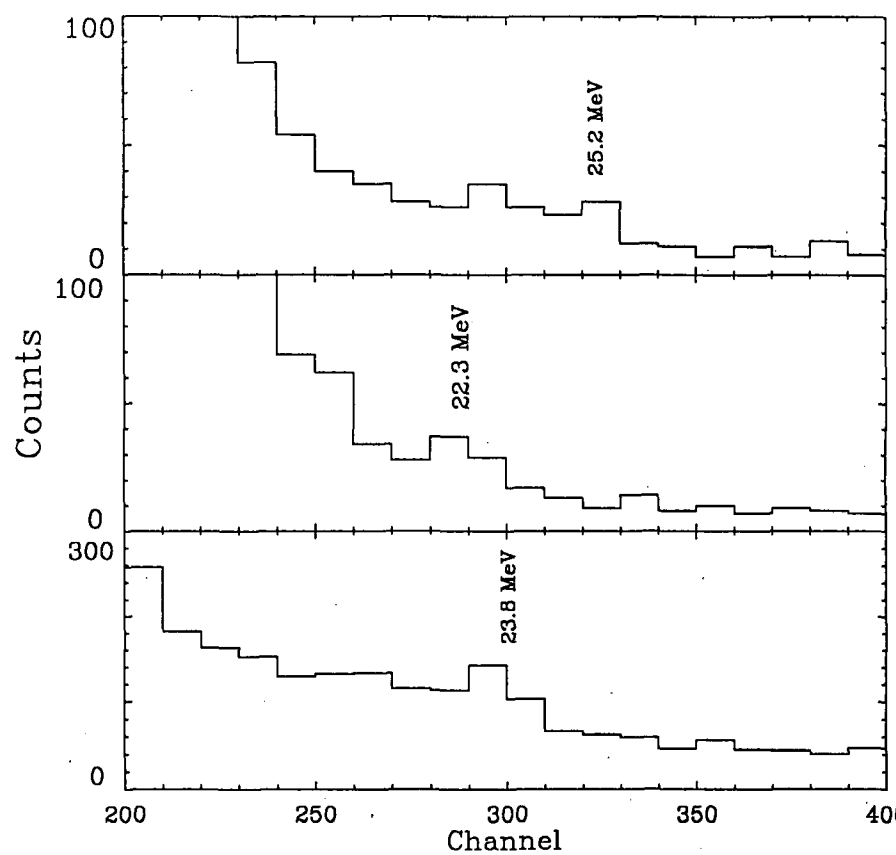

Figure 2. Spectra of gamma rays measured during deuteron bombardment of 2H (bottom), 6Li (middle) and 10B.

From the measured particle and gamma spectra, the branching ratios were deduced, The ratios are plotted in Figure 3. We should note that the ratios presented are the ratios of the ground state gamma transitions to the total charged particle yields. Of particular theoretical interest is the fact that the D-D branching ratio appears independent of energy down to a c.m. energy of 20 keV.

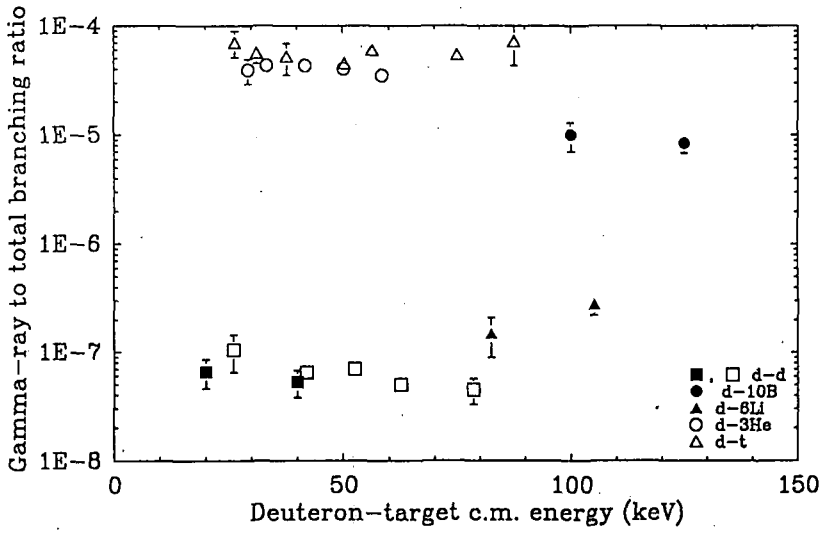

Figure 3. Branching ratios of ground state gamma ray transitions to total charged particle yields. The present measurements (solid symbols) are compared to our earlier branching ratio measurements (open symbols).

2. Investigation of Oppenheimer-Phillips Effect.

We have been investigation the possible enhancement of (d,p) reactions by low energy deuterons on light nuclei for several years. Preliminary results in this investigation were included in previous reports to the DOE Nuclear Data Committee. Significant improvements in our experimental techniques have now allowed us to draw the definitive conclusion that there appears to be no enhancement of the (d,p) reactions by deuterons on either 2H, 6Li or 10B down to c.m. energies of 3, 19, and 50 keV respectively.

In the case of the reaction 2H(d,p)T, the enhancement of the (d,p) reaction was measured by comparing the yield of the 1.01 MeV tritons from the reaction 2H(d,p)T to the yield of the 3He ions from the reaction 2H(d,n)3He. A typical spectrum is shown in Fig. 4.

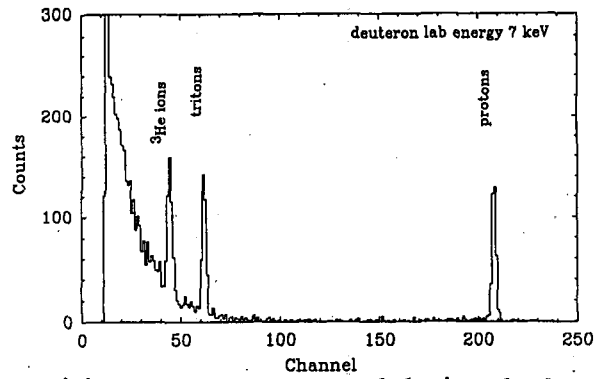

Figure 4. Charged particle spectrum measured during the bombardment of LiD target with 7 keV deuterons.

The ratio of the yields are compared in Figures 5. In this figure, our measured ratios are compared to previous measurements by Brown and Jarmie[2] and Krauss et al.[3] and to calculations of the ratio by Hale[4] and Koonin and Mukerjee[5]. Excellent agreement with the calculations of Hale is noted as is the fact the there is no evidence of an enhancement of the 2H(d,p)T reaction at low energies.

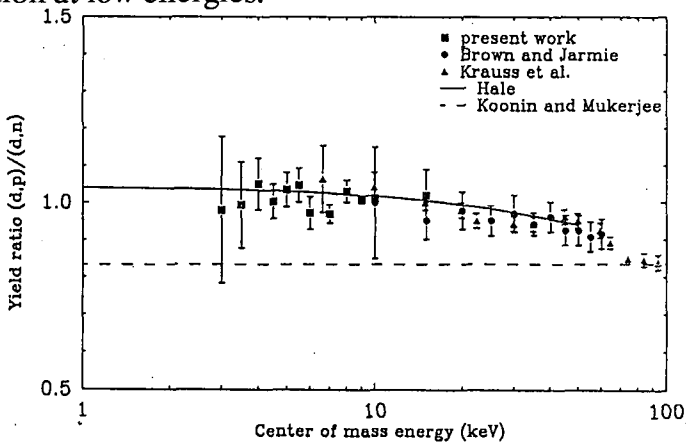

Figure 5. The ratio of the yields of the reactions D(d,p)T and D(d,n)3He.

For the D-6Li and D-10B reactions, the final charge symmetric nuclei, 7Li, 7Be, 11B and 11C were too low in energy to be detectable. Possible evidence for the enhancement of the (d,p) reactions was based upon a comparison of the energetic protons and alpha particles from the (d,p) and (d,α) reactions. In both cases it was necessary to utilize a two detector telescope consisting of a 150 μm front detector and a 500 μm back detector. In the case of the D-6Li reaction, the telescope was used to eliminate the pile-up of the 3 MeV protons from the D(d,p)T reaction due to deuterium build-up in the target. In the case of the D-10B reaction, the telescope was used to separate the protons and alpha particles which were overlapping in energy (see Table 1). The energy spectra of the gated and ungated spectra in the case of the D-6Li reaction are shown in Figure 6. The proton and alpha particle spectra from the D-10B reaction are shown in Figure 7.

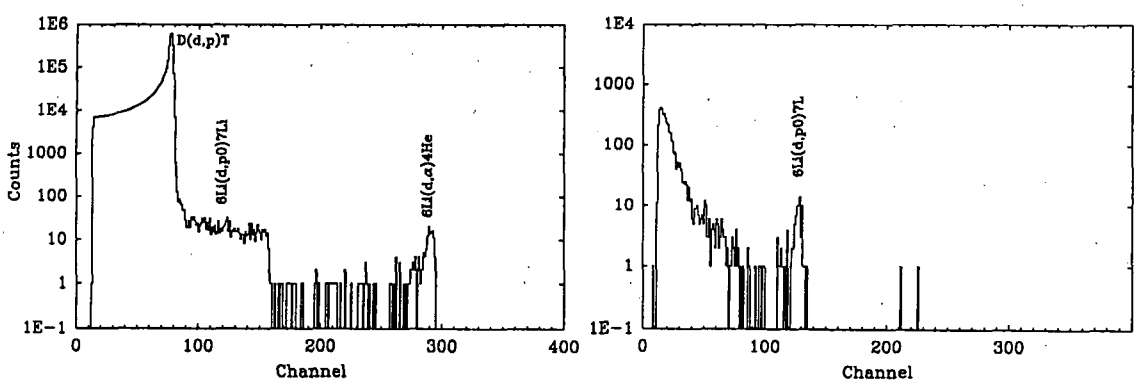

Figure 6. Ungated spectrum of sum of front and back detectors for D-6Li reaction (left). Spectrum of sum of front and back detectors for D-6Li reaction gated on back detector (right).

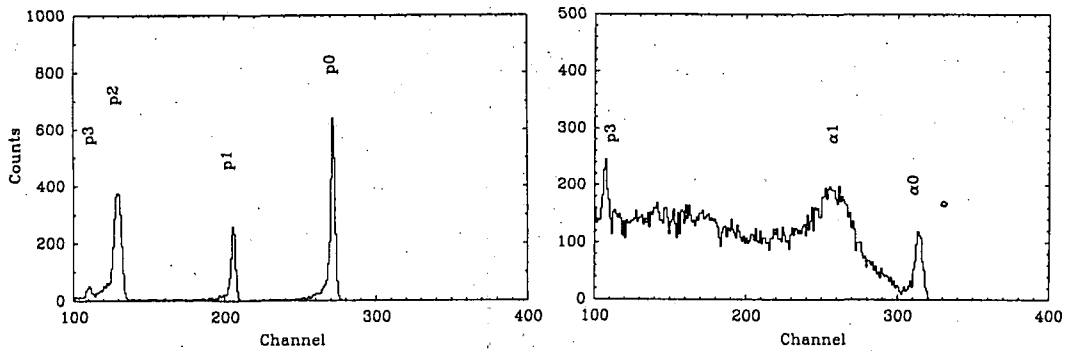

Figure 7. Spectrum of protons from D-10B reaction in which sum of front and back detectors is gated on back detector (left), Spectrum of alpha particles from D-10B reaction in which sum of front and back detectors is vetoed by the back detector (right).

By comparing the yields of the protons and alpha particles from the D-6Li and D-10B reaction, we are able to conclude that any enhancement of the (d,p) to (d,α) reactions down to c.m. energies of 19 and 63 keV respectively cannot exceed about 10%. These yield ratios are shown in Figure 8.

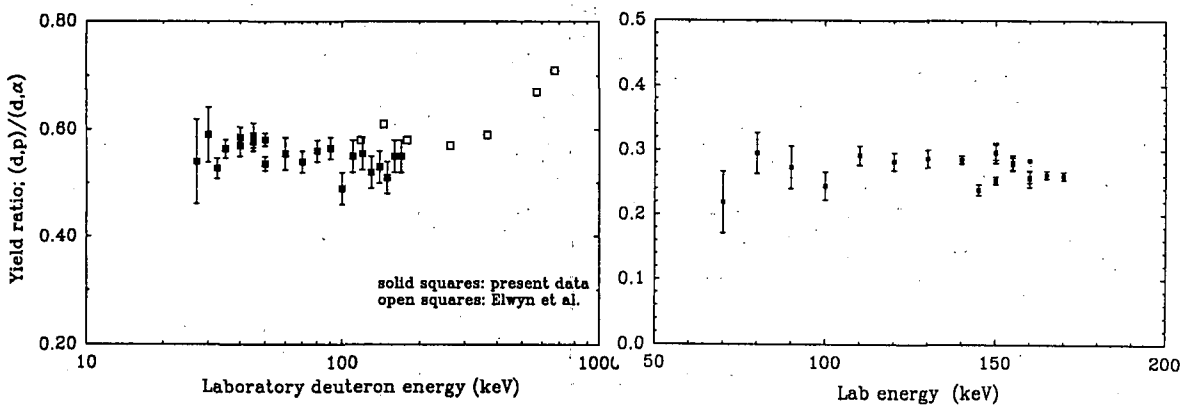

Figure 8. Ratio of (d,p) to (d,α) yields for D-6Li (left) and D-10B (right) reactions.

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1. F.E. Cecil and F.J. Wilkinson, *Physical Review Letters,* 53 (1984) 767
2.Ronald E. Brown and Nelson Jarmie, *Nuclear Instruments and Methods* **B40/41**, 405 (1985).
3. A. Krauss *et al.*, *Nuclear Physics* **A465**,150 (1987).
4. G.M. Hale, Los Alamos National Labs, private communication (1991).
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IDAHO NATIONAL ENGINEERING LABORATORY

A. EXPERIMENTAL STUDIES

1. Beta-decay Strength Functions for Fission Isotopes (R. C. Greenwood, R. G. Helmer, M. A. Oates, M. H. Putnam, K. D. Watts)

Work has continued on the measurement of beta-feeding (beta-strength) distributions of fission product isotopes using the total absorption gamma-ray spectrometer (TAGS). These measurements are aimed toward the development of a "systematics" of the distribution of beta strength in selected regions of the periodic table.

In addition to the importance of these data to fission-reactor technology and nuclear astrophysics it has become clear that the summed gamma-ray spectra measured with the TAGS system have yet another important application. That is, these data represent a sensitive and straightforward test of the quality, and provide quantitative information on the deficiencies, of nuclide decay data in the Evaluated Nuclear Structure Data File (ENSDF). The value of this application to such nuclear decay data files is well illustrated by the deficiencies found earlier in the relatively long-lived (18 min) ^{141}Ba, which does not have a particularly complex decay scheme. However, methods of incorporating these cascade-summed gamma-decay data into traditional nuclide decay data files such as ENSDF, which currently only incorporate discrete line structures, have as yet to be worked out.

During this year, the TAGS system was modified to (1) include a new 300mm^2 x 1.0-mm thick Si detector installed in a new thin-walled tape transport line inside the well of the NaI(Tl) detector, (2) add a dual 8-mm high capacity tape storage unit, and (3) install increased disk capacity to allow for the option of storing list-mode coincidence data directly into disk. New ISOL measurements were made for ^{139}Ba, ^{142}La, ^{143}Ba, ^{144}Ba, ^{146}Ce, ^{146}Pr, ^{147}Ce, ^{147}Pr, ^{148}Ce, ^{148}Pr, ^{149}Pr, ^{149}Nd, ^{151}Pr and ^{151}Nd to add to the already existing data on ^{138m}Cs, ^{138g}Cs, ^{139}Cs, ^{140}Cs, ^{141}Cs, ^{141}Ba, ^{142}Ba, ^{143}La, ^{144}La, ^{145}La and ^{145}Ce. These sets of TAGS measurements thus now include all of the heavy-mass fission-product nuclides between Z=55 and Z=60, and between A=138 and A=151, having decay half-lives in the range of ~10 s to 2 hr.

In parallel with this measurement activity to obtain beta-strength function distributions and ground-state beta-branching intensities using the TAGS system, there is a continuing effort to upgrade and implement the techniques and computer codes necessary to analyze the spectra obtained. As a result of the previous analyses of the TAGS spectra for ^{141}Ba, ^{139}Cs, and ^{140}Cs, it was determined that there were several modifications of the methodology that would be useful in future analyses. These include (1) more precise gamma response

functions for the NaI(Tl) detector; (2) better representation of the response of the NaI(Tl) detector to beta particle emission in singles spectra (i.e., counting of bremsstrahlung photons and beta particles); (3) similar improvement in the coincidence spectra (i.e., bremsstrahlung photons); (4) ability to simulate the coincidence summing between gamma rays and the bremsstrahlung and beta particles; and (5) a method to approximate the contribution of random summing.

The precision of the gamma response functions is being improved by repeating the Monte Carlo calculations of these functions (1) using a more complete representation of the source-detector geometry than previously; (2) increasing by a factor of 10 the number of events followed; and (3) computing more response functions (i.e., every 10 keV rather than every 20 or 40 keV).

For the response of the NaI(Tl) detector to beta particles (i.e., bremsstrahlung photons and the electrons themselves), the approximate analytical expression used previously is being replaced. Instead, the CYLTRAN Monte Carlo code is being used to generate a library of response functions for monoenergetic electrons. These response functions can then be convoluted with a theoretical beta spectrum to simulate the complete detector response to a beta spectrum when the counting system is operated in the singles mode. Also, studies are being made to develop a suitable method for simulating the response for spectra measured in the coincidence mode. In this case, there is a much smaller probability that the electron itself can reach the NaI(Tl) detector. Further, the bremsstrahlung spectrum is modified by the fact that an amount of energy that is greater than the beta-gate discriminator setting must be deposited in the beta detector before a coincidence event can be recorded. For both singles and coincidence TAGS spectra, methods are being developed to allow for an accounting of internal bremsstrahlung in addition to the external bremsstrahlung which is straightforwardly accounted for in the CYLTRAN computations.

The computer code used to simulate the spectrum for a whole decay scheme is being extended to compute the coincidence summing between gamma-ray components and the response functions for the electrons (previously, only coincidence cascade summing between gamma-ray components was computed). Another modification will allow the code to correctly normalize these new beta and bremsstrahlung coincidence summing components to the contributions from just the gamma ray summing, and thereby generate a simulation of the whole decay scheme including the effects of the beta branches.

2. Ground-State Beta-Branching Intensities for Fission Isotopes (R. C. Greenwood and K. D. Watts)

Initially, when it was first recognized that the INEL design of a TAGS system (to study β^- decay nuclides), operating in a beta-gamma

coincidence mode as a $4\pi\gamma$-β spectrometer, could also be used to measure ground-state beta-branching intensities, B_{gs}, in a rather straightforward way, from the beta-gamma coincidence to beta singles counting ratio, it was anticipated that the method, while expected to have wide applicability, would be of limited precision. In fact, during this year, as the method has been fully evaluated and the necessary correction terms delineated (including that resulting from bremsstrahlung associated with the ground-state beta transition), and all sources of uncertainty carefully explored, it has come to be recognized that for even moderately complex nuclide decays it is quite generally the most precise method available as well as being the simplest to interpret. In this regard then, the method represents an innovative and a major advance in nuclide decay data measurements, and one which addresses a long-standing problem in this area; namely, the reliable measurement of ground-state beta-branching intensities.

The degree of suspicion with which many of the reported values of the non-zero ground-state beta-branching intensities must be treated, for many of the shorter-lived fission-product nuclides, results directly from the experimental limitations of the traditional nuclear spectroscopic methods hitherto available for obtaining them. Thus, for example, the method which is conceptually the simplest way to obtain B_{gs} values in β^- decay, by unfolding the beta-decay components to each level including the ground state from the total measured spectrum, can only reasonably be applied in those cases where the ground-state beta-branching end-point energy is sufficiently well separated from those of beta branches to excited states. In the more common, but less direct, approach, beta-branching intensity values in a specific nuclide decay are derived by first measuring absolute gamma-ray branching intensities (using techniques such as $4\pi\beta$-γ spectrometry or the simultaneous measurement of beta and gamma-ray spectra with calibrated detectors) and then deriving beta-branching intensities, $B_{ex}(E_L)$, for each excited state from transition feeding and de-exciting intensity imbalances. The B_{gs} value is then the difference between the summed $B_{ex}(E_L)$ values and 100%. This approach depends on the availability of a complete knowledge of the decay scheme including any significant internal-conversion coefficients, and is thus particularly time consuming for complex nuclear decays. Furthermore, with this method, incorrect transition multipolarity assignments can lead to large errors in the inferred B_{gs} values.

On the other hand, in this new method, using the TAGS system as a $4\pi\gamma$-β spectrometer, accurate values of B_{gs} are obtained for even complex nuclear β^- decays in a straightforward manner without the necessity of having an a priori knowledge of the specifics of the decay scheme above a few hundred keV.

The initial studies with the TAGS system to measure ground-state beta-branching intensities have concentrated on fission-product nuclides with complex but reasonably well understood decay schemes. Specifically, such measurements had been made and the analyses completed for ^{138g}Cs, ^{138m}Cs, ^{139}Cs, ^{140}Cs, ^{141}Cs, ^{142}Ba, ^{142}La, ^{143}La, ^{144}La, ^{145}La, ^{145}Ce and ^{106}Rh (available commercially as a long-lived ^{106}Ru - ^{106}Rh source). Based upon a detailed review of previously published work it was apparent that, in fact, for these nuclide decays, there are only a few cases where prior work, or the degree of beta-forbiddenness, provide B_{gs} values of sufficient certainty to compare with the present data. Cases where such comparisons can reasonably made include ^{106}Rh, ^{138m}Cs, ^{138g}Cs, ^{139}Cs and probably ^{142}Ba, ^{142}La and ^{144}La. In each of these cases, the published and present values are in acceptable agreement (within less than 2 standard deviations of each other). For two other cases, the present values obtained for B_{gs} are significantly lower then the current evaluated values; namely 35.6% versus 57% for ^{141}Cs and 2.1% versus ~52% for ^{145}La. In both cases, these gross errors in the previous evaluated values can be traced to the uncertainties in multipole assignments for some gamma rays, i.e., incomplete decay scheme information. These examples, however, serve to emphasize the utility of data obtained with the present method to assist in the evaluation of decay scheme data.

In measurements with the TAGS system it is our general practice to acquire singles and coincidence list-mode data simultaneously in such a way as to provide the necessary information to derive both beta-feeding distributions to excited states and the corresponding B_{gs} values. Thus, experimental data necessary to obtain B_{gs} values currently exist for all of the heavy-mass fission-product nuclides between Z=55 and Z=60, and between A=138 and A=151, with decay half-lives in the range of ~10 s to 2 hr.

B. NUCLEAR DATA EVALUATION ACTIVITY

1. Mass-Chain Evaluations for the Nuclear Data Sheets (R. G. Helmer, C. W. Reich)

As part of our involvement in the work of the International Nuclear Structure and Decay Data Evaluation Network, which carries out the evaluation of basic nuclear-physics data for publication in the Nuclear Data Sheets, we now have the evaluation responsibility for the A=87 mass chain and the eleven mass chains in the region $153 \leq A \leq 163$. Our policy for the evaluation of these mass chains continues to be to work on them in order of elapsed time since the previous publication, with those being evaluated at any given time being those that are the most out of date.

The current status of the A-chain evaluations within our area of responsibility is as follows:

A-chain	Status (according to currency)
A=155	evaluation underway
A=154	evaluation underway
A=160	in the review process
A=156	Nuclear Data Sheets 65 (1992)
A=162	Nuclear Data Sheets 64 (1991)
A=87*	Nuclear Data Sheets 62 (1991)
A=153	Nuclear Data Sheets 60 (1990)
A=161	Nuclear Data Sheets 59 (1990)
A=158	Nuclear Data Sheets 56 (1989)
A=163+	Nuclear Data Sheets 56 (1989)
A=157	Nuclear Data Sheets 55 (1988)
A=159	Nuclear Data Sheets 53 (1988)

* Permanent assignment from the German evaluation group. The publication was from that group.

\+ Permanent assignment from the BNL evaluation group. The publication is from the BNL group.

We anticipate no difficulties in maintaining, even with the additional two A-chains that have been assigned to us, a cycle time of 5 years, one of the objectives of the international evaluation network.

2. Evaluation of Decay Data for ENDF/B-VI (C. W. Reich)

Within the framework of the Cross Sections Evaluation Working Group (CSEWG), we have had for many years the responsibility for evaluating the experimental decay data to be included in ENDF/B. The involvement in the decay-data evaluation for Version VI of ENDF/B finally wound down this year. During this period, a request was received from CSEWG for detailed L-x-ray intensity evaluations for a number of "important" actinide nuclides. These evaluations were carried out and the results incorporated into ENDF/B-VI. The nine nuclides requested were U-234, U-237, Np-237
(K x-rays only), Pu-237, Pu-238, Pu-239, Pu-240, Pu-242 and Am-241.

An invited paper on the INEL-based decay-data evaluation work for ENDF/B-VI was presented at the 1991 Annual Meeting of the American Nuclear Society, June 2-6, 1992, in Orlando, Florida. The relevant information about this paper is "The File of Evaluated Decay Data in ENDF/B", C. W. Reich and T. R. England (LANL), Trans. Am. Nucl. Soc. 63, 163 (1991).

The major item remaining to be done for the ENDF/B-VI decay-data work is to prepare a paper (or papers) describing and documenting the information that is included. The schedule for doing this (which also involves individuals at other laboratories) remains to be worked out.

3. IAEA Coordinated Research Program on Transactinium Nuclide Decay Data (C. W. Reich)

At the meeting of the former participants in the IAEA Coordinated Research Program (CRP) on the Measurement and Evaluation of Transactinium Isotope Nuclear Decay Data, held November, 1989 at the IAEA Headquarters in Vienna, it was decided to prepare an updated edition of the 1986 report on Transactinium Isotope Decay Data that was produced by this CRP. This decision was reached because the supply of copies of this report was essentially exhausted, because of its popularity and utility, and the desire to include, where possible, more recent data in a second edition of the report. Responsibilities for certain evaluations were assigned at this meeting; and the INEL participant was given responsibility for the ^{237}Np decay data. During the past year, references to these data have been accumulated, including three to work that was underway in three European laboratories. The evaluation of these data was completed this fiscal year, and the results sent to Vienna for inclusion in the updated version of the CRP report. The actual publication date of this updated report is not yet established.

4. Additional Activities (R. G. Helmer)

The evaluation work related to the IAEA Coordinated Research Program on Decay Data for Ge Detector Efficiency Calibration, discussed in our report for last year, has been completed with the publication of the results in IAEA-TECDOC-619 (September, 1991). In addition, R. G. Helmer has terminated his appointment as Coordinator of the Gamma- and Beta-Ray Spectrometry Working Group of the International Committee for Radionuclide Metrology (ICRM), but was elected as an Associate Member of ICRM.

A. HIGHLIGHTS

The neutron scattering experiments for 8 MeV neutrons incident upon ^{48}Ca, which were completed last year, led to determining the separate roles played by target neutron and target proton excitations in ^{48}Ca structures. We were able to show that the unusually large collective octupole strength in ^{40}Ca is actually split into two states in ^{48}Ca, the lower one dominated by proton excitations and the upper equally dominated by neutron excitations. Most of the even parity excitations of ^{48}Ca are dominated by neutron excitations. These findings are not terribly surprising when one thinks of the shell structures involved. But it is surprising when one recalls that we are used to thinking of low-lying nuclear excitations as exhibiting strong isospin symmetry.

The very extensive data set which had been accumulated for levels of ^{116}Sn from the study of (n,n'γ) reactions has been combined with a large neutron capture data set provided by S. Raman form ORNL. The combined data sets led to *complete* level and decay schemes for this nucleus, up to about 4 MeV excitation energy. The level scheme has been well described by Bonsignori and Allaart using their two broken-pair shell model calculations. Some, but not many levels are clearly outside their model space, and their behavior suggests that these are excellent candidates for collective excitations.

This complete level scheme gives us complete and accurate level density information from 0 to 4 MeV excitation, and we also have the recently published information from Russia on the density of s-wave resonances at the neutron binding energy, corresponding to 9.56 MeV excitation in ^{116}Sn. Thus we can test level density models over one of the widest energy ranges for a given nucleus. The consequent tests of level density models showed that the popular and widely accepted back-shifted Fermi gas model cannot reproduce the level density over the whole range. In fact, with conventional use, it fails to reproduce level densities somewhere in the experimental energy range by at least an order of magnitude!

These results led to tests of Ignatyuk's new model. Anatoly Ignatyuk, director of the theory program at Obninsk, came to Kentucky and assisted us in applying his model to our complete density information; the results were surprisingly good. Ignatyuk's main departure from previous models was to find a mechanism for including shell structure, pairing interactions, and vibrational excitations properly. These inclusions are now seen as important if one wants to fit level densities over a wide range of excitation energy.

We have completed some neutron scattering data for study of excitation of 3^- levels in ^{88}Sr and ^{140}Ce at one incident neutron energy, 7.5 MeV. It is important that further work be done at higher energy, but already one can see that in these nuclei the 3^- excitations are not particularly strong. Thus the expected large strength in ^{142}Ce, and known enormous strength in ^{96}Zr, do not appear in the nuclei we are now studying. That is more than a little surprising for ^{140}Ce; the actual strengths need to be determined, and tests need to be run at higher neutron bombarding energies to be sure that the results are neutron energy independent.

The study of the (n,n'γ) reactions in near magic and in shape transitional nuclei just below the deformed rare earths showed strong electric octupole excitations, or susceptibility to octupole deformations. This susceptibility to octupole deformation is indicated by multiplets of levels in ^{144}Sm which correspond to two phonon octupole-octupole and octupole-quadrupole multiplets.

We expect to complete the new determination of the ^{81}Br-^{81}Kr mass difference using new methods not considered in previous efforts to get at this mass difference. The result will be important should ^{81}Br solar neutrino detection be taken seriously. An important problem involving the branching of the s-process in stars at A = 113 will also be examined, through study of the ^{113}Cd excitations.

B. NEUTRON SCATTERING IN COLLECTIVE NUCLEI WITH NEUTRON DETECTION

1. Separate Neutron and Proton Dynamics

(M.T. McEllistrem, J.R. Vanhoy, Sally F. Hicks, G. Chen, Pei-hua Zhang)

We have compared neutron scattering to collective levels in shape-transitional Pt and Os nuclei[1], and in ^{48}Ca, to electromagnetic excitation of 3^- levels.[2,3] These comparisons have shown clearly a very strong separation of neutron and proton dynamics in the target nuclei. In the case of ^{48}Ca, we were able to show[3] that the E3 excitation matrix elements per neutron for one of the two dominant E3 levels were about the same as that per proton for the other 3^- level,[4,5] and vice versa. In other words, these two levels are orthogonal mixtures of the same configurations. Together their E3 strengths exhaust that of the single E3 excitation of ^{40}Ca. We also saw that the E2 strength of the lowest 2^+ excitation was dominated by neutron particle-hole (p-h) excitations.

We had earlier examined the E2 excitation strengths of the nuclei near A = 190, and have seen that while the ground bands of (probably deformed) ^{190,192}Os nuclei show neutron-proton symmetry,[1] the gamma-bands show strong neutron p-h dominance, vis-a-vis protons. On the other hand, as we have reported earlier,[6] ^{194}Pt shows neutron p-h dominance in the ground band. The ground band symmetry found in Os nuclei follows the conventional expectations of strong i-spin symmetry, particularly for nuclei far from closed shells. That makes the behavior of ^{194}Pt hard to grasp. On the other hand, the departure from such symmetry for the low-lying gamma band in Os is almost as unusual. Such neutron-proton separations are possible within the IBM-2 model, but to date neither we nor anyone else has generated them.

We are currently installing the Fermion Dynamical Symmetry Model (FDSM) code of Cheng-Li Wu, for the model as developed by Wu, Da Hsuan Feng, and Mike Guidry.[7] This is a nucleon-pair basis expansion of wave functions, with fermion pairs instead of the bosons of an IBM model. Its advantage, like that of the boson models, is that it has expected group symmetries built into the model framework. This provides a method of truncating shell-model calculations using symmetry as a truncation guide. The E2 transition rates directly reflect these symmetries, as do the level schemes. Thus the relative rates, and the degree that they show different strengths depending upon how they are excited, will be a sharp test of the FDSM. The model automatically contains Pauli exclusion effects, since

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1 M. T. McEllistrem, in *Proc. Int'l. Conf. High Spin Physics and Gamma-Soft Nuclei*, Pitt/Carnegie Mellon, Pittsburgh, PA., Sept. 17-21 (1990).

2 Vanhoy, McEllistrem, Hicks, Gatenby, Baum, Diprete, and Yates, Phys. Rev. C**45** (1992).

3 M. T. McEllistrem, in *Proc. Int'l Conf. Fast Neutron Physics*, ed. by Hongqing Tang and Cheng-Lie Jiang, Beijing, PRC, Sept. 9-13, 1991 (World Scientific Press, Singapore, (1992)).

4 Hicks, Hicks, Shen, and McEllistrem, Phys. Rev. C**41**, 2560 (1990).

5 Vanhoy, McEllistrem, Hicks, Gatenby, Baum, Johnson, Molnár, and Yates, to be published in The Physical Review C**45**.

6 Clegg, Haouat, Delaroche, Lagrange, Hicks, Shen, and McEllistrem, Phys. Rev. C**40**, 2527 (1989), and references cited therein.

7 Chen, Feng, and Wu, Phys. Rev. C**34**, 2269 (1986); Wu, Feng, Chen, Chen, and Guidry, Phys. Lett. **B168**, 313 (1986).

it is a fermion based model. We would expect this to be important, when considering the shell effects likely to be responsible for neutron-proton symmetry breaking. These exclusion effects are not in boson based models.

At present, the FDSM code available does not include broken-pair contributions; which would be caused by residual interaction components that do not follow the basic symmetries of the model. The code can only work in the symmetry limits, whereas the different IBM-2 codes do allow residual couplings which depart from symmetry limits. It will be quite interesting to see what the FDSM is able to tell us abou the Pt and Os nuclei.

The same sort of dynamical, neutron-proton differences as seen for E2 rates in the Os and Pt nuclei are quite strongly expected for E3 excitations. Indeed, if the p-h effects and neutron skin effects projected to affect E3 amplitudes are as sensitive as expected,[8] we may well see stronger hadron dependence of scattering to those levels than to E2 collective levels. The whole subject of E3 amplitudes, the causes of them and the way they manifest themselves in nuclear structure, is a very interesting topic at this juncture.

2. <u>Exploration of E3 Excitations</u> (M. T. McEllistrem, D. Wang, G. Chen, and Li Min)

The E3 collective strength at low excitation energies can be distributed by at least two mechanisms. One is the splitting between neutron and proton particle-hole excitations caused by the occupancy of very different shells, as is so powerfully evident in comparing the single E3 excited level of ^{40}Ca with the split strength[2] in ^{48}Ca, caused by the fact that neutrons in the latter nucleus fill the $f_{7/2}$ shell. Alternatively the E3 strength can be fragmented by E2 collective strength, as Cottle[9] has proposed in interpreting the fragmented strength in ^{196}Pt. Strong E3 excitations have been expected and reported[8] near A = 140, particularly for ^{144}Nd. Thus we chose to search for such strengths in enhanced neutron scattering to 3^- levels near that nucleus.

The greatest known E3 strength in a single nucleus is that reported for the lowest 3^- level of ^{96}Zr, reported[10] to be 66 Weiskoppf units (W.u.). Thus we expected to see enhanced E3 strengths also near that nucleus. The first, benchmark test was to examine the strengths in ^{88}Sr and in ^{140}Ce. Partly we chose these two nuclei because an enriched isotopic sample of ^{88}Sr was needed for other studies, discussed later in this document, and scattering in ^{140}Ce could be studied with a natural sample, since ^{140}Ce is 88% abundant in natural Ce.

We have completed experimental data sets for 7.5 MeV neutron scattering to both nuclei, though some of the ^{140}Ce work may have to be repeated since machine operating conditions and backgrounds were not optimum at the time that work was done. It will be important to extend these measurements to an incident neutron energy of 8.5 MeV, so we can ascertain that the properties of collective excitations we determine are target excitation properties, and not those of the particular experiment being done. The usual method of searching for low-lying E3 excitations in nuclei has been to attempt to interpret E1 decay speeds of levels together with decay patterns of levels. Since there may be causes of fast E1 transitions other than E3 excitation susceptibility, it is valuable to be able to look for direct signatures of E3 amplitudes, such as we find in neutron scattering excitations.

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8 P.A. Butler, in *Proc. Int'l. Conf. High Spin Physics and Gamma-Soft Nuclei*, Pitt/Carnegie Mellon, Pittsburgh, PA., Sept. 17-21 (1990).

9 Cottle, Stuckey, and Kemper, Phys. Rev. C**38**, 2843 (1988).

10 Molnár, Belgya, Fazekas, Veres, Yates, Kleppinger, Gatenby, Julin, Kumpulainen, Passoja, and E. Verho, Nucl. Phys. **A500**, 43 (1989).

The early impressions from scattering in both nuclei at 7.5 MeV incident is that the E3 excitations do not look exceptionally strong; collective enhancements in neither of them may be very large. But solid evidence will have to wait until the data are fully reduced and interpreted.

We plan to develop the hardware in the neutron scattering hall to reduce the backgrounds which we encountered in the 7.5 MeV experiments, reduce thoroughly the data from those runs, and make new measurements under substantially improved conditions at 8.5 MeV incident neutron energy. The next phase of this project will be to advance to ^{142}Ce, where we have reason to expect much larger E3 enhancements than we appear to be finding in ^{140}Ce.

3. Neutron Scattering from Five Even-A Sn Isotopes (J. L. Weil, M. C. Mirzaa, and A.A. Naqvi)

The remaining calculations of the dispersion theory corrections to the optical potentials for describing neutron scattering from $^{116\text{-}124}$Sn have been completed. A comparison can now be made between the dispersion corrected potentials for a spherical optical model (SOM) analysis and a coupled channel optical model (CCOM) analysis. This comparison is now under way, and a paper is in preparation.

C. PROBING EXOTIC NUCLEAR EXCITATIONS WITH THE (n,n'γ) REACTION

1. DSAM Lifetime Measurements (S. W. Yates, T. Belgya, E. Baum, L. Johnson, D. Diprete)

A recent and very important advance in our laboratories has been the development of the capability to measure lifetimes in heavy nuclei with the Doppler-shift attenuation method (DSAM) following INS. Prior to our measurements[11] on ^{96}Zr, this method with INS had been confined to lighter nuclei. We have shown that this method can be extended to much heavier nuclei, and the use of this technique to determine the lifetimes of excited states of these special, heavy nuclei is a major focus of our work.

The Doppler-shifted γ-ray energy, $E_\gamma(\theta)$, measured at a detector angle of θ with respect to the incident neutrons can be related to E_γ, the energy of the γ-ray emitted by a nucleus at rest, by the expression,

$$E_\gamma(\theta) = E_\gamma[(1 + F_{exp}(\tau)v_{cm}\cos(\theta)/c)]$$

where v_{cm} is the velocity of the center of mass in the inelastic neutron scattering collision with the atom, and c is the speed of light. $F_{exp}(\tau)$ is the experimental attenuation factor for v/c determined from the measured Doppler shift and must be compared with the theoretical attenuation factors to determine the lifetime. In our initial study of the lifetimes of levels in ^{96}Zr, a number of difficulties inherent to our measurements were encountered. These problems, which have been partially considered in our recent work[11], will be addressed further in the studies proposed here.

We anticipate testing lifetime determinations for states in medium mass nuclei that have a number of well-known lifetimes. We will use samples that have differing chemical and physical compositions, so that our approach can be generalized to any scattering sample. The nucleus ^{48}Ti is currently our best candidate for these studies and, with the high natural abundance (73.7%) of this isotope, we should be able to perform measurements in varying matrices -- e.g., pure metal, oxide, and carbonate -- with natural (not enriched) titanium. Similar measurements will then be performed with different matrices in several of the studies proposed later. Specific nuclear structure questions to which these methods can be applied are discussed below.

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[11] Belgya, Molnár, Fazekas, Veres, Yates, and Gatenby, Nucl. Phys. **A500**, 77 (1989).

2. Studies of Magnetic Dipole Excitations

(E. Baum, L. Johnson, D. Diprete, D. W. Wang, and S. W. Yates)

Magnetic dipole excitations are typically weaker than their electric counterparts and are not as well understood. They can be either of orbital type, which is associated with the convection current, or of spin type. INS measurements are complementary to other methods of investigation and can contribute significantly to our understanding of M1 excitations.

a. Spin-Flip M1 Excitations in N = 50 Nuclei.

Investigations of M1 transitions to and from 1^+ states provide an ideal means for studying the distribution of spin excitation strengths in nuclei, as well as the spin and isospin dependent parts of the particle-hole residual interaction. A long-standing problem has been the paucity of experimental information on low-lying 1^+ states.

Nuclear resonance fluorescence is frequently used to identify 1^+ states, but it suffers from a high bremsstrahlung background at lower energies that makes it difficult to observe the decay branches to states other than the ground state. On the other hand, the INS reaction, combined with the DSAM method, provides a means for identifying complete sets of such states and for determining the M1 strengths, if the parities can be confirmed independently, for example, from the scattering of polarized photons or from large-angle electron scattering. We are performing a detailed search for candidates for spin-flip 1^+ states in the N = 50 nuclei ^{88}Sr and ^{90}Zr with the INS reaction.

In ^{88}Sr, a 1^+ state at 3487 keV is strongly excited from the ground state in nuclear resonance fluorescence[12]. This state arises, according to shell model[13] and quasiparticle-RPA[14] calculations, primarily from the $\pi(2p_{1/2}, 2p_{3/2}^{-1})$ proton spin-flip configuration. The experimental M1 ground state strength of $0.92 \pm 0.15\ \mu_N^2$ (corresponding to a partial level width[12] of 0.150 ± 0.024 eV) is well-reproduced by the shell model calculations of Cecil and coworkers[15]. That calculation also predicts a second 1^+ state at 8.82 MeV, i.e., in the region of the giant M1 resonance[16], with the principal configuration of $\pi(g_{7/2}, g_{9/2}^{-1})$. Six candidates for 1^+ states were found[17] in the energy range between 6 and 8 MeV in (γ,γ') resonance scattering; however, similar experiments with polarized photons have demonstrated[18] that all of these states are of negative parity. Therefore, low-lying fragments of the GMR have remained unidentified.

In ^{90}Zr, a low-lying 1^+ proton spin-flip state is not expected (and none has been observed), but there is evidence for

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widely distributed M1 strength in the 8 - 10 MeV range of excitation energies[19]. This wide distribution of strength, which may extend to quite low energies, has been attributed to various nuclear structure effects, among them the influence of 2p-2h configurations[20], and is not fully understood. In our (n,n'γ) reaction experiments on ^{90}Zr, we have indications of a large number of heretofore unobserved states in the 4 to 6 MeV energy range that decay to the ground state. Since only spin 1 or spin 2 states are expected to exhibit observable ground state decay branches, it will be possible to identify M1 excitation candidates through γ-ray angular distribution and DSAM measurements. Verification of parity assignments should, of course, be made by other means.

b. Collective M1 Scissors Mode States

(L. Johnson, E. Baum, D. DiPrete, D. W. Wang, T. Belgya and S. W. Yates)

Collective M1 scissors mode states have been observed in deformed nuclei from ^{46}Ti to ^{238}U and their excitation energies scale as $E_x = 66\delta A^{-1/3}$, where δ is the nuclear deformation parameter. The B(M1) values are of the order of 1 to 3 μ_N^2, which is extraordinarily large. It is now generally agreed that, in any successful description of these states, protons and neutrons must be treated as distinguishable, and that this is dominantly an orbital mode[21].

While magnetic dipole excitations are never very collective, questions have recently been raised about the degree of collectivity of these excitations, and an experimental finding confirming these doubts has emerged. Freeman et al[22], in a study of two-quasiproton configurations of the form 7/2-[523] x 5/2-[532] in ^{164}Dy with the proton pickup reaction ^{165}Ho(t,α), found that the 2539-keV state observed previously in inelastic electron and photon scattering with a large M1 strength (1.67 μ_N^2) is dominated by this single two-quasiparticle configuration. This observation is inconsistent with a collective interpretation for the structure of this state.

Additional states in ^{164}Dy near 3.1 MeV which were also found in (γ,γ') and (e,e') reactions to exhibit large M1 strength (3.15 μ_N^2) were not observed in this proton transfer reaction. This latter result could either be taken as evidence that the higher-lying states are the true isovector M1 states or, simply, that these states do not involve 7/2-[523] x 5/2-[532] components but may involve other quasiparticle configurations not accessible with the reaction employed. Interestingly, intermediate energy proton scattering measurements[23] seem to suggest that ^{164}Dy may be unique in having a significant (15%) spin-flip admixture in the nuclear wave functions of these M1 excitations. Clearly, a number of questions remain about the nature of these presumably orbital M1 scissors mode states.

Prior to the proton-transfer measurements of Freeman and coworkers[22], the only probes that had been brought to bear on the question of the nature of these isovector M1 scissors states in heavy nuclei had been electron, photon, and proton inelastic scattering (as noted above, intermediate energy proton scattering at small angles has been used to confirm that the spin contributions are small[23], except possibly in ^{164}Dy). The heavy stable Dy nuclei have been

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studied by inelastic electron and photon scattering and the locations and M1 strengths of the scissors mode states are supposedly well established. In our (n,n'γ) measurements on ^{162,164}Dy, we observe all of the excited 1^+ states suggested as scissors mode states. With the DSAM method, we have measured the lifetimes of these states and have thus been able to assess their collectivity in an independent manner. At the energies of our measurements, the maximum shifts in the γ-ray energies are only about 1.5 keV, so a premium has been placed on precise energy measurement. Most of the B(M1)'s we have determined are in good agreement with previous measurements, but problems remain for a few crucial states. These experiments are being repeated under better conditions in hopes that these discrepancies can be resolved.

3. Studies of Multiphonon Octupole Excitations

(E. Baum, D. W. Wang, D. DiPrete, T. Belgya and S. W. Yates)

In closed shell nuclei, the octupole vibrations have relatively low excitation energies and compete successfully with the quadrupole mode. Data on multiphonon octupole vibrational states are lacking -- i.e., no two-phonon quartet of states has yet been clearly characterized. In certain nuclei these typically high-lying vibrations are expected to occur low in energy. We have chosen to study ^{96}Zr and the isotones ^{144}Sm and ^{142}Nd, because these nuclei have low-lying octupole states and the two-phonon levels, at approximately twice the energy of the one-phonon vibration, should also be fairly low-lying. While we have suggested possible members of the two-phonon octupole quartet in each of these nuclei, additional confirmatory information is needed.

With a B(E3) of about 70 W.u., the octupole excitation in ^{96}Zr is one of the most collective known[25,26]. In our earlier work, we found a higher-lying 5^+ level which decays to the octupole state by a moderately collective E2 transition, suggesting coupling between the quadrupole and octupole modes[10]. At somewhat less than twice the energy of the octupole vibration is a group of states that decay to the first 3^- state by relatively fast transitions (B(E1)'s of 10^{-4} to 10^{-3} W.u.) [27]. It may be tempting to suggest that these states in ^{96}Zr are of two-phonon octupole character. IBM calculations with the spdf boson model[28] have been performed[29] generally support this interpretation, but the definitive data required in characterizing these excitations is still lacking.

There have been a number of searches for a two-phonon octupole quartet of states with spins and parities of 0^+, 2^+, 4^+, and 6^+ at about twice the energy of the 3^- phonon in nuclei such as ^{146}Gd and ^{208}Pb, but no clear cut identification of the members of the two-phonon quartet has emerged. Despite thes failures, stretch-coupled states of the two-phonon type have been established[30,31] in ^{147}Gd and ^{148}Gd. The identification of these states by the characterisitic cascades of two enhanced E3 transitions was possilbe because they occur as yrast states in these nuclei and lower multipolarity decays do not occur readily. However, because these states involve the coupling of one or

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two neutrons to the two-phonon octupole excitation ($\nu f_{7/2} \otimes (3^- x 3^-)$) in ^{147}Gd and $\nu^2 \otimes (3^- x 3^-)$ in ^{148}Gd, their descriptions are not as straightforward as would be the case in a doubly closed-shell nulceus. We anticipate that, if two-phonon ocutpole excitations are to be observed, they should persist in other nuclei in the ^{146}Gd region. Stable ^{144}Sm is only two protons removed from ^{146}Gd, and B(E3;$3^- \rightarrow 0^+$) has recently been measured[32] to be 38 ± 3 W.u. Furthermore, the low energy of the one-phonon state suggests that exciting and observing two-phonon excitaiton is practical.

We have recently completed a study of ^{144}Sm, and our work on ^{142}Nd, another N = 82 nucleus, is in progress. The identificaiton and characterization of candidates for two-phonon excitations is a diffuclut and laborious process. Mearuements of the level lifetimes with the aforementioned DSAM technique, primarily to search for the expected fast E1 transitions to the one-phonon state, have been completed. But, as we have shown in the case of ^{96}Zr, this information alone is insufficient for the characterization of two-phonon octupole states, and we must employ additional probes. Indeed, as striking observation from our work[33] has been that nearly all of the observed E1 transitions are fast. Therefore, E1 transition rates cannot alone be regarded as unambiguous signatures of octupole vibrations in this mass region. We hope to obtain new information about the role of multiphonon vibrational excitations by combining the results of our INS measurements with those from complementary experiments, such as charged-particle scattering, and by studying other N = 82 nuclei.

Also to be studied during these experiments are the low-lying negative-parity states that are superpositions of the elementary one-quadrupole and one-octupole modes[34]. These quadrupole-octupole collective states occur in the same energy region as the two-phonon quadrupole and octupole excitations, and their identification will impose stringent requirements on the description of collective vibrations in nuclei. Barfield and coworkers[32] have recently measured B(E1; $3^- \rightarrow 2^+$ = (2.8 ± 0.4) x 10^{-3} W.u. in ^{144}Sm and argue that this large E1 matrix element, along with the previously known B(E1;$1^- \rightarrow 0^+$) value of the 3225-keV state from (γ,γ') measurements[12], supports the interpretation of the 1^- state in this nucleus as a two-phonon 2^+ x 3^- excitation. However, our data from INS on this nucleus indicates that the expected $1^- \rightarrow 2^+$ transition from a member of the quadrupole-octupole multiplet in ^{144}Sm is absent. This example points to one of the many advantages of INS spectroscopy, where we are able to observe low-energy branches that are obscured by the intense bremsstrahlung present in the resonance fluorescence measurements. We hope to be able to identify all of the members of this multiplet and to characterize these states through the determination of their absolute transition rates, i.e., with DSAM measurements.

C. Stoyanov and his colleagues at the Institute of Nuclear Research and Nuclear Power in Sofia, Bulgaria have recently joined us in our efforts to understand the rates of dipole transitions from two-phonon excitations in ^{144}Sm. Their calculations within the quasiparticle-phonon model should be appropriate for these nuclei and will, hopefully, provide us with new insights into the properties of multiphonon excitations.

4. (n,n'γ) Studies of A = 116 and 120 Sn Isotopes

(J. L. Weil, Z. Gacsi, Shi Xiamin and A. V. Ignatyuk)

a. ^{120}Sn Level Scheme.

The extraction of yields of the strong gamma rays and their conversion to cross sections is essentially

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complete, and the weaker, but oftentimes more interesting, gamma rays are now being analyzed. The program GTOL, obtained from BNL, is being used to aid in the construction of the decay scheme. A careful analysis of the feeding of the levels, as well as the angular momentum information derived from analysis of the angular distributions is also being used to insure the correct placement of gamma rays in the decay scheme. A comparison of measured cross sections for excitation of each level to calculated statistical model cross sections will be used in the later stages of the analysis.

Calculations of the level structure expected for the neutron quasi-particle excitations based on the two-broken pair model are available from Bonsignori[35], and will be compared to the experimental decay scheme when the above analysis is complete. It is expected that neutron collective excitations and proton single particle and collective excitations can also be identified, as was done in the case of ^{116}Sn (see below). A very interesting paper on the systematics of the level structure for Cd, Sn and Te isotopes was recently published by Demidov and Mikhailov[36], and should be of help in this comparison.

b. ^{116}Sn Level Scheme.

The first phase of the work on the ^{116}Sn(n,n′γ) study has been completed. Based on our (n,n′γ) results and the (n,γ) results of S. Raman of ORNL, a complete level scheme for ^{116}Sn up to 4.0 MeV excitation has been constructed and a paper on these results has been published[37]. The level scheme contains 101 levels up to 4.5 MeV, and over half of these have unique spin-parity assignments. In collaboration with K. Allaart of the Free University of Amsterdam, we have compared these levels to the predictions of the two-broken pair model of Bonsignori and Allaart[38], the Interacting Boson Model, and the deformed collective model[39]. In particular, three previously unobserved bands have been identified containing nine new members of a proton quasi-rotational band.[39] In addition, several states have been phenomenologically identified as proton 1p-1h and collective quadrupole-octupole two-phonon excitations. It is concluded that all expected states of these models have been experimentally identified, and that no experimental states fall outside of these models, to a first approximation. It is on this basis that it is believed that a complete level scheme up to 4.0 MeV excitation has been established for ^{116}Sn.

c. Level Densities.

With a complete level scheme now available for ^{116}Sn, and newly determined information on the density of s-wave resonances at the neutron binding energy[40], it has been possible to test whether generally accepted theories of level density[41] are able to successfully account for the energy dependence of the level density of a

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35 S. Raman, et al. Phys. Rev. C**37**, 1203 (1988).

36 A.M. Demidov and I.V. Mikhailov, Sov. J. Nucl. Phys. **53**, 721 (1991).

37 S. Raman, J.L. Weil, et al. Phys. Rev. C**43**, 521 (1991).

38 Bonsignori, Savoia, Allaart, van Egmond, and TeVelde, Nucl. Phys. **A432**, 389, (1985).

39 Wenes, van Isacker, Waroquier, Heyde, and van Maldegham, Phys. Rev. C**23**, 2291 (1981).

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41 von Egidy, Schmidt, and Behkami, Nucl. Phys. Phys. A**481**, 189, (1988).

given nucleus over a wide range of excitation. It was found that neither of the most commonly used level density formulas, the Fermi-gas model and the Constant Temperature model, were capable of simultaneously describing the level density of ^{116}Sn in the bound state region and the neutron resonance region. When fitted to the density in one region, both models predicted a density in the other region which was incorrect by at least an order of magnitude. Both of these models are at least 40-50 years old, and are based on rather simple physical assumptions, so this result is not too surprising.

In recent years, a more sophisticated model of level density incorporating effects of pairing, collectivity and shell structure has been put forward by Ignatyuk and coworkers[42,43]. Known as the Generalized Superfluid Model (GSM), it has had much success in explaining the energy dependence of level density over a wide energy range above the neutron binding energy. However, until the present time it has not been carefully tested for its applicability all the way down to the bound state region of excitation.

Dr. A. V. Ignatyuk, of the Physics and Energy Institute, Obninsk, USSR was invited to work with us on this problem and spent six weeks here applying his new model of level densities to the present ^{116}Sn data. The Generalized Superfluid Model was found to work very well in simultaneously describing the energy dependence of the level density over several MeV of excitation in the bound state region and the level density in the neutron resonance region. It does so with essentially only one free parameter, the other parameters being well determined by systematics of their values for many other nuclei. Since parity information is available for most of the bound states, as well as for the neutron resonances, we are presently checking the dependence of the parameters of all three models on the density of levels of a given parity, which has never been done before. A paper is being written on these results.

d. ^{116}Sn Lifetimes.

The data reduction for the extraction of Doppler shifts from the (n,n'γ) angular distributions was continued, and shifts for sixty γ rays have been determined so far. From these shifts, the lifetimes of over 40 levels have been extracted. Last summer, an undergraduate in the REU program analyzed all the Doppler shifts of ^{116}Sn gamma-rays measured at neutron bombarding energies of 3.05 and 3.75 MeV. At these energies, the effects of feeding can be neglected. It is thought that with careful analysis, at least 10 more lifetimes can be determined.

5. <u>Search for Octupole Excitations in ^{196}Pt</u> (P. Cottle, T. Belgya, S.W. Yates, and M.T. McEllistrem)

The lowest-lying negative-parity states in many nuclei have been attributed to octupole excitations and have been the subject of study in our laboratories for many years. We have recently joined with Prof. Paul Cottle of Florida State University in studying octupole fragmentation effects in the platinum nuclei and in performing detailed (n,n'γ) measurements on ^{196}Pt.

In a survey of the systematic behavior of low-energy octupole states, Cottle[44] demonstrated that the behavior of the lowest 3^- state is generally not strongly affected by fragmentation when $\beta_2 < 0.3$. Fragmentation effects in the Pt isotopes seemed to violate strongly this general rule. Experimental support for this fragmentation comes from

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42 A.V. Ignatyuk, 'Statistical Properties of Excited Atomic Nuclei" IAEA Report INDC(CCP)-233/L, (1985).

43 Ignatyuk, Istekov, and Smirenkin, Sov. J. Nucl. **29**, 450 (1979).

44 P.D. Cottle, Proc. Int. Conf. on Capture Gamma-ray Spectroscopy and Related Topics, Pacific Grove, CA 1990, AIP Conference Proceedings 238, (Amer. Inst. of Physics, R.W. Hoff, ed., 1991) pp. 98-104.

(p,p′γ) measurements by Yates et al.[45] who suggested the existence of a 3^- state in ^{198}Pt at 2.603 MeV, almost 1 MeV above the lowest 3^- (presumably octupole) state. Additional supporting evidence was found[9] by examining the results of earlier studies of the ^{194,196,198}Pt(p,p′) reactions at 35 MeV. A total of eleven states were found in these three nuclei at energies between 2.1 and 2.9 MeV that could be assigned $J^\pi = 3^-$ on the basis of their inelastic proton scattering angular distributions. Furthermore, these states contain enough E3 strength that, when they are included in calculating the octupole centroids for the Pt isotopes, the apparent anomaly in the octupole behavior was resolved.

The resolution of this problem raised new questions about the octupole behavior in the Pt isotopes. These isotopes do not have large quadrupole deformations, as do the rare earth and actinide nuclei, with which strong Coriolis interactions and octupole fragmentation are usually associated. The unique fragmentation in the Pt isotopes is puzzling, but, surprisingly, this behavior emerges from the f-boson IBM calculations of Engel[46]. The importance of these results argues for further experimental confirmation of the fragmentation in the Pt nuclei. We have measured detailed excitation functions in the energy region between 2 and 3 MeV with the ^{196}Pt(n,n′γ) reaction to search for additional octupole excitations, and γ-ray angular distributions have been used to aid in characterizing the newly identified states. This nucleus was studied several years earlier in our laboratories, so much of the groundwork for this study was already in place.

6. Search for an M0 Transition in ^{170}Yb (S. W. Yates, LLNL Group)

Magnetic monopole transitions between nuclear levels with identical spins but different parities have not been observed experimentally and are not normally expected. Gamma-ray emission is forbidden in this case, but monoenergetic internal conversion electron emission may be possible, according to the nuclear-electron bridge mechanism proposed by Krutov[47].

Grigor'ev has recently reported the possible observation of an M0 transition following the decay of ^{170}Lu ($J^\pi = 0^+$, $t_{1/2}$ = 48.2 h). This assertion is based on the claim that an internal conversion transition occurs between the 2820-keV 0^- state populated directly in the β^+ decay and the 0^+ ground state of ^{170}Yb. Indeed, Dzhelepov et al.[48] list a weak internal conversion electron line at 2819.9 keV, with no corresponding γ ray, in their compilation of data from the decay of ^{170}Lu. Such an astounding claim demands greater scrutiny.

The superconducting solenoidal electron spectrometer at LLNL is an ideal instrument to document the possibility of an M0 transition in ^{170}Yb. This instrument has high transmission and, with detector improvements made during Steve Yates's stay in Livermore in 1989-90, this spectrometer has unusually good efficiency for high-energy electrons.

The ^{170}Lu activity was produced with the (p,2n) reaction by bombarding thin, self-supporting enriched ^{171}Yb foils with 200 nA beams of 16-MeV protons from the LLNL Tandem Van de Graaff accelerator. After one day of irradiation, these foils were counted without further processing, and the ^{170}Lu β+/EC decay was followed for several days. Gamma rays were observed with large-volume (80% relative efficiency) and Compton-suppressed Ge detectors, and electrons were detected with the aforementioned spectrometer. In separate measurements, internal

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45 Yates, Julin, Kumpulainen, and Verho, Phys. Rev. C**37**, 2877 (1988).

46 J. Engel, Phys. Lett. **171B**, 148 (1986).

47 V.A. Krutov and O.M. Knyazkov, Ann. Phys. **25**, 10 (1970).

48 Dzhelepov, Ter-Nersesyants, and Shestopolova, Decay Schemes of Radioactive Nuclei. A = 169, 170 (in Russian), Nauka, Leningrad, 1988.

conversion electrons and internal pairs (an alternate and possibly more likely decay mode) in the 2.6 to 3.0 MeV energy region were detected. While Dzhelepov et al.[48] present their data in tabular form only and direct spectral comparisons are not possible, our measurements appear to be of greater sensitivity. In neither the internal conversion electron nor the internal pair spectra was the sought 2819.9-keV transition observed, and we are in the process of establishing upper limits for its presence. Therefore, the possibility of an M0 transition in ^{170}Yb has been discounted.

7. (n,n'γ) Studies of ^{140}Ce and ^{142}Ce.

(J. F. Vanhoy, Sally F. Hicks, S. W. Yates, and M. T. McEllistrem)

An excellent start was made last summer on the joint studies of ^{140}Ce and ^{142}Ce, done as a collaboration between the Kentucky group, Sally Hicks and students from the University of Dallas, and Prof. Vanhoy and a student from the U. S. Naval Academy. The Dallas group included two undergraduate students, who received their first actual experience with research methods. They rose to the occasion beautifully and worked with the intensity of the graduate students with whom they were associating during their summer period. Jeff Vanhoy indicates that he also expects to involve students on his next extended period here, which will occur in the summer of 1992. The two faculty members spent one short period of research with us during the middle of the winter, and will be here next summer. The extensive (n,n'γ) data which the two groups took last summer is now largely analyzed, and a couple of abstracts have been presented on the results obtained to date.

D. NUCLEAR ASTROPHYSICS STUDIES

1. s-Process Nucleosynthesis and the ^{113}Cd(n,n'γ) Reaction

(Z. Németh, T. Belgya, D. W. Wang and S. W. Yates)

Within the framework of the existing collaboration between the University of Kentucky and the Institute of Isotopes in Budapest, Hungary, we have recently initiated experiments with Dr. Zsolt Németh and his colleagues to study ^{113}Cd by the inelastic neutron scattering reaction at the University of Kentucky Van de Graaff facility. This work and companion studies are designed to clarify the role of the s-process in the nucleosynthesis of elements in the Cd-In-Sn region.

The nucleus ^{113}Cd plays a key role in understanding the s-process[49]. From the viewpoint of nuclear astrophysics, the $1/2^+$ long-lived ground state ($t_{1/2} = 9 \times 10^{15}$ years) and the 14.6-year $11/2^-$ isomer are two different species. For example, ^{113g}Cd shields ^{113}In against the r-process, while ^{113m}Cd leads to its production via the ^{113}Ag $\rightarrow$ ^{113m}Cd $\rightarrow$ ^{113}In decay chain.

While ^{113g}Cd and ^{113m}Cd must be treated separately, it does not mean that they are physically decoupled. Under stellar conditions the ^{113g}Cd(γ,γ)^{113m}Cd reaction can occur through intermediate levels. The lowest known activation level is the 1194.4-keV $3/2^-$ state which couples the ground and metastable states in ^{113}Cd[50]. The ^{113m}Cd(γ,γ)^{113g}Cd reaction can also occur in the hot stellar plasma. In this case the lowest-lying activation level is a $7/2^-$ state at 522.1 keV which decays via a two-step cascade to the ground state; but contradictory branching ratio data exist for the depopulating transitions.

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49 R.A. Ward and H. Beer, Astron. Astrophys. **103**, 189 (1981).

50 Z. Németh, Phys. Rev. C, submitted.

The primary goal of our (n,n'γ) studies of ^{113}Cd is to determine the relevant nuclear parameters--e.g., location of the activation levels and the branching of their decays -- necessary for improved s-process abundance determinations, as discussed above. In addition, the new experimental data should significantly widen our knowledge of the level structure of ^{113}Cd. To date, initial excitation function measurements at neutron energies from 1.0 to 2.5 MeV have been performed, and angular distribution measurements have been completed at energies of 1.75 and 2.50 MeV. A wealth of new spectroscopic information has emerged and is being assimilated. Until these data are fully evaluated, it is difficult to assess in which direction this work will proceed. Additional measurements planned include (γ,γ') measurements at Giessen, Germany to measure directly the photon activation cross sections of states identified in the (n,n'γ) work, the ^{110}Pd(α,nγ) at Fribourg, Switzerland, and (n,γ) experiments at the high-flux reactor of the Institute Laue-Langevin, Grenoble, France. (While the (n,γ) measurements have been approved, the reactor at Grenoble is presently undergoing major modifications that will significantly delay these experiments.)

2. Q-values for (p,n) Reactions -- Possible Solar Neutrino Detection (S.M. Grimes, K. Hoffman, S. Al-Quraishi, and M.T. McEllistrem)

We have worked, as time would permit from other projects, on measurements of the ^{81}Br(p,n)^{81}Kr Q-value, since experimental calibration of the neutrino detection efficiency could depend on the energy release. The accepted value is Q = -1.063 ± 0.003 MeV. We had hoped to obtain a more accurate value. Our preliminary results suggest a value a few keV smaller, but with an uncertainty of ± 2 keV.

Our method relies on comparing centroids of neutron time-of-flight peaks (TOF) from the (p,n) reactions to those from "standard" reactions. One of the standards we had chosen was the ^{55}Mn(p,n)^{55}Fe reaction; another was the ^{51}V(p,n)^{51}Cr reaction, whose Q-value is indeed well known, with an uncertainty no worse than about 0.25 keV. But the Mn reaction turned out to be a problem. It develops, in fact, that there are very few Q-values known with sub-keV uncertainties.

A much more reliable method of determining these Q-values would come from high-confidence measurements of thresholds. A new method of doing this was suggested recently by one of us (SMG). The method involves detecting neutrons from (p,n) reactions in TOF, but just above threshold, and using ^{6}Li-loaded glass scintillators, which have efficiencies near 100% in the few keV region. We will test this method during the next year.

E. OPTICAL POTENTIAL STUDIES (C.E. Laird, S. Arole, Q. Shen, S. Rucker, and B. Rose)

During the first half of 1991 analysis of data taken the previous year was continued, resulting in a more detailed model analysis of ^{62}Ni data and in the reduction to cross section of (p,n) and proton elastic and inelastic scattering, and radiative capture data on ^{46,47,49,50}Ti targets. Since each titanium target was only 80% abundant in a specific isotope, an important feature of the titanium study was the separation of the contribution to the (p,n) yield from the isotopes which make up the other 20% of the target. A paper on proton-induced reactions on ^{62}Ni was presented at the Fall Meeting of Nuclear Physics Division of the American Physical Society at Michigan State University.

During 1991 additional data was collected on proton radiative capture and inelastic scattering on ^{46,47,49,50}Ti targets, as well as to study a probable tungsten contamination in the Ti targets. Also, the elastic scattering data for the titanium targets for energies below 7 MeV was reanalyzed after a delay caused by the above mentioned contamination. This analysis involved correcting the elastic scattering data for the tungsten contaminant, as well as separating the contributions from the other Ti isotopes present in each target at about the 20% level. These analyses should be completed soon. The data analysis for all titanium targets for all reactions studied should be completed during the summer of 1992. Target thickness measurements and contamination profiling have been done on ^{57}Fe in anticipation of further studies to be done soon.

A. NUCLEAR DATA EVALUATION (E. Browne, R.B. Firestone, V.S. Shirley, C.M. Baglin, and B. Singh)

The LBL Isotopes Project has permanent responsibility for evaluating 41 mass chains with 89≤A≤93, 167≤A≤194, 206, 210, 211, 212, 215, 219, 223, and 227; temporary responsibility for 8 mass chains with A=59, 76, 79, 80, 81, and 83; and is responsible for converting 33≤A≤44 to ENSDF format. A summary of the current evaluation status of LBL mass chains is given in the table on the following page.

The Isotopes Project contributed approximately 2.5 full-time equivalent (FTE) effort into mass-chain evaluation in 1990. This includes off-site personnel Dr. C.M. Baglin who evaluates for LBL from her residence in Morgan Hill, Ca. and Dr. B. Singh who evaluates for LBL in Canada. In 1991 the Isotopes Project evaluated 10 mass chains.

B. ISOTOPES PROJECT PUBLICATIONS

1. Table of Isotopes, 8th Edition (R.B. Firestone)

The 8th edition of the Table of Isotopes is presently being prepared. This edition will contain all adopted level, γ-ray and decay data from the ENSDF file. It will feature summary mass-chain decay schemes and combined decay schemes similar to those in the 7th edition. In addition, rotational band drawings will be shown in this volume. The publication is being prepared directly from ENSDF with highly automated production software. Limited updating of the primary ground-state isotope properties and rotational band data is being done. The first draft of the summary mass-chain decay scheme drawings has been completed and production of the other tables and drawings is in progress. The 8th edition of the Table of Isotopes is expected to go to the publisher in early 1993. We plan to continuously update the Table of Isotopes as new mass-chains are evaluated. These updates will be available as PostScript files on various computer media. Future versions of the book will be published on approximately a five-year cycle.

2. Electronic Table of Isotopes (R.B. Firestone and C.A. Stone)

The Nuclear Data Sheets are expected to cease publication in the near future. We have been asked to prepare an electronic publication system for ENSDF to replace the printed version. The Electronic Table of Isotopes is under development and will provide access to ENSDF on personal computers and workstations. The goal of this project is to provide a chart of the nuclides format graphical interface to ENSDF which supports the capability of searching the data by nuclear level or transition properties. Tabular and graphical displays of the data will be supported for both the display terminal and the printer. In addition to ENSDF, Nuclear Structure References (NSR), atomic data, nuclear masses, and application software will be provided. We expect to complete the development of this system in 1994.

Status of LBL Mass-Chain Assignments		
Mass Chain	Publication Year	Status
33-44[ab]	1990	Nucl. Phys. A521, 1 (1990)
59[c]	1983	Submitted 1991 (LBL)
76[c]	1985	Published (Kuwait)
79[bc]	1982	Published (Kuwait)
80[c]	1982	Submitted 1991 (LBL)
81[c]	1985	Submitted 1991 (LBL)
83[c]	1986	Submitted 1991 (LBL)
89	1989	Published (Germany)
90	1975	Submitted 1991 (Sweden)
91	1990	Published (Germany)
92	1980	Submitted 1990 (LBL)
93[b]	1988	Published (Germany)
167	1989	Published (LBL)
168	1988	Published (LBL)
169	1982	Submitted 1990 (LBL)
170	1987	Published (China)
171[b]	1984	Published (LBL)
172	1987	Published (China)
173	1988	Published (LBL)
174	1991	Published (LBL)
175	1976	Submitted 1990 (LBL)
176	1990	Published (LBL)
177[b]	1975	Published (ORNL)
178	1988	Published (LBL)
179	1988	Published (LBL)
180	1987	Published (LBL)
181	1991	Published (LBL)
182	1988	Published (LBL)
183	1992	Published (LBL)
184	1989	Published (LBL)
185	1989	Published (LBL)
186	1988	Published (LBL)
187	1991	Published (LBL)
188	1990	Published (LBL)
189	1991	Published (LBL)
190	1990	Published (LBL)
191	1989	Published (LBL)
192	1983	Submitted 1991 (LBL)
193	1990	Published (LBL)
194	1989	Published (LBL)
210	1992	Published (LBL)
211	1991	Published (BNL)
212	1979	Submitted 1991 (BNL)
215	1992	Published (LBL)
219	1992	Published (LBL)
223	1992	Published (LBL)
227	1992	Published (LBL)

[a] A=33-44 is currently being entered into ENSDF by LBL.

[b] Presently being evaluated.

[c] Temporary assignment

A prototype Electronic Table of Isotopes will be released in 1992. This version supports menu-driven access to all adopted and decay data in ENSDF. The data may be searched by A, Z, N, level energy, half-life, J^{π}, rotational structure, magnetic moments, transition multipolarities, sequence order, and cross-references to experimental measurements. Output can be viewed on the screen or saved on an external file. The code has been developed on VAX-VMS computers and is being ported to IBM-PC and Macintosh personal computers.

3. The Nuclear CD-ROM (J.Z. James and R.B. Firestone)

In April, 1992 the Isotopes Project expects to prepare a demonstration version of a Compact Disk Read-Only Memory (CD-ROM) containing both the entire Evaluated Nuclear Data Files (ENDF) library and the Evaluated Nuclear Structure Data Files (ENSDF). The CD-ROM will also contain codes for processing and visualizing the data (NJOY91 for ENDF and TREND for ENSDF) and a sample of "real" nuclear physics codes for use with the ENDF data. Finally, the data and program files will be accompanied by book-formatted documentation in a format (RTF) that can be read by word processor programs on many different computers.

The ENDF library is the nation's central repository of information on nuclear reactions, and was developed over the last 40 years first by the Atomic Energy Commission and more recently by the Department of Energy. Nuclear engineers and physicists are usually limited to predigested "multigroup sets" of reaction data for selected nuclides in specified energy ranges. With the entire ENDF library on a CD-ROM, including the necessary documentation and preprocessing codes, nuclear engineers will be able to do computation on desktop systems like PC's and Macintoshes.

The ENSDF library is the repository for nuclear structure data and is widely used by nuclear physicists and chemists. As with ENDF, the large file size of ENSDF has limited its availability mainly to researchers with mainframe computers. Publication of ENSDF on a CD-ROM is expected to encourage the development of more applications and stimulate its use.

The primary purpose of the demonstration CD-ROM is to demonstrate the concept of CD-ROM publishing of standard nuclear data and test the performance of this technology. A "beta-test version" of the CD-ROM is planned for December, 1992. The main development effort planned for this version includes formatting the documentation so that it can be viewed and printed on a variety of computers without requiring commercial word-processing software, and porting the preprocessing codes to microcomputer platforms.

C. GLENN T. SEABORG INSTITUTE OF TRANSACTINIUM SCIENCE

The Lawrence Livermore National Laboratory and the Lawrence Berkeley National Laboratory, in collaboration with the University of California/Berkeley are pleased to announce the establishment of an Institute of Transactinium Science. The Institute, to be centered at Livermore, will be devoted to the study of transactinium elements with special emphasis on education and training of the future generation of scientists in heavy-element research.

The Institute will provide a unique focus and mechanism for cooperation and collaboration between the system-wide campuses and laboratories of the University of California and with the transactinium community world-wide. Institute facilities will be made available to students, visiting faculty and others for the specialized experimental programs characteristic of this field.

In recognition of the enormous contributions that Professor Glenn T. Seaborg has made to the field and to science education in his many years of affiliation with the University, the Institute is named in his honor and will be known as the Glenn T. Seaborg Institute.

Professor Darleane C. Hoffman of UC Berkeley and LBL will serve as the Institute's first Director.

John H. Nuckolls
Director, LLNL

Charles V. Shank
Director, LBL

Read on 2/22/91 by Roger Batzel at banquet for 50th anniversary of plutonium.

A. NUCLEAR DATA EVALUATIONS AND CALCULATIONS

1. Charged-Particle Evaluations (R. M. White and D. A. Resler)

Integrated cross sections for the five most important thermonuclear reactions for fusion applications, $^2H(d,p)^3H$, $^2H(d,n)^3He$, $^3H(d,n)^4He$, $^3H(t,2n)^4He$, and $^3He(d,p)^4He$, were submitted and accepted for the charged-particle sub-libraries of ENDF/B-VI and have been released. These evaluations were also adopted for inclusion in the IAEA's FENDL/C charged-particle sub-library. They have been extensively intercompared with similar evaluations carried out at Arzamas-16 in Russia. Based upon our analysis of the experimental data for these reactions and the intercomparisons of our evaluations with those of Arzamas and LANL, we believe the integrated cross sections have now been established to accuracies of ±3%, ±3%, ±2%, ±8% and ±8% respectively at the 95% confidence level over the energy range important to fusion applications. Further, we believe these uncertainties represent the lower limit of what can be accomplished with the experimental databases. An article describing this work will appear in the Proceedings of the International Conference on Nuclear Data for Science and Technology, Jülich, Germany, to be published, and is available as UCRL-107158.

2. TDF and TDFLIB (S. I. Warshaw and R. M. White)

The processed ASCII data file TDF and FORTRAN77 file TDFLIB containing the access routines for implementation of the TDF data into application codes, were released to the National Nuclear Data Center at Brookhaven National Laboratory, the Radiation Shielding Information Center at Oak Ridge National Laboratory, and the International Atomic Energy Agency Nuclear Data Section during the last quarter of 1991. TDF contains processed or calculated quantities from the basic integrated reaction cross sections such as Maxwellian-averaged reaction rates, Maxwellian-averaged average energies of interacting and outgoing particles of a reaction, and spectral information on the reaction products (thermal broadening of the outgoing particles) for two-body reactions. The basic integrated reaction cross sections used in TDF are taken from the new LLNL charged-particle evaluations. As an example of information contained in TDF, Fig. A-1 shows a plot of the thermally-broadened neutron emission spectra for the $^3H(d,n)^4He$ reaction at plasma temperatures of 5, 10, 20, and 50 keV. This information can be obtained from TDF by a simple subroutine contained in TDFLIB. In Fig. A-2, we show a plot of the 10.0 keV thermally-broadened neutron spectrum from the $^3H(d,n)^4He$ reaction along with the results of 20000 calls to a spectrum lookup routine in TDFLIB which can be used in a Monte-Carlo type thermonuclear burn routine. The documentation is available as UCRL-109082.

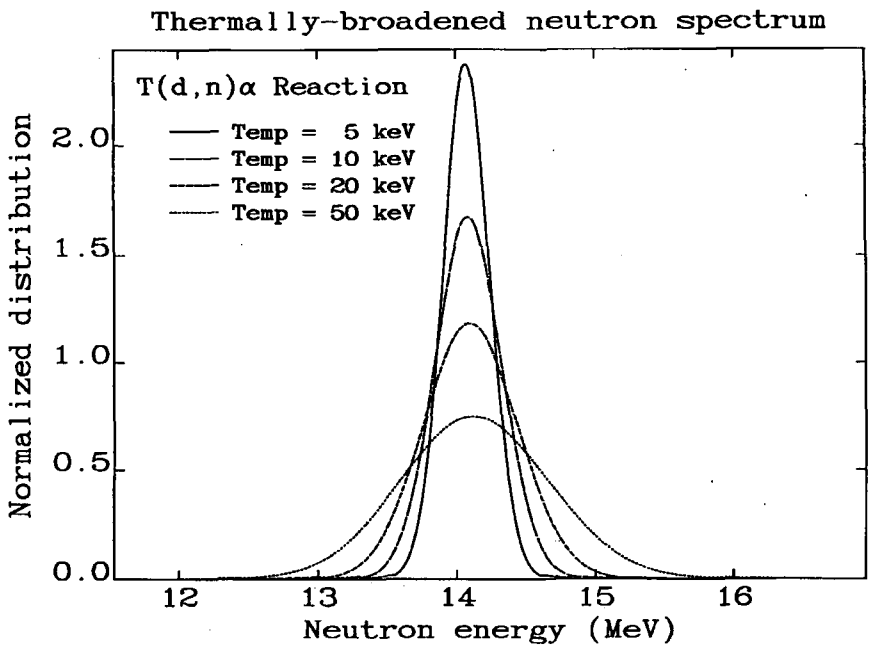

Fig. A-1. Plot of the thermally-broadened neutron emission spectra for the $^3H(d,n)^4He$ reaction at plasma temperatures of 5, 10, 20, and 50 keV. This information can be obtained from TDF by a simple subroutine contained in TDFLIB. All spectra are normalized to unit area.

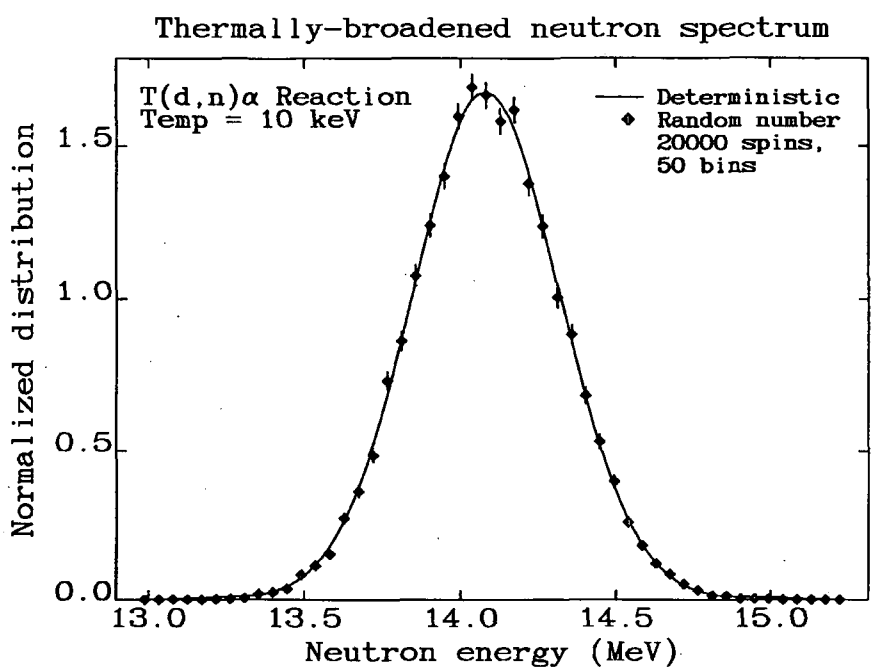

Fig. A-2. Plot of the 10 keV thermally-broadened neutron spectrum from the $^3H(d,n)^4He$ reaction along with the results of 20,000 calls to a spectrum lookup routine in TDFLIB which can be used in a Monte-Carlo type thermonuclear burn routine.

3. Effective Interactions, Structure, and Calculating Reaction Cross Sections (D. A. Resler, S. D. Bloom, and S. A. Moszkowski*)

In collaboration with Ohio University, we have used the shell model/R-matrix technique of modeling resonance reactions for the light nuclei to calculate cross sections for reactions involving ^{10}Be and ^{14}C as the compound systems. Calculations for the ^{9}Be(n,2n) cross section have been performed and the contributions to individual inelastic channels agree with experimental data to within a factor of two. We are currently comparing calculated results for ^{9}Be(n,α)^{6}He and ^{13}C(n,α)^{10}Be reactions with measured data. These calculations have been performed using a relatively simple interaction. The non-physical mixing seen in the large model spaces required for these cross section calculations has been corrected empirically. In general, this will not always be possible.

We are developing an effective nucleon-nucleon interaction which does not suffer from this non-physical mixing in large model spaces. By using a phenomenological potential model, we have adjusted the parameters to agree with what is known about the meson exchange nature of the nucleon-nucleon interaction and also to require our interaction to match the ground state energies and charge radii of the closed shell nuclei ^{4}He, ^{16}O, and ^{40}Ca. Further, we match the average energy per nucleon at the accepted Fermi momentum for symmetric nuclear matter. This is similar to the development of the Skyrme interaction for Hartree-Fock calculations, except that it is done in the framework of the nuclear shell model using finite-ranged components. In using an interaction based on those constraints, we have found no evidence in large model spaces for the non-physical mixing seen when using simpler interactions. We are presently refining the parameters of this model to properly describe the location of excited states and will soon be using this interaction with the shell model/R-matrix technique to calculate cross section where we have previously performed evaluations on reactions leading to the A=4 and A=5 compound systems. This will allow us to further determine how well we can expect this fundamental approach to be used where we have no experimental information.

*Department of Physics, UCLA.

4. Intermediate Energy Modeling Improvements in ALICE (M. Blann)

Several significant additions and improvements to the ALICE code have been made. The inclusion of shell-dependent level densities using the approach of Kataria and Ramamurthy has been successfully tested in analyzing product yields for nuclei near closed shells. The systematic treatment of precompound angular distributions due to Kalbach has been implemented and successfully compared with data in the incident energy regime from 80 to 160 MeV. The hybrid precompound decay model has been successful in reproducing (p,xn) single-differential cross sections up to 160 MeV for targets from A=27 to A=208. The use of exciton densities based on shell model single-particle levels to better reproduce precompound spectra for near-closed-shell nuclei has been explored. Bound and unbound gamma-ray deexcitation channels have been added. The hybrid model in ALICE has been used to compute differential cross sections for neutron-induced reactions up to 30 MeV on structural materials to be used in fusion reactors.

To support model development, measurements of double-differential cross sections for (p,xn) reactions on ^{90}Zn and ^{208}Pb at incident energies of 18, 25, 80, 120, 160, 256, and 800 MeV have been completed. The purpose of these measurements is to serve as benchmarks for modeling this type of reaction up to 1 GeV. In addition, initial measurements of the gamma-ray spectrum from n-p Bremsstrahlung have been made for deducing properties of the nucleon-nucleon interaction.

5. Evaluation of Nuclear Data for Medical Applications (R. M. White and D. A. Resler)

In the area of nuclear data needed for radiation therapy, we have identified and completed the most important data evaluations needed to optimize neutron therapy. Standard man consists of hydrogen (10%), carbon (18%), nitrogen (3.0%), oxygen (65.0%), and various trace elements (4%). A typical tissue substitute material used for dose determination such as A-150 plastic has the corresponding percentages: 10.1%, 77.6%, 3.5%, 5.3%, and 3.5%. Hydrogen, which contributes most significantly to the kerma and absorbed dose, is well-matched for these mixtures. For A-150 plastic, and most other substitute materials, carbon is exchanged for oxygen. Thus, information about the hydrogen kerma factor and the carbon-to-oxygen kerma factor ratio are essential for accurate fast-neutron-absorbed-dose determinations.

We have calculated the hydrogen kerma factors for neutron energies from 10 to 70 MeV from cross sections obtained from the "VL40" phase shift analysis of Arndt and have assigned an uncertainty of ±1.0% (one standard deviation). This uncertainty is based on comparing kerma factor values calculated with the VL40 phase shifts to those calculated from the cross sections in the ENDF/B-VI evaluation. The kerma factors calculated from ENDF/B-VI and VL40, based on 1988 and 1992 phase shift analyses by Arndt, disagree by less than 0.5% over the 30 to 70 MeV region. In the 10 to 30 MeV region, the cross sections for the two kerma factor calculations were based on two completely different analyses (phase shift vs. R-matrix) of the cross sections and the resulting kerma factors disagreed by up to 1.0%. The LLNL recommended values for the hydrogen neutron kerma factors are given in Table A-1.

Table A-1. Recommended neutron kerma factor for hydrogen. The table is designed for linear-linear interpolation. The uncertainty (1 standard deviation) is ± 1% at all energies.

E_n (MeV)	K_f ($Gy \cdot m^2 \cdot 10^{-15}$)
10.00	45.69
12.38	46.59
15.62	46.93
20.46	46.50
31.42	44.21
46.19	41.11
59.79	38.92
70.00	37.80

We have evaluated the carbon kerma factor from 10 to 70 MeV and assigned an uncertainty of ±8% as the *minimum* uncertainty in the recommended kerma factor up to neutron energies of ~50 MeV. That is, given the current database, no realistic uncertainty of less than ±8% can be assigned to the recommended values. A greater uncertainty could be assigned. Above ~50 MeV, a minimum uncertainty of ±16% was assigned based on the only two sets of experimental data available. Figure A-3 shows the ^{12}C database and the LLNL recommended carbon kerma factor as a function of neutron energy. Table A-2 gives the recommended values in numeric form.

We have also evaluated the oxygen kerma factor from 10 to 70 MeV and the results are shown in Fig. A-4. There exists reasonable agreement in shape and normalization between most measurements and calculations up to 40 MeV. However, with the limited database for oxygen, the uncertainties are much greater than in the case of carbon. We have assignment of ±15% from 10 to 30 MeV for the minimum uncertainty in the recommended kerma factors which is dictated by the spread in the experimental data. Above 30 MeV, a minimum uncertainty of ±20% has been assigned. The corresponding recommended numeric values are given in Table A-3. Because the differential between the dose necessary to control the tumor and that which is unacceptable to the patient is less than 5%, we have clearly demonstrated that the basic nuclear data necessary for optimal neutron therapy is inadequate.

Table A-2. Recommended neutron kerma factor for carbon. The table is designed for linear-linear interpolation. The minimum uncertainty (see text) is ± 8% below 50 MeV and ± 16 % above 50 MeV.

E_n (MeV)	K_f ($Gy \cdot m^2 \cdot 10^{-15}$)
10.0	1.20
12.1	1.75
19.5	3.12
23.1	3.51
30.1	3.86
70.0	5.14

Table A-3. Recommended neutron kerma factor for oxygen. The table is designed for linear-linear interpolation. The minimum uncertainty (see text) is ± 15% below 30 MeV and ± 20 % above 30 MeV.

E_n (MeV)	K_f ($Gy \cdot m^2 \cdot 10^{-15}$)
10.0	0.70
13.2	1.28
15.8	1.67
18.9	1.99
22.5	2.19
30.5	2.42
40.7	3.03
70.0	4.91

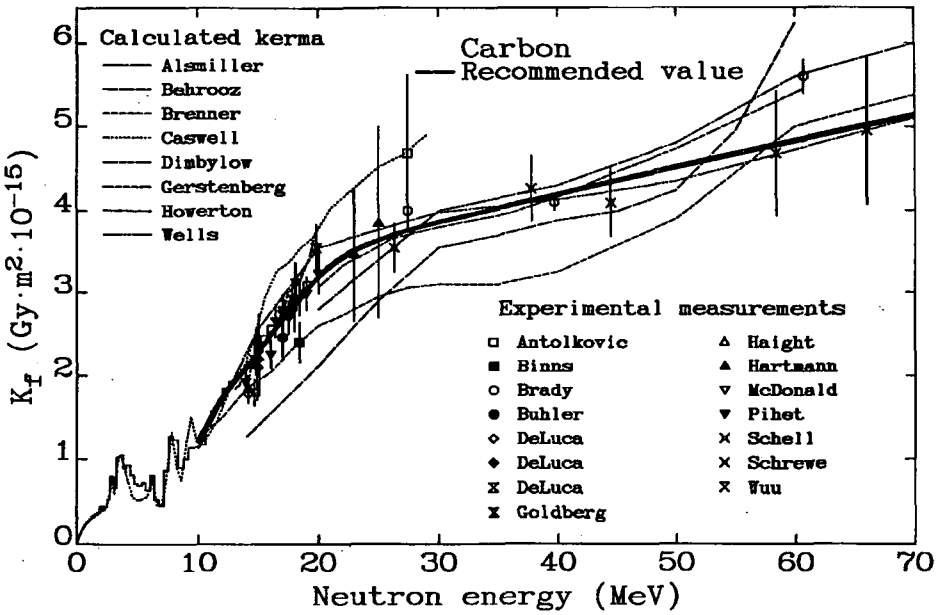

Fig. A-3. Plot of the ^{12}C experimental and calculated neutron kerma factor data as a function of neutron energy with the LLNL evaluation indicated from 10 to 70 MeV. The recommended values are given in numerical form in Table A-2.

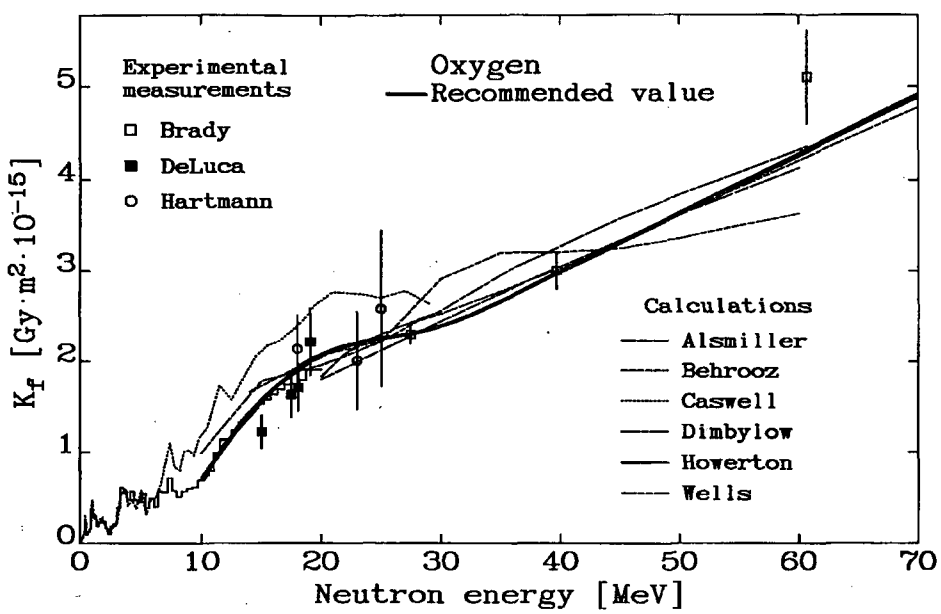

Fig. A-4. Plot of the ^{16}O experimental and calculated neutron kerma factor data as a function of neutron energy with the LLNL evaluation indicated from 10 to 70 MeV. The recommended values are given in numerical form in Table A-3.

6. An Evaluation of Fast-Neutron-Induced Reactions on Zinc Isotopes (M. H. MacGregor and G. Reffo)

We have carried out an evaluation of neutron-induced reactions on the Zn isotopes in the energy range of 1 to 30 MeV. Isotopic calculations were made for reactions on ^{64}Zn, ^{66}Zn, ^{67}Zn, and ^{68}Zn. Results were combined to give an evaluation for natural zinc. The IDA set of nuclear modeling codes was used for the initial calculations, and the post-processing codes ALPHA and BETA were used to combine the individual isotopic calculations of cross sections and spectra into the natural evaluation, apply energy checks and data renormalizations, and convert the output files into the ENDL format.

The IDA codes ESTIMA and AMLETO were used to analyze neutron resonance parameters and nuclear excitation levels for the 38 isotopes of Zn, Cu, Ni, Co, and Fe required for the evaluations. Gilbert-Cameron level density parameters were obtained for all of these nuclei and were used in the IDA codes POLIFEMO and PENELOPE to carry out Hauser-Feshbach calculations. Neutron cross sections, output particle spectra, and output gamma spectra were obtained and comparisons were made to the available experimental data. Statistical analyses were made of both experimental and calculated radiative widths and were used to optimize the input parameter sets.

7. Evaluation of Neutron Cross Sections for ^{178m}Hf (M. H. MacGregor and G. Reffo)

We have carried out an evaluation of neutron cross sections for the 16^+ metastable state of ^{178}Hf. This metastable state is a shape isomer and has an excitation energy of 2.45 MeV and a half-life of 31 years. If a neutron inelastically scatters from a ^{178m}Hf nucleus and leaves the nucleus in a lower excited state than the 2.45 MeV level, the inelastically scattered neutron will receive an energy gain. Thus a quantity of ^{178m}Hf could represent a potential energy source.

The important channels are ordinary inelastic scattering (energy loss), super-inelastic scattering (energy gain), and neutron capture (energy loss). We calculated the branching ratios for these three channels at neutron energies up to 10 MeV. These branching ratios depend critically on the distribution of high-spin levels in ^{178m}Hf, since these high-spin levels determine the decays of the ^{179}Hf compound nucleus that is formed. The IDA nuclear modeling codes AMLETO and BRANCH were used to carry out a detailed statistical analysis of the experimental excitation levels in the various residual nuclei, supply missing levels, and fill in missing spins, parities, and branching ratios. The codes ESTIMA and AMLETO were used to analyze the resonance parameters for these nuclei and determine the Gilbert and Cameron parameters needed for the Hauser-Feshbach calculations, which were carried out with the IDA codes POLIFEMO and PENELOPE. The Moldauer and Camarda-Phillips-White optical models were used to provide neutron transmission coefficients for neutron energies below and above 1 MeV, respectively

Figure A-5 shows the calculated net neutron energy gain as a function of incident neutron energy. The shaded region indicates the current uncertainty in the calculation. There is a net

energy loss for neutron energies above 1 MeV. Pu-Be and Po-Be (α,n) neutron sources have neutron spectra that are predominantly above 1 MeV, and they each yield an energy loss of about 20%. An Sb-Be photoneutron source gives a modest energy gain, but its low intrinsic neutron flux and large neutron capture rate limit its practicality.

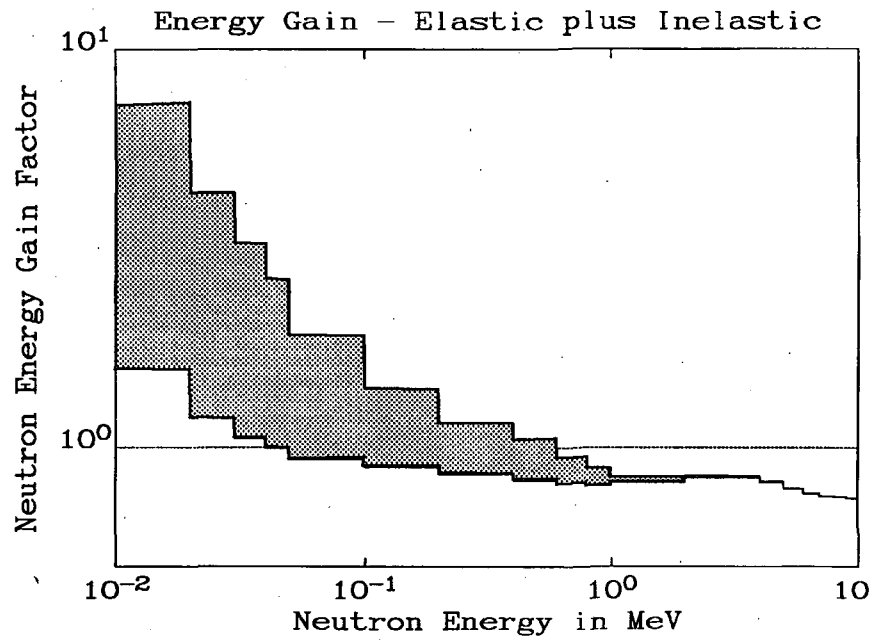

Fig. A-5. The net neutron energy gain factor for the elastic plus inelastic scattering of neutrons from the 16^+ metastable state of ^{178}Hf as a function of neutron energy. The shaded region indicates the current uncertainty in the calculation.

8. Development of Neutron Cross-Section Libraries for Europium and Gadolinium Isotopes (D. Gardner and M. Gardner)

Europium has been used as a radiochemical detector to obtain information on the neutron and charged-particle fluences in underground explosions of thermonuclear devices. Accurate interpretation of the radiochemical results requires complete sets of excitation functions for the neutron-induced reactions of the europium isotopes and isomers and for the neutron-induced destruction of the gadolinium daughter isotopes produced by charged-particle reactions. The neutron-capture cross sections of the Eu and Gd isotopes are all expected to be large, and because of the magnitudes of the neutron-separation energies, the (n,γ) cross sections of the even-mass Eu targets and the odd-mass Gd targets (for which little or no experimental data exist) will be significantly greater than those of their isotopic neighbors. This leads to substantial (n,γ) destruction corrections to the (n,xn), (p,xn) and (d,xn) products. The calculational modeling in this mass region is challenging for a number of reasons. The Eu and Gd isotopes lie close to the N = 82 closed neutron shell but between the closed-proton shells at Z = 50 and Z = 82, and the deformation of these isotopes changes rapidly with the mass number. Thus, a deformed neutron potential[1] that works well for the heavier-mass isotopes, may not be suitable for the lighter, more spherical isotopes of interest. Also, it appears that the Gd potential required at low neutron energies is quite different

from that required for Eu. The nuclear structures for these isotopes have not been studied well experimentally, especially in the case of Eu. Many levels of the Eu isotopes are completely uncharacterized and gamma-ray branching information among the discrete levels is scant. Because of the rapid change in deformation, the Eu and Gd level densities are difficult to model. The modeling approach that we are taking is to achieve best agreement between our calculated cross sections, resonance parameters, etc., and those measured experimentally for the stable isotopes ^{151,153}Eu and ^{152,154,155,156}Gd using as consistent a set as possible of all necessary calculational parameters. This consistent parameter set will then be used to predict all required cross sections for the unstable isotopes. In the case of Eu, this involves some 57 (n,γ), (n,n′), (n,2n), and (n,3n) reaction cross sections calculated from their thresholds up to an energy of 20 MeV among nine Eu isotopes with four isomeric states. For Gd, some 24 (n,γ), (n,2n), and (n,3n) excitation functions among eight Gd isotopes must be calculated.

[1]P. G. Young and E. D. Arthur, "Deformed Optical Model Analysis of Rare Earth Nuclei," Los Alamos National Laboratory Report, LA-10915-PR (1986).

9. Importance of E2 Transitions in Calculating ^{175}Lu(n,γ) Isomer Production (D. Gardner and M. Gardner)

We have investigated the importance of including E2 transitions from all band-head members of ^{176}Lu in the calculation of the isomer production for the ^{175}Lu(n,γ)^{176m,g}Lu reaction. In previous cross-section calculations, we had used a set of 291 modeled discrete levels[1] for ^{176}Lu. This set included 62 rotational band heads, as well as computed gamma-ray decay branching fractions for all levels; only dipole transitions were allowed during the depopulation of the discrete levels including the band heads. Our recent development of the NUSTART code[2] has given us the capability to include allowed E2 transitions from all band heads in the computation of the branching fractions. We have found that the inclusion of E2 transitions from the 62 band-head members of ^{176}Lu led to an isomer fraction of 0.82 at E_n = 30 keV, compared to the 0.62 isomer fraction obtained previously when no E2 transitions from the band heads were considered. This higher isomer fraction agrees with recent experimental measurements. The computed isomer fraction was not sensitive to the magnitude of the E2 strength. A range of 10^3 in the E2 strength function provided isomer fractions that varied by about 5%. Changing the relative magnitudes and the shapes of the E1 strength functions led to variations in the isomer fractions of only a few percent. In a series of calculations, we truncated the 291 discrete levels used in ^{176}Lu below a band head and found that we needed significantly fewer levels, when including the E2 transitions, to achieve convergence in computing the isomer fraction. We are interested in calculating neutron cross sections for the lutetium isotopes ^{170}Lu to ^{180}Lu because lutetium is used as a neutron-fluence monitor in thermonuclear device diagnostics. ^{176}Lu is also of interest in astrophysics as a stellar chronometer and/or thermometer. Because the (n,γ) cross sections on the two states of the ^{176}Lu are similar, the 30% increase in the population of the isomer from the ^{175}Lu(n,γ) reaction does not produce a large effect in our diagnostics effort. However, the observation of this kind of modeling deficiency causes concern and indicates that other permanent rotors, including other Lu isotopes, should be reexamined to determine if a similar isomer fraction change can be obtained. Preliminary studies of ^{174}Lu and ^{236}Np indicate that inclusion of the E2 transitions does not affect their

isomer-production cross sections significantly. The importance of E2 transitions may depend on the band-head structure.

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[1]R. W. Hoff *et al.*, Nucl. Phys. **A437**, 285 (1985).

[2]G. L. Larsen, D. G. Gardner, and M. A. Gardner, Lawrence Livermore National Laboratory Report UCRL-53946 (1990).

10. Optical Model Code Development (D. Gardner, M. Gardner, and S. Koopman)

Because of our interest in the calculation of neutron and charged-particle excitation functions in the mass region that includes the elements samarium, europium and gadolinium, we require an accurate, coupled-channel optical-model computer code. The several versions of the ECIS code[1] available at LLNL were in single precision on the CRAY computers, and were not "user- friendly." We have developed a controller-version that is in double precision in the critical subroutines, including those for the Coulomb wave functions. The controller program reads a grid of incident particle energies, the optical model parameters and their energy dependencies, and the usual information supplied to a coupled-channel code. Such information includes model type (rotor or vibrator), energy levels that are coupled, deformations, the convergence criteria for the minimum sizes of the s-matrix elements and various functions and potentials, and the maximum channel spin. This information is sent by the controller to ECIS, and for each incident energy ECIS returns the total, direct elastic and the sum of the direct inelastic cross sections in tabular form, along with the information to compute the particle transmission coefficients. Next, the controller sends the information to another code, TC7, which computes the reaction cross sections and the transmission coefficients (either T_l or T_j) in one of five different formats for use in our Hauser-Feshbach statistical model codes. Files convenient for plotting are produced containing all of the direct and compound nucleus cross sections, the s-wave transmission coefficients, and, for incident charged particles, the WKB barrier penetration approximation for the s-wave coefficients. We have also added the calculation of a table of Wronskian values for the ground state and each open level, and the s-wave and p-wave strength functions when the incident particle is a neutron. A change was made in the ECIS subroutine QUAN, to correct the calculation of the channel spin limit, SJ2. Figure A-6 illustrates the accuracy of our new ECIS system. Here we compare the s-wave transmission coefficients for protons on ^{153}Eu(Z=63) as calculated by ECIS and by the WKB approximation. Transmission coefficient values as low as 10^{-40} are well calculated, and follow the energy dependence of the WKB approximation, even though ECIS used a deformed Coulomb potential. The reduced Coulomb radius, r_c, is shown for each calculation.

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[1]J. Raynal, "Optical Model and Coupled-Channel Calculations in Nuclear Physics," International Atomic Energy Agency Report IAEA SMR-9/8 (1970).

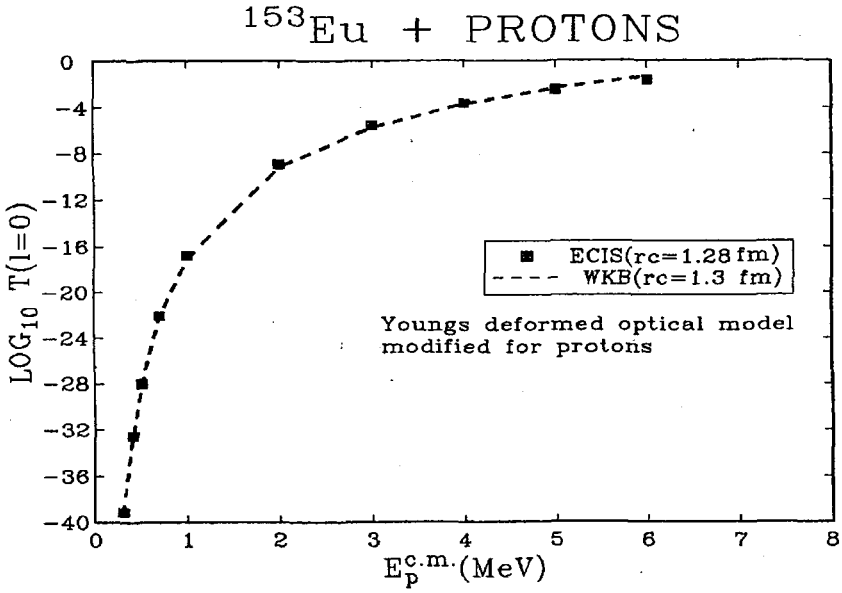

Fig. A-6. The s-wave transmission coefficients for incident protons on ^{153}Eu(Z=63) as calculated by ECIS and by the WKB approximation. The reduced Coulomb radius, r_c, is shown for each calculation.

11. Photonuclear Data Evaluation (S. I. Warshaw)

We have started to generate photonuclear data files and evaluations in collaboration with V. V. Varlamov from the Center for Photonuclear Experiments Data (CDFE) of the Institute of Nuclear Physics at Moscow State University in Russia. During the past year, we reviewed and upgraded IAEA/NDS's criteria for compiling photonuclear reaction data. The new criteria were accepted by IAEA/NDS without reservations. We established an isotope priority list for carrying out evaluations (as distinct from compilations) of photonuclear reaction cross-sections. We began to digitize photonuclear cross-section data presented in graphical form from about 40 journal articles published within the last decade which are not available in tabular form. The digitized results are currently being processed to be compatible with the EXFOR format.

We have started an evaluation of photofission reactions for ^{235}U, ^{238}U and ^{239}Pu. Since the last evaluation was done by CDFE for ^{235}U and ^{238}U in 1987, we initiated an effort to update these evaluations and also establish one for ^{239}Pu. The reason for this update is that significantly more monochromatic data have become available on these isotopes since the CDFE effort. About 40 monochromatic and quasi-monochromatic photofission experiments reported in published journal articles have been identified for input to our evaluation process. Tables were published for 15 of these, tables for 10 were retrieved from the NNDC at BNL, and the graphs for the remainder were digitized. The digitized data will be put into the CSISRS format for transmittal back to the NNDC.

B. NUCLEAR DATA MEASUREMENTS

1. Observation of a Superdeformed Band in ^{192}Pb* (E. A. Henry,[†] A. Kuhnert,[†] J. A. Becker,[†] M. J. Brinkman,[†] T. F. Wang,[†] J. A. Cizewski,[‡] W. Korten, F. Azaiez,[a] M. A. Deleplanque, R. M. Diamond, J. E. Draper,[b] W. H. Kelly,[c] A. O. Macchiavelli, and F. S. Stephens)

We have identified a new superdeformed (SD) band and assigned it to ^{192}Pb, extending the region where superdeformation is known in the Hg, Tl, and Pb nuclei near A = 190. The ^{173}Yb(^{24}Mg,5n) reaction with beam energies of 128 and 132 MeV was used to produce ^{192}Pb. Data were acquired with the HERA spectrometer at the Lawrence Berkeley Laboratory 88-Inch Cyclotron. A channel-by-channel search of the data revealed at least nine mutually coincident transitions extending from 262 to 570 keV (Fig. B-1). The relative intensity pattern of the transitions in the band is shown in the inset. The assignment of this new band to ^{192}Pb is based on excitation function data and coincidences of the band members with known ^{192}Pb transitions. A gamma-ray spectrum generated by double gating on three- and higher-fold events (Fig. B-1) shows the 855-keV (2^+ - 0^+), 503-keV (4^+ - 2^+), and 566-keV (6^+ - 4^+) transitions in ^{192}Pb. Transitions in ^{193}Pb, such as the 521-keV (19/2,21/2 - 17/2) transition, are not observed in this double-gated spectrum. The method of Becker, *et al.*[1] has been used to determine the spins of the levels in this SD band. The assignment to ^{192}Pb limits the spins to integer values. Spins of 10 or 11 are equally probable for the level populated by the 262-keV transition. This work extends the region of superdeformation near A = 190 to ^{192}Pb. The increase in spin of the lowest observed SD band

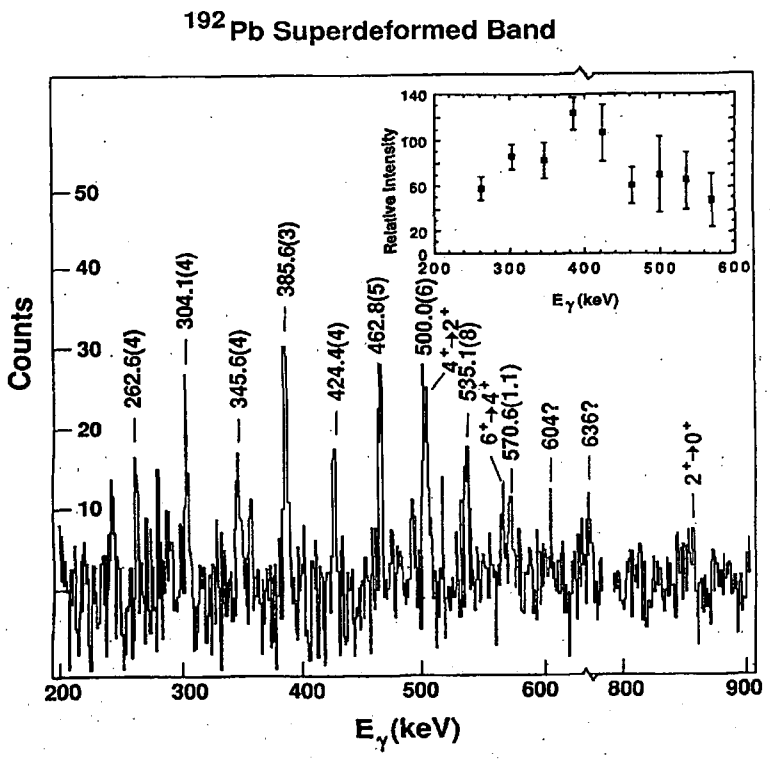

Fig. B-1. A spectrum of the SD band produced in the ^{173}Yb(^{24}Mg,5n) reaction at 132 MeV, and assigned to ^{192}Pb. This spectrum is obtained by double gating three- and higher-fold events. SD band transitions are indicated by their energy. Known transitions in ^{192}Pb are indicated by the spin and parity of the levels they connect. The SD band transition intensities include internal conversion (inset).

member in ^{192}Pb compared to ^{194}Pb suggests that ^{192}Pb is near the edge of the SD band region. In Pb, the SD bands do not show identical transition energies when compared among themselves; this is in contrast to a number of cases in the Hg and Tl nuclei. Finally, SD bands are now known in four even mass Pb nuclei, but a SD band has yet to be found in an odd mass Pb nucleus.

*Condensed from Z. Phys. **A388**, 469 (1991).
†Lawrence Livermore National Laboratory, Livermore, CA 94550.
‡Rutgers University, New Brunswick, NJ 08855.
[a]Permanent address: CEN-BF, IN2P3, Le Haut-Vigneau--33170 Gradigan, France.
[b]Permanent address: Univ. of Cal., Davis, CA 95616.
[c]Permanent address: Iowa State University, Ames, IA 50011.
[1]J. A. Becker, et al., Nucl. Phys. **A520**, 187c (1990); and to be published.

2. ^{79}Br, ^{81}Br, and ^{127}I (p,n) and (d,2n) Excitation Functions (H. I. West, Jr., R. A. Nuckolls, B. Hudson, M. G. Mustafa, and B. Ruiz)

We have measured the excitation functions for the charged-particle reactions ^{79}Br[(p,n)&(d,2n)]^{79}Kr, ^{81}Br[(p,n)&(d,2n)]^{81}Kr and ^{127}I[(p,n)&(d,2n)]^{127}Xe from reaction threshold to 17 MeV using the LLNL Tandem Van de Graff accelerator. The targets consisted of KBr and KI imbedded in a plastic matrix (the equivalent of DuPont's Kapton) made into thin sheets 5 to 15 mg/cm^2. The irradiated targets were counted off line with germanium detectors. ^{81}Kr, having a half life of 2.1x10^5 years, was measured using mass spectrometry. Cross-checks between γ-counting and mass spectrometry, backed up by proportional-counter work, showed that the Iγ for the 261-keV γ-ray in the ^{79}Kr decay could not be 0.127 as reported by Collé and Kishore[1]. We find Iγ(261) = 0.118(2). The experimental work is complete. Earlier measurements of ^{79}Br(p,n)^{79}Kr and ^{127}I(p,n)^{127}Xe by Collé and Kishore[2] agree quite well with our results when the proper Iγ's are used. Prior measurements of ^{127}I(d,2n)^{127}Xe by Balestrini[3] using mass spectrometry, are about 30% low compared to our results. No prior measurements were available for the other reactions. Figure B-2 shows the results of the ^{79}Br(p,n)^{79}Kr and ^{81}Br(p,n)^{81}Kr reactions compared. Figure B-3 shows the results of the ^{79}Br(d,2n)^{79}Kr and ^{81}Br(d,2n)^{81}Kr reactions compared.

We are in the process of modeling the data using the LLNL versions of the Hauser-Feshbach statistical-model code STAPRE.[4] Preliminary modeling of the (p,n) excitation functions in Fig. B-2 shows that most of the difference between the two sets of data are due to the differences in mass number. For the (d,2n) data in Fig. B-3 we must allow for about 25% breakup of the deuteron in the entrance channels. We then find that although there are differences between the two excitation functions due to mass number, the major difference is due to reaction threshold.

[1]R. Collé and R. Kishore, Phys. Rev. C **9**, 981 (1974).
[2]R. Collé and R. Kishore, Phys. Rev. C **9**, 2166 (1974).
[3]S. J. Balestrini, Phys. Rev. **95**, 1502 (1954).
[4]M. Uhl and B. Strohmaier, Institut fur Radiumforschung und Kernphysik, Vienna, IRK76/01 (LLNL version updated 1981)

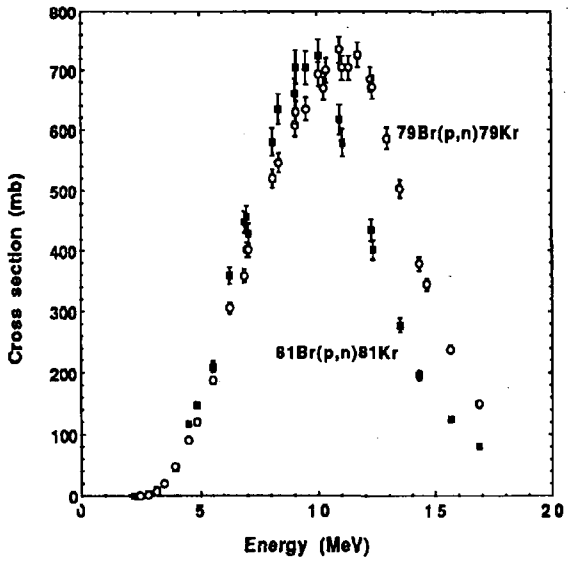

Fig. B-2. Comparison between the $^{79}Br(p,n)^{79}Kr$ and the $^{81}Br(p,n)^{81}Kr$ excitation functions.

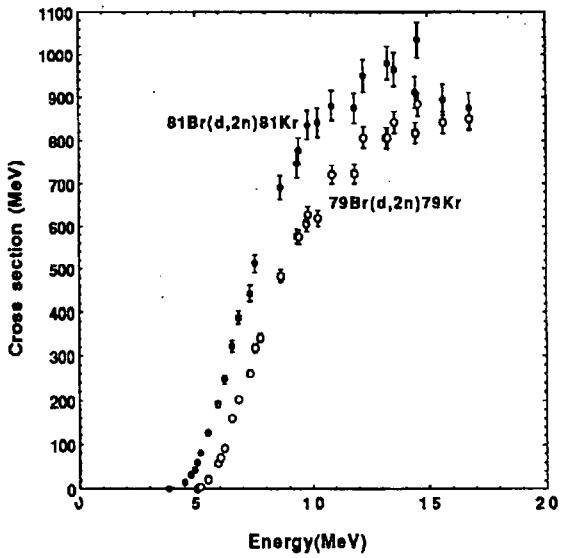

Fig. B-3. Comparison between the $^{79}Br(d,2n)^{79}Kr$ and the $^{81}Br(d,2n)^{81}Kr$ excitation functions.

LOS ALAMOS NATIONAL LABORATORY

A. NUCLEAR DATA MEASUREMENTS

1. Neutron Resonance Parameters of the ^{113}Cd p-wave Levels (C. M. Frankle)

Until the recent discovery of the 7.0 eV level[1], there were no known p-wave levels in ^{113}Cd. The neutron capture gamma ray yield was measured from 4 eV to 500 eV using both natural cadmium and highly enriched ^{113}Cd targets. A total of 22 new resonances were located. A Bayes' theorem analysis[2] indicated that nearly all are consistent with an assignment of l=1. Resonance parameters, E_0 and $g\Gamma_n$, were obtained for the newly identified levels. The p-wave strength function was determined to be $10^4S_1=2.8\pm0.8$ and the average level spacing $\langle D_1\rangle=14$ eV. Comparison of the reduced widths with a Porter-Thomas distribution is consistent with having missed 15% of the p-wave levels. (Fig. A1.)

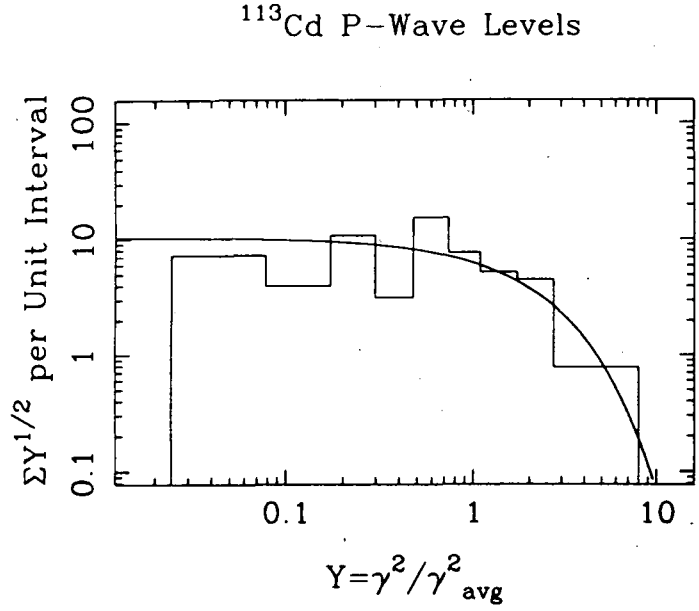

Fig. A1. Porter-Thomas distribution overlay comparison for binned experimental widths with 10 bins of equal probability.

[1] V. P. Alfimenkov *et al.*, *Sov. J. Nucl. Phys.* **52**, 589 (1990).
[2] L. M. Bollinger and G. E. Thomas, *Phys. Rev.* **171**, 1293 (1968).

2. Thermal Neutron Capture Gamma Ray Spectra [E. T. Jurney, W. Starner and S. Raman (ORNL)]

The capture gamma ray facility at the Omega West Reactor is one of the World's premier instruments in this field, now capable of sensitivity of a few tens of μb for gamma transitions in the isotopes of light elements, and precision and accuracy in energy of rather less than 100 eV throughout its wide range from a few hundred keV to more than 10 MeV. In recent work the spectra of nitrogen, the magnesium isotopes and the silicon isotopes have been measured. In the magnesium and silicon sets 30 to 50 gamma rays

have been observed for each of the even mass target nuclides and 100-200 for the odd mass nuclides. Overall, the number of known gamma rays in these nuclides has been more than doubled. Because of the detail and accuracy of the data it has been possible to place the vast majority of the gammas in reliable level schemes that are mostly consistent with other available reaction data as well as internally consistent in the gamma ray intensity balances. The high accuracy of the $^{14}N(n,\gamma)$ transitions has been used in conjunction with other reaction data on light nuclides (^{12}C, ^{13}C and ^{2}D) to infer that the recommended value[1] of the binding energy of the triton is too high by about 100 eV, An abstract has been submitted to the APS 1992 Washington meeting on this topic. A paper on the magnesium isotopes has been submitted to Physical Review, and one on silicon is about to be submitted.

[1]A. H. Wapstra, *Nucl. Inst. Meth.* **192**, 671 (1990)

3. Low-Energy (n,p), (n,α) and (n,γ) Cross Sections [P. E. Koehler, S. M. Graff (LANL), H. Beer, F. Kaeppeler (KFK, Karlsruhe), M. Wiescher, J. Gorres (U. of Notre Dame)]

In collaboration with colleagues at Kernforschungszentrum Karlsruhe and The University of Notre Dame, we have measured the $^{14}C(n,\gamma)^{15}C$ cross section at a stellar temperature of kT=25 keV. Calculations[1] had indicated that ^{14}C acts as a bottleneck to possible heavy element nucleosynthesis in nonstandard models of the big bang. We measured[2] the cross section to be 1.7 μb, about a factor of five smaller than predicted; hence ^{14}C is even a more effective barrier to heavy element nucleosynthesis than previously thought. We also measured[3] the $^{17}O(n,\alpha)^{14}C$ cross section from 0.025 eV to 1 MeV. If a way can be found around the ^{14}C bottleneck, then nucleosynthesis is calculated to proceed through ^{17}O and onto the heavier elements via a series of neutron captures. However, our data show that the $(n,\alpha)/(n,\gamma)$ ratio for ^{17}O is between 10^3 and 10^4 at big bang temperatures, so most of the flow returns to ^{14}C instead of proceeding on to heavier elements. We also measured[4] the $^{35}Cl(n,p)^{35}S$ cross section from 0.025 eV to 100 keV. Our data show that this cross section is about 6 times smaller than $^{35}Cl(n,\gamma)^{36}Cl$ at s-process temperatures and hence does not provide a significant branch to subsequent production of the rare isotope ^{36}S.

[1]M. Wiescher, J. Gorres and F. K. Thielemann, *Astrophys. J.* **363**, 340 (1990).

[2]Hermann Beer, M. Wiescher, F. Kaeppeler, J. Gorres, and P. E. Koehler, accepted for publication in *Astrophys. J.*

[3]P. E. Koehler and S. M. Graff, *Phys. Rev. C* **44**, 2788 (1991).

[4]P. E. Koehler, *Phys. Rev. C* **44**, 1675 (1991).

4. Development of a 4π Barium Fluoride Detector for (n,γ) Measurements Radioactive Targets (P. E. Koehler)

During the 1991 run cycle we installed a new collimator in order to reduce the large background we experienced in our barium fluoride (BaF_2) detector during the 1990 run cycle tests. With the new collimation, the background was reduced by a factor of about 4000. MCNP calculations had indicated that the new collimator would be about 250 times more effective than this. However we had neglected to include the walls around the collimator in these calculations. New MCNP calculations reveal that the walls contribute substantially to the background. Based on tests run during the 1991 run cycle, and new MCNP calculations, we are redesigning the shielding around the collimator and detector. If

the background rate cannot be reduced we should currently be able to make measurements with samples in the mg range. We hope to push the sample size down to the 100 μg range.

5. Thermal and Fast Neutron Capture by ^{7}Li [J. E. Lynn, E. T. Jurney and S. Raman (ORNL)]

The capture gamma ray spectrum and cross section have been measured at the Omega West Facility. The capture cross section is 45.4±3.0 mb. The single particle spectroscopic factors of the two final states for the capture transitions and the thermal scattering lengths for the two spin configurations of the scattering state are known. The direct capture cross sections calculated with this information for the two primary E1 transitions agree with the measurements. By fitting the total cross section and differential scattering cross sections of ^{7}Li up to a neutron energy of over 1 MeV using R-matrix theory we have been able to establish reliably the energy dependent behavior of the s-wave scattering lengths up to several hundred keV and thus calculate the direct E1 capture cross section into this energy range, which is important for theories of the early stages of nucleosynthesis. It is found that the deviation from the standard inverse velocity relationship below neutron energy 100 keV is quite small, but the calculation disagrees (being a factor of about two greater) with a recent measurement[1] of the fast neutron capture cross section, which is in turn substantially lower than a much older measurement.[2] Above 100 keV a magnetic dipole contribution to the capture cross section arises from the strong p-wave scattering resonance at 255 keV. From the capture cross section data, normalized to the direct capture theory (and hence to the measured thermal neutron value within experimental error), we have deduced the radiative width of the resonance to be 0.09 eV. This is in good agreement with a valence model of M1 capture. This work has been published in *Phys. Rev. C* **44**, 764 (1991). Since its publication new measurements of the fast neutron capture cross section have been published[3] that are in excellent agreement with the E1 direct capture theory.

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[1] M. Wiescher, R. Steininger and F. Kaeppeler, *Astrophys. J.* **244**, 464 (1989)

[2] W. L. Imhof *et al. Phys. Rev.* **114**, 1037 (1959)

[3] Y. Nagai *et al.. Astrophys. J.* **381**, 444 (1991)

6. Analysis of Thermal Neutron Capture by ^{14}N [J. E. Lynn, E. T. Jurney, W. Starner and S. Raman (ORNL)]

Following our recent comprehensive measurements of the capture gamma spectrum and cross section of nitrogen at the Omega West Facility we have made a theoretical analysis of the ^{14}N(n,γ) reaction. There has been a very long-standing qualitative discrepancy between the thermal neutron capture gamma spectrum and that from the ^{14}C(p,γ) reaction made at the same excitation energy of ^{15}N, even though the nearby resonances in the latter reaction were believed to have the same spin and parity as those involved in the former. Direct neutron capture (which now appears to be the predominant capture mechanism for the majority of light nuclides, including many close neighbors of ^{14}N) could, however, possibly account for this discrepancy. It turns out that direct capture theory on its own is unable to explain the thermal neutron capture E1 transitions, the summed cross sections for which are an order of magnitude smaller than those calculated. Clearly the contributions of local, bound resonance levels are of major importance in this reaction. We have used R-matrix theory to fit the total cross section of ^{14}N up to about 1 MeV, its (n,p) cross section at thermal and the proton capture cross section of ^{14}C over an extended energy range around the neutron separation energy to obtain the reduced neutron widths $\gamma_\lambda(n)^2$ of these neutron-bound resonance levels, the most important of which is at ~25 keV. We find that the (p,γ) spectrum of this level, if treated as pure compound

nucleus capture, cannot be combined with the direct neutron capture spectrum to give a result in agreement with the measured data. Instead, if the valence radiation widths of the bound level are computed, using its reduced neutron width, and the CN amplitudes are then deduced from the (p,γ) spectrum, allowing for these valence amplitudes, full agreement with the (n,γ) data can be achieved. This agreement extends to the Ml primary transitions. The analysis demonstrates that potential capture, neutron valence capture and CN capture amplitudes are of rather similar importance in establishing the features of the $^{14}N(n_{th},\gamma)$ reaction, and it also shows the existence of neutron valence capture in a resonance excited by a different type of incident particle. The parameters established for the most weakly (neutron-) bound level of ^{15}N are:

$E_\gamma = -25$ keV, $\gamma_\lambda(n)^2 = 35$ keV (at channel radius 3.5 fm), $\Gamma_\lambda(\gamma,tot) = 420$ meV.
$\Gamma_\lambda(p) = 200$ meV.

7. Direct Capture Mechanism in Thermal Neutron Capture by Magnesium and Silicon Isotopes [J. E. Lynn, E. T. Jurney, W. Starner and S. Raman (ORNL)]

Direct capture at thermal neutron energies arises from the gamma ray transition from the initial s-wave scattering state to the single-particle component of the final state, which is determined by its (d,p) spectroscopic factor. In practice, the scattering state contains some admixture from local (compound nucleus) levels, which also contribute a non-direct (CN) component to the capture. The direct capture thus contains amplitudes from the potential scattering (potential capture) and from resonance scattering (valence capture). The relative contributions of these two components can be calculated from the difference between the thermal neutron scattering length and the potential scattering length calculated from a realistic optical model. In most light nuclides the valence component is considerably smaller than the potential capture amplitude, but nevertheless its interference is important for a sound quantitative calculation of the direct capture cross section. The agreement between the direct capture theory and the cross sections measured at the Omega West spectrometer for primary E1 transitions in slow neutron capture by the silicon isotopes is good (like that for several other light nuclides that have been studied), the discrepancy usually being much smaller than 50%. The agreement between theory and experiment is poorer for the magnesium isotopes, but even in these cases the maximum discrepancies are not much greater than 50%. In both sets of isotopes the differences between direct capture theory and experiment can be attributed to compound nucleus radiative capture amplitudes from the wings of local resonance levels, and the likely parameters of these are physically reasonable. The analogous direct capture theory for M1 transitions fails to explain the magnitude of the measured cross sections for production of these gammas by about two orders of magnitude.

8. Scattering Length and Direct Capture for ^{46}Ca (S. Raman, J. A. Fernandez-Baca, R. M. Moon (ORNL) and J. E. Lynn)

The even mass number isotopes of calcium. $^{40,42,48}Ca$, have cross sections for their primary E1 transitions that show remarkably good agreement with direct capture theory, while the measured cross sections of ^{44}Ca are systematically low by almost a factor of two. It has been conjectured that this nuclide, being midway between the 20 and 28 neutron shells, has vibration-particle coupling that modifies the direct capture in a systematic way. It is of particular interest therefore to test the missing nuclide in the sequence, ^{46}Ca, against the direct capture theory. While the thermal neutron capture gamma ray spectrum and the spectroscopic factors of the final states have been known for

some time, the thermal neutron scattering length that is also required for the calculation of the direct capture cross section was unknown. This has now been measured by Bragg diffraction at the ORNL High Flux Isotope Reactor on samples of calcite enriched to 32% in ^{46}Ca. With the scattering length value of 3.55±0.21 fm employed in the calculation of the direct capture cross section of the primary E1 transitions we find quite good agreement with the measured cross sections. This is consistent with the findings for ^{40,42,48}Ca and the expectation that ^{46}Ca will be stiffer against vibrations about its spherical shape than ^{44}Ca. This work has been published in *Phys. Rev. C* **44**, 518 (1991).

9. ^{236}U Fission Cross Section (W. E. Parker, G. Morgan, P. W. Lisowski, E. Lynn, A. Carlson, N. Hill)

The fission cross section of ^{236}U has been measured with the LANSCE while neutron source using a fast parallel plate ionization chamber at a flight path of 56 m. In the energy range from 2 eV and 10 keV, very little of the previously reported structure was seen: Only five resonances were found, and only one of these groups exhibits any further substructure. A preliminary summary of the fission resonances and the associated fission widths is shown in Table A1. The width of the 5.45 eV resonance is more than 100 times smaller than previously reported. The average level spacing for the five resonances is 2.6 ± 0.4 keV.

Table A1
Fission Widths

Resonance Energy (eV)	Fission Width (meV)
5.45	0.00213
1291.7	2.563
1281.7	11.731
1268.8	1.274
2958.9	2.513

10. High Resolution (n,xγ) Measurements [R. O. Nelson, S. A. Wender, R. C. Haight, P. G. Young (LANL), H. Vonach (IRK, Vienna), A. Pavlik (IRK, Vienna)]

The program of measurements of absolute cross sections for (n,xγ) reactions begun in 1989 was continued with additional data obtained for ^{16}O and ^{208}Pb samples. The data were measured in the neutron energy range, $3 < E_n < 200$ MeV using HPGe detectors at 90 and 125 degrees. Gamma rays from product nuclei were measured in the range $0.2 < E_\gamma < 8$ MeV. The beam was obtained from the WNR spallation neutron source facility on a 40 m flight path at 30 degrees with respect to the incident 800 MeV proton beam from LAMPF.

Analysis of the new and previous data is continuing. Preliminary results on the $^{206,207,208}Pb(n,x\gamma)$ data were presented at a meeting of the nuclear physics sections of the European Physical Society in Salzburg, Austria in March, 1992. Some results from ^{56}Fe and ^{207}Pb were presented at the International Conference on Nuclear Data for Science and Technology in Juelich, Germany in March 1991.

11. Measurements of the Activation Cross Section for the Reaction $^{93}Nb(n,n')^{93m}Nb$ in the Neutron Energy Range 6-9 MeV (M. Wagner (IRK, Vienna), H. Vonach (IRK, Vienna), and R. C. Haight)

The reaction $^{93}Nb(n,n')^{93m}Nb$ is used as a long-term activation monitor. The half-life of ^{93m}Nb is 16 years. Much work has been carried out in recent years to improve the knowledge of the cross section below 6 MeV. Above 6 MeV, the data were uncertain by 14-18%. To reduce these uncertainties, a series of activation measurements was performed. Samples of niobium were irradiated at the LANL Ion Beam Facility using the intense, monoenergetic source of the $^{1}H(t,n)$ reaction. X-rays following internal conversion of ^{93m}Nb were detected at the Institut fuer Radiumforschung und Kernphysik, Vienna, Austria. Activation cross sections were deduced relative to the $^{58}Ni(n,p)^{58}Co$ activation cross section. Within the experimental uncertainties, the results confirm the recommended cross sections for $^{93}Nb(n,n')$ ^{93m}Nb in the International Reactor Dosimetry File, IRDF-90. Uncertainties in the cross section in this energy region are reduced by factors of 2-3.

12. Measurements of (n,charged particle) Reactions Below 50 MeV at WNR in the Study of Nuclear Level Densities [R. C. Haight, S. M. Sterbenz, D. S. Sorenson, T. Lee, S. M. Grimes (Ohio University), F. Bateman (Ohio University), H. Vonach (IRK, Vienna), P. Maier-Komor (Technical University, Munich)]

The WNR "white" neutron source is being used to study (n,p) and (n,alpha) reactions with the goal of furthering our understanding of nuclear level densities. The charged-particle emission spectra shape in compound nuclear reactions is determined by the nuclear level density in the residual nucleus. Competing de-excitation by neutron emission depends on the level density of excited states in the target nucleus. The "white" neutron source allows experiments in the energy range from threshold to above 30 MeV. It is important to check that the inferred level densities be the same regardless of the incident neutron energy. Effects of pre-compound particle emission are evident at the higher end of the range and can be estimated, and corrected for, at lower energies. In the past year we have completed (n,α) measurements on ^{56}Fe and begun (n,α) investigations of ^{59}Co.

13. Properties of Neutron Induced Fission on ^{238}U (A. Gavron, P. W. Lisowski, W. E. Parker, C. Zoeller)

In our ongoing program to measure various properties of fission induced by neutron reactions on ^{238}U, we have completed our analysis of mass-distribution data obtained in the 1990 run cycle at WNR. A thin (200 mg/cm^2) ^{233}U target was irradiated with neutrons between 2 and 200 MeV. Fission fragments were detected in two PIN diode arrays, and their energy was determined by comparison to ^{252}Cf fission fragments.

The masses of the fragments were obtained using momentum conservation, and correcting for neutron emission and energy loss in the foil. Results of the valley-to-peak ratio are presented in A-2 as a function of the energy of the incoming neutron. We note the rapid increase that does not level off even at the highest energies.

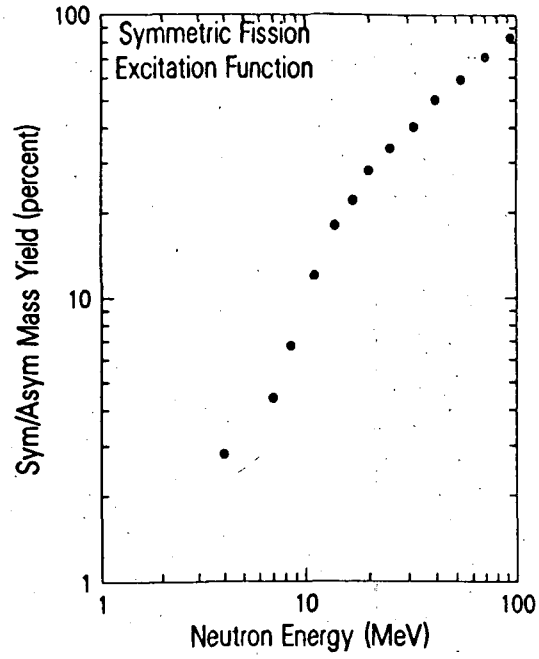

Fig. A-2. Fission fragment valley-to-peak ratio plotted as a function of incoming neutron energy.

14. Study of the Isovector Giant Quadrupole Resonance in the $^{40}Ca(n,\gamma_0)$ Reaction [C. M. Laymon, R. O. Nelson, S. A. Wender, L. R. Nilsson (The Svedberg Laboratory, Uppsala)]

The fore-aft asymmetry and the 90° differential cross section in the $^{40}Ca(n,\gamma_0)$ reaction were measured from E_n = 8 to 44 MeV. An energy dependent asymmetry was observed. This asymmetry was interpreted as the result of the isovector giant quadrupole resonance interfering with background E1 amplitudes. The present data agree with previous low-energy data. At higher incident neutron energies, the present data do not agree with the predictions of a direct semidirect (DSD) model calculation based on the low-energy data alone. Our attempts to adjust the resonance parameters in the DSD calculation give unreasonably large E2 strengths. In addition, the calculated 90° direct E1 differential cross section is larger than the data at high energies. If the direct E1 component is reduced to agree with the data, the calculated asymmetry is in good agreement with the data. Calculations using the pure resonance model reproduce the high energy cross section and also the measured asymmetry.

15. Accelerator Driven Systems for Commercial Waste Transmutation and Energy Production (C. D. Bowman)

The evaluation of accelerator-driven subcritical systems for (1) commercial waste transmutation and (2) energy production with concurrent waste transmutation has continued with an increasing level of support. The predicted performance is strongly dependent on nuclear data for specific fission products and actinides. Total and/or capture cross sections are required for ^{135}Cs, ^{137}Cs and ^{90}Sr in the thermal to 100 keV range. The experiment sensitivity should allow the detection of small p-wave resonances and the measurement of their parameters.

The transmutation of actinides depends significantly on the energy dependence of the fission and capture cross sections for a number of short-lived nuclei including ^{234}Pa (6.7 h), ^{238}Np (2.1 d), ^{243}Pu (5 h), ^{242}Am (16 h), ^{244}Am (10 h), and ^{242}Cm (163 d). Data is needed from 0.01 eV to 30 eV. Methods for fission cross section measurements have been

LANSCE pulsed neutron facility at Los Alamos. Similar studies might be done at the Rutherford Laboratory or at Dubna. A lead slowing-down spectrometer at a less intense source might also be useful.

16. Studies of Gamow-Teller and Giant Resonance Excitation in the (n,p) reaction at the WNR [J. L. Ullmann , J. Rapaport (Ohio Univ.), R. C. Haight, D. S. Sorenson, A. G. Ling (TRIUMF), P. W. Lisowski, B. K. Park (Ohio Univ.), X. Yang (Ohio Univ.), L. Wang (Ohio Univ.), J. L. Romero (UC-Davis), F. P. Brady (UC-Davis), C. R. Howell (Duke Univ.), W. Tornow (Duke Univ.)]

In nuclei with a neutron excess, the (n,p) reaction provides information on nuclear structure that is fundamentally different from that measured in the (p,n) reaction. The WNR "Target 4" White Neutron source at LAMPF provides an intense continuum of medium-energy neutrons, and an experiment to measure the (n,p) reaction at energies from 50 to 250 MeV has been under way. This experiment uses a "wall" of CsI detectors to measure the proton energy. The neutron energy maps out the region of rapid change in the $v_{\sigma\tau}/v_t$ ratio, and therefore provides a tool for studying spin versus non-spin excitations.

The first stage of the experimental program concentrated on Gamow-Teller strength in light nuclei. These experiments provided a "calibration" of cross section vs measured beta-decay B(GT) strengths.[1] Of particular interest was the first measurement of this ratio for the (n,p) reaction in the fp-shell, using the ^{64}Ni(n,p) reaction.[2]

The second stage involved studying giant resonances and Gamow-Teller strength in heavier self-conjugate nuclei, ^{32}S and ^{40}Ca.[3] The giant dipole resonance in these nuclei is obvious as a single bump at a beam energy of 60 MeV, but has been replaced by a broader structure identified as the giant spin-dipole resonance by 250 MeV beam energy.

A detailed multipole analysis of the spectra was made over the angle range 0 to 40 degrees.[3] In Ca, the Gamow-Teller strength for two states at 2.7 and 4.3 MeV was found to be 0.14 ± 0.02 and 0.17 ± 0.02, in substantial agreement with (p,n) measurements.[4] The total GT strength up to 15 MeV was found to be B(GT)=1.6 ± 0.1. The very existence of GT strength in spin-saturated nuclei like ^{40}Ca is taken to be evidence for ground-state correlations. Recent calculations for ^{40}Ca predict GT strength of the same order of magnitude as measured in this experiment, but are quite sensitive to the interaction that was used.[5]

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[1] D. S. Sorenson, J. L. Ullmann, A. G. Ling, P. W. Lisowski, N. S. P. King, R. C. Haight, F. P. Brady, J. L. Romero, J. R. Drummond, C. R. Howell, W. Tornow, J. Rapaport, B. K. Park, X. Aslanoglou, *Phys Rev C* **45**, R500 (1992).

[2] A. G. Ling, X. Aslanoglou, F. P. Brady, R. W. Finlay, R. C. Haight, C. R. Howell, N. S. P. King, P. W. Lisowski, B. K. Park, J. Rapaport, J. L. Romero, D. S. Sorenson, W. Tornow, J. L. Ullmann, *Phys. Rev. C* **44**, 2794 (1991).

[3] B. K. Park, PhD Thesis, Ohio University (unpublished) and B.K. Park, et al., to be published.

[4] T. N. Taddeucci, et al., *Phys. Rev.* C28, 2511 (1983).

[5] S. Adachi, E. Lipparini, N. Van Giai, *Nucl. Phys.* **A438**, 1 (1985).

B. NUCLEAR DATA EVALUATION

1. Neutron-Induced Data for ^{127}I at Incident Energies Between 10^{-5} eV and 30 MeV (P. G. Young and R. E. MacFarlane)

Because of the use of NaI in gamma-ray detectors, knowledge of neutron-induced cross sections of ^{127}I is necessary for analysis and interpretation of many measurements. Because no general purpose evaluated data file exists in the ENDF/B system, we have performed an evaluation of all neutron-induced reactions on ^{127}I covering the neutron energy range 10^{-5} eV to 30 MeV. Resolved resonance parameters were taken from the analysis of Mughabghab[1] for use in the multilevel Breit-Wigner formalism. Resonance parameters are used to define cross sections for total, elastic, and capture cross sections from an incident neutron energy of 10^{-5} eV to 1 keV. Above the resonance region the evaluation is based on a theoretical analysis using various nuclear models parameterized to match the available experimental data.

The GNASH nuclear theory code[2] was used to perform Hauser-Feshbach statistical theory calculations covering the incident neutron energy range between 0.001 and 30 MeV. Calculations were carried out for all reactions that produce neutrons, protons, alpha particles, or gamma rays for incident neutron energies between 1 keV and 30 MeV. The RECOIL code by MacFarlane and Foster[3] was used to analyze and unfold the GNASH output for representation in ENDF/B MF=6 format, including energy-angle correlations in all light particle and recoil emission spectra. Angular distribution systematics by Kalbach[4] were used to describe angular distributions for continuum particles, as well as discrete reactions where direct reaction data were lacking. Compound nucleus and direct reaction/preequilibrium cross-section and angular distribution components were combined appropriately for (n,n') reactions to discrete states. Radioactivity data are supplied in the evaluation for the $^{127}I(n,\gamma)$ to the 24.99-m ground state of ^{128}I, the $^{127}I(n,p)$ reactions to the 9.35-h ground and 109-d 88-keV isomeric states of ^{127}Te, and the $^{127}I(n,\alpha)$ reactions to the 60.2-d ground, the 93-s 11-keV, and the 20.2-m 37-keV isomeric states of ^{124}Sb.

By way of example results, a comparison between the evaluation and measurement[6] of the nonelastic neutron emission spectrum that results from 14.6-MeV neutron bombardment of ^{127}I is given in Fig. B-1. The structure in the curve at higher energies results from the direct reaction calculations; the large cross section at lower energies is caused by compound nucleus/statistical processes; and the preequilibrium component accounts for much of the cross section in the 5-12 MeV range.

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[1]S. F. Mughabghab, *Neutron Cross Sections*, V. 1, Part B, Z = 61-100 (Academic Press Inc., 1984).

[2]P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," lectures presented during the *Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety*," International Centre for Theoretical Physics, Trieste, Italy, 10 February–13 March 1992 (LA-UR 92-205), to be published.

[3]R.E.MacFarlane and D.G.Foster,Jr., *J. Nucl. Mat.* **122** & **123**, 1047 (1984).

[4]C.Kalbach, *Phys. Rev. C* 37,2350(1988).

[5]D.Hermsdorf *et al.*, personal communication to NNDC of revisions to data published originally in *Kernenergia* 19, 241 (1976).

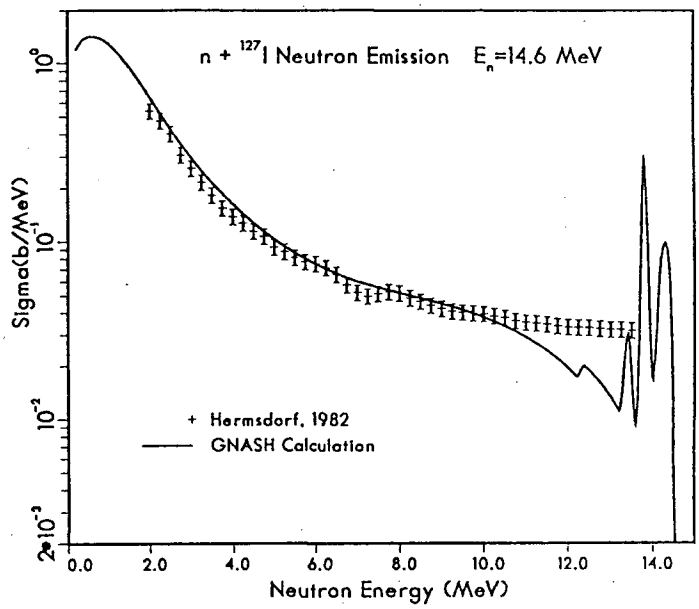

Fig. B-1. Angle-integrated neutron emission spectrum from n + ^{127}I reactions with 14.6-MeV incident neutrons. Only neutrons from nonelastic processes are included. The solid curve is the evaluation (taken directly from the GNASH calculations), and the crosses are the data of Hermsdorf et al.[5]

2. GNASH Nuclear Theory Code Development (P. G. Young, E. D. Arthur, and M. B. Chadwick)

A series of four lectures and three computer exercise sessions detailing the theory and use of the GNASH statistical Hauser-Feshbach plus preequilibrium theory code were prepared for presentation at the International Centre for Theoretical Physics in Trieste in March of 1992.[1] The short course demonstrates input setups for neutron- and charged-particle-induced calculations for a variety of problems and includes a detailed description of output quantities. An updated version of the code was provided for the computer exercises. Major improvements include addition of a simple photon decay mechanism that permits preequilibrium configurations to decay by E1 photon emission through the giant dipole resonance, thus permitting simple estimates of the direct-semidirect capture gamma-ray spectrum to be made within the framework of the exciton model.[2] A second improvement to the code is the incorporation of a new gamma-ray strength function capability by Kopecky and Uhl[3] that makes use of a generalized Lorentzian form for the strength function. The written version of the lecture notes is the basis for a new user's manual for the code.[1]

[1]P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," lectures presented during the *Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety*," International Centre for Theoretical Physics, Trieste, Italy, 10 February - 13 March 1992 (LA-UR 92-205), to be published.

[2]J. M. Akkermans and H. Gruppelaar, "Analysis of Continuum Gamma-Ray Emission in Precompound-Decay Reactions," *Phys. Lett.* **157B**, 95 (1985).

[3]J. Kopecky and M. Uhl, "Test of Gamma-Ray Strength Functions in Nuclear Reaction Model Calculations," *Phys. Rev. C* **42**, 1941 (1990).

3. Calculations of Long-Lived Isomer Production in Neutron Reactions

(M. B. Chadwick and P. G. Young)

We have carried out theoretical calculations for the production of the long-lived isomers ^{93m}Nb (1/2$^-$,16 yr), ^{121m}Sn (11/2$^-$, 55yr), ^{166m}Ho (7$^-$, 1200 yr), ^{184m}Re (8$^+$, 165 d), ^{186m}Re (8$^+$, 2 x 10^5 yr), ^{178m}Hf (16$^+$, 31 yr), ^{179m}Hf (25/2$^-$, 25 d), and ^{192m}Ir (9$^+$, 241 yr), all of which pose potential radiation activation problems in nuclear fusion reactors from 14-MeV neutron-induced reactions.[1] The work was performed in support of the U. S. and U. K. fusion reactor programs and is part of an IAEA Coordinated Research Programme. The statistical Hauser-Feshbach plus preequilibrium code GNASH was used to calculate (n,2n), (n,n'), and (n,γ) production modes, and the results were compared to experimental results (where available) and to systematics. In Fig. B-2 we show our results for 14-MeV (n,n') isomer ratios with the Kopecky and Gruppelaar[2] systematics and the limited experimental data. From all our comparisons we conclude that while such systematics are very useful, in many cases a full calculation (with a realistic description of the nuclear structure) is important in accurately determining isomer ratios. The isomeric ratios for states formed in (n,γ) reactions are particularly resistant to simple systematics-based descriptions. Additionally, we found that for high-spin isomers there can be a dramatic decrease in isomer ratio with decreasing energy, due to the decreasing amount of angular momentum that is brought into the reactions.

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[1]M. B. Chadwick and P. G. Young, "Calculations of Long-Lived Isomer Production in Neutron Reactions," M. B. Chadwick and P. G. Young, (invited) Proc. Consultant's Mtg. on *Methods of Calculation of Fast Neutron Nuclear Data for Structural Materials*, IAEA, Vienna, Austria, 14-15 November 1991 (LA-UR-91-3454), to be published.

[2]J. Kopecky and H. Gruppelaar, "Systematics of Neutron-Induced Isomeric Cross Sections Ratios at 14.5 MeV", ECN report ECN-200 (1987).

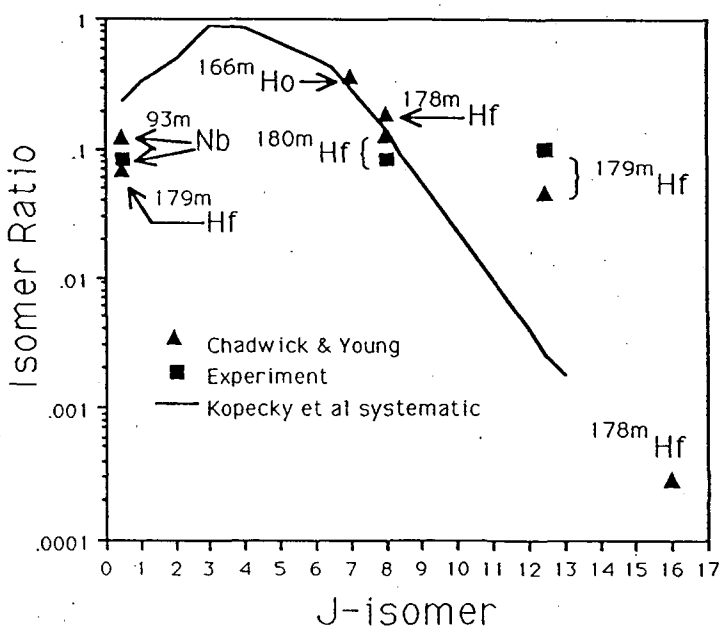

Fig. B-2. The (n,n') isomeric cross-section ratio as a function of isomer spin for 14-MeV incident neutrons. The Kopecky[2] systematics for one-step reactions are compared with GNASH calculations and with experimental data.

4. Theoretical Analyses of (n,2nγ) Reactions (M. B. Chadwick and P. G. Young)

Experiments at WNR/LAMPF have measured (n,xng) cross sections for individual gamma-rays for a number of different target nuclei covering incident neutron energies up to 200 MeV.[1,2] The nuclear reaction code GNASH was used to analyze these data up to 100 MeV for Fe and Pb isotopes.[3] The calculations are reasonably successful at describing many of the measurements, particularly below $E_n = 40$ MeV. One difficulty that was encountered in the original calculations concerned the prediction of (n,2nγ) cross sections above 30 MeV. To describe such processes, we have found it necessary to include the possibility that multiple preequilibrium emission occurs. In other words, more than one high-energy preequilibrium particle emission may occur before nuclear equilibration is reached. The dominant mechanism for this process is 1st-particle preequilibrium emission from the *2p1h* stage, followed by 2nd-particle preequilibrium emission from the residual *1p1h* stage. This mechanism describes a process in which an incident projectile may knock out two high-energy nucleons in the early stages of the reaction. Even though the inclusion of this multiple preequilibrium mechanism modifies the total neutron emission spectrum by only a small amount, the effect on the production cross sections of certain residual nuclei is considerable. In Fig. B-3 we compare our GNASH calculations plus the multiple preequilibrium contribution to the WNR/LAMPF measurement of the ^{56}Fe(n,2nγ) cross section for the 931-keV gamma-ray line in ^{55}Fe. It is evident that the multiple-preequilibrium mechanism must be included for incident energies above 30 MeV, and we conclude that measurements of (n,2nγ) cross sections for individual gamma rays provide a sensitive test of such mechanisms.

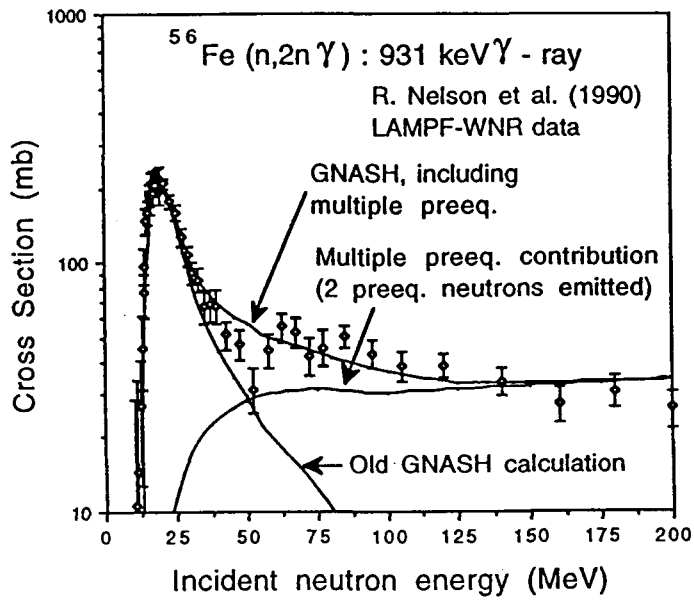

Fig. B-3. Comparison of calculated values of the ^{56}Fe(n,2nγ)^{55}Fe cross section for the 931-keV gamma-ray with measured data.[1,2]

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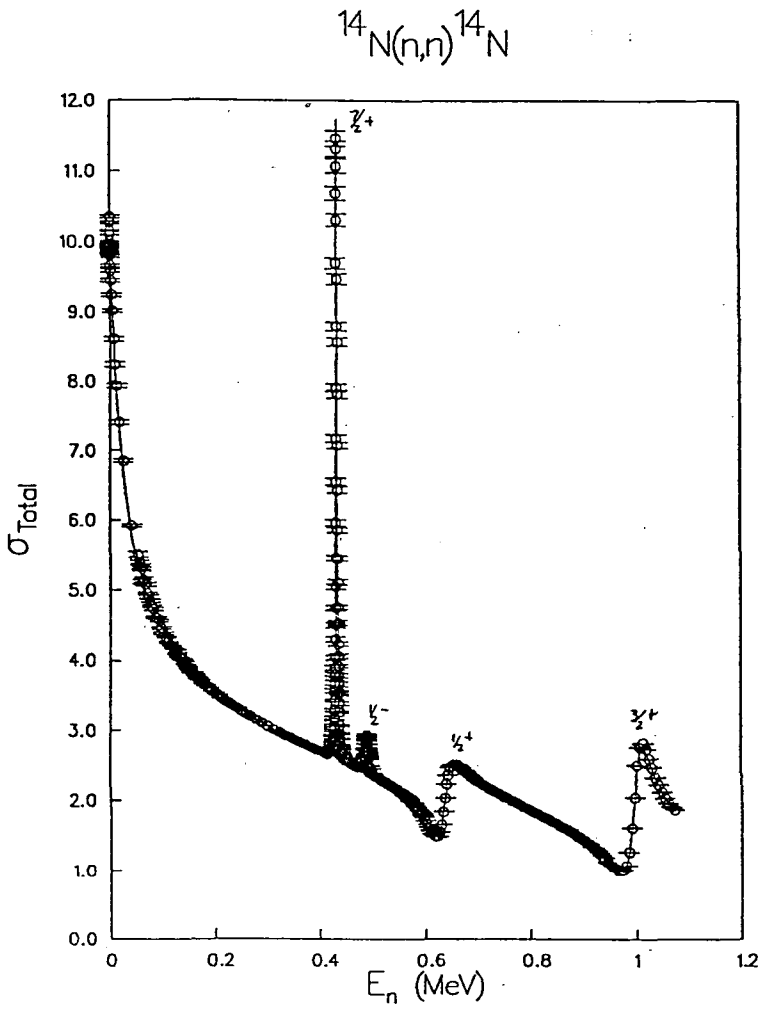
[1]R. C. Haight, D. M. Drake, M. Drosg, C. M. Laymon, G. L. Morgan, R. O. Nelson, S. A. Wender, P. G. Young, H. Vonach, A. Pavlik, S. Tagesen, D. C. Larson, and D. S. Dale, "Cross Sections for the Reactions ^{204,206,207,208}Pb(n,xn), $1 \leq x \leq 11$, from Threshold to Over 100 MeV," *Bull. Am. Phys. Soc.* 35, 1038, I6.8 (1990).

2R. O. Nelson, D. M. Drake, R. C. Haight, C. M. Laymon, S. A. Wender, P. G. Young, M. Drosg, A. Pavlik, H. Vonach, and D. C. Larson, "Neutron-Induced Gamma-Ray Production," Proc. 7th Int. Symp. on Capture Gamma-Ray Spectroscopy and Related Topics, Asilomar, California, LA-UR-90-3498 (1990).

3P. G. Young, R. C. Haight, R. O. Nelson, S. A. Wender, C. M. Laymon, G. L. Morgan, D. M. Drake, M. Drosg, H. Vonach, A. Pavlik, S. Tagesen, D. C. Larson, and D. S. Dale, "Calculation of (n,xγ) Cross Sections between Threshold and 100 MeV for Fe and Pb Isotopes: Comparisons with Experimental Data," Proc. IAEA Third Research Coordination Mtg. on Methods for the Calculation of Neutron Nuclear Data for Structural Materials of Fast and Fusion Reactors, 20-22 June 1990, IAEA, Vienna, Austria (LA-UR90-2129), INDC(NDS)-247, p. 239.

5. R-matrix Analysis of Reactions in the ^{15}N System (G. M. Hale, P. G. Young, and M. B. Chadwick

We have restarted the ^{15}N analysis[1] that was used to provide the ENDF-VI neutron cross sections for ^{14}N at energies below 2.3 MeV, including the precise neutron total cross sections[2] measured recently at Oak Ridge National Laboratory. These new data indicate that the first visible resonance above the neutron threshold at 433 keV has J=7/2, and we have found that more reasonable R-matrix parameters result when the parity is taken to be positive.



The fit to the total cross section in the region below 1 MeV is shown in Fig. B-4. The next three structures visible in the total cross section above the $7/2^+$ resonance have J^π assignments of $1/2^-$, $1/2^+$, and $3/2^+$, respectively. In addition, the fits to the data for other reactions included have been improved by trying other J^π assignments for some of the levels occurring at excitation energies below 13 MeV in ^{15}N. Fits to integrated cross sections and excitation functions for these other reactions are shown in Fig. B-5.

Fig. B-4. R-Matrix fit to the recent n+^{14}N total cross section measurement of Harvey *et al.*[2] at energies below approximately 1 MeV.

[1]G. M. Hale, P. G. Young, M. Chadwick, and Z.-P. Chen, "New Evaluations of Neutron Cross Sections for ^{14}N and ^{16}O," Proc. Int. Conf. on Nuclear Data for Sci. and Tech., Jülich, Germany, 13-17 May 1991.

[2]J. A. Harvey, N. W. Hill, N. M. Larson, and D. C. Larson, "Measurement of the Nitrogen Total Cross Section from 0.5 eV to 50 MeV, and Analysis of the 433-keV Resonance," Proc. Int. Conf. on Nuclear Data for Sci. and Tech., Jülich, Germany, 13-17 May 1991.

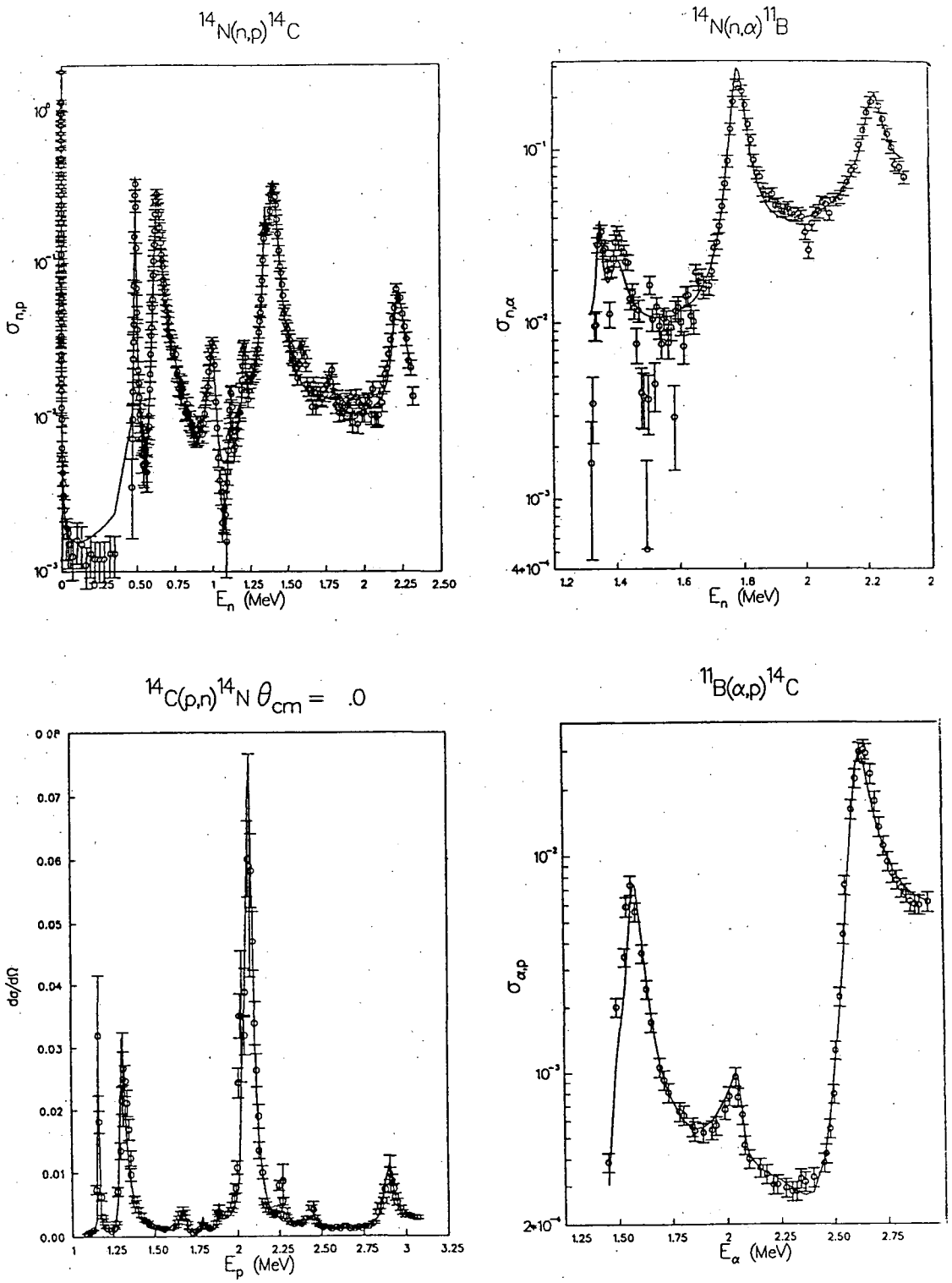


Fig. B-5. R-matrix fits to the integrated cross sections for $^{14}N(n,p)^{14}C$ (upper left), $^{14}N(n,\alpha)^{14}C$ (upper right), $^{11}B(\alpha,p)^{14}C$ (lower right), and to the zero-degree excitation function for the $^{14}C(p,n)^{14}N$ differential cross section (lower left).

6. R-matrix Analysis of Reactions in the ^{5}He System (G. M. Hale)

New data provided by M. Drosg (U. Vienna) for the T(d,n)^{4}He differential cross section at deuteron energies ≤ 7 MeV have been included in our ^{5}He system R-matrix analysis. The new fit, which required partial waves up through l = 4 in the d+t channel, gives a very good description of the added differential cross-section data, as is shown in Fig. B-6, while maintaining a good representation of the large body of cross-section and polarization measurements that had been considered previously. In particular, the low-energy T(d,n)^{4}He cross sections important in the thermonuclear regime changed by less than 1% from their previous values.[1]

[1]G. M. Hale, "d-t Cross Section and Reaction Rate," Los Alamos National Laboratory memorandum T-2-M-1767 (September 1986); H.-S. Bosch and G. M. Hale, "Improved Formulas for Fusion Cross Sections and Thermal Reactivities," to appear in *Nuclear Fusion* (April 1992).

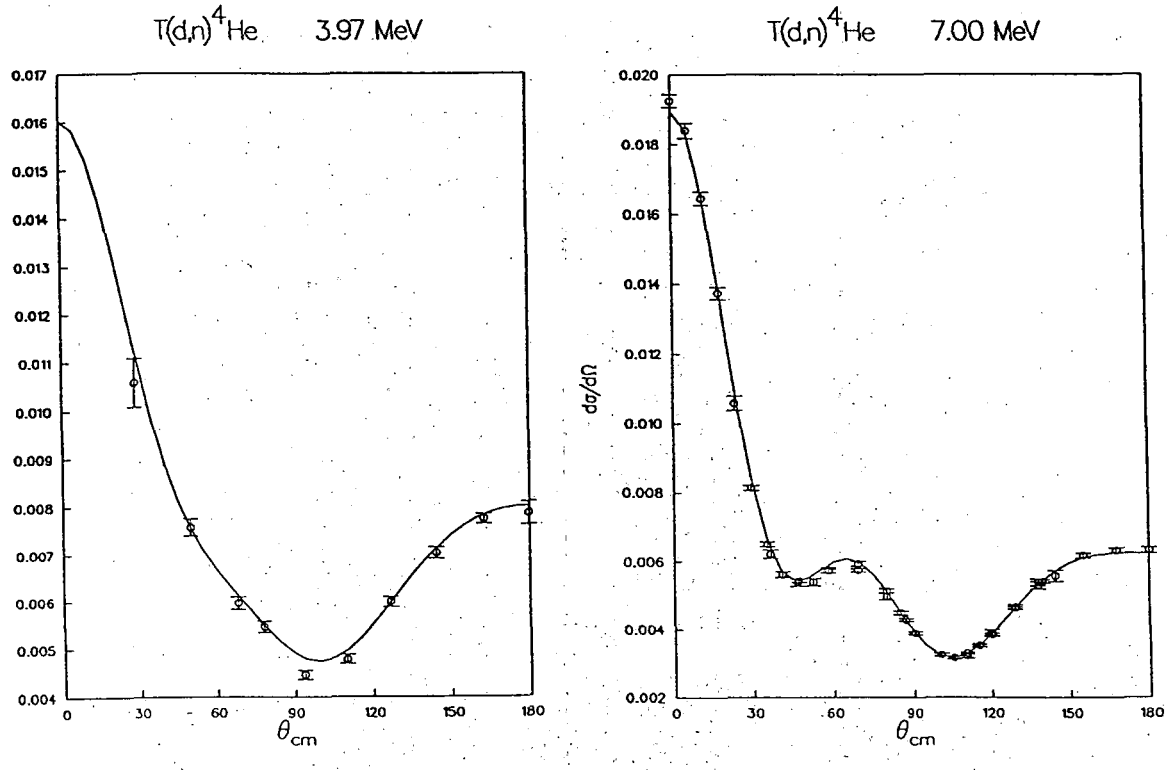


Fig. B-6. R-matrix fits compared with the T(d,n)^{4}He differential cross section measurements of Drosg at E_d=3.97 MeV (left) and 7.00 MeV (right).

7. Refined Study of Nuclear Masses and Deformations [P. Möller, J. R. Nix, W. D. Myers (LBL), and W. J. Swiatecki (LBL)]

We have completed a comprehensive calculation of ground-state masses and deformations for 8979 nuclei ranging from oxygen to A = 339 and extending from the proton drip line to the neutron drip line.[1] The macroscopic contribution to the mass is calculated with the finite-range droplet model, and the microscopic corrections are calculated by use of Strutinsky's method with a folded-Yukawa single-particle potential. By including ε_3 and ε_6 shape degrees of freedom in addition to the usual ε_2 and ε_4 deformations, we have eliminated most of the systematic discrepancies that previously existed for heavy nuclei. We have also demonstrated the contribution to nuclear masses of the Coulomb redistribution energy, which becomes increasingly important for heavy nuclei. With a theoretical error of 0.778 MeV, the present calculation can be reliably extrapolated to nuclei far from the region of known nuclei.

[1]P. M Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, "The Coulomb Redistribution Energy as Revealed by a Refined Study of Nuclear Masses," Nucl. Phys. A536, 61-71 (1992).

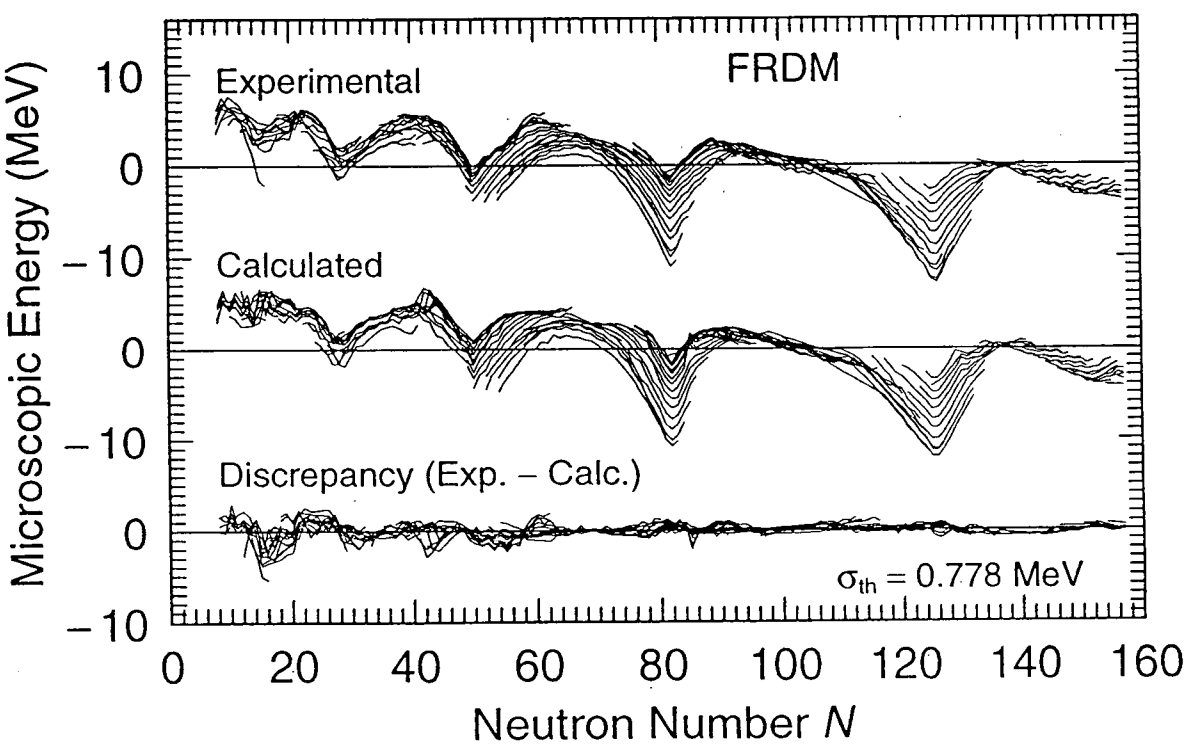


Fig. B-7. Comparison of experimental and calculated microscopic corrections for 1654 nuclei, for a macroscopic model corresponding to the finite-range droplet model. The bottom part showing the difference between these two quantities is equivalent to the difference between measured and calculated ground-state masses.

8. Nuclear Ground State Properties in a Relativistic Point Coupling Model
[D. G. Madland, T. Hoch and B. A. Nikolaus (Inst. für Kernphysik, Technische Hochschule Darmstadt, Darmstadt, Germany)]

We have obtained initial results in the calculation of nuclear ground state properties in a relativistic Hartree-(Fock) approximation.[1] Our model consists of Skyrme type interactions in four-, six-, and eight-fermion point couplings in a manifestly nonrenormalizable Lagrangian, which also contains derivative terms to simulate the finite ranges of the mesonic interactions. A self-consistent procedure has been developed to solve the model equations for several nuclei simulataneously by use of a generalized nonlinear least-squares adjustment algorithm. With this procedure we determine the nine coupling constants of our model so as to reproduce measured ground state binding energies, rms charge radii, and spin-orbit splittings of selected closed major shell and closed subshell nuclei in non-deformed regions. The coupling constants obtained in this way predict these same observables for a much larger set of closed shell spherical nuclei to good accuracy and also predict these quantities for similar nuclei far outside the valley of beta stability, for example, neutron-rich fission fragment nuclei. Finally, they yield properties of saturated nuclear matter in agreement with recent relativistic mean meson field approaches.

We show in Figures B-8 and B-9 two examples of our calculations of the effective potentials for neutrons and for protons moving in the fission-fragment nuclei ^{78}Ni and ^{132}Sn, respectively.

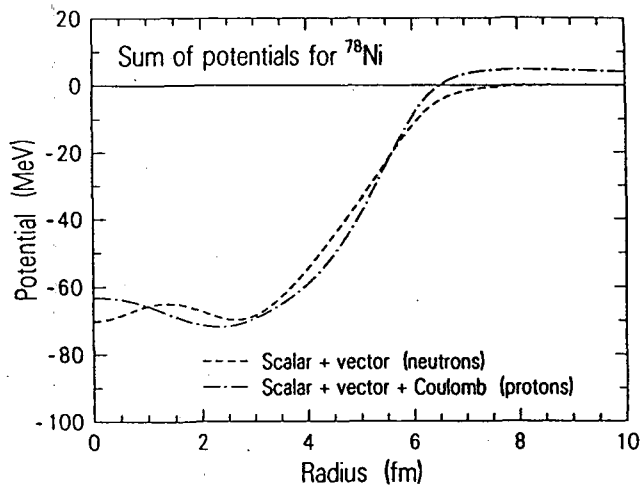


Fig. B-8. Effective neutron and proton potentials for the fission-fragment nucleus ^{78}Ni

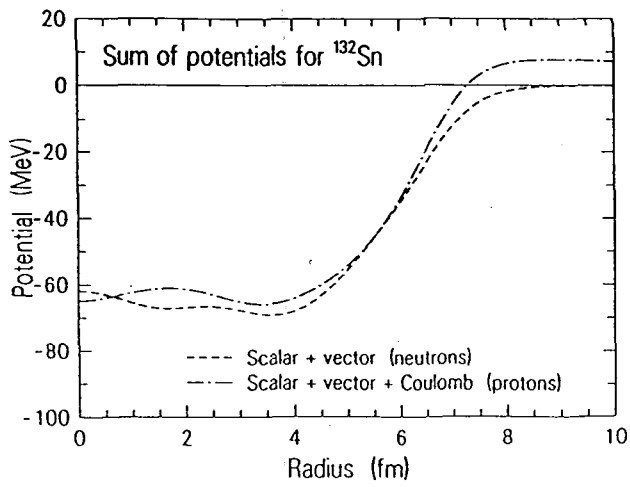


Fig. B-9. Effective neutron and proton potentials for the fission-fragment nucleus ^{132}Sn.

[1]B. A. Nikolaus, T. Hoch, and D. G. Madland, "Nuclear Ground State Properties in a Relativistic Point Coupling Model," submitted for publication to Phys. Rev. C. (March 1992).

9. Yields and Decay Data [T. R. England, W. B. Wilson, F. Mann (HEDL), B. F. Rider (G.E., retired), C. W. Reich (INEL), J. Katakura (JAERI), and M. C. Brady (ORNL)]

a. Decay Data

The ENDF/B-VI decay files are described in Refs. 1-4 as follows: References 1-2 are summaries of the data base; Reference 3 provides delayed neutron spectra comparisons and decay heat information; and Reference 4 provides extensive beta and gamma spectra comparisons.

The initial file contains 979 nuclides, all having complete beta, gamma, and delayed neutron spectra, and many having additional spectra. 750 of the nuclides are in the range of fission products, and the rest are either actinides or activation products. The initial file was further checked at LANL, HEDL, and BNL and was released in September 1991. For the first time we have included delayed neutron spectra in this file (271 nuclides). In addition, for nuclides in the fission product range, we have used nuclear model calculations to complete the partially measured spectra or added model spectra where no measurements existed (420 nuclides).

b. Yields

Complete fission product yield sets for 34 fissioning nuclides at one or more neutron fission energies and spontaneous fission were also released in September 1991. There are 50 sets of independent and cumulative yields, each set containing about 1200 yields and uncertainties. These initial data are based on our evaluation in early 1989. All sets are now being evaluated again with new data and distribution parameters plus an additional 10 sets (see Ref. 5). These new evaluations will replace the initial ENDF/B-VI release.

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[1]T. R. England, F. M. Mann, C. W. Reich, and R. E. Schenter, "ENDF/B-VI Radioactinide Decay and Yield Libraries," Trans. Am. Nucl. Soc. **60**, 614 (1989).

[2]C. W. Reich and T. R. England, "The File of Evaluated Decay Data in ENDF/B," Trans. Am. Nucl. Soc. **63**, 163 (1991).

[3]T. R. England, W. B. Wilson, B. F. Rider, C. W. Reich, F. M. Mann, R. E. Schenter, M. C. Brady, and J. Katakura, "Activation, Actinide, and Fission-Product Yields as Decay Data," in *Nuclear Theory and Applications Progress Report, January 1, 1989.*

[4]J. Katakura and T. R. England, "Augmentation of ENDF/B Fission Prosduct Gamma-Ray Spectra by Calculated Spectra," Los Alamos National Laboratory report LA-12125_MS (ENDF-352) (November 1991).

[5]T. R. England and B. F. Rider, "Evaluation and Compilation of Fission-product Yields in 1991," Los Alamos National Laboratory informal document (ENDF-349), in preparation.

10. Nuclear Data for Neutron Transmutation Calculations [W. B. Wilson, T. R. England, R. J. LaBauve, F. M. Mann (HEDL), and P. G. Young]

Transmutation calculations, describing the temporal inventory of all stable and radioactive nuclides in irradiated materials, have been required for several medium-energy (*e.g.*, LAMPF, GTA, ATW, APT) and high-energy (*e.g.*, SSC) facilities. Radiation transport in these problems is calculated at higher energies with the LAHET Monte-Carlo code[1] using nuclear reaction models; neutrons and photons below 20 MeV are transported with the MCNP Monte-Carlo code[2] using evaluated neutron reaction data. Transmutation calculations couple spallation- and high-energy fission-product production from LAHET with neutron transmutation in CINDER'90 using the MCNP-calculated neutron flux and evaluated nuclear data libraries. These data must include radioactive-decay, neutron-reaction, fission-product yield, and radiological-hazard data for a wide range of targets, products, and reactions.

A cooperative HEDL-LANL effort in the collection and evaluation of nuclear data for this wide range of nuclides and parameters has led to the formation of libraries with accuracy and completeness far exceeding that previously accumulated--due largely to the availability of products of recent US and foreign nuclear data efforts.

Radioactive decay data for over 3000 nuclides have been accumulated from ENDF/B-VI;[3-5] HEDL's Master Decay Library (MDL;[6] Browne and Firestone;[7] and Walker, Parrington, and Feiner.[8] The use of ENSDF[9] based data in the MDL resulted in many incomplete decay schemes, which were completed with data from the other sources or from estimates.

Reaction cross sections were taken largely from the European Activation File version EAF-2[10] for $Z \leq 84$. However, reaction branchings to ground- and isomeric-state products in EAF-2 at all neutron energies are, in general, those applicable at E_n= 14.5 MeV; a few of the (n,γ) reactions have step-function branchings to account for energy dependencies. The thermal cross-section and resonance integral data of Walker *et al* [8] have been used, where applicable, with the EAF-2 14.5-MeV branching to create a set of linear-linear interpolants for branching. Resulting multigroup branchings were imposed upon total reaction data from EAF-2, processed ENDF/B-V data collapsed with the TOAFEW-V code,[11] or processed GNASH-calculated cross sections.[12] Cross sections for some particularly important reactions on Ta, W, and Pb were produced in more complete LANL evaluations.

Fission-product yield data were formed by combining the fifty fission-yield sets from the '83 pre-ENDF/B-VI evaluation[13] with the ten yield sets produced in a recent '89 evaluation.[14] This combined library describes the distribution of fission products associated with thirty-six nuclides undergoing spontaneous fission and/or neutron-induced fission at one or more incident neutron energies.

Radiological hazard data are combined with any calculated inventory of radionuclides to indicate the hazard associated with the inventory. These data, which define the dilution in air or water required for acceptable release to the environment, were recently reevaluated by the Nuclear Regulatory Commission for 10CFR10.[15] The data were examined and extended to missing nuclides or diluents using the rationale of the NRC documentation, forming a single set of conservative dilution requirements.[16]

The result of this data evaluation-collection effort includes data required for most transmutation problems for targets of $1 \leq Z \leq 100$, with accuracy generally decreasing near the limits of increasing Z and decreasing halflife. Additional data, particularly decay spectra, will be added as they become available.

References:

[1]R. E. Prael and H. Lichtenstein, "User Guide to LCS: The LAHET Code System," Los Alamos Nat. Lab. informal document LA-UR-89-3014 (September 1989).

[2]J. F. Briesmeister, Ed., "MCNP--A General Monte Carlo Code for Neutron and Photon Transport, Version 3A," Los Alamos Nat. Lab. report LA-7396-M, Rev. 2 (Sept. 1986).

[3]Evaluated Nuclear Data File (ENDF/B), Versions V and VI, maintained and distributed by the National Nuclear Data Center, Brookhaven Nat. Lab., Upton, N.Y.

[4]T. R. England, F. M. Mann, C. W. Reich and R. E. Schenter, "ENDF/B-VI Radioactive Decay and Yield Libraries," Trans. Am. Nucl. Soc. **60**, 614 (1989).

[5]C. W. Reich and T. R. England, "The File of Evaluated Decay Data in ENDF/B," Trans. Am. Nucl. Soc. **63**, 163 (1991).

[6]F. M. Mann, F. Schmittroth, T. R. England, and C. R. Reich, "Master Decay Library," in Reports to the DOE Nuclear Data Com., Nat. Nuclear Data Center report BNL-NCS-46173; DOE/NDC-58/U; NEANDC(US)-229/U; INDC(USA)-104/L (May 1991), 152.

[7]E. Browne and R. B. Firestone, Table of Radioactive Isotopes, John Wiley & Sons, NY, NY (1986).

[8]F. W. Walker, J. R. Parrington and F. Feiner, Nuclides and Isotopes, 14th Edition, General Electric Co., San Jose, Calif. (1989).

[9]Evaluated Nuclear Structure Data File (ENSDF), maintained and distributed by the National Nuclear Data Center (NNDC), Brookhaven Nat. Lab., Upton, N.Y.

[10]J. Kopecky and D. Nierop, "Contents of EAF-2: A Supplement to the EAF-2 Data File," Netherlands Energy Research Foundation report ECN-I-91-053 (July 1991).

[11]W. B. Wilson, T. R. England, R. J. LaBauve, and R. M. Boicourt, "TOAFEW-V Multigroup Cross-Section Collapsing Code and Library of 154-Group Processed ENDF/B-V Fission-Product and Actinide Cross Sections," Electric Power Research Institute report EPRI NP-2345 (April 1982).

[12]M. Bozoian, E. D. Arthur, R. T. Perry, W. B. Wilson, and P. G. Young, "Calculated Neutron-Activation Cross Sections for $E_n \leq 100$ MeV for a Range of Accelerator Materials," *Proc. Int. Conf. on Nuclear Data for Science and Technology*, May 30-June 3, 1988, Mito, Japan (1988), pp. 1199-1203.

[13]T. R. England and B. F. Rider, "Status of Fission Yield Evaluations," in R. E. Chrien and T. W. Burrows, Eds., *Proc. Speciaists Meeting on Yields and Decay Data of Fission Product Nuclides*, Brookhaven Nat. Lab., October 24-27, 1983; Brookhaven Nat. Lab. report BNL 51778 (1984).

[14]T. R. England, B. F. Rider, and M. C. Brady, "Yield Data for the Japan/US Actinides Program," Los Alamos Nat. Lab. informal document LA-UR-89-4023 (1989).

[15]*"Standards for Protection Against Radiation: Final Rule (May 21, 1991)."* **Code of Federal Regulations, Title 10, Part 20.**

[16]T. R. England, W. B. Wilson, and A. J. Martinez, "Radiation Protection Data to be Used in Assessing the Relative Ionization Toxicity of Calculated Mixtures of Radionuclides," Los Alamos Nat. Lab. informal document LA-UR 92-392 (Jan. 1992).

UNIVERSITY OF MASSACHUSETTS LOWELL

A. NEUTRON SCATTERING AND PROMPT FISSION STUDIES

(G.H.R. Kegel, J.J. Egan, A. Mittler, W.L. Chang, D.J. DeSimone, C.A. Horton, C.K.C. Jen, C. Narayan, M. O'Connor, P.A. Staples, M.L. Woodring, R. Venugopal and G. Yue.)

1. Neutron Scattering in ^{239}Pu from 0.2 to 1.0 MeV

Neutron elastic and inelastic scattering in ^{239}Pu are being studied via the time-of-flight technique. Individual levels and level groups up to 386 keV in excitation can be resolved in the time-of-flight spectra. So far we have obtained angular distributions at 550 keV and 700 keV. The results show that the elastic scattering data are in good agreement with ENDF/B-VI, but the inelastic data do not agree well with the evaluation. These results were presented in the 1991 Fall Meeting of the Division of Nuclear Physics of the APS. Measurements are in progress on excitation functions at 125° between 200 keV and 1 MeV.

2. Neutron Scattering in ^{181}Ta and ^{197}Au

We have initiated elastic and inelastic neutron scattering measurements for the low-lying levels in ^{181}Ta. The studies are being conducted via the time-of-flight technique. As in our ^{239}Pu measurements, the detector consists of a 1-cm thick disk of BC-418 mounted on a RCA 8850 photomultiplier tube. Currently, we are optimizing our time-of-flight spectrometer to obtain premium resolution. Our goal is to resolve inelastic doublets of the low-lying levels for incident neutron energies in the range 0.2 to 1.0 MeV. Our measurements will be compared to those of Smith et al.[1], as well as to ENDF/B-VI. Preliminary angular distribution results presented at the Fall Meeting of the Division of Nuclear Physics of the American Physical Society, for an incident neutron energy of 700 keV, agreed well with ENDF/B-VI for the elastic+6.24keV doublet, but the angular distribution for the 136.6-158.6 keV doublet has more structure than indicated by ENDF/B-VI. These preliminary results will be supplemented by further measurements in the coming year after we: decide on optimal experimental parameters; incorporate a new multiple scattering correction code into our analysis: update some in-house data reduction software. We are also contemplating performing similar measurements on ^{197}Au.

3. Prompt Fission Spectra Measurements

Several prompt fission spectra have been measured for neutron energies greater than the incident energy via the time-of-flight technique to determine the response of our detection system and to enable the experimental parameters to be optimized. Figure 1 shows the ratio of a ^{235}U fission neutron spectrum for an incident neutron energy of 2.5 MeV to that of the ^{235}U fission spectrum for an incident neutron energy of 0.57 MeV. Figure 2 shows the ratio of the ^{239}Pu fission spectrum for an incident neutron energy of 0.57 MeV to that of ^{235}U at an incident neutron energy of 0.57 MeV. Figure 2 does show the fission neutron spectrum dependence on mass as predicted by Madland and Nix.[2] Two considerable sources of error in the measurements to date

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1 A.B. Smith, P.T. Guenther and J.F. Whalen, Phys. Rev. 168(4), 1344 (1968).

2 D.G. Madland and J.R. Nix, Nucl. Sci. & Eng. 81,213-271 1982.

are the efficiency of the detector and the calibration of the energy scale. In the coming year we shall reduce these uncertainties by making use of the $^{9}Be(^{3}He,n)^{11}C$ and $^{2}H(d,n)^{3}He$ reactions for calibration.

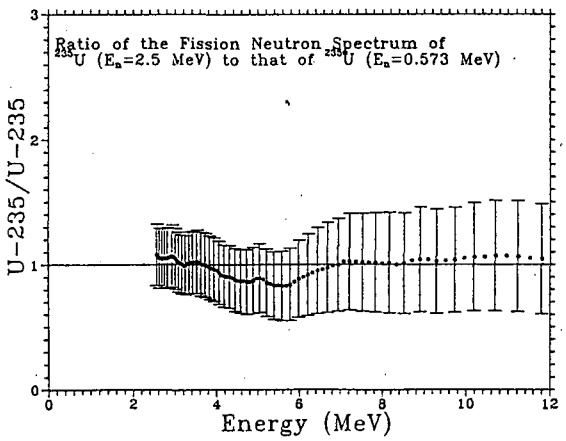

Figure 1.

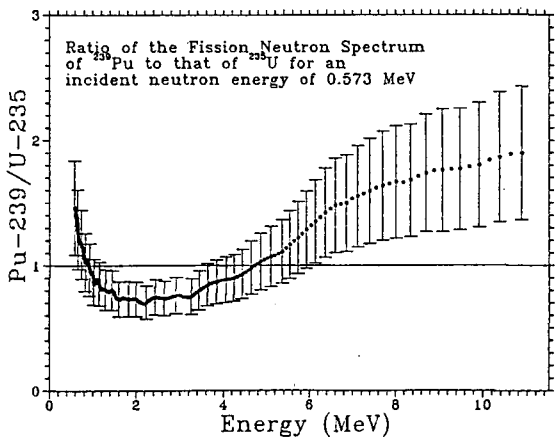

Figure 2.

4. A Neutron Standard Based on the $^{7}Li(p,n)^{7}Be$ Reaction

We plan to develop a fast neutron standard based on the $^{7}Li(p,n)^{7}Be$ reaction. Neutrons will be produced by bombarding a thick metallic lithium target with protons. Neutron time-of-flight techniques will be used to measure the zero-degree neutron energy spectrum. Differences in zero degree neutron energy spectra for different incident proton energies will be used to determine the zero-degree differential cross section. The cross section will be used in the future to perform neutron detector efficiency checks on neutron detectors employed in time-of-flight spectrometers. The utility of this standard is illustrated in the following. At our laboratory a time-of-flight spectrum from a thick metallic lithium target was obtained with a BC418 neutron scintillation detector placed at zero degrees to the incident proton beam. Figure 3 shows this spectrum after removal of the gamma ray peak and the background. This spectrum was divided into 100 keV wide energy bins to obtain the number of counts in each bin. The efficiency curve for this detector shown in Fig. 4 was obtained by dividing the number of counts in each bin by the number of neutrons emitted into the solid angle subtended by the detector in the energy range of interest as computed from a knowledge of the number of incident protons, the differential cross section for $^{7}Li(p,n)$ and the atomic stopping power for protons in lithium. The advantages of this technique over a ^{235}U fission chamber comparison are that: (1) there is a high neutron flux; (2) the measurement is rapid; (3) the data analysis is routine; (4) a quick efficiency determination is obtained. Preliminary results were presented at the DNP meeting in October of 1991. An investigation of experimental parameters and their effects on the neutron energy spectrum is underway at our laboratory.

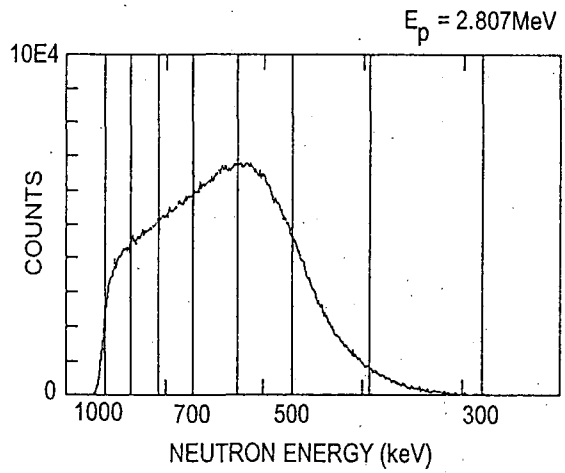

Fig. 3. Neutron time-of-flight spectrum obtained with a BC418 scintillation de--tector after removal of the main gamma ray and background. Spectrum was divided into 100-keV wide energy bins.

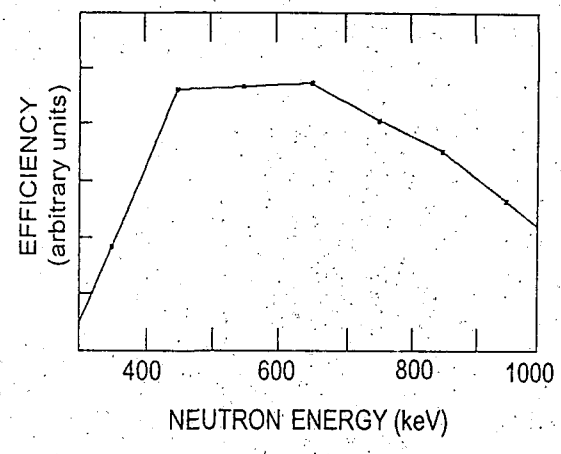

Fig. 4. Efficiency curve for BC418 scintillation detector.

5. Development of BaF_2 Scintillation Detectors as Triggers to Identify Fission Events

The second phase of our fission neutron spectra experiment, involving measurements at energies below the incident neutron energy, requires multi-parameter data acquisition and fast timing to identify fission events by the observation of fission gamma rays. Multiple-parameter data acquisition hardware and software has been developed and installed in the HP2100A microcomputer system and environment at our laboratory. Fission gamma rays will be observed with a scintillation detector array using BaF_2 scintillators noted for fast-timing characteristics. To test the fast timing capability of these detectors, as well as the multiple-parameter data acquisition system, lifetimes of low-lying nuclear states of several nuclides populated by Coulomb excitation will be measured by observing the de-excitation gamma rays. These lifetime measurements will be compared to values obtained previously.

6. Neutron Multiple Scattering Corrections

We have developed a multiple scattering correction scheme for cross-section measurements using a Monte Carlo simulation. A new direction biasing technique was used to attain the maximum Monte Carlo efficiency. A random number generator with a period of 2^{114} was used in the program. This generator has passed all known statistical "randomness" tests. The Monte Carlo code is written in C language and is portable to any computer. The results from the simulation are being applied to ^{238}U, ^{235}U and ^{232}Th cross-section data. We also pursued an analytical study of the multiple scattering integral for disk geometry.

7. Theoretical Investigations

The CN/DI calculations (with CINDY-COMNUC/KARJUP) of neutron inelastic scattering cross sections from 2.3 to 3.0 MeV incident energy on ^{232}Th and ^{238}U for individual or grouped excited states described in the previous report have been completed, in a collaboration with P.G. Young and E.D. Arthur of Los Alamos Scientific Laboratory. Results obtained from unmodified and slightly modified Bruyeres-le-Chatel optical-potential parameters were reported at the 1991 Spring Meeting of the American Physical Society/New England Section[3], the 1991 Julich International Conference on Nuclear Data for Science and Technology[4] and the 1991 Mazurian International Summer School on Nuclear Physics[5]. The latter also contained results for ^{239}Pu(n,n) and (n,n') for an incident neutron energy of 0.57 MeV, which were incorporated within a further contributed paper at the 1991 Fall Meeting of the American Physical Society/New England Section, held at Bates College[6].

Also in a global intercomparison project organized by the Nuclear Energy Agency's Nuclear Data Committee[7] compound-nuclear cross section computations were performed with CINDY for the ^{60g,m}Co(n,α)^{57}Mn reaction from 1 to 20 MeV incident energy with a special set of optical-potential parameters, allowing for competing n,p and α exit channels and continuum competition. A report on the findings from this project is in preparation[6] similar to that previously issued for nuclear-model code comparisons[8] and Hauser-Feshbach calculations[9].

B. DECAY HEAT STUDY
(W. Schier, D.J. Pullen, G.P. Couchell, M.F. Villani and J.M. Campbell)

Our report last year summarized a feasibility study demonstrating the measurement of premium quality beta and gamma-ray spectra from ^{235}U aggregate fission products using a helium-jet type transport system developed over the past decade in our study of delayed neutron spectra. The successful completion of this preliminary study has resulted in a research grant from the DOE in support of a program expected to provide decay heat information from the fission of ^{235}U, ^{238}U and ^{239}Pu over a delay time range extending from 0.1 to 50,000s. The study will entail:

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3 E. Sheldon, J.J. Egan, G.H.R. Kegel, A. Mittler and A. Aliyar, Bull Am. Phys. Soc. 36(7), 2041-2042, Paper S1 4.

4 E. Sheldon, A. Aliyar, J.J. Egan, G.H.R. Kegel, A. Mittler and E.D. Arthur, in Abstracts, Internat. Conf. on Nuclear Data for Science and Technology, Julich, Germany, 13-17 May, 1991, edited by S.M. Qaim (KFA Julich, Germany 1991), Paper D40, p.350.

5 E. Sheldon, E.D. Arthur, J.J. Egan, G.H.R. Kegel, A. Mittler and P.J. Young, Report SINS-2124/A (Otwock-Swierk, Poland, 1991), p.88.

6 E. Sheldon, A. Mittler and P.G. Young, Bull. Am. Phys. Soc. (in publication).

7 C. Nordborg and S. Cierjacks, Report NEANDC-297 "u" (1991)(unpublished).

8 H.K. Vonach and P. Nagel, Report NEANDC-253 "U"/INDC(NEA) 7 (1989) (unpublished).

9 P.E. Hodgson, E. Sartori and K. Shibata, Report NEANDC-298 "U"/INDC(NEA) 8 (1991) (unpublished).

a) measurement of gamma-ray spectra using NaI(Tl) for gamma decay heat and high-purity Ge for individual precursor lines as a function of delay time;

b) measurement of beta spectra and total beta count rates as a function of delay time.

The study will extend to long delay times so as to overlap with a number of previous aggregate measurements, but more importantly will include times well below 1s where no previous studies exist. Measurements below 10s serve as stringent checks to decay heat predictions based on summation calculations using individual fission-product data bases. Such comparisons will be greatly facilitated by our collaboration with T.R. England of the Los Alamos National Laboratory. As part of this collaboration, one of our graduate students (Ms. Joann Campbell) spent three months last summer at LANL under the supervision of Dr. England, and plans to continue summer residencies at LANL to assist in making detailed comparisons between summation calculation predictions of the beta and gamma-ray decay heat spectra and the experimental results (including the high resolution Ge spectra).

During the first year of the study we plan to:

1) acquire and calibrate a new 5"x5" NaI(Tl) and a high-purity Ge detector,

2) further refine and calibrate the beta spectrometer,

3) make more refined studies of the uniformity of fission product transfer by the helium jet system and their retention by the tape transport system,

4) measure ^{235}U beta and gamma-ray spectra for delay times 0.1 - 50,000s after a thermal-neutron-induced fission "pulse",

5) develop beta and gamma-ray unfolding codes for determining average energies from measured spectra and for extracting photopeak yields from Ge spectra,

6) compare individual gamma peak yields with summation calculation predictions.

The study of ^{238}U and ^{239}Pu will be conducted during the second and third years of our project funding period. The extension of these studies to include the thermal fission of ^{233}U and fast fission of ^{232}Th is planned for a succeeding project period.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)

(formerly the National Bureau of Standards)

A. NUCLEAR DATA MEASUREMENTS

1. The $^{10}B(n,\alpha_1\gamma)$ Cross Section from 5 keV to 4 MeV (R. A. Schrack and O. A. Wasson, NIST; D. C. Larson, J. K. Dickens and J. H. Todd, Oak Ridge National Laboratory)

The measurement of this important cross section standard has been completed in the neutron energy range from 0.2 to 4 MeV using the ORELA facility at Oak Ridge National Laboratory. The results were presented at the International Conference on Nuclear Data for Science and Technology[1] held in Jülich, Germany May 13-17, 1992. A more extensive paper has been accepted for publication. Although the present results are in good agreement with the ENDF/B-VI evaluation below about 2 MeV, discrepancies greater than 40% occur at the higher energies.

The measurements have been extended to lower neutron energies in order to obtain a more complete normalization of the cross section. A hydrogen gas proportional counter, which was thoroughly tested in previous work at NIST, replaced the plastic scintillator (black detector) for neutron fluence measurement. This measurement covers the 5-keV to 1-MeV neutron energy region. Data analysis is well advanced. We anticipate a further improvement in the accuracy of this vital neutron cross section standard.

2. Measurements of Neutron Fission Cross Sections Below 1 MeV (A. D. Carlson, NIST; G. L. Morgan, W. E. Parker, P. W. Lisowski, and S. J. Balestrini,[†] Los Alamos National Laboratory; N. W. Hill, Oak Ridge National Laboratory)

Data have been obtained on the $^{237}Np(n,f)$ and $^{239}Pu(n,f)$ cross sections at the Los Alamos Neutron Scattering Center (LANSCE) facility. These fission chamber measurements extend from about 1 MeV down to the resonance region. The $^{237}Np(n,f)$ cross section work is motivated by the need to improve the accuracy of this important materials dosimetry standard. This cross section has been utilized in crucial detectors for investigating pressure vessel degradation problems and providing information on the lifetime of these pressure vessels. The $^{239}Pu(n,f)$ cross section work is in response to the observation that the most

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[1] R.A. Schrack, O.A. Wasson, D.C. Larson, J.K. Dickens, and J.N. Todd, Measurement of the $^{10}B(n,\alpha,\gamma)^7Li$ Cross Section in the 0.3 to 4 MeV Neutron Energy Interval. Proceedings of the International Conference on Nuclear Data for Science and Technology, 13-17 May, 1991, Jülich, Fed. Rep. of Germany, to be published.

[†] Deceased

recent measurements of this cross section which were made at ORNL are about 4% lower than the average of the previously reported data in the energy range from about 20 eV to 100 keV. These data combined with ORNL transmission measurements for ^{239}Pu were the basis for a proposed ENDF/B-VI evaluation of the cross section in this energy region.

The measurements were made relative to the ^{235}U(n,f) and ^{10}B(n,α) standard cross sections by having ^{235}U and ^{10}B deposits in the ionization chamber. The ^{10}B(n,α) response which has a smooth energy dependence, also allows estimates of the background to be obtained with notch filters.

The data were stored in event mode so that they could be analyzed after the conclusion of the data-taking under different biasing conditions. These measurements are now being analyzed. It is expected that additional data to improve statistics on these nuclides will be obtained this summer, in addition to measurements on ^{233}U(n,f).

3. ^{235}U Fission Cross Section Measurements in the MeV energy Region (A. D. Carlson and O. A. Wasson, NIST; P. W. Lisowski, J. L. Ullmann, A. Gavron and S. Balestrini,† Los Alamos National Laboratory; N. W. Hill, Oak Ridge National Laboratory)

The results of this work which was performed at the target 4 neutron facility of LAMPF at LANL were presented[2] at the Jülich nuclear data conference. A more comprehensive report[3] of the work was given at the NEANDC Specialists Meeting on Neutron Cross Section Standards for the Energy Region above 20 MeV at Uppsala, Sweden. The fission rate for the work was determined with a multi-plate ionization chamber. The neutron fluence for this measurement was determined with the NIST Annular Proton Telescope (APT) which provides data up to about 30 MeV neutron energy. In a separate experiment[4] using two

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[2] A.D. Carlson, O.A. Wasson, P.W. Lisowski, J.L. Ullmann, and N.W. Hill, Measurements of the ^{235}U(n,f) Cross Section in the 3 to 30 MeV Neutron Energy Region, Proc. of the International Conference on Nuclear Data for Science and Technology, 13-17 May, 1991, Jülich, Fed. Rep. of Germany, to be published.

3. P.W. Lisowski, A. Gavron, W.E. Parker, J.L. Ullmann, S.J. Balestrini, A.D. Carlson, O.A. Wasson, and N.W. Hill, Fission Cross Sections in the Intermediate Energy Region, Proc. of the NEANDC Specialists Meeting on *Neutron Cross Section Standards for the Energy Region above 20 MeV*, 21-23 May, 1991, Uppsala, Sweden, NEANDC-305 U, pp. 177-186.

4. A.D. Carlson, O.A. Wasson, P.W. Lisowski, J.L. Ullmann, and N.W. Hill, Measurements of the ^{235}U(n,f) Cross Section for Neutron Energies from 3 to 30 MeV, Proc. of the NEANDC Specialists Meeting on *Neutron Cross Section Standards for the Energy Region above 20 MeV*, 21-23 May, 1991, Uppsala, Sweden, NEANDC-305 U, pp. 165-176.

different neutron fluence detectors, data greater than 250 MeV neutron energy were obtained. These data agree well and suggest that the ENDF/B-VI evaluation is low above 15 MeV neutron energy.

4. Neutron-Induced Charged-Particle Production Measurements on Oxygen for Neutron Energies from 1 to 40 MeV. (O. A. Wasson, NIST; R. C. Haight and S. Sterbenz, Los Alamos National Laboratory; and H. Vonach, University of Vienna)

The neutron-induced charged-particle production cross sections from oxygen are important for the determination of kerma factors for medical therapy and radiation protection. They are also required for the use of manganese baths in neutron source calibrations. Preliminary measurements of this reaction in the neutron energy interval from 2 to 40 MeV have been completed. The 90-degree left 10-m flight path on the target 4 neutron time of flight beam at the LAMPF accelerator facility at Los Alamos National Laboratory was utilized. The initial measurements were performed at the end of the 1991 LAMPF running cycle in August, 1991. The detection system was optimized for the measurement of alpha particles during this test. Particle identification and particle energy measurements were done at angles of 30, 60, 90 and 135 degrees in the laboratory system. The sample consisted of 2.7 microgram per cm^2 of ZrO_2 evaporated onto a thin tantalum backing. The neutron fluence was determined from ^{238}U and ^{235}U fission chambers located downstream from the scattering chamber.

Spectra were obtained from the oxide sample and also from a tantalum sample for background determination. Three-parameter data (flight time, energy loss in the proportional counter, and energy loss in the solid state detector) were recorded in event mode on the VAX computer disk for later analysis. Selected spectra were also accumulated during each run for system monitoring and initial analysis. The preliminary analysis indicates that suitable cross section and charged particle energy spectra can be obtained during a future two-week running period.

5. Absolute Thermal Neutron Counter Development (W. M. Snow, D. M. Gilliam, M. S. Dewey, and G.P. Lamaze, NIST; J. Richardson, Harvard University)

Two absolute total-absorption neutron counters are being developed for thermal and cold neutron beam experiments. In addition, a new set of ^6LiF and ^{10}B reference deposits is being prepared and assayed in cooperation with the Central Bureau for Nuclear Measurements, Geel, Belgium and the Scottish Universities Research and Reactor Centre, Glasgow, Scotland. The "black" neutron counters will be compared with the thin boron and lithium counters in a monochromatic beam at the NIST Research Reactor (NBSR). Both the black neutron counters and the thin 1/v transmission counters are expected to have independent calibrations approaching 0.1% in accuracy. There are three major motivations for this work: (1) accurate neutron density measurements for a free-neutron lifetime experiment, (2) improvement of isotopic neutron source emission standards, and

(3) development of improved isotopic standards for chemical analysis of lithium and boron. The first black counter tested was a boron capture gamma apparatus, which was calibrated both by alpha standards and by alpha-gamma coincidence measurements. The second black counter tested was a low-temperature calorimeter with a lithium-lead alloy target. About five months of preliminary testing of the new devices in a cold neutron beam has been completed, and tests in a monochromatic beam will begin during the next reactor cycle in April, 1992. Initial results are encouraging, with no systematic effects requiring corrections larger than about 2%.

B. NUCLEAR DATA COMPILATIONS, EVALUATIONS AND MEETINGS

1. The Evaluation of The Standards for ENDF/B-VI (A. D. Carlson, NIST; W. P. Poenitz, Argonne National Laboratory: R. W. Peelle, Oak Ridge National Laboratory; G. M. Hale, Los Alamos National Laboratory)

The documentation of the ENDF/B-VI standards is nearly complete. It will be published as a NIST Internal Report "The ENDF/B-VI Neutron Cross Section Standards" and will also be ENDF-351. The document contains a discussion of the evaluation procedure; references and some information for all the experimental data sets for the R-Matrix and simultaneous evaluations; plots and tabulated results of the evaluation.

2. NEANDC Endorsed International Inter-Laboratory Collaboration Group on The $^{10}B(n,\alpha)$ Cross Section Standards (A. D. Carlson, NIST, Chairman)

The $^{10}B(n,\alpha)$ cross sections have been actively used as neutron cross section standards, particularly in the low energy region. At the higher neutron energies, the quality of the standard is significantly reduced due to inconsistencies in the experimental measurements. There is general interest on the part of the community of cross section measurers, evaluators and users in improving these neutron cross section standards. The ^{10}B standard has received much attention lately as a result of its relatively poor data base and the problems resulting from it in the evaluation of the ENDF/B-VI standards.

An Inter-Laboratory collaboration group has been formed in order to provide a mechanism for improving these cross sections. The group was endorsed by the NEANDC. Representatives from the measurement, evaluation and user communities are members of this group.

At the first meeting of this group, concerns were expressed about the problems with the data base. There are discrepancies in the $^{10}B(n,\alpha_1\gamma)$, $^{10}B(n,\alpha_0)$ and even the total cross sections. It was noted that many of the discrepancies present in the total cross sections may be largely due to poor quality transmission samples.

A second meeting of this collaboration group was held during the Jülich nuclear data conference in May of 1991. Presentations were given on the status of the $^{10}B(n,\alpha)$ standard cross sections, recent measurements of the $^{10}B(n,\alpha_1\gamma)$ cross section in a NIST-ORNL collaboration, new results of the branching ratio from ORNL, new work on the angular distributions at LANL, plans for the fabrication of highly characterized transmission samples and proposals for new highly accurate total cross section measurements. It was concluded that sintered $^{10}B_4C$ should be a good form for transmission samples since it is expected that water and oxidation should not cause a problem. Also it is convenient to make transmission measurements with carbon to remove the contribution of the carbon in the sample. There was a discussion of further measurements which could improve the $^{10}B(n,\alpha)$ cross sections. Several suggestions were made for more work on the $^{10}B(n,\alpha_0)$ cross section since there were indications of problems in that area. Proposals were made to measure the $^{7}Li(\alpha,n)^{10}B$ cross section and use reciprocity to get the $^{10}B(n,\alpha_0)$ cross section. A new possibility which requires further thought is to accelerate ^{7}Li ions onto a helium gas target so that neutrons would be produced in a narrow cone in the forward direction. The neutron detection could then be done more easily.

Since the meeting, CBNM has ordered samples of $^{10}B_4C$ for measurements of the ^{10}B total cross section. CBNM has also made available to NIST a number of small area $^{10}B_4C$ samples which will be used in a NIST-ORNL collaboration for determinations of the ^{10}B total cross section. The total cross section facility at ORNL can use very small area samples. NIST is now characterizing the small area samples.

3. Photon and Charged-Particle Data Center (S. M. Seltzer, M. J. Berger, J. H. Hubbell, NIST)

a. Proton and Alpha Particle Stopping Powers and Ranges.

As part of the work of the ICRU Stopping Power Committee, an extensive set of proton and alpha-particle stopping powers (electronic and nuclear), ranges and penetration depths has been prepared for 25 elements and 48 compounds of dosimetric interest. The energy regions covered are 1 keV to 10000 MeV for protons and 1 keV to 1000 MeV for alpha particles. The results incorporate current theoretical and experimental information on heavy charged-particle stopping powers. The final version of the draft manuscript has been submitted to the ICRU, along with PC diskettes containing computer-readable versions of the tables.

b. Photon Energy-Absorption Coefficients.

A new calculation of photon energy-absorption coefficients has been completed. The methods are based on: (1) our current database of photon interaction cross sections, (2) current values of the fluorescence yield, with inclusion of fluorescence escape from the complete relaxation of the atom following creation of vacancies in all subshells due to the

ejection of orbital electrons in photoelectric absorption, incoherent scattering, and triplet production, (3) recent calculations of the bremsstrahlung yields of electrons and positrons slowing down, including the effects of energy-loss straggling and the build-up of secondary knock-on electrons, (4) inclusion of fluorescence energy escape due to electron- and positron-impact ionization in the course of slowing down, (5) updated calculations of positron annihilation-in-flight corrections, including the effects of energy-loss straggling, (6) a critical evaluation of the underlying secondary electron and positron spectra. The preparation of a manuscript and extensive tables is in progress. A follow-on task will be to revise the PC code that performs the calculations for any material so as to be suitable for distribution to interested users.

c. Electron and Positron Elastic-Scattering Cross Sections.

A database of elastic-scattering cross sections for electrons and positrons has been revised and re-organized. The results are from exact phase-shift calculations using Hartree-Fock potentials, and cover all neutral atoms with atomic numbers from 1 to 100, and electron and positron energies from 1 keV to 1 MeV (above which simpler methods are adequate).

OAK RIDGE NATIONAL LABORATORY

Highlights of this past year include a successful measurement of the charge distribution in the neutron. Nucleon models suggest that the neutron has a quark core with three electrically charged quarks (two negative and one positive) surrounded by gluons. The present problem is to determine the mean square charge radius of the neutron, normally quoted as the "charge radius". Two recent measurements give values of + 0.014 ± 0.003 and - 0.012 ± 0.004 fm^2 for this quantity.

To obtain the charge radius of the neutron, a neutron transmission measurement was done at the Oak Ridge Electron Linear Accelerator (ORELA) using a sample of liquid natural lead (to remove crystalline effects) by Jack Harvey and Nat Hill (ORNL) and Stefan Kopecky and Peter Riehs (University of Vienna). The energy range covered was 0.0014 eV to 100 eV, with time-of-flight techniques used to determine the neutron energy. This energy range is much larger than that covered by any previous experiment, and is possible because of the clean ORELA beam and well-characterized neutron detectors. The total cross section data were corrected for absorption, liquid state effects, Schwinger scattering and neutron electric polarizability. The resulting data, accurate to 0.1%, were subjected to a least-square fit to obtain a charge radius value of 0.0148 ± 0.0028 fm^2. This value is in agreement with the first value quoted above. Further measurements on samples of liquid ^{208}Pb and tin are planned to further reduce the experimental uncertainties.

Knowledge of the neutron resonance parameter values for nitrogen are necessary for studies involving transport of neutrons through air. For example, Hiroshima-Nagasaki dose studies attempt to derive doses to persons based on the source term and data obtained up to 2000 m from ground zero. A recent evaluation of the neutron cross sections for nitrogen, done for the (newly released) Sixth Version of the Evaluated Neutron Data Files, ENDF/B-VI, again demonstrated the inadequacy of the data base for the neutron total cross section. The most recent measurement below 500 keV was in 1961, with considerably poorer energy resolution than available at present. Of particular interest is the peak cross section, spin and orbital angular momentum ℓ of the lowest energy resonance at 433 keV. Present values given in ENDF/B-VI are 7.0 b for the peak cross section, 3/2 for the spin, and $\ell = 1$.

The ORELA neutron source was used for a series of transmission measurements to provide data from 0.5 eV to 50 MeV. A nitrogen gas sample was used. For the low-energy measurements from 0.5 eV to 300 keV the 80-m flight path was used, collimated to view the water moderator portion of the tantalum neutron producing target. A lithium glass detector was used to register the neutrons. To obtain the higher-energy data, the 200-m flight path was used, collimated directly on the tantalum portion of the neutron target. A separate high energy measurement using the beryllium block target was also done, to provide improved statistics above 10 MeV. Overall backgrounds were low, ranging from 0.1% to 1% of the total counts at a given energy for the sample out measurement. The corrected counts were normalized to a monitor counter, and converted to total cross sections. An uncertainty analysis and associated covariance matrix is available.

Analyzing our new high resolution data with our R-matrix code SAMMY, we find a peak cross section of 11.5 b (was 7.0 b) for the 433 keV resonance, and a spin of J = 7/2 (was 3/2), which requires an orbital angular momentum value of at least $\ell = 2$ (was $\ell = 1$). This combination of a larger peak cross section and a different angular distribution implied by $\ell = 2$ are expected to impact the long-standing problem of reconciling measured and calculated dose values following neutron transport through up to 2000 m of air for the Hiroshima-Nagasaki studies. In addition this

improved data base for the total cross section of nitrogen will be useful in studies of nitride fuels for fast and thermal reactors.

New experimental efforts include further measurements to pin down the normalization of the high-resolution ^{239}Pu fission data (part of a cooperative program with Geel), a measurement of the capture to fission ratio in ^{235}U from subthermal to several keV using the photon multiplicity detector, a measurement of the capture width of the 2.25-keV ^{60}Ni resonance with the redesigned 40-m capture system, and an extension to lower energies of the ^{10}B(n,$\alpha\gamma$) measurement (with NIST).

A measurement related to production of isotopes in the ORELA target was done. It yielded some interesting physics results, as well as providing useful information for handling used ORELA targets. Twenty-three radionuclides, including isomers, from ^{168m}Lu to ^{180}Ta, having half lives between 7 min and 1.4 yr, were produced by photon interactions with a sample of elemental tantalum. Yields of production were deduced from decay gamma-ray data obtained using high-resolution detection systems and range over six orders of magnitude. The measured yield data for masses ≥171 were compared with calculated values based on models of nuclear electro-excitation followed by excitation reactions. Good agreement was obtained for masses ≥174, but for lighter masses the calculations tend to overestimate the experimental yields by up to a factor of eight. These results should have practical use not only for present electron accelerator operation but also for shielding calculations needed for future accelerator designs and applications.

Significant progress in meeting OHSA and other federal standards continues to be made, resulting in a safer and better-characterized facility.

A. CROSS SECTION MEASUREMENT

1. Capture, Total and Reaction

a. Measurement of the ^{10}B (n, α_0)/^{10}B (n, $\alpha\gamma$) Ratio Versus Neutron Energy[1] (L. W. Weston and J. H. Todd)

b. Electric Properties of the Neutron from Precision Cross Section Measurements[2] (J. Schmiedmayer, J. A. Harvey, N. W. Hill, and P. Riehs)

In neutron nuclear interaction the electric charge structure of the neutron (first inferred by its high magnetic moment and now established by the quark picture for hadrons) interacts with the Coulomb field of atomic nuclei. Contributions are expected from the electric polarizability α_1, because of an induced electric dipole moment, and from a nonzero mean squared charge radius $<\rho r^2>$. The latter is a lowest order term of the intrinsic neutron electron interaction seen on top of the Foldy interaction, which comes from the magnetic moment of the neutron. Both α_n and $<\rho r^2>$ change the scattering cross section σ_s as much as 0.2 percent. To determine $<\rho r^2>$, the

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1 *Nucl. Sci. Eng.* **109**, 113 (1991).

2 International Conference on Nuclear Data for Science and Technology, Julich, Federal Republic of Germany, May 13-17, 1991; proceedings will be published.

corrected shape of σ_s in first born approximation is $4\pi\ b_{Nc}^2 - 2b_{Nc}(b_F + b_1)Z(1-f(k)+\cdots)$. Z is the nuclear charge number and $f(k)$ the atomic form factor, b_{Nc}, b_F and b_1 are the scattering lengths of nuclear, Foldy, and intrinsic n-e^- interaction. From b_1 a value of $<\rho r^2>$ is derived. Preliminary measurements have been made at ORELA to study count rates and backgrounds down to 0.15 eV using a flight path length of 18 m. Additional measurements using liquid Pb samples, are planned for December 1990. Results are expected for the date of the meeting.

c. <u>^{56}Fe Resonance Parameters for Neutron Energies up to 850 keV</u>[3] (C. M. Perey, F. G. Perey, J. A. Harvey, N. W. Hill, N. M. Larson)

High-resolution neutron measurements for ^{56}Fe-enriched iron targets were made at the Oak Ridge Electron Linear Accelerator (ORELA) in transmission below 20 MeV and in differential elastic scattering below 5 MeV. Transmission measurements were also performed with a natural iron target below 160 keV. The transmission data were analyzed from 5 to 850 keV with the multilevel R-matrix code SAMMY which uses Bayes' theorem for the fitting process. This code provides energies and neutron widths of the resonances inside the 5- to 850-keV energy region, as well as possible parameterization for resonances external to the analyzed region to describe the smooth cross section from a few eV to 850 keV. The resulting set of resonance parameters yields the accepted values for the thermal total and capture cross sections.

The differential elastic-scattering data at several scattering angles were compared to theoretical calculations from 40 to 850 keV using the R-matrix code RFUNC based on the Blatt-Biedenharn formalism. Various combinations of spin and parity were tried to predict cross sections for the well defined $\ell > 0$ resonances; comparison of these predictions with the data allowed us to determine the most likely spin and parity assignments for these resonances.

The mean values and standard deviations of the distributions of the radiation widths are 0.92 ± 0.41 eV for the s-wave resonances, 0.45 ± 0.23 eV for the p-wave and 0.75 ± 0.27 eV for the d-wave resonances. The correlation coefficient between the s-wave reduced neutron widths and radiation widths using the parameters of the 10 s-wave resonances below 300 keV is equal to 0.29 ± 0.15; a markedly smaller value than the ones found for other nuclides in this mass region.

d. <u>^{10}B(n, $\alpha_1\gamma$)^{7}Li Cross Section Between 0.3 and 4.0 MeV</u>[4] (R. A. Schrack, O. A. Wasson, D. C. Larson, J. K. Dickens, and J. H. Todd)

Relative cross-section measurements for the ^{10}B(n, $\alpha_1\gamma$)^{7}Li reaction were made using the ORELA neutron source. The cross sections were measured by observing the 478-keV photon using a 30% "efficiency" intrinsic germanium detector. The neutron flux was monitored with a high efficiency plastic scintillator. Monte Carlo calculations were used to provide for multiple-scattering and neutron-attenuation corrections to the data. The measured cross sections differ as much as 40% from the ENDF/B-VI evaluation for incident neutron energies greater than 1.5 MeV.

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[3] ORNL/TM-11742 (December 1990)

[4] Submitted to *Nucl. Sci. Eng.,* January 1992.

e. Nitrogen Cross-Section Measurements at ORNL[5] (D. C. Larson)

Recent measurements of the neutron total cross section for nitrogen made at the Oak Ridge Electron Linear Accelerator (ORELA) are presented. A description of the measurements and data reduction, as well as comparisons with previous data and ENDF/B-VI, are given. Plans for measurement of the scattering cross-section angular distributions are described.

2. Actinides

a. Status of the ^{235}U, ^{239}Pu, and ^{241}Pu Resonance Parameters[6] (H. G. Derrien and G. de Saussure)

The situation with the neutron resonance parameters for ^{235}U and the fissile plutonium isotopes is reviewed following the major improvements in experimental data, resonance analysis tools, and processing capabilities that occurred in the 1981--1988 time period.

b. High Energy Resolution Measurement of the ^{238}U Neutron Capture Yield from 1 keV to 100 keV[7] (R. L. Macklin, R. B. Perez, G. de Saussure, and R. W. Ingle)

The purpose of this work is the precise determination of the ^{238}U neutron capture yield (i.e., the probability of neutron capture) as a function of neutron energy with the highest available neutron energy resolution. The motivation for this undertaking arises from the central role played by the ^{238}U neutron capture process in the neutron balance of both thermal reactors and fast breeder reactors. The present measurement was performed using the Oak Ridge Electron Linear Accelerator (ORELA) facility.

The pulsed beam of neutrons from the ORELA facility is collimated on a sample of ^{238}U. The neutron capture rate in the sample is measured, as a function of neutron time-of-flight (TOF), by detecting the gamma rays from the $^{238}U(n, \gamma)^{239}U$ reaction with a large gamma-ray detector surrounding the ^{238}U sample. At each energy, the capture yield is proportional to the observed capture rate divided by the measured intensity of the neutron beam. The constant of proportionality (the normalization constant) is obtained from the ratio of theoretical to experimentally measured areas under small ^{238}U resonances where the resonance parameters have been determined from high-resolution ^{238}U transmission measurements. The cross section for the reaction $^{238}U(n, \gamma)^{239}U$ can be derived from the measured capture yield if one applies appropriate corrections for multiple scattering and resonance self-shielding.

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5 Oral presentation, National Research Council's Subcommittee on A-Bomb Dosimetry, Washington, DC, July 25, 1992.

6 The INDC/NEANDC Joint Discrepancy File, B. H. Patrick and N. P. Kocherov, INDC(NDS)-235 (June 1990).

7 *Annals of Nuclear Energy*, (Submitted, January 1991).

Some 200 ^{238}U neutron resonances in the energy range from 250 eV to 10 keV have been observed which had not been detected in previous measurements.

c. High Resolution Fission Cross Section Measurements of ^{235}U and ^{239}Pu[8] (L. W. Weston and J. H. Todd)

The fission cross sections of ^{235}U and ^{239}Pu have been measured with very high neutron energy resolution (0.17 ns/m) in the energy region from 100 to 2,000 eV for ^{235}U and to 20,000 eV for ^{239}Pu. The purpose of this measurement was to provide fission cross sections with energy resolution comparable to that available from transmission measurements for the purpose of deriving multi-level resolved resonance parameters. Fission ion chambers were used to detect fission fragments and a ^{10}B ionization chamber was used to measure the relative neutron flux at the 86 meter flight path of ORELA. The measured fission cross sections are the highest resolution measurements of good accuracy reported in the neutron energy range above 300 eV.

B. DATA ANALYSIS

1. Theoretical

a. Pairing Corrections and Spin Cutoff Parameters in Exciton Level Densities for Two Kinds of Fermions[9] (C. Y. Fu)

b. Analysis of Beta-Ray Data Important to Decay Heat Predictions[10] (J. K. Dickens)

c. An R-Matrix Analysis of the ^{235}U Neutron Induced Cross Sections Up to 500 eV[11] (L. C. Leal, G. de Saussure, and R. B. Perez)

d. TNG Calculation of $^{60g}Co(n,p)$ and $^{60m}Co(n,p)$ Cross Sections and Proton Emission Spectra from 1 to 20 MeV[12] (C. Y. Fu)

$^{60g}Co(n,p)$ and $^{60m}Co(n,p)$ cross sections are needed for low-activation fusion material development. Since the targets are radioactive, there are no measured data. The NEANDC Working Group on Activation Cross Sections proposed at its 1989 Argonne Meeting a blind

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8 *Nucl. Sci. Eng.* (submitted May 1991).

9 *Nucl. Sci. Eng.*, **109**, 18 (1991).

10 *Nucl. Sci. Eng.*, **109**, 92 (1991).

11 *Nucl. Sci. Eng.*,**109(1)**, 1-17 (1991).

12 Contribution to NEANDC Blind Intercomparison of Model Calculations, summarized by S. Cierjacks at Julich, Germany, May 16, 1991.

intercomparison of calculations for these cross sections as a first step in assessing uncertainties of calculated data which dominate all of the existing fusion activation libraries, some of which contain nearly 10,000 reactions. The calculation presented in this paper was performed with the TNG code developed at ORNL. A brief description of the computational methods and parameters is given. The present calculated cross sections and proton-production spectra are presented in tables. A summary of the results of the intercomparison will be made by Dr. S. Cierjacks of Karlsruhe, Germany and Dr. C. Nordborg of the NEA Data Bank, Saclay, France, and will be presented at the Jülich Conference in May, 1991.

e. Status of Integral and Differential Consistency for Fe(n,n')[13] (C. Y. Fu)

Upgrades since 1986 of evaluated (ENDF/B) files for neutron inelastic scattering in ^{56}Fe were based on known physical deficiencies and a series of integral experiments. The nature of these upgrades is reviewed. The upgrades are all included in the ENDF/B-VI evaluation.

f. Calculation of (n,x) Cross Sections Between Threshold and 100 MeV for Fe and Pb Isotopes: Comparisons with Experimental Data[14] (P. G. Young, R. C. Haight, R. O. Nelson, S. A. Wender, C. M. Laymon, G. L. Morgan, D. M. Drake, M. Drosg, H. Vonach, A. Pavlik, S. Tagesen, D. C. Larson, and D. S. Dale)

g. Computed Secondary-Particle Energy Spectra following Nonelastic Neutron Interactions with ^{12}C for E_n Between 15 and 60 MeV: Comparisons of Results from Two Calculational Methods[15] (J. K. Dickens)

The organic scintillation detector response code SCINFUL has been used to compute secondary-particle energy spectra, $d\sigma/dE$, following nonelastic neutron interactions with ^{12}C for incident neutron energies between 15 and 60 MeV. The resulting spectra are compared with published similar spectra computed by Brenner and Prael who used an intranuclear cascade code, including alpha clustering, a particle pickup mechanism, and a theoretical approach to sequential decay via intermediate particle-unstable states. The similarities of and the differences between the results of the two approaches are discussed.

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[13] The INDC/NEANDC Joint Discrepancy File, B. H. Patrick and N. P. Kocherov, INDC(NDS)-235, 21 (June 1990).

[14] Proc. International Atomic Energy Agency, Final Meeting of a Coordinated Research Program, Vienna, Austria, June 20-22, 1990, pp. 239-250.

[15] ORNL/TM-11812, (April 1991).

h. Analysis of ^{249}Cf Neutron Cross Sections in the Resolved Resonance Region[16] (G. de Saussure, and N. M. Larson)

The purpose of the present work was to validate the ENDF/B-VI representation of the ^{249}Cf neutron cross sections in the resolved resonance region. Large discrepancies were observed in comparing fission cross section and transmission measurements with calculations based on ENDF/B-VI. Therefore, a new consistent analysis of the available data was done. The resonance parameters obtained in this new analysis are a significant improvement over the representation of the cross sections in the resolved resonance region in ENDF/B-VI.

The data are not sufficiently accurate to search for capture widths or to determine the spin of the resonances, so we have assumed a constant capture width of 30 meV and one open fission channel. Following ENDF/B-VI we have assumed $\ell = 0$ for all resonances and have distributed the resonances somewhat randomly between the two accessible J-values, $J = 4$ and $J = 5$.

2. ENDF/B Related Work

a. Chromium and Nickel Inelastic Scattering "Discrepancies"[17] (D. C. Larson)

The status of important data for the nickel and chromium isotopes is reviewed. No integral data are available. Differential data for incident energies up to 8 MeV exist for a number of isotopes, but differences often exceed quoted uncertainties. For the 8 to 14 MeV region important to fusion technologies, the data base is inadequate. For fast reactor applications, high resolution data in and just above the resonance region would remove the unphysical smooth cross sections from the evaluated files.

b. NEACRP/NEANDC Working Group on International Evaluation Cooperation[18] (D. C. Larson, C. L. Dunford, and C. Nordborg)

In the last three years, several newly evaluated nuclear data libraries have been released. Japan completed JENDL-3 in late 1989, JEF-2/EFF-2 was completed by Europe in 1991, and ENDF/B-VI was completed by the U. S. in 1989. With the support of the NEACRP and the NEANDC, (recently combined into the NEA Nuclear Science Committee NEANSC,) a Working Group was formed in 1989 to promote cooperative activities among the evaluation groups in OECD countries. Technical activities of the Working Group are carried out by subgroups formed to carry out specific investigations. Seven subgroups are currently active, with four more initiated by the Working Group at its meeting in May 1991. Brief descriptions of current subgroup activities are given.

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16 *Trans. Am. Nucl. Soc.* **64**, 540-541 (1991).

17 The INDC/NEANDC Joint Discrepancy File, B. H. Patrick and N. P. Kocherov, INDC(NDS)-235 (June 1990)

18 American Nuclear Society topical Meeting on New Horizons in Radiation Protection and Shielding, Pasco, WA, April 26-30, 1992; proceedings will be published.

c. Potential Improvements to ENDF/B-VI for Fusion Data[19] (D. C. Larson and C. Y. Fu)

While ENDF/B-VI is a significant improvement over previous versions for fusion reactor design calculations, several areas have not received attention and may need improvement. In addition, broadening of the contents of the evaluations to contain information not easily derived at present should be considered.

d. Progress and Problems in Energy-Related Nuclear Data (Summary Report)[20] (R. W. Peelle)

The International Conference is reviewed relative to needs for measured data in nuclear energy applications. Notable achievements were recorded in several research areas. Elsewhere, obstacles have inhibited development of adequate data. Major data areas are identified with various levels of progress during recent years. The present energy-related nuclear data base is characterized as inadequate relative to a rising standard of quality. Ongoing efforts can achieve the continual improvement required for future technology.

3. Standards

a. Current Status and Proposed Improvements to the ANSI/ANS-5.1 American National Standard for Decay Heat Power in Light Water Reactors[21] (J. K. Dickens, T. R. England, and R. E. Schenter)

C. FACILITY ACTIVITIES

1. Phase I Hazard Screening for the Oak Ridge Electron Linear Accelerator, Building 6010[22] (R. W. Peelle, J. A. Harvey, and T. A. Lewis)

Operations associated with the Oak Ridge Electron Linear Accelerator (ORELA) facility were reviewed in detail in accord with the Martin Marietta Energy Systems, Inc. (MMES) Safety Analysis Report Update Program Phase I Implementation Documents CSET-1 and CSET-2. Nearly all of the identified hazards were determined by the authors to be normal industrial hazards.

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[19] NEANDC Topical Conference on Nuclear Data for Fusion Reactor Technology, Karlsruhe, Germany, October 23, 1991; proceedings to be published.

[20] International Conference on Nuclear Data for Science and Technology, Julich, Germany, May 13-17, 1991; proceedings will be published.

[21] *Nuclear Safety*, 32(2), 209-221 (1991).

[22] HS/6010-EPM/F/1/Rev. 0 (November 1991)

The hazards that required scenario development are all related to accident conditions in which a sample under study in an ORELA neutron beam contains a hazardous amount of radioactive material such as ^{239}Pu. Scenarios involve hypothetical breaches of sample integrity such that some of the sample could become airborne as finely divided particulate matter and subsequently be breathed by a worker or member of the public. Each scenario examined was consistent with the associated hazard being "generally accepted."

The operational boundaries associated with these scenarios are discussed. It is assumed that a Laboratory Director's Safety Review Committee will continue to review ORELA, and it is recognized that experiments proposed in the future will require a safety assessment if the proposals extend outside the operational envelope covered in the present document. Following review of the hazards and based on the complex nature of the facility, the Plant Safety Evaluation Team classified the ORELA as a "Low" hazard facility.

2. Quality Assurance Plan Supplement for the Oak Ridge Electron Linear Accelerator[23] (J. A. Harvey, T. A. Lewis, and R. W. Peelle)

This Quality Assurance Plan Supplement covers the operation of the Oak Ridge Electron Linear Accelerator (ORELA) within the Nuclear Data Measurement and Evaluation Section of the ORNL Engineering Physics and Mathematics Division (EPM). The Engineering Physics and Mathematics Division Quality Assurance Plan, QAP-X-89-EPM-001, Rev. 1.0, applies to the ORELA; this supplement contains material on the additional quality assurance activities appropriate for the operation of the accelerator. ORELA operation activities are placed in Category III for QA planning purposes. Quality for the ORELA is measured by the consistent availability of appropriate neutron beams to experimenters, and by maintenance of worker safety and environmental releases within applicable standards. This Plan outlines the systematic actions taken to help assure the quality of the ORELA output.

3. Study of Radionuclides Created by ^{181}Ta (γ,xn yp) Reactions for Bremsstrahlung Photons Produced by 150-MeV Electrons[24] (M. A. Miller and J. K. Dickens)

Twenty-three radionuclides, including isomers, from ^{168m}Lu to ^{180}Ta, having half lives between 7 min and 1.4 yr, were produced by photon interactions with a sample of elemental tantalum. Yields of production were deduced from decay gamma-ray data obtained using high-resolution detection systems and range over six orders of magnitude. The measured yield data for masses ≥ 171 were compared with calculated values. Good agreement was obtained for masses ≥ 174, but for lighter masses the calculations tend to overestimate the experimental yields by up to a factor of eight. These results should have practical use not only for present electron accelerator operation but also for shielding calculations needed for future accelerator designs and applications.

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[23] QAP-X-89-EPM/ORELA-001, Rev. 1.0 (December 1991)

[24] ORNL/TM-11944 (January 1992).

4. Time Dependent Monte Carlo Calculations of the ORELA Target Neutron Spectrum[25] (S. N. Cramer and F. G. Perey)

The time dependent spectrum of neutrons in the water-moderated Oak Ridge Electron Linear Accelerator (ORELA) target has been calculated using a modified version of the MORSE multi-group Monte Carlo code with an analytic hydrogen scattering model. Distributions of effective neutron distance traversed in the target are estimated with a time and energy dependent algorithm from the leakage normal to the target face. These data are used in the resonance shape analyses of time-of-flight cross section measurements to account for the experimental resolution function. The 20 MeV-10 eV energy range is adequately represented in the MORSE code by the 174 group VITAMIN-E cross section library with a P_5 expansion. An approximate representation of the ORELA positron source facility, recently installed near the target, has been included in the calculations to determine any perturbations the positron source might create in the computed neutron distributions from the target. A series of coupled Monte Carlo calculations was performed from the target to the positron source and back to the target using a next-event estimation surface source for each step. The principal effect of the positron source was found to be an increase in the distance for the lower energy neutron spectra, producing no real change in the distributions where the ORELA source is utilized for experiments. Different configurations for the target were investigated in order to simulate the placement of a shadow bar in the neutron beam. These beam configurations included neutrons escaping from: (1) the central tantalum plates only, (2) the entire target with the tantalum plates blocked out, and (3) only a small area from the water. Comparisons of the current data with previous calculations having a less detailed model of the tantalum plates have been satisfactory.

[25] Submitted to *Nucl. Sci. Eng.*, March 1991.

OHIO UNIVERSITY

A. MEASUREMENTS

1. Inelastic Neutron Scattering from ^{13}C[1] (E.F. Saito, T.N. Massey, J.E. O'Donnell, J.F. Guillemette and R.O. Lane)

Neutron scattering from ^{13}C in the energy range from 8.75 to 11.50 MeV with laboratory angles from 15° and 160° has been performed at the Ohio University Accelerator Laboratory. Using the swinger facility, time–of–flight tunnel and neutrons produced by the $^{2}H(d,n)^{3}He$ reaction, scattering to the unbound levels was studied for the first time. The secondary neutron background prevents quantitative analysis at this time. However, from a qualitative point of view, it is clear that the inelastic scattering to the 7.55 MeV level, which is first observed at ~ 8.3 MeV, is dominant for neutrons with incident energy from ~ 9.5 to 11.5 MeV. Scattering to the 6.86 MeV level, which is first observed at ~ 8.0 MeV, is comparable to the 7.55 MeV level for incident neutrons up to ~ 9.5 MeV. Scattering to the 9.0 MeV level is first observed at ~ 11.0 MeV and produces a weak peak up to 11.5 MeV incident neutron energy.

2. Level Density of ^{57}Co[2] (V. Mishra, N. Boukharouba, C.E. Brient, S.M. Grimes and R.S. Pedroni)

Three techniques have been used to improve our knowledge of the level density of ^{57}Co. High resolution (ΔE ~ 5 keV) measurements of the spectrum from the $^{57}Fe(p,n)^{57}Co$ reaction have led to the identification of 14 new levels, while measurements of the spectrum from the same reaction with resolution of about 100 keV at a number of bombarding energies have been fit with Hauser–Feshbach calculations to deduce values for the level density parameter. Finally, Ericson fluctuation measurements of the $^{56}Fe(p,n)^{56}Co$ have yielded a value for the level density of ^{57}Co at 13 MeV. These results have been compared with compilations and with microscopic calculations.

3. Asymptotic S–Wave Normalization of the Deuteron by n–d Scattering (C.R. Howell*, R.J. Braun*, C.E. Brient, D.E. Gonzaley*, S.M. Grimes, G. Mertens**, R.S. Pedroni, C.D. Roper* and W. Tornow*)

The asymptotic S–wave normalization of the deuteron can be shown to be related to the elastic n–d cross section at backward angles. Recent measurements of this cross section[3-4] agree at 8 MeV but show significant disagreement at and above 10 MeV. An initial set of measurements at 8 and 10 MeV was performed at Ohio University. The spectrometer was then moved to TUNL to make measurements possible at 14 MeV. Data covering the angular range 140° to 180° in the center of mass system have been acquired. preliminary analysis indicates that cross sections in better agreement with

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1 Bull. Amer. Phys. Soc. 36, 2118 (1991).
2 To be submitted to Phys. Rev. C.
3 P. Schwartz et al., Nucl. Phys. A398, 1 (1983)
4 G. Jansen et al., Proceedings of the 10th International Conference on Few Body Problems, 1983, ed. B. Zeitnitz (North Holland, Amsterdam), p. 529
* Duke University and Triangle Universities Nuclear Laboratory, Durham, NC 27706
** Tübingen University, D–7400 Tübingen, Germany

Ref. 2 than Ref. 1 have been obtained. These values would also support values of the S–wave normalization obtained from electron scattering.[1]

4. Neutron Total Cross Section Measurements at Intermediate Energy[2] (R.W. Finlay, G. Fink*, W. Abfalterer, P. Lisowski**, G.L. Morgan** and R.C. Haight**)

New measurements of the neutron total cross sections have been performed as a function of neutron energy up to 600 MeV using the WNR facility at Los Alamos National Laboratory. Transmission measurements were performed for eighteen target nuclei with $9 < A < 209$ including isotopically–enriched samples of ^{40}Ca, ^{90}Zr and ^{208}Pb. While the goal of the experiment was to measure total cross sections about 100 MeV in small energy bins and with 1% statistical accuracy, much of the data at lower energy is significantly better than that. Rapid fluctuations in the cross sections of light nuclei below 20 MeV provide information on nuclear level density at high excitation energy. The overall dependence of the cross section on neutron energy can be interpreted in terms of optical models ranging in complexity from simple Ramsauer pictures to Dirac phenomenology. Preliminary results of some of these calculations will be presented.

5. Precision Total Cross Sections and the Optical Model at Intermediate Energy[3] (R.W. Finlay)

New measurements of neutron total cross sections between 5 MeV and 600 MeV are presented. These data do not provide an adequate basis for the development of an optical model potential, but they certainly can be used to test existing models. This presentation describes preliminary comparisons of theory with experiment for both phenomenological and microscopic models using both the Schroedinger equation and the Dirac equation. These comparisons indicate the need for additional information about the neutron–nucleus interaction at intermediate energy.

6. A Search for Neutron Total Cross Section Fluctuations in Nuclei with $9 < A < 209$[4] (V. Mishra, W. Abfalterer, S.M. Grimes and R.W. Finlay)

Neutron total cross sections for various nuclei in the above range have been measured from 4 to 600 MeV with exceptional statistics (1%) and time resolution (0.7 ns for a flight path of 38 m) using a white neutron source.[5] Level widths at rather high excitation energies in the compound nucleus can be derived from the excitation functions using Ericson analysis, provided that the energy resolution (ΔE) is smaller than the

1 R.W. Berard et al., Phys. Lett. 47B, 355 (1973)
2 Contributed paper to the International Conference on Nuclear Data for Science and Technology, May 13–17, 1991, Jülich, Germany
3 Invited paper at the Beijing International Symposium on Fast Neutron Physics, September 9–13, 1991, Beijing, People's Republic of China
4 Bull. Amer. Phys. Soc. 36, 2120 (1991)
5 R.W. Finlay et al., Intern. Conf. on Nucl. Sci. and Techn., Jülich (1991)
* Eugen–Richter Str. 159, D–7500 Karlsruhe 21, Germany
** P–Division, Los Alamos National Laboratory, Los Alamos, NM 87545

level widths (Γ). The extracted Γ is expected to increase with neutron energy until the compound nuclear processes are significant and decrease with increasing A. We will analyze excitation functions for F, Na, Al, Si, Ca, Sr, Nb and Bi for Γ as a function of energy resolution. The results will be compared with previous determinations and theoretical predictions. For large A, Γ can be small enough that ΔE becomes a limiting factor. This study would enumerate the limits and applicability of extracting level densities at high excitation energies via Ericson fluctuations as a function of A, ΔE and the excitation energy.

7. Neutron Emission Cross Sections on ^{93}Nb and ^{209}Bi at 20 MeV Incident Energy[1-2] (A. Marcinkowski*, J. Rapaport, R. Finlay, X. Aslanoglou** and D. Kielan*)

Double–differential neutron emission cross sections at 20 MeV incident energy have been studied for monoisotopic samples of ^{93}Nb and ^{209}Bi. Time–of–flight spectra were taken at several angles between 15° and 153° using a beam–swinger spectrometer. The data are averaged over 0.5 MeV energy bins and compared with quantum–mechanical, statistical multistep calculations.

8. Ground–State Gamow–Teller Strength in ^{64}Ni(n,p)^{64}Co Cross Sections at 90–240 MeV[3] (A. Ling†, X. Aslanoglou**, F.P. Brady††, R.W. Finlay, R.C. Haight†, C.R. Howell#, N.S.P. King†, P.W. Lisowski†, B.K. Park†, J. Rapaport, J.L. Romero††, D.S. Sorenson†, W. Tornow# and J.L. Ullmann†)

Cross sections have been measured for the reaction ^{64}Ni(n,p)^{64}Co at laboratory angles between 0° and 10° for incident neutron energies from 90 to 240 MeV. The ground–state cross sections together with the β^- decay ft value for the transition ^{64}Co(g.s.) $\rightarrow$ ^{64}Ni(g.s.) are used to normalize the q = 0 differential cross section in units of mb/sr per unit Gamow–Teller (GT) strength. This is the first absolute measurement of the A(n,p) unit cross section for a nucleus in the (fp) shell, and it may be used to calibrate the GT strength measured in other (n,p) reactions of similar mass nuclei. Since the (e^-,ν_e) channel involves the same nuclear matrix element as the (n,p) channel, knowledge of GT strength in these nuclei is important for supernova modeling codes which depend on knowledge of e^- capture rates of (fp)–shell nuclei to determine parameters of stellar core collapse.

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1 This work was supported in part by the National Science Foundation and the Polish Central Research Project CPBP–01.09

2 Nucl. Phys. A530, 75 (1991)

3 Phys. Rev. C 44, 2794 (1991)

* Soltan Institute for Nuclear Studies, 00–681 Warsaw, Poland

** Institute of Nuclear Physics, N.C.R.S., Demokritos, Aghia Paraskevi, Greece

† Los Alamos National Laboratory, Los Alamos, NM 87545

†† University of California, Davis, CA 95616

Duke University and Triangle Universities Nuclear Laboratory, Durham, NC 27706

9. Energy Dependence of the Gamow–Teller Strength in p–Shell Nuclei Observed in the (n,p) Reaction[1] (D.S. Sorenson*, X. Aslanoglou**, F.P. Brady†, J.R. Drummond†, R.C. Haight*, C.R. Howell††, N.S.P. King*, A. Ling*, P.W. Lisowski*, B.K. Park*, J. Rapaport, J.L. Romero†, W. Tornow†† and J.L. Ullmann*)

Cross sections from 0° to 10° (lab) have been measured for ground–state Gamow–Teller transitions for the reactions $^{6}Li(n,p)^{6}He$, $^{12}C(n,p)^{12}B$ and $^{13}C(n,p)^{13}B$ from 60 to 260 MeV. The 90–meter station at the Weapons Neutron Research facility at Los Alamos National Laboratory was used to obtain these data. Unit cross sections ($\hat{\sigma}$) have been obtained and are compared with existing (n,p) and (p,n) data. The volume integrals ($J_{\sigma\tau}$) for the spin–flip isospin–flip part of the effective nucleon–nucleon interaction have also been obtained and are compared with theoretical predictions.

10. Gamow–Teller and Dipole Strength Distribution in $^{40}Ca(n,p)^{40}Ka$ Reaction[2] (P.K. Park*, J. Rapaport, J.L. Ullmann*, A.G. Ling*, D.S. Sorenson*, F.P. Brady†, J.L. Romero†, C.R. Howell††, W. Tornow†† and C.T. Ronnqvist#)

Double–differential cross section angular distributions covering $0° \leq \theta_{lab} \leq 40°$ have been measured for the $^{40}Ca(n,p)^{40}K$ charge–exchange reaction. With the white neutron source at LAMPF–WNR, we were able to study not only the angular distribution but also the energy dependence of this charge–exchange reaction covering simultaneously incident neutron energies between 60 and 260 MeV. The identification of Gamow–Teller transitions and L = 1 dipole resonance was carried out using a multipole decomposition technique. The empirically–deduced GT strength in the $^{40}Ca(n,p)^{40}K$ reaction evaluated up to 15 MeV excitation energy is compared to theoretical values. We have used a simple one–particle one–hole shell model calculation to study the excitation of the Giant Dipole Resource and the Giant Spin Dipole Resonance, which are compared with empirical results.

11. Multipole Strength in $^{16}O(n,p)^{16}N$ at 298 MeV[3] (K.H. Hicks, A. Celler##, O. Hausser@, R. Henderson@, K.P. Jackson@, B. Pointon@@, J. Rapaport, M. Vetterli@@ and S. Yen@@)

The $^{16}O(n,p)^{16}N$ reaction was measured at an incident neutron energy of 298 MeV at average center–of–mass angles of 2.0°, 6.5° and 10.6°. The Gamow–Teller (GT) and

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1 Phys. Rev. C 45, R500 (1992)
2 Phys. Rev. C, April 1992 (in press)
3 Phys. Rev. C 43, 2554 (1991)

* Los Alamos National Laboratory, Los Alamos, NM 87545
** Institute of Nuclear Physics, N.C.R.S., Demokritos, Aghia Paraskevi, Greece
† University of California, Davis, CA 95616
†† Duke University and Triangle Universities Nuclear Laboratory, Durham, NC 27706
\# Uppsala University, Uppsala, Sweden
\#\# University of Western Ontario, London, Ontario, Canada N6A 3K7
@ TRIUMF, 4004 Webrook Mall, Vancouver, British Columbia, Canada V6T 2A3
@@ Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

spin–dipole strength functions were extracted using a multipole decomposition technique with theoretical angular distributions with L transfers of 0, 1 and 2 from distorted–wave impulse–approximation (DWIA) calculations. The extracted strengths are compared to distributions expected from shell–model calculations which include $2\hbar\omega$ and $4\hbar\omega$ excitations. The pure spin–dipole multiplet at 0.2 MeV excitation shows a different shape than the angular distribution from the DWIA calculations, which may affect the amount of GT strength extracted from the multipole decomposition.

12. Spin Transfer Measurements in the Quasifree $(\vec{p},\vec{n})$ Reactions at 500 MeV[1] (X.Y. Chen*, D.J. Mercer*, T.N. Taddeucci**, L.J. Rybarcyk**, J.B. McClelland**, W.C. Sailor**, B. Luther†, S. Delucia†, D. Marchlenski†, E.R. Sugarbaker†, C.D. Goodman††, Y. Wang††, E. Gülmez# and J. Rapaport)

Complete sets of polarization transfer observables in the quasifree $(\vec{p},\vec{n})$ reactions have been measured for the first time. Experiments were performed using the newly calibrated neutron polarimeter and newly–developed neutron time–of–flight facility (NTOF) at LAMPF. Measurements were made at 18° and over a broad excitation energy range. The resulting energy loss spectra of the spin–longitudinal and and spin–trasverse response functions are presented and discussed for Ca, C and ^{2}H at 500 MeV and for a momentum transfer of 350 MeV/c.

13. Quasifree Polarization Transfer Measurements in the $(\vec{p},\vec{n})$ Reaction at 495 MeV[2] (J.B. McClelland**, T.A. Carey**, L.J. Rybarcyk**, W. Sailor**, T.N. Taddeucci**, X.Y. Chen*, D. Mercer*, S. DeLucia†, B. Luther†, D.G. Marchlenski†, E.R. Sugarbaker†, J. Rapaport, E. Gülmez#, C. Whitten, Jr.#, C.D. Goodman††, Y. Wang†† and W.P. Alford##)

A complete set of polarization transfer observables for quasifree scattering in the $(\vec{p},\vec{n})$ reaction at 495 MeV is reported. Measurements were carried out on CD_2, natural carbon and calcium targets at a momentum transfer of 1.72 fm^{-1} using the new neutron time–of–flight facility at LAMPF. The spin–longitudinal and spin–transverse responses are extracted from the data. The ratio of these responses are compared to DWIA–RPA calculations in which the particle–hole interaction is taken to be of the form $g+\pi+\rho$. No evidence for these RPA correlations is seen in the data at this momentum transfer.

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1 Contribution to the 4th Conference on the Intersections Between Particle and Nuclear Physics, May 24–29, 1991, Tucson, AR

2 Submitted to the Proceedings of the International Workshop on Pions in Nuclei, Pensicola, Spain, June 3–8, 1991.

* University of Colorado, Boulder, CO 80309–0446

** Los Alamos National Laboratory, Los Alamos, NM 87545

† The Ohio State University, Columbus, OH 43210

†† Indiana University Cyclotron Facility, Bloomington, IN 47405

University of California, Los Angeles, CA 90024–1547

University of Western Ontario, London, Ontario, Canada N6A 3K7

B. MODEL CALCULATIONS AND ANALYSIS

1. The Shell Model/R–Matrix Calculation for p–Shell Nuclei[1] (T.N. Massey, D.A. Resler* and H.D. Knox**)

Initial shell model calculations have been carried out using a simple PMM interaction and a model space which included up to two particles in the sd–shell for ^{10}Be. The results of the R–matrix calculations match the known data for elastic scattering and are within a factor of two of the measured inelastic neutron scattering. A comparison of the predicted and the measured Legendre moments resulted in the deduction that the differences in the angular distribution is caused by missing positive parity states, i.e., $2\hbar\omega$ states.

Calculation of the full $2\hbar\omega$ states in the spsdpf space is ongoing for both ^{10}Be and ^{14}C compound nuclei. For the current work, the energies of the $2\hbar\omega$ states are manually adjusted relative to the $0\hbar\omega$ states to match known states in the compound nucleus. The R–matrix calculations match the elastic scattering data when a r_0 of 1.1 Fermi is used to calculate the channel radii of rather than the traditional 1.3 Fermi.

2. Analysis of Neutron Inelastic Scattering from ^{13}C Using Monte Carlo Techniques[2] (E.F. Saito, T.N. Massey, J.E. O'Donnell, J.F. Guillemette and R.O. Lane)

Analysis of recent ^{13}C(n,n*)^{13}C experiments at the Ohio University Accelerator Laboratory have been performed using the MACHO experimental simulation code. The code has been modified to account for the secondary neutrons from sequential decay to ^{12}C from neutron scattering to the unbound levels of ^{13}C. This modification was necessary since the secondary neutrons often have the same energy as the primary neutrons from scattering to the unbound levels of ^{13}C. With this improvement, cross sections from inelastic neutron scattering from ^{13}C can be extracted and will be discussed.

3. Parameterization of the Nuclear Level Density at Energies Above 100 MeV[3] (S.M. Grimes)

The intensive studies of equilibration processes in heavy ion reactions have produced a need for information on nuclear level densities at high energies. In a recent paper, it was concluded that standard Fermi gas formulas will be incorrect by exponential factors at energies above 100 MeV. Exact calculations of the nuclear level density in based as large as 10^{38} have been made and are compared with Fermi gas formulas. Two possible alternative forms are considered. both forms produce much better agreement at high energies than does the Fermi gas model. All calculations reported are for non–interacting Fermions, but the effects expected from the two–body interaction are briefly

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1 Supported by Department of Energy Grant DE–FG02–88ER40387
2 Bull. Amer. Phys. Soc. 37, 902 (1992)
3 Submitted to Zeitschrift für Physik
* Lawrence Livermore National Laboratory, Livermore, CA 94550
** Knolls Atomic Power Laboratory, Schenectady, NY 12301

examined. These considerations have consequences not only in heavy ion physics but also in astrophysics.

4. Nuclear Level Densities at High Excitation[1] (M.G. Mustafa*, M. Blann*, A.V. Ignatyuk** and S.M. Grimes)

Level densities for ^{20}Ne, ^{40}Ca and ^{100}Ru are calculated using unrestricted uniform single particle levels (Fermi gas) and for realistic levels restricted to those bound by centripetal and Coulomb forces. for the latter we use single particle levels due to Seeger and results from a Woods–Saxon model. We show that the Fermi gas formula become completely inadequate at temperatures well within the range relevant to heavy ion reaction studies. Likely consequences of these discrepancies with respect to the likelihood of forming equilibrated nuclei at these temperatures.

5. Low Energy Optical Model Studies of Proton Scattering on ^{54}Fe and ^{56}Fe[2] (N. Boukharouba†, C.E. Brient, S.M. Grimes, V. Mishra and R.S. Pedroni)

Proton elastic and inelastic cross sections have been measured at a number of energies between 3.73 and 7.74 MeV on targets of ^{54}Fe and ^{56}Fe. The (p,γ) cross section was also measured at the same energies. Coupled channel effects on the cross sections are examined and an analysis in terms of dispersion theory is presented. A detailed understanding of coupled–channel effects on absorption at and below the Coulomb barrier is important for Hauser–Feshbach calculations.

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1 Accepted for publication in Phys. Rev. C
2 Submitted to Phys. Rev. C
* Lawrence Livermore National Laboratory, Livermore, CA 94550
** FEI, Obninsk, Russia
† 1 Rve Ben Brouk Hocine, Heliopolis Guecma 2400, Algeria

A. OVERVIEW

The work outlined here is a condensation prepared by Richard Walter from the annual report TUNL XXX. For a more complete statement of the research, one should refer to that report or contact the first author listed in each section.

B. FEW NUCLEON SYSTEMS

1. Asymptotic S-wave Normalization of the Deuteron by n-d Scattering (C.R. Howell, N. Al-Niemi,* R.T. Braun, C.E. Brient,* D.E. Gonzalez, S.M. Grimes,* G. Mertens,† R.S. Pedroni,* C.D. Roper, W. Tornow)

The present experimental value for the asymptotic S-wave normalization A_S of the deuteron wavefunction is extracted from *e-d* elastic scattering data in the low-q^2 region.[1] The value of A_S extracted from the *e-d* data is $A_S = 0.8802 \pm 0.0020$. An alternate method for determining A_S utilizes the strong relationship between A_S and the differential cross section $\sigma(\theta)$ for *n-d* elastic scattering to backward angles.[2] These authors have shown that scattering beyond 150°(c.m.) for neutron energies below 20 MeV is mainly due to the $^3S_1$ part of the nucleon-nucleon NN interaction; that is, at 20 MeV the $^1S_0$ force only accounts for about 3% of $\sigma(\theta)$ for $\theta_{c.m.} = 150°-180°$ and the P-wave and the D-waves contribute less than 2% and 3%, respectively.

To resolve a discrepancy between published *n-d* data sets and to corroborate the value of A_S determined from *e-d* elastic scattering, but using a strongly interacting probe, we made $\sigma(\theta)$ measurements to better than ±4% for *n-d* elastic scattering to $\theta_{c.m.} = 140°-178°$ at 8, 10, and 14 MeV. Recoil deuterons were detected in a charged-particle spectrometer developed at Ohio Univ. for A(n,z) studies. By simultaneously measuring *n-d* and *n-p* elastic scattering, the *n-d* yields could be normalized to *n-p* scattering to obtain an absolute cross section. Our results at 8 MeV (obtained at Ohio) are in good agreement with existing data and indicate that the techniques are solid. Preliminary data were obtained at Ohio at 10 MeV, and then the spectrometer was moved to TUNL for completion of the 10-MeV data and to measure at 14-MeV. The 14-MeV data (shown in fig. B-1) are in good agreement with the 3-body calculations and indicate that the Karlsruhe data are too high beyond 150°. We expect that our data will enable us to determine A_S to 0.5%.

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* Ohio University, Athens, Ohio.

† University of Tübingen, Tübingen, Germany.

1 T.E.O. Ericson, Nucl. Phys. **A416**, 281c (1984).

2 Y. Koike and Y. Taniguchi, Few-Body Systems **1**, 13 (1989).

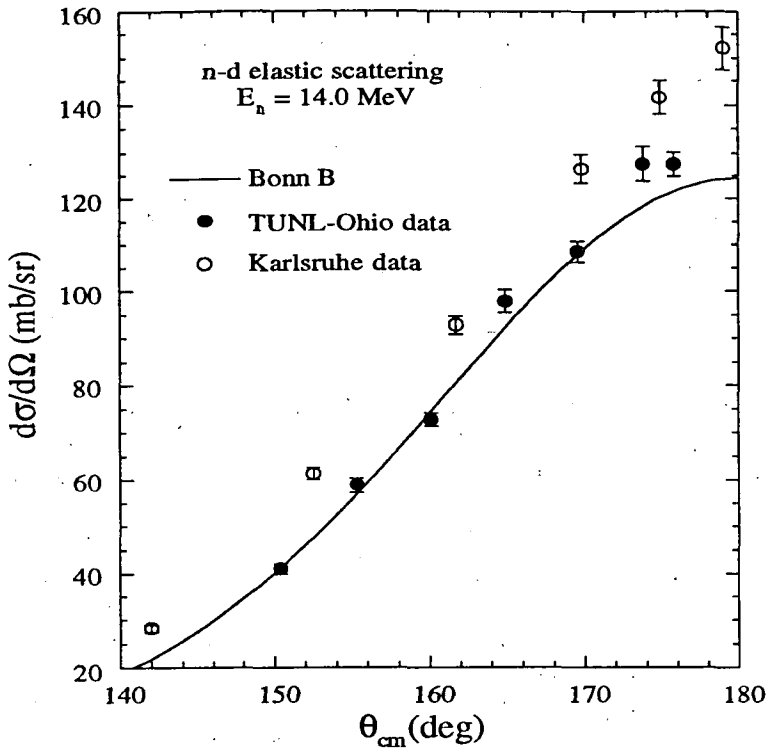

Fig. B-1 Backward-angle σ(θ) for elastic scattering at 14 MeV. The curve is a 3N calculation based on the Bonn-B potential.[3]

2. Dynamics of n-d Elastic Scattering above E_n = 70 MeV

(C.R. Howell, X. Aslanoglou,* F.P. Brady,† J.R. Drummond,† R.W. Finlay,* R.C. Haight,§ N.S.P. King,§ A. Ling,§ P.W. Lisowski,§ C.L. Morris,§ B.K. Park,* J. Rapaport,* J.L. Romero,† D.S. Sorenson,† W. Tornow, J.L. Ullmann,§ B. Vlahovic)

Computational advances[4] permit three-nucleon (3N) scattering observables[5] to be calculated using the exact forms of the Paris and Bonn nucleon-nucleon (N-N) potentials. The underlying assumptions used in most 3N calculations are: (1) nucleons only interact via pairwise forces, thus no 3N force; (2) the dynamics of the interacting nucleons can be treated nonrelativistically; and (3) charge symmetry and charge independence are assumed to hold for all N-N angular momentum states with $\ell \geq 1$. The calculations are limited to *n-d* scattering observables since the Coulomb

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* Ohio University, Athens, OH.

† University of California, Davis, CA.

§ Los Alamos National Laboratory, Los Alamos, NM.

[3] R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).

[4] Witala, Glöckle, and Cornelius, Few-Body Systems Suppl. **2**, 555 (1987).

[5] C.R. Howell *et al.*, Phys. Rev. Lett. **61**, 1565 (1988).

force cannot be included in these calculations in an exact way. High-accuracy measurements from TUNL and elsewhere of *n-d* scattering observables at low energies (E<20 MeV) are critically testing assumptions (1) and (3). The 3N calculations at c.m. energies above 50 MeV made by Witala at TUNL mentioned below are useful for investigating the item (2). The comparison of these "exact" non-relativistic 3N calculations to nucleon-deuteron (*N-d*) scattering data over an incident nucleon energy range from 50 to 300 MeV provides a continuous test of the reaction dynamics in the 3N scattering system. To fill a gap between 70 and 200 MeV in the database, we have measured $\sigma(\theta)$ at backward-angles ($\theta_{c.m.}$ = 155°-180°) for *n-d* elastic scattering from 60 to 260 MeV. All measurements were conducted at the LAMPF/WNR continuous-energy neutron beam facility. The same spectrometer was used as that in the A(n,p) project below in Sect. C.I. The stripping of these data is underway.

3. Three-Nucleon-Force and Off-Shell Effects in ^{2}H(n,nnp) Breakup (H.R. Setze, C.R. Howell, J.M. Lambert,* G. Mertens,† I. Slaus,§ W. Tornow, R.L. Walter, G.J. Weisel)

The influence of three-nucleon forces (3NF) is dependent on the spatial arrangement of the interacting nucleons.[6] The kinematic richness of the n+d → n+n+p breakup reaction makes it excellent for studying 3N systems in extreme geometric configurations, since one has the ability to vary continuously the arrangement of the nucleons in the exit channel. Meier and Glöckle calculated that the influence of the 3NF is extremely angle and energy dependent.[7] They found that the cross section for the colinear configuration (the three outgoing nucleons form a line in the c.m. system) was enhanced by 10% at E = 14.4 MeV, and for the star configuration (the three outgoing nucleons have equal momenta and inter-particle angles of 120°) to be enhanced by 5% at E = 18 MeV when the 2π exchange 3NF was inserted into the calculation.

Our motivation for measuring cross sections for *n-d* breakup stems from the recent experiment by Strate *et al.*[8] who obtained cross-sections for ^{2}H(n,nnp) breakup at 13 MeV. There are sizable disagreements between their data and the 3N calculations using the Bonn and Paris N-N potentials. If their data are correct, *this would be the clearest evidence of the 3NF yet observed in a scattering system.* Because of the significant consequences, measurements are underway at TUNL to check their results. A shielded neutron source has been constructed and

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* Georgetown University, Washington, DC.

† University of Tübingen, Tübingen, Germany.

§ Ruder Boskovic Institute, Zagreb, Croatia.

6 J.L. Friar, Proc. Conf. on the Interaction between Medium Energy Nucleons in Nuclei, Indiana University, 1982, AIP Conf. Proc. No. **97**, p. 378.

7 W. Meier and W. Glöckle, Phys. Lett. **138B**, 329 (1984).

8 J. Strate *et al.*, J. Phys. G: Nuclear Physics **14**, L229 (1988).

tested. The neutron production target is a water cooled deuterium gas cell. The efficiencies of the 11 neutron detectors have been measured using a ^{252}Cf source; the efficiency data are being worked up. Preliminary D(n,nnp) breakup data were obtained and are under study now. We estimate that a cross-section measurement to an accuracy of ±5% will require one month of beam time.

4. Rigorous Three-Nucleon Elastic Scattering and Breakup Calculations (H. Witala, W. Glöckle, W. Tornow)

During a two-month visit at TUNL, H. Witala, Jagellonian University, Cracow, Poland, installed his 3N continuum Faddeev code on the local Cray Y-MP at the North Carolina Supercomputation Center (NCSC). This code, developed in collaboration with W. Glöckle of Bochum, is presently the only code that calculates rigorously elastic and breakup processes in the neutron-deuteron reaction above the deuteron breakup threshold. Several important areas were studied. Details can be found in TUNL XXX.

a. Charge-Symmetry Breaking Effects in ^3P NN Forces

One of the open questions of the NN force deals with such aspects as the charge-independence and charge-symmetry breaking (CIB, CSB) in higher angular momentum NN states. The Nd analyzing power A_y is a good candidate to search for CIB and CSB effects in ^3P_J NN states. In reference 9 we investigated what kind of modifications to the ^3P_J phase shifts is required to bring the calculated *nd* A_y in closer agreement with the data. Starting from the Bonn-B potential parameters, the ^3P_J phases were varied by searching on 2N and 3N observables simultaneously. We demonstrated that it is possible to simultaneously describe the A_y data in the *pp* and *np* systems together with the A_y data in the 3N *pd* system by modifying the 2N interaction in the ^3P_J states. This approach introduces CIB in these NN interactions. The *nd* analyzing-power data, which are slightly higher in the maximum than the *pd* data, can also be very well reproduced by assuming an additional CSB the ^3P_J forces. However, in reference 9 the Coulomb interaction was totally neglected. In reference 10 we pointed out that if the proton slows down in the Coulomb field of the deuteron, then the CSB effects in the ^3P_J NN interactions are probably not as large as found in reference 9. We have made additional calculations below 10 MeV which indicate that the CSB interaction is energy dependent; it would be extremely interesting to measure the *n-d* analyzing power at energies below 6 MeV.

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[9] H. Witala and W. Glöckle, Nucl. Phys. **A528**, 48 (1991).
[10] W. Tornow, *et al.*, Phys. Lett. **257B**, 273 (1991).

b. Energy Dependence of Nucleon-Deuteron Scattering and ^3P Interactions (W. Tornow, H. Witala, W. Glöckle)

The energy dependence of n-d elastic scattering observables was calculated from 5 to 45 MeV by rigorous three-nucleon calculations using the Bonn-B NN interaction. The goal was to identify energy and angular regions which may be investigated experimentally to study the question of CSB and/or Coulomb effects in the ^3P_J N-N interactions. The end result is to propose the accurate measurement of $A_y(\theta)$ in *nd* elastic scattering at E_{lab} = 16 and 22.7 MeV in order to compare to existing *pd* data at the same bombarding energies, as this comparison at these energies is particularly sensitive to the ^3P_J N-N interactions.

c. Two-Nucleon j=4 Contributions to 3N-Scattering Observables (H. Witala, W. Glöckle, W. Tornow)

In order to extend the calculations into the 100 to 200 MeV energy regime and to simultaneously check on the reliability of the $j_{max}=3$ restriction at lower energies, the influence of $j=4$ contributions ($^3G_4$, $^1H_4$, $^1G_4$ and $^3F_4$-$^3H_4$) must be investigated. However, until now this has not been possible. At NCSC, it was possible to perform a complete $j_{max}=4$ calculation using the Bonn-B NN potential at an incident nucleon laboratory energy of 116 MeV in 10 hours of CPU time. As expected, the $j_{max}=4$ partial waves contribute to $\sigma(\theta)$ mainly in the forward-angle region. For $A_y(\theta)$ the difference between $j_{max}=3$ and $j_{max}=4$ is very small. Sizable differences are noticed for polarization transfer coefficient $K_y^y(\theta)$, not only at forward angles but also near 125°. We conclude from this first rigorous $j \leq 4$ 3N scattering calculation that $j=4$ NN interactions play a non-negligible role for most 3N observables at incident nucleon energies of about 100 MeV. We will extend these calculations up to 250 MeV.

5. Charge-Symmetry-Breaking Effects

The problems of charge-independence and charge-symmetry-breaking in the nucleon-nucleon interaction remain provocative and puzzling. During the past year we performed tests that bear on these problems.

a. Charge-Symmetry Breaking Versus Coulomb Effects in Three-Nucleon Scattering (W. Tornow, C.R. Howell, R.L. Walter, I. Slaus*)

To investigate the effect of the Coulomb repulsion in *p-d* scattering the *n-d* $\sigma(\theta)$ and $A_y(\theta)$ data at 10 MeV were "fitted" using an optical-model approach with Woods-Saxon form factors that is standard for heavier nuclei. For the real central potential we obtained V_R = 38.6 MeV, r_R = 1.24 fm and a_R = 0.75 fm. The spin-orbit potential parameters are V_{SO} = 2.24 MeV, r_{SO} = 1.105 fm and a_{SO} = 0.65 fm and the imaginary (surface absorptive) potential is characterized by W_I = 2.70 MeV, r_I = 1.24

* Rudjer Boskovic Institute, Zagreb, Croatia.

fm and a_I = 0.675 fm. The shape of the measured $A_y(\theta)$ is qualitatively reproduced. Next the $\sigma(\theta)$ and $A_y(\theta)$ were calculated for *p-d* scattering using exactly the same nuclear potential as for *n-d*. For the Coulomb potential we used that of a uniform charge distribution of radius parameter r_C = 1.24 fm. Qualitatively, the curves exhibit the same difference at A_y(max) as observed experimentally. In addition, the forward-angle difference is also predicted. Carrying this optical-model approach farther, we used an energy dependence for the real potential that is common for heavier nuclei (V_0-0.3E_N, V_0 = 41.6 MeV) and calculated the $A_y(\theta)$ at lower energies. The prediction compares favorably with the experimental trend. It also should be noted that $\sigma(\theta)$ is described quite well at scattering angles forward of 120° c.m. The observed differences at the maximum of $A_y(\theta)$ between *n-d* and *p-d* $A_y(\theta)$ measurements can be reproduced by applying a simple correction to remove the effect of the Coulomb interaction in *p-d* scattering. That is, a straightforward treatment of the Coulomb correction reveals that the major part of the observed differences between *n-d* and *p-d* $A_y(\theta)$ data is most likely an electromagnetic effect and not a charge-symmetry-breaking effect. It now appears likely that CSB effects in the ^{3}P NN interactions are too small to be observed in the Nd scattering systems at low energies with present experimental techniques. It might well be that CSB effects account for only about 10% of the observed differences, similar to what was found for the 3N bound-state binding energy difference.

b. Low-Energy n-d Analyzing Powers and ^{3}P Interactions in NN Potentials (W. Tornow, C.R. Howell, M. Al-Ohali, Z.P. Chen, P. Felsher, J. Hanly, R. Walter, G. Weisel, G. Mertens, I. Slaus, H. Witala, W. Glöckle)

This work was published recently in Phys. Lett. **B257**, 273 (1991). The abstract follows: Data for $A_y(\theta)$ for scattering of neutrons from deuterons have been measured at 5.0, 6.5 and 8.5 MeV to of ±0.0035. Surprisingly large differences have been observed at these low energies between the data and rigorous Faddeev calculations using the Paris and Bonn-B NN potentials. The $A_y(\theta)$ data provide a stringent test for our present understanding of the on-shell and off-shell ^3P_J NN interactions.

c. Charge-Symmetry Breaking in Deuteron-Induced Deuteron Breakup (P. Felsher, C. Howell, I. Slaus, W. Tornow, M. Roberts, J. Hanly, G. Weisel, M. AlOhali, R. Walter, J. Lambert,* G. Mertens, Y. Koike†)

In the A = 4 system attempts have been made to observe CSB by comparing data for the $D(\vec{d},p)^3H$ and $D(\vec{d},n)^3He$ stripping reactions [Grü89]. Although the Coulomb force in the entrance channel is identical for these two reactions, there are difficulties because of the differences in the *Q*-values and the Coulomb force in the exit channels. For this reason we used the spin observables from the $D(\vec{d},dp)n$ and $D(\vec{d},dn)p$ charge symmetric reactions as a probe of CSB. Even though the four-nucleon (4N)

* Department of Physics, Georgetown University, Washington, DC 20057.

† Department of Physics, Hosei University, Tokyo, Japan.

system is inherently more complicated than the three-nucleon (3N) system and rigorous calculations do not exist for these reactions, we use this probe because of a number of advantages due to the symmetry of these reactions. (See TUNL XXX.) We investigated the reactions $D(\vec{d},dp)n$ and $D(\vec{d},dn)p$ at 12 MeV for angle pairs chosen to make measurements in the kinematic region corresponding to *dN* quasi-free scattering (QFS). We also measured at two angle pairs for CSB tests: $(\theta_d, \theta_N) = (+17.0^\circ, -17.0^\circ)$ and $(+17.0^\circ, -34.5^\circ)$. If charge symmetry (CS) is valid, then the observables for $D(\vec{d},dp)n$ and $D(\vec{d},dn)p$ with $(\theta_d, \theta_p) = (\theta_d, \theta_n)$ should be equal. Also, we investigated the process $D(\vec{d},pn)d$ with $(\theta_p, \theta_n) = (+17.0^\circ, -17.0^\circ)$, where if CS is valid then the A_{yy} and A_{zz} along the kinematic locus in a plot of E_p versus E_n should be symmetric (A_y is antisymmetric) with respect to the $E_p = E_n$ point. The data for the two reactions are indistinguishable, except for A_y around the $E_p = E_n$ point $S = 6$ MeV. The A_{yy} and A_{zz} data are symmetric to within ±0.02, and the A_y data are antisymmetric to within ±0.016. However, in the interval around the $E_p = E_n$ point, the value of A_y is 0.031±0.012; it should be zero if CS holds.

6. <u>$D(d,p)^3H$ and $D(d,n)^3He$ Spin Observables at Very Low Energies</u> (A.W. Ackley, R.K. Das, K. Fletcher, E.J. Ludwig, H.J. Karwowski, W.J. Thompson)

There is renewed interest in d+d reactions at low energies. Recent $\sigma(\theta)$ measurements indicate that entrance channel P-waves and D-waves are important even at c.m. energies below 50 keV; this dramatically increases the number of matrix elements needed to describe the reactions and thereby increases the number of observables needed for an unambiguous description. We measured analyzing powers for $D(d,p)^3H$ and $D(d,n)^3He$ below 100 keV. Preliminary analyses of A_{zz} at 60 keV and 80 keV have been obtained. Once the Lamb-shift polarimeter is on-line and the LEBF polarization monitor is calibrated, these data will be reanalyzed.

7. <u>Analyzing Powers in $^2H(d,\gamma)^4He$ at Low Energies and the D-State of ^4He</u> (L.H. Kramer, M.J. Balbes, R.M. Chasteler, M.A. Godwin, E. Hayward, R.M. Prior, G. Schmid, D.R. Tilley, H.R. Weller, J.Z. Williams)

The low energy $^2H(d,\gamma)^4He$ cross section has been shown to be much larger than that predicted if the reaction proceeds by E2 capture from the $^1D_2$ scattering state to the $^1S_0$ component of the ^4He ground state (GS) [Wel88]. The larger cross section is thought to come from $^5S_2$(E2) capture to the $^5D_0$ component of ^4He GS, as this eliminates the centrifugal barrier. If capture proceeds purely through s-wave capture to the D-state, then A_y and A_{yy} are isotropic with values of 0.0 and 0.25, respectively.

We are investigating $^2H(\vec{d},\gamma)^4He$ at very low energies by measuring the vector and tensor analyzing powers. We obtained A_y and A_{yy} at E_d(lab)= 80 keV and θ(lab)= 0°, 45°, and 82°. Data analysis is underway. At $\theta = 0°$, we extracted preliminary results of $A_y = 0.001 \pm 0.140$ and $A_{yy} = -0.419 \pm 0.085$, indicating that the reaction does not proceed purely by

s-wave capture to the D-state. A recent microscopic resonating-group-model calculation has been obtained from Hofmann *et al.* and will be used for comparison. A second anticoincidence-shielded NaI detector and in-line polarimeter have been setup and further measurements are scheduled for 80 keV and lower. A calculation at E_{cm} < 500 keV by Arriaga *et al.* using a variational Monte Carlo method has recently been completed. An attempt is being made to extend it to our energies. Comparing this to our results will further our understanding of the $^2H(d,\gamma)^4He$ reaction as we approach the energy region of astrophysical relevance.

8. Radiative Capture of Polarized Deuterons by ^3He
(M.J. Balbes, R. Chasteler, L.H. Kramer, M.A. Godwin, G. Schmid, D.R. Tilley, H.R. Weller, J.Z. Williams)

The tensor analyzing power $T_{20}(\theta)$ of the $^3He(d,\gamma)^5Li$ reaction has been measured at 6 angles (30° to 150°) with a deuteron-beam energy integrated from 0-800 keV. Here s-wave-capture contributions are expected to dominate. Also, the $3/2^+$ fusion resonance, lying just above the $d+^3He$ threshold, is expected to make the $^4s_{3/2}$ partial wave contribution dominate over the $^2s_{1/2}$ contribution. Our previous data for $A_y(\theta)$ and $A_{yy}(\theta)$ left an ambiguity in the fitting of transition matrix elements to the data. Unfortunately, this ambiguity was not resolved by the inclusion of $T_{20}(\theta)$ in the fit. The observables $\sigma(\theta)$, $A_y(\theta)$, and $A_{yy}(\theta)$ were also measured for a beam which entered the target with E_d = 600 keV and exited with 300 keV. A detailed analysis is underway. We have continued to improve our calculations of capture observables by using the Resonating Group Model. At the fusion resonance, the $^4s_{3/2}$(E1) transition matrix element was found to dominate the photo-nuclear cross section. The tensor force, and to a lesser degree the spin-orbit force, is important because it couples the $[d+^3He]^{S=3/2}$ incoming channel to the $[p+^4He]^{S=1/2}$ channel, allowing the photonuclear transition to the S = 1/2 ground state to proceed by the dominant $\Delta S = 0$ term of the E1 operator. At E_d = 8.6 MeV, the $^4s_{3/2}$(E1) transition matrix element contributes only 45% of the cross section while 22% comes from the $^2d_{5/2}$(E1) TME and 6% from the $^2p_{3/2}$ (E2) TME.

C. MEDIUM-WEIGHT AND HEAVY NUCLEI

1. Gamow-Teller Strength Functions for Light- and Medium-Mass Nuclei (C.R. Howell, X. Aslanoglou,* F.P. Brady,† J.R. Drummond,† R.W. Finlay,* R.C. Haight,§ N.S.P. King,§ A. Ling,§ P.W. Lisowski,§ C.L. Morris,§ B. Park,* J. Rapaport,* J. Romero,† D. Sorenson,† W. Tornow, J. Ullmann,§ X. Yang*)

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* Ohio University, Athens, OH.

† University of California, Davis, CA.

§ Los Alamos National Laboratory, Los Alamos, NM.

Our group is measuring $\sigma(\theta)$ for the (n,p) charge-exchange reaction near zero momentum transfer (q) and zero energy loss (ω) on light and medium mass nuclei. The measurements are made using the continuous-energy neutron beam at LAMPF/WNR. The combination of this neutron beam and the multiple target chamber array makes the setup extremely efficient for (n,p) measurements. For the first time the Gamow-Teller (GT) strength function has been extracted at all energies continuously between 60 and 260 MeV. So far, we have completed measurements on ^{6}Li, ^{12,13}C, ^{NAT}S, ^{40}Ca, and ^{60,64}Ni. A manuscript on our results for the ^{6}Li and ^{12,13}C nuclei has been submitted to Physical Review Letters. The result of the ^{64}Ni analysis has been submitted to Physical Review C. The abstract from the ^{64}Ni paper follows: Cross sections have been measured for the reaction ^{64}Ni(n,p)^{64}Co at laboratory angles between 0° and 10° for incident neutron energies from 90 to 240 MeV. The ground-state cross sections together with the ß decay *ft* value for the transition ^{64}Co(g.s.) $\rightarrow$ ^{64}Ni(g.s.) are used to normalize the $q = 0$ differential cross section in units of mb/sr-GT. This is the first absolute measurement of the A(n,p) unit cross section for a nucleus in the (fp)-shell and it may be used to calibrate the GT strength measured in other (n,p) reactions of similar mass nuclei. Since the (e^-,ν_e) channel involves the same nuclear matrix element as the (n,p) channel, knowledge of GT strength in these nuclei is important for supernova modeling codes which depend on knowledge of e^- capture rates of (fp)-shell nuclei to determine parameters of stellar core collapse. Last summer we began investigating energy dependences of giant resonances and studying the *NN tensor force* by measuring stretched transitions in the ^{10}B(n,p) reaction. To measure at angles greater than 20°, the spectrometer was modified. Data were acquired at 20°-50°.

2. <u>DR Optical Model and Coupled-Channel Model for n+^{27}Al and n+^{59}Co</u>
(M.M. Nagadi, J.P. Delaroche, C.R. Howell, W. Tornow, R.L. Walter)

Although it is important to develop an optical model (DOM) that incorporates the dispersion relation (DR) in order to test the extension of the DOM to negative energies (bound states) for single particle nuclei, it is also important to investigate the applicability of the DOM to deformed nuclei, such as ^{27}Al. In preliminary DOM calculations we showed that the strength of the spin-spin potential obtained in fitting the spin-spin total cross section is sensitive to the inclusion of dispersive terms. We have now obtained a DOM model which describes A_y at 14 and 17 MeV and $\sigma(\theta)$ from 7-26 MeV, the latter being the highest energy at which data are available. The A_y data constrained the spin-orbit parameters.

Even though the DOM calculation for the total cross section σ_T gives a very good fit to the data for $E_n > 7$ MeV, the data below 5 MeV are not fit well. This problem is attributed partially to angular-momentum dependent absorption and to reorientation effects. To investigate the latter, a simple coupled channel model was developed that

included only the coupling of the ground state to itself (reorientation effect). Starting with the CCM of $^{28}Si(n,n)^{28}Si$ by Howell *et al.*, we obtained a model that improved the description of σ_T at low energy. From our calculations of the spin-spin cross section with both DOM and CCM for ^{27}Al we found that both give qualitatively a good description of the data of Gould *et al.* (except at 7.6 MeV), and Heeringa *et al.*[11] The models give a surface spin-spin potential with V_{SS} = 1.5 MeV, W_{SS} = 0 MeV, r_{SS} = 1.0 fm, and a_{SS} = 0.654 fm for CCM and V_{SS} = 0.8 MeV, r_{SS} = 1.0 fm and a_{SS} = 0.654 fm for DOM.

As in the case for ^{27}Al, finding a good model for n+^{59}Co to describe the spin-spin cross-section data, especially at low energy, was the main motivation to develop a CCM and a DOM for ^{59}Co. The spin-spin cross section for ^{59}Co had been measured from 250 keV to 31 MeV by Heeringa *et al.* and by Fisher *et al.* In this case we used σ_T and $\sigma(\theta)$ data, as well as A_y data of the Stuttgart group. The CCM was developed starting from the CCM of Pedroni *et al.* for ^{58}Ni. The DOM is still being developed. Both models will be used to determine the spin-spin potential for ^{59}Co in the same manner as for ^{27}Al.

3. Measurement of $\sigma(\theta)$ and A_y (θ) for ^{27}Al and ^{59}Co (M.M. Nagadi, M.Al-Ohali, G. Weisel, R. Setze, C.R. Howell, W. Tornow, R.L. Walter, J. Lambert)

In order to improve our ability to develop the models for neutron scattering from ^{27}Al and ^{59}Co, high accuracy $\sigma(\theta)$ and A_y (θ) measurements were performed at 15.5 MeV for both nuclei. In addition, $\sigma(\theta)$ data for ^{59}Co were obtained between 10 and 19 MeV. The measurement for A_y (θ) has been extended to larger angles than were reported in TUNL XXIX.

4. The Nuclear Mean Field for n + ^{28}Si between -60 and 80 MeV (M.A. Alohali, C.R. Howell, W. Tornow, R.L. Walter)

Previously, Howell *et al.* reported a conventional spherical optical model (SOM) analysis of n+^{28}Si from 8 to 40 MeV. The model gave a good representation for $\sigma(\theta)$, $A_y(\theta)$ and σ_T. One constraint in the SOM, which followed the procedure that was common at that time, was that the strength of the surface and volume absorptive terms varied linearly with E. Such approximations have now been superseded with the DOM which allows for a more realistic determination of the E-dependence of the real and imaginary terms. We applied the DOM method to the n+^{28}Si system. The data base consisted of $\sigma(\theta)$, $A_y(\theta)$ and σ_T data measured at TUNL and elsewhere. The energy range for $\sigma(\theta)$ extended from 2-40 MeV, for $A_y(\theta)$ from 10-17 MeV and for σ_T from 0.2-80 MeV. We find that the DOM gives a fairly good description of σ_T up to 80 MeV. It gives less overestimation of σ_T than the SOM for E < 6 MeV. The fits to $\sigma(\theta)$ and $A_y(\theta)$ are moderately good and of similar quality to Howell *et al.* whose data base

[11] W. Heeringa *et al.*, Phys. Rev. Lett. **63**, 2456 (1989).

started at 8 MeV. The DOM model reasonably predicts the energies of some of the bound states, in particular of the particle states and the deepest hole state ($1s_{1/2}$) (which is expected to have less fragmentation).

5. The n+^{93}Nb Interaction: Conventional and Dispersion Optical Models (R.L. Walter, R.S. Pedroni, C.R. Howell, M. Cheves, Z.M. Chen, G. Weisel, W. Tornow)

A paper reporting our measurement of $\sigma(\theta)$ and $A_y(\theta)$ from 8-17 MeV and a conventional spherical OM analysis of the data was published in Phys. Rev. **C43** 2336 (1991). The abstract follows: Differential cross sections and analyzing powers for neutron elastic scattering from ^{93}Nb were measured from 8-17 MeV using pulsed-beam time-of-flight methods. These data plus σ_T data from 1-20 MeV are interpreted in terms of the spherical OM. Several sets of optical potential parameters with systematic E-dependences were derived in searches that used different initial parameter sets. In addition, comparisons of the data to calculations based on previously reported OM potentials are presented. It is concluded that the data favor the inclusion of an imaginary spin-orbit term.

We recently extended our interpretation of these data in the more exact framework of the DOM, in order to allow for E-dependencies in the potential parameters that are not inherent to the conventional SOM, and to examine the model by comparing predictions of the DOM to known bound-state energies. Recently, Finlay and co-workers in reference 12 reported on σ_T measurements from 5 to 100 MeV and we have formed a collaboration with him and P.W. Lisowski of LANL to include these data in the DOM analysis. Our analysis also includes $\sigma(\theta)$ and σ_T data from Smith *et al.* at ANL and data from several other labs. The DOM gives a very good description of the data base. Because we recently introduced the dispersion relation explicitly into our search code GENOA, and also sped up the integration for the dispersive corrections by using analytic forms, we are able to investigate sensitivities and parameter space in a more detailed fashion than has ever been possible before. The ^{93}Nb data base seems well-matched for DOM studies, in that the agreement shown is as good, if not better, than any DOM model for any other nucleus to date.

6. Dispersive Optical-Model Analysis for n+^{120}Sn (R.L. Walter, C.M. Cheves, Z.M. Chen, G. Weisel, W. Tornow)

As in the case of ^{93}Nb, spherical OM analyses were made previously at a number of laboratories, including TUNL, where $\sigma(\theta)$ and $A_y(\theta)$ have been measured from 10 to 17 MeV. We have initiated a DOM analysis of these data in order to connect the wealth of scattering information up to 80 MeV with known bound-state energies, i.e., negative energies. The ^{120}Sn scattering data appear to be compatible with a DOM model whose

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[12] R.W. Finlay *et al.*, Nuclear Data for Science and Technology, Jülich, Germany (1991) (to be published).

parameters fall in a reasonable range when compared to those for ^{93}Nb and ^{208}Pb. The preliminary results for predicting bound-state energies look encouraging.

7. Improvements to Optical-Model Software and Analysis of n+^{208}Pb and n+^{209}Bi (G.J. Weisel, M.L. Roberts, W. Tornow, C.R. Howell, R.L. Walter)

Over the past four years, TUNL has added significantly to the data base for ^{208}Pb(n,n); the work of Roberts *et al.*, reference 13, at TUNL obtained $\sigma(\theta)$ at 8 MeV and A_y at 6, 7, 8, 9 and 10 MeV. Recently, we completed detailed A_y measurements of ^{209}Bi(n,n) at 6 and 9 MeV. We also recently initiated a project to produce improved DOM descriptions for these nuclei using the new data and new developments in computer hardware and software. While the new system of networked micro-VAX workstations installed at TUNL has enhanced our computing power, considerable effort was expended on our OM search code GENOA and other support software to incorporate the formalism of the dispersive optical model (DOM). Our new version of GENOA makes it possible to search on the energy dependence of the imaginary volume (W_V) and surface (W_D) potentials efficiently.

The project underway will make improvements over recent DOM analyses of ^{208}Pb(n,n) and ^{209}Bi(n,n). Roberts *et al.* in reference 13 reported a ^{208}Pb(n,n) DOM with a linearly segmented E-dependence for the imaginary potentials. Secondly, because of the previous software complications in handling ΔV_V and ΔV_D, both the studies of Roberts in reference 13 for ^{208}Pb(n,n) and of Das in reference 14 for ^{209}Bi(n,n) make only one iteration between the determination of dispersive corrections. With our new GENOA software, iterations are easily made.

A third step was to prepare two new data sets for ^{209}Bi(n,n) and ^{208}Pb(n,n), spanning the energy range 0.8-80 MeV. For ^{209}Bi we included the new TUNL A_y data at 6 and 9 MeV, as well as new σ_T data of Finlay *et al.* In addition, the data sets for both ^{208}Pb and ^{209}Bi were corrected for the presence of compound nucleus CN contributions. We developed a new version of OPSTAT, a CN code obtained from Ohio Univ. Our contribution was to cast OPSTAT in the DOM parameterization so that our potentials may be used in CN calculations. This enables a feed-back loop which insures that the final DOM yields a CN correction consistent with the data set. This work on ^{208}Pb(n,n) and ^{209}Bi(n,n) is underway. We expect these analyses to be sufficiently thorough that definitive conclusions may be drawn, demonstrating the subtle similarities and differences between the ^{208}Pb(n,n) and ^{209}Bi(n,n) systems.

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[13] M. Roberts *et al.*, Phys. Rev. C (in press).
[14] R.K. Das and R. Finlay, Phys. Rev. **C42**, 1013 (1990).

D. NUCLEAR DATA EVALUATIONS FOR A = 3-20 (D.R. Tilley, H.R. Weller, G.M. Hale,* P. Atkinson, R. Huffman)

The transfer of the project for evaluation of nuclear data in the mass range A = 5-20, carried out for many years by Prof. Fay Ajzenberg-Selove at Pennsylvania, has been completed, thus implementing the recommendation to DOE by the Panel on Basic Nuclear Data Compilations. TUNL carried out continuing literature coverage for A = 3-20, worked on the A = 16,17 review and, in collaboration with Los Alamos, brought the review on A = 4 to completion.

A = 4 system. During the 1990-1991 period we collaborated with Gerry Hale of LANL to complete the A = 4 review and prepare a preprint. During the summer, revisions based on responses were carried out to complete a manuscript for publication in Nuclear Physics A.

A = 5-20 systems. Professor Ajzenberg-Selove, working closely with TUNL, transferred reference cards for each item, reprints, reports and conference proceedings, as well as original drawings. She consulted extensively with Tilley and Weller. She provided full printouts and computer files of all reaction-by-reaction bibliographical lists for A = 5-20. TUNL assumed the responsibility for further literature coverage and data compilations. We are preparing the review of the A = 16,17 systems with the intention of completing most of the review by early spring. Tilley visited the NNDC to learn the procedures for entering data for A = 5-20 into ENSDF format. During this visit NNDC installed the computer software onto the TUNL VAX to enable convenient ENSDF data entry at TUNL.

* Los Alamos National Laboratory, Los Alamos, NM.