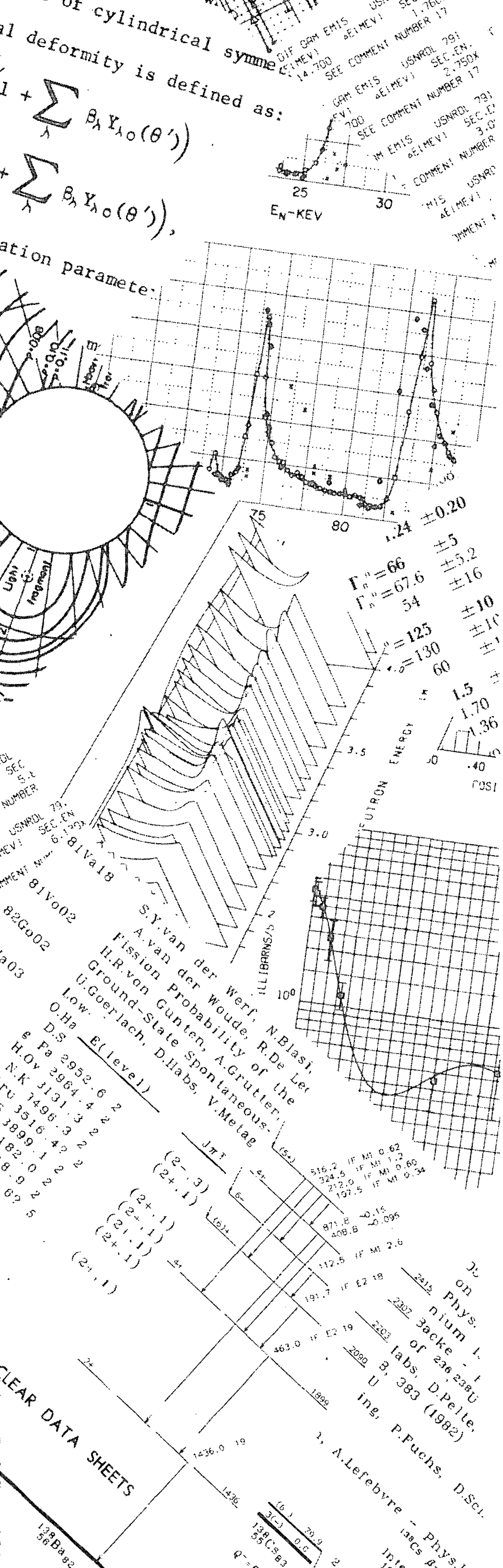

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REPORTS TO THE DOE NUCLEAR DATA COMMITTEE

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

May 1990

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

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PREFACE

The reports in this document were submitted to the Department of Energy Nuclear Data Committee (DOE-NDC) in April, 1990. 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.

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ARGONNE NATIONAL LABORATORY

A. NEUTRON TOTAL AND SCATTERING CROSS–SECTION MEASUREMENTS

1. The Interaction of Fast Neutrons with Beryllium. (M. Sugimoto*, P.T. Guenther, J.E. Lynn**, A.B. Smith and J.F. Whalen)

A preliminary report of this work is documented in the 1989 Report to the DOE Nuclear Data Committee. The effort is now complete, and the results have been formally published.[1] The experimental values indicate that there are major errors in the corresponding ENDF/B–V evaluation in the area of neutron emission spectra. The results of this work have been incorporated into the draft ENDF/B–VI evaluation.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

** Argonne Fellow. Present address: Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico.

1 M. Sugimoto, P.T. Guenther, J.E. Lynn, A.B. Smith and J.F. Whalen, Nucl. Sci. and Eng. 103, 38 (1989).

2. Inelastic Neutron Scattering from the Even Isotopes of Palladium. (S. Chiba,* P.T. Guenther and A.B. Smith)

Cross sections for the elastic–scattering of 5.9, 7.1 and 8 MeV neutrons from elemental palladium were measured at 40 scattering angles distributed between ≈ 15° and 160°. Inelastic–scattering cross sections for the excitation of palladium levels at energies of 260–560 keV were measured with high resolution at the same energies, and at a scattering angle of 80°. The experimental results were combined with low–energy values previously reported by this group to provide a comprehensive database extending from the inelastic–scattering threshold to 8 MeV. The data were interpreted in terms of a coupled–channels model including the excitation of one– and two–phonon vibrational states for the even isotopes of palladium. It was concluded that the palladium inelastic–scattering cross sections are large (≈ 50% greater than given in widely used evaluations) at the low energies which are important to fission–reactor concepts. Their excitation primarily involves compound–nucleus processes, with only a small direct–reaction component which can be attributed to excitation of the 2^+ vibrational levels of the even isotopes of palladium. This work has been completed and formally published.[1]

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

1 S. Chiba, P.T. Guenther and A.B. Smith, Ann. Nucl. Energy 16, 637 (1989).

participants of an IAEA–sponsored Coordinated Research Programme[2] in order to be used in conjunction with (p,n) and (α,n) data for nuclear level studies. Spectral information from this experimental work is also used in the evaluation effort done by this group. For example, neutron–emission spectral shapes for In have been included in the recent evaluation, and measurements on elemental Zr will be exploited in a similar manner.

During the last year, a number of experimental investigations have been carried out with the aim of clarifying some experimental uncertainties and improving the measurement technique. Thus, for example, a single–angle, low–background, long–flight-path verification confirmed the absence of beam contaminant contributions in the high-emission–energy end of the spectra. On the other hand, contaminants in the low–emission-energy portion of the spectra could be identified, and this resulted in the replacement of the original deuteron–gas–target filling system. The methodology of these experiments is currently being documented for inclusion in the Argonne ANL/NDM report series.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

1 P. T. Guenther. "Double–Differential Neutron Scattering at the Argonne Fast–Neutron Generator." Talk given at the Sixth Coordination Meeting of the DOE–ER Program to Meet the Nuclear Data Needs for Fusion Energy, Ohio University Athens, Ohio, September 19–21, 1989

2 P.T. Guenther. "1989 Progress Report for Research Agreement #4412/CF", IAEA Coordinated Research Programme on the Measurement and Analysis of Double–Differential Neutron–Emission Spectra in (p,n) and (α,n) Reactions, Bologna, Italy, 13–14 November 1989.

3 E.D. Arthur, P.T. Guenther, A.B.Smith and D.L. Smith, "Applied Uses of Level Density Models", Proceedings, NEANDC Specialists' Meeting on Level Density Models, Bologna, Italy, November 15–17, 1989.

2. <u>Spectrum–Averaged Cross Section Measurement for $^{9}Be(n,2n)^{8}Be$ in the Be(d,n) Thick–Target Neutron Spectrum</u>. (D.L. Smith, J.W. Meadows, L.R. Greenwood*, D.W. Kneff** and B. Oliver**)

Plans and preliminary investigations for this experiment were discussed in the 1989 Report to the DOE Nuclear Data Committee. This endeavor was established as a collaboration involving the Argonne Chemical Technology Division as well as Rockwell International Corporation. During the past year, a packet containing Be metal samples and a collection of activation dosimeters was irradiated for several weeks at the Argonne FNG. The Be samples were sent to Rockwell for the extraction and measurement of the accumulated He resulting from the breakup of ^{8}Be. Preliminary He production studies indicate that sufficient He was produced in the samples by the irradiation to insure very good (few percent) statistics in the helium–production results for these samples. The activation dosimeter foils have been counted in the Argonne Chemical Technology Division. An evaluated cross–section database has been assembled in preparation for the

3. Neutron Elastic–Scattering Cross Sections of Indium. (S. Chiba*, P.T. Guenther, R.D. Lawson and A.B. Smith)

Comprehensive measurements of the neutron differential elastic–scattering cross sections of indium have been completed from 4.5 to 10 MeV. These results, combined with those previously obtained at this laboratory, provide a very detailed database extending from 0.3 to 10 MeV. The experimental results have been interpreted in terms of a conventional spherical optical–statistical model. The interpretation is now being extended to the dispersive optical model, including correlations with bound–state phenomena.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

4. Fast–Neutron Total and Scattering Cross Sections of ^{58}Ni. (A.B. Smith, P.T. Guenther and R.D. Lawson)

The measurement effort described in the 1989 Report to the DOE Nuclear Data Committee has been completed. Neutron total cross sections of ^{58}Ni were measured from 1 to 10 MeV with broad resolutions, using white–source techniques. Differential elastic–scattering cross sections were measured from 4.5 to 10 MeV at ≈ 0.5 MeV incident–neutron–energy intervals, with at least 75 differential values per angular distribution. Differential neutron inelastic–scattering cross sections were measured for 13 levels to excitations of ≈ 4.8 MeV. Initial physical interpretations, using spherical optical and coupled–channels models, provide a quantitative description of the measured results, particularly with respect to direct–reaction effects. These physical investigations are now being extended in an effort to better understand the interaction of neutrons with ^{58}Ni in the few–MeV energy range.

5. Fast–neutron Scattering from Elemental Calcium ($\approx 97\%$ ^{40}Ca). (A.B. Smith, S. Chiba*, P.T. Guenther and R.D. Lawson)

A very extensive set of neutron differential elastic– and inelastic–scattering data for elemental calcium has been accumulated, extending from incident energies of 1.5 MeV to 10 MeV. The experimental detail is sufficient to define the energy–average cross section throughout this wide energy range. Large cross–section fluctuations are observed over much of this region. Together with information assembled from the literature, these data comprise a rather complete neutron scattering database for this doubly–magic nucleus. The interpretation of this database is now in progress, with the objectives of: i) giving quantitative definition to fundamental physical concepts (particularly the impact of Fermi–surface effects on neutron scattering), and ii) providing comprehensive data for nuclear energy applications.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

6. Fast–Neutron Scattering from Elemental Zirconium. (S. Chiba*, (P.T. Guenther, R.D. Lawson and A.B. Smith)

The scattering measurements have been completed from 1.5 to 10 MeV. The results provide a unique database. An optical–statistical model interpretation of these data is now in progress. It utilizes a specially adapted optical–model code which enables explicit chi–square fitting of the elemental experimental data, while at the same time giving attention to the properties of each of the constituent isotopes (e.g., isovector effects, isotopic discrete–level structures, and various statistical level properties). The interpretation will include consideration of the dispersive optical model and the bound–state regime.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

7. The Contributions of a Direct–Reaction Component to Continuum Neutron–Emission Spectra. (A.B. Smith, S. Chiba* and P.T. Guenther)

The measurements cited in the 1989 Report to the DOE Nuclear Data Committee have been completed. In some cases (e.g., 8 MeV neutrons incident on Nb and Bi), there is a very prominent direct–reaction peak at the upper–energy end of the conventional continuum–emission–neutron spectrum. Quite inappropriately, this peak is generally ignored in evaluations.

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8. Elastic– and Inelastic–Scattering Cross Sections of Magnesium. (A. B. Smith, S. Chiba*, P.T. Guenther and J.E. Lynn**)

Elastic– and inelastic–scattering cross sections of magnesium (primarily ^{24}Mg) have been measured in considerable detail from 2.5 to 3.5 MeV. The data interpretation is now in progress, with the objective of determining the effect, if any, of collective deformation on the obvious resonance properties of the interaction.

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** Argonne Fellow. Present address: Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico.

9. Ambiguities in the Elastic Scattering of 8 MeV Neutrons from Adjacent Nuclei. (R.D. Lawson, P.T. Guenther and A.B. Smith)

This extensive work, which was cited earlier in the 1989 Report to the DOE Nuclear Data Committee, has been completed. A Laboratory report has been prepared[1] and a manuscript has been submitted to the journal Nuclear Physics for publication. The abstract of the latter reads as follows: "Ratios of the cross sections for the elastic scattering of 8–MeV neutrons from adjacent nuclei are measured over the angular range $\approx 20^{o}$–160^{o} for the target pairs ^{51}V/Cr, ^{59}Co/^{58}Ni, Cu/Zn, ^{89}Y/^{93}Nb, ^{89}Y/Zr, ^{93}Nb/Zr, In/Cd and ^{209}Bi/Pb. The observed ratios vary from unity by as much as a factor of ≈ 2 at some angles for the lighter pairs. The ratios are generally consistent with a model based upon a Woods–Saxon potential whose geometry is essentially constant between pairs, and whose strength has an (N–Z)/A (symmetry) component with a magnitude of ≈ 16 MeV. For pairs with $A > 100$, a constant–geometry derivative Woods–Saxon imaginary potential, with a symmetry strength of ≈ 15 MeV, explains the ratios. However, for the lighter nuclei, the diffuseness of the imaginary potential varies rapidly near the $N = 28$ and $N = 50$ shell closures, and for the ^{59}Co – ^{58}Ni and Cu – Zn pairs, the imaginary symmetry–potential strength is about twice the 15 MeV global value. A method of approximating the spin–spin potential is given, and it is shown that this interaction makes a negligible contribution to the calculated ratios. However, channel coupling can lead to large reorientation effects which can substantially change the calculated ratios. Differences in the spin–orbit interaction between neighboring pairs can significantly affect the calculated ratios."

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1 A.B. Smith, R.D. Lawson and P.T. Guenther, Report ANL/NDM–114, Argonne National Laboratory, Argonne, Illinois (1989).

B. CONTINUUM NEUTRON STUDIES

1. Double–Differential Inelastic–Neutron Emission Measurements and Analysis. (P.T. Guenther, A.B. Smith and S. Chiba*)

An extensive data base of neutron–emission spectra has been measured for mono–isotopic elements, covering the mass numbers A=89 to 195 for incident–neutron energies of 5 to 8 MeV over an angular range of 30^{o} to 160^{o}. These data have been reduced to cross sections and the results were reported at three meetings during the Fall of 1989.[1-3] In addition to providing information on nuclear level densities, this work has quantified the contribution of the pre–equilibrium process to the continuum neutron spectrum. When comparing our cross sections to those calculated with widely used nuclear model codes (e.g. ALICE), the importance of appropriate optical–model parameterization was demonstrated. In particular, it was shown that the use of default global potentials could lead to cross-section values differing by as much as a factor of two from those measured and predicted by nucleus–specific potentials. In fact, where the compound–nucleus decay is dominated by neutron emission, the quality of the optical–model parameterization is more critical to the accuracy of the calculated cross sections than that of the level–density representation.[3] The experimental cross sections have been collected into a library for distribution to the determination, by detailed computer modeling, of various data corrections, including neutron multiple scattering.

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* Chemical Technology Division, Argonne National Laboratory, Argonne, Illinois.
** Rocketdyne Division, Rockwell International Corporation, Canoga Park, California.

C. STANDARDS MEASUREMENTS

1. Inter Comparison of ^{238}U Deposits Employed for Neutron Fluence Determination in Neutron Activation Cross–Section Measurements. (J.W. Meadows, D.L. Smith, G. Winkler*, H. Vonach* and M. Wagner*)

Discrepancies arose in the calibration of a ^{238}U fission deposit used for neutron–cross–section measurements at CBNM–Euratom (Geel, Belgium), IRK–Vienna (Austria) and PTB–Braunschweig (Federal Republic of Germany). There was a disagreement of several percent (well beyond the errors) between calibration measurements based on low–geometry alpha counting and neutron reaction yield measurements involving $^{238}U(n,f)$ and $^{27}Al(n,\alpha)^{24}Na$ reactions at 14.7 MeV where both cross sections were presumed to be very well known. In order to resolve this discrepancy, this deposit was intercompared with several standard ^{238}U deposits at Argonne National Laboratory. The measurements at Argonne indicate consistency between the alpha counting and neutron-fission results, and suggest that the mass of the IRK deposit should be reduced by about 3–4% from the value previously assumed. The results of this work were reported[1] at an NEANDC Specialists' Meeting on Activation Cross Sections held at Argonne in September 1989. The abstract of this paper follows: "An intercomparison is made between a collection of five uranium deposits used for neutron fluence determination in neutron activation experiments at Argonne National Laboratory, Illinois, U.S.A. (ANL), and a single corresponding deposit from the Institut für Radiumforschung und Kernphysik, Vienna, Austria (IRK). The predominant uranium isotope in each of these deposits is ^{238}U. Two methods were used in the study: low–solid–angle alpha counting and the measurement of fast–neutron fission yield ratios. This investigation produced the following calibration values for the IRK deposit: (160.7 ± 1.7) microgram from alpha counting and (163.3 ± 2.0) microgram from fission ratio measurements. The latter value is a weighted average of twenty–four separate measurements."

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* Institut für Radiumforschung und Kernphysik, University of Vienna, Vienna, Austria.

1 J.W. Meadows, D.L. Smith, G. Winkler, H. Vonach and M. Wagner, Proceedings, NEANDC Specialists' Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications, Argonne National Laboratory, September 13–15, 1989.

2. A Search for Possible Structure in the $^{238}U(n,f)$ Cross Section near 2.3 MeV. (J. W. Meadows, D. L. Smith and L. P. Geraldo*)

This work has been completed and published.[1] The abstract for the journal article reads as follows: "The shape of the $^{238}U(n,f)$ cross section was measured relative to the $^{237}Np(n,f)$ cross section over the neutron energy region 1.9–2.6 MeV to search for possible gross structure in the ^{238}U cross section. Forty–two measurements were made in this energy interval with $\sim$ 24 keV energy resolution and a statistical accuracy of < 1 % using the $^{7}Li(n,p)^{7}Be$ reaction as the neutron source. No structure was observed. Absolute measurements were made at 2.150 and 2.453 MeV to normalize the shape data."

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* Visiting Scientist. Present address: IPEN–CNEN/SP, C. P. 11049 Pinheiros, 01000 Sao Paulo, Brazil.

1 J.W. Meadows, D.L. Smith and L.P. Geraldo, Ann. Nucl. Energy 16, 471 (1989).

D. ACTIVATION CROSS SECTION MEASUREMENTS

1. Activation Cross Section Measurements near Threshold for the $^{24}Mg(n,p)^{24}Na$ and $^{27}Al(n,\alpha)^{24}Na$ Reactions. (L.P. Geraldo*, D.L. Smith and J. W. Meadows)

This work was mentioned in the 1989 Report to the DOE Nuclear Data Committee. The project has been completed and the results published.[1] The abstract from the journal paper reads as follows: "Differential cross sections have been measured for the $^{24}Mg(n,p)^{24}Na$ and $^{27}Al(n,\alpha)^{24}Na$ reactions in the neutron energy range from near threshold to approximately 10 MeV using ^{238}U fast–neutron fission as a cross section standard. The present data generally support previous work, although the cross sections tend to be somewhat larger for $^{27}Al(n,\alpha)^{24}Na$, particularly in the 8–9 MeV range. These data contribute significantly to reducing the uncertainty in contemporary knowledge of the cross sections for these reactions in the threshold region."

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* Visiting Scientist. Permanent address: IPEN–CNEN/SP, C.P. 11049–Pinheiros, 01000 Sao Paulo, Brazil.

1 L.P. Geraldo, D. L Smith, and J. W. Meadows, Ann. Nucl. Energy 16, 293 (1989)

2. A Search for Neutron–Induced Long–Lived Activities in Copper, Silver, Hafnium, Europium and Terbium. (J.W. Meadows, D.L. Smith, L.R. Greenwood*, R.C. Haight**, Y. Ikeda† and C. Konno†)

This project was mentioned in the 1989 Report to the DOE Nuclear Data Committee. The program was undertaken under the sponsorship of an International Atomic Energy Agency Coordinated Research Program. During the past year investigators from the Japan Atomic Energy Research Institute (JAERI) joined in this multi–laboratory collaboration. The responsibilities (and status) for various aspects of this experiment are divided as follows: Argonne [irradiations in the Be(d,n) spectrum – done, sample counting in progress, computation of corrections – in progress, and overall coordination]; Los Alamos [irradiations in the p–T neutron field – done]; JAERI [irradiations at 14 MeV – done, sample counting–in progress]. A number of activities have been observed and preliminary cross section values derived. Several issues are emerging. First, some of the more interesting activities are still being masked by shorter–lived components. Since these competing activities generally involve other isotopes of the same element, there are no clear alternatives (e.g., chemical separation) to simply waiting for the shorter–lived components to die away. Other investigators in the Coordinated Research Program have found that it takes more than two years, in some cases, before satisfactory counting conditions can be achieved. Another problem area is competition between (n,2n) and (n,γ) processes in producing the same activities. This is proving to be a rather serious problem for the Be(d,n) spectrum measurements. The problems with competing activities mentioned above would have been greatly reduced if isotopically enriched sample materials had been available for this experiment; they were not. The most time–consuming aspects of the data analysis are proving to be the sample geometry, absorption and multiple–scattering corrections for the multiple–sample packets. It has been found that the effects of the corrections for multiple scattering, which were previously anticipated to be a potentially serious problem, are actually rather modest. Work on the task of their determination is moving along well. A progress report[1] on this project was presented on the occasion of a meeting of the participants in the Coordinated Research Program which took place during September 1989. The abstract from this paper follows: "Identical sample packets, each containing samples of elemental copper, silver, europium, terbium and hafnium, as well as titanium, iron and nickel as dosimeters, have been irradiated in three distinct accelerator neutron fields (at Argonne National Laboratory and Los Alamos National Laboratory, in the U.S.A., and Japan Atomic Energy Research Institute, Tokai, Japan) as part of an inter-laboratory research collaboration to search for the production of long–lived radionuclides for fusion waste disposal applications. This paper is a progress report on this project. To date, we have detected the following activities and have obtained preliminary experimental cross–section values for several of these: $^{106m,108m,110m}Ag$; $^{150m,152g,154}Eu$, $^{158,160}Tb$; and $^{175,178m2,179m2,181}Hf$."

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* Chemical Technology Division, Argonne National Laboratory, Argonne, Illinois.
** Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico.
† Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.
1 J.W. Meadows, D.L. Smith, L.R. Greenwood, R.C. Haight, Y. Ikeda and C. Konno, "A Search for Long–Lived Radionuclides Produced by Fast–Neutron Irradiations of Copper, Silver, Europium, Terbium and Hafnium," Proceedings, IAEA Consultants' Meeting on Long–Half–Life Activation Reactions for Fusion Waste Disposal Applications, Argonne National Laboratory, September 11–12, 1989.

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

In the course of performing a comprehensive evaluation of Y for ENDF/B–VI[1] it was found that the experimental database for the $^{89}Y(n,p)^{89}Sr$ reaction is quite uncertain. The main reason is that ^{89}Sr decays solely by beta emission (with no signature gamma rays). Beta counting is difficult, and it is rapidly becoming a "lost art" in the community of nuclear data experimenters. The University of Michigan group has had recent experience in this area, so this prompted a collaboration to address this reaction. Samples of Y metal have been irradiated at Argonne at energies in the range from 6–10 MeV. Thinner samples of Y were also irradiated in the University of Michigan research reactor in order to investigate certain beta–absorption corrections which are required for this work. The beta counting of these samples is now in progress.

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* Graduate student. Nuclear Engineering Department, University of Michigan, Ann Arbor, Michigan.

1 A.B. Smith, D.L. Smith, P. Rousset, R.D. Lawson and R.J. Howerton, Report ANL/NDM–94, Argonne National Laboratory (1986).

4. Measurement of the $^{47}Ti(n,p)^{47}Sc$ Reaction Cross Section. (W. Mannhart*, D.L. Smith, and J.W. Meadows)

Work on this project was completed during 1989 and the final results reported at a conference.[1] The abstract of this paper reads as follows: "In the neutron energy range between 1.2 and 8 MeV, the cross section of the reaction $^{47}Ti(n,p)^{47}Sc$ was measured relative to the fission cross sections of $^{235}U(n,f)$ or $^{238}U(n,f)$. In parallel, the integral responses of this reaction in a ^{252}Cf and a ^{235}U fission–neutron spectrum were experimentally determined. All experiments were related to a common radioactivity counting detector. Final numerical data figures are given. A complete uncertainty covariance matrix of this experiment has been derived from the analysis."

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* Physikalisch–Technische Bundesanstalt, Braunschweig, Fed. Rep. of Germany.

1 W. Mannhart, D.L. Smith, and J.W. Meadows, Proceedings, NEANDC Specialists' Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications, Argonne National Laboratory, September 13–15, 1989.

E. NEUTRON SPECTRUM INVESTIGATIONS

1. Investigation of the Low–Energy Portion of the Neutron Spectrum from Bombardment of Thick Be–Metal Targets. (J.W. Meadows)

The intense continuum–neutron spectrum produced by deuteron bombardment of thick Be–metal targets continues to play a considerable role in the experimental activities of this laboratory (e.g., see Items B.2 and D.2, above). Precise characterization of the spectrum is a necessity for accurate quantitative applications. Emphasis continues to be on the lower–energy range of this spectrum (i.e., < 2 MeV) because many applications of this spectrum in our laboratory environment are sensitive to these neutrons. The effort involves detailed spectrum measurements with a fission chamber containing uranium deposits enriched in ^{235}U, and use of the time–of–flight method. Current emphasis is on determining just where the primary Be(d,n) spectrum yield goes to zero at low energies. Very careful measurements are being made with low pulse–repetition rates in order to answer this question. The main emphasis is on 7–MeV deuterons, since much of the integral data taken in this laboratory is at this energy. Once some of the basic questions about the low–energy portion of the spectrum are answered, measurements will be made at other deuteron energies, and with a scintillation detector and longer flight paths (to carefully define the high–energy part of the spectrum).

F. NUCLEAR DATA EVALUATION ACTIVITIES

1. Comprehensive Evaluated Neutronic Data File for Indium. (A.B. Smith, S. Chiba*, D.L. Smith, J.W. Meadows, P.T. Guenther, R.D. Lawson and R.J. Howerton**)

A comprehensive evaluated nuclear–data file for elemental indium has been completed and is now undergoing a final numerical checking process. It will be submitted for consideration as a part of ENDF/B–VI. It is the first comprehensive elemental indium file available to the ENDF/B system. The work was carefully coordinated with the complementary measurement and analysis program cited in Item A.3, above, and it gives particular attention to quantitative uncertainty specification. Associated with the comprehensive neutronic file is a special–purpose file for the ^{115}In(n,n′)^{115m}In dosimetry reaction. These two files are documented in a laboratory report.[1]

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** Lawrence Livermore National Laboratory, Livermore, California.

1 A.B. Smith, S. Chiba, D.L. Smith, J.W. Meadows, P.T. Guenther, R.D. Lawson and R.J. Howerton, Report ANL/NDM–115, Argonne National Laboratory (1990).

2. Comprehensive Evaluated Neutronic File for Elemental Zirconium. (A.B. Smith, S. Chiba*, P.T. Guenther, J. W. Meadows, R.D. Lawson and R. J. Howerton**)

Since the corresponding measurement program, cited above, is completed, work on this file is progressing well. The total–cross–section portion of the file is now complete. The portions of the file dealing with capture, inelastic–scattering, and the (n,2n) reaction are nearing completion. It is clear that there will be significant changes from ENDF/B–V, and that the experimental database for elemental zirconium is deficient.

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** Lawrence Livermore National Laboratory, Livermore, California.

3. ^{58}Ni Evaluation. (A.B. Smith, P.T. Guenther and D.L. Smith)

This partial evaluation (600 keV to 20 MeV) makes use of the new experimental information and its interpretation, as cited in Item A.4, above. Portions of the file are already complete at this time, and work is progressing on the others.

4. Elemental Calcium. (A.B. Smith, J.W. Meadows, R.J. Howerton*, and D.L. Smith)

Work on a comprehensive evaluated data file for elemental calcium has started, thereby complementing the measurement program cited in Item A.5, above.

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* Lawrence Livermore National Laboratory, Livermore, California.

5. An Evaluated Neutronic Data File for Bismuth. (P.T. Guenther, R.D. Lawson, J.W. Meadows, A.B. Smith, D.L. Smith, M. Sugimoto*, and R. J. Howerton**)

Work on the evaluation project has been completed and the file transmitted to the National Nuclear Data Center, Brookhaven National Laboratory. The work is documented in a laboratory report.[1] The abstract of this report reads as follows: "A comprehensive evaluated neutronic data file for bismuth, extending from 10^{-5} eV to 20.0 MeV, is described. The experimental database, the application of the theoretical models, and the evaluation rationale are outlined. Attention is given to uncertainty specification, and comparisons are made with the prior ENDF/B–V evaluation. The corresponding numerical file, in ENDF/B–VI format, has been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory."

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** Lawrence Livermore National Laboratory, Livermore, California.

1 P.T. Guenther, R.D. Lawson, J.W. Meadows, A.B. Smith, D.L. Smith, M. Sugimoto, and R.J. Howerton, Report ANL/NDM–109, Argonne National Laboratory (1989).

G. NUCLEAR THEORY, MODELS AND CODES

1. Decays of Millisecond Isomers in Odd–Odd N=81 Nuclei ^{146}Tb, ^{148}Ho and ^{150}Tm. (R. Broda*, P.J. Daly**, J.H. McNeill†, Z.W. Grabowski**, R.V.F. Janssens, R.D. Lawson, and D.C. Radford††)

Following reactions induced by 245–MeV ^{60}Ni ions, isomers have been identified in the odd–odd N=81 isotones ^{146}Tb, ^{148}Ho and ^{150}Tm with half–lives of 1.18(2), 2.35(4) and 5.2(3) ms, respectively. Their decays have been characterized by γ–ray spectroscopy. The isomers are interpreted as $(\pi h_{11/2} \nu h_{11/2}^{-1})10^+$ states decaying to members of $\pi h_{11/2} \nu d_{3/2}^{-1}$ and $\pi h_{11/2} \nu s_{1/2}^{-1}$ multiplets. The observed level spectra and Ml branching ratios are found to be in good agreement with shell model predictions based on empirical and Schiffer–True $\pi\nu^{-1}$ residual interactions.

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†† Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

1 R. Broda, P.J. Daly, J.H. McNeill, Z.W. Grabowski, R.V.F. Janssens, R.D. Lawson, and D.C. Radford, Zeit. für Physik, A334, 11 (1989)

2. Resonance Effects in Neutron Scattering Lengths. (J. E. Lynn*)

The nature of neutron scattering lengths is described and the nuclear effects giving rise to their variation is discussed. Some examples of the shortcomings of the available nuclear database, particularly for heavy nuclei, are given. Methods are presented for improving this database, in particular for obtaining the energy variation of the complex coherent scattering length from long to sub–Ångstrom wave lengths from the available sources of slow neutron cross section data. Examples of this information are given for several of the rare earth nuclides. Some examples of the effect of resonances in neutron reflection and diffraction are discussed. The results of this work are summarized in a laboratory report.[1]

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* Argonne Fellow. Present address: Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico.

1 J.E. Lynn, Report ANL/NDM–113, Argonne National Laboratory, Argonne, Illinois (1989).

3. Optical Model Spin–Spin Interaction. (R. D. Lawson, P. T. Guenther, and A. B. Smith)

A report on this work was presented at a conference.[1] The abstract of this paper reads as follows: "The residual nucleon–nucleon interaction is taken to be the Schiffer-True potential[2] and, on the basis of this, the requisite spin–spin potential to be used in an optical model (OM) calculation of the elastic scattering of neutrons from vanadium is deduced. If the nucleon–nucleus spin–orbit interaction is neglected, it is shown that the usual spherical OM codes can be used, without modification, to calculate angular distributions when this force is considered. The angular distribution of the ratios of V/Cr elastic–scattering cross sections at 8 MeV is examined using a regional OM potential which includes the isovector changes in the real and imaginary potential strengths proposed by

Walter and Guss.[3] The addition of this spin–spin interaction has little effect on the calculated ratios which disagree with the experimental results."

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1 R.D. Lawson, P.T. Guenther and A.B. Smith, Bull. Am. Phys. Soc. 34, No. 8, 1831 (1989).
2 J. P. Schiffer and W. W. True, Rev. Mod. Phys. 48, 191 (1976).
3 R. Walter and P. Guss, Proc. Conf. on Nucl. Data for Basic and Applied Science, Gordon and Breach, N.Y. (1986).

4. Fifty Years of Nuclear Fission. (J. E. Lynn*)

This work, first presented as a colloquium talk, has now been issued as a laboratory report.[1] The abstract is as follows: "This report is the written version of a colloquium first presented at Argonne National Laboratory in January 1989. The paper begins with an historical preamble about the events leading to the discovery of nuclear fission. This leads naturally to an account of early results and understanding of the fission phenomena. Some of the key concepts in the development of fission theory are then discussed. The main theme of this discussion is the topography of the fission barrier, in which the interplay of the liquid–drop model and nucleon shell effects lead to a wide range of fascinating phenomena encompassing metastable isomers, intermediate–structure effects in fission cross–sections, and large changes in fission product properties. It is shown how study of these changing effects and theoretical calculations of the potential energy of the deformed nucleus have led to a broad qualitative understanding of the nature of the fission process."

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* Argonne Fellow. Present address: Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico.
1 J.E. Lynn, Report ANL/NDM–111, Argonne National Laboratory, Argonne, Illinois (1989).

5. Modification of ANL–ECIS. (S.Chiba*)

The option of fitting composite–level experimental scattering data has been included in the coupled–channels code ECIS in order to facilitate the fitting of data where experimental resolution does not permit the definition of individual level cross sections.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

6. Modification of ABAREX. (S. Chiba*)

An option has been added to this code to allow the fitting of elemental scattering cross sections with elemental composites of isotopic contributions whose real and imaginary potentials are related by an isospin term. This new feature of the code is essential for the analysis of scattering data from multi–isotope elements where no single isotope is clearly dominant, e.g., Zr (see Item A.6).

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H. ANALYTICAL METHODS DEVELOPMENT

1. Neutron–Scattering On–Line–Data–Acquisition Software Development. (P.T. Guenther and S. Chiba*)

The neutron–detector–efficiency determination has been revised to include a calculated high–energy relative–efficiency extrapolation for the ^{252}Cf–spectrum–based one that has been used thus far. This procedure will improve cross–section accuracy, particularly in those situations requiring a wide sensitivity range as, for example, the double–differential emission spectra described in Item B.1, above. Work is in progress on a complete revision of the 10–angle–spectrometer on–line–data–acquisition software package (see Item I.1, below). This effort is warranted by the greater power of the 386 PC (relative to the system presently used), with its attendant possibility of more flexible handling of the data stream. Improvements continue to be made on the down–stream data–processing code SCATTER. They allow the consolidation of numerous data reduction tasks that were formerly performed piecemeal.

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* Visiting Scientist. Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki–ken, Japan.

2. Basic Concepts of Probability and Statistics for Nuclear Data Applications. (D.L. Smith)

A reference manual dealing with the basic concepts of probability, as applied to the field of nuclear data, has been prepared and issued as a laboratory report.[1] The abstract of this document reads as follows: "Some basic concepts of probability theory are presented from a nuclear–data perspective, in order to provide a foundation for thorough understanding of the role of uncertainties in nuclear data research. Topics included in this report are: events, event spaces, calculus of events, randomness, random variables, random–variable distributions, intuitive and axiomatic probability, calculus of probability, conditional probability and independence, probability distributions, binomial and multinomial probability, Poisson and interval probability, normal probability, the relationships existing between these probability laws, and Bayes' theorem. This treatment emphasizes the practical application of basic mathematical concepts to nuclear data research, and it includes numerous simple examples."

The writing of an entire monograph on probability and statistics for the NEANDC Monograph Series was completed during 1989, and the typing of the manuscript is in progress.

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1 D.L. Smith, Report ANL/NDM–92, Argonne National Laboratory (1988).

3. Covariance Analysis and Fitting of Germanium Gamma–ray Detector Efficiency Calibration Data. (L.P. Geraldo* and D.L. Smith)

Measurement of neutron–induced reaction cross sections often requires detecting either prompt gamma rays or gamma rays emitted in the decay of radioactive samples. This paper describes the analytical procedures used in our laboratory to generate calibrations for germanium gamma–ray detector full–energy–peak efficiency (ϵ) versus photon energy (E), and to predict the associated uncertainties. The general method, which involves fitting a curve to measured data by the principle of least squares, is widely applicable beyond the specific problem considered here. Random and systematic (correlated) errors associated with the calibration process are included through formation of a calibration–data covariance matrix. Objective prediction of the errors in derived quantities (e.g., detector efficiencies at energies not directly represented in the calibration data) is achieved through error propagation. Specifically, this work discusses fitting the empirical formula

$$\ell n\, \epsilon = \sum_{k=1}^{m} p_k (\ell n\, E)^{k-1}$$

to measured calibration data at gamma–ray energies above 200 keV. A numerical example is provided to demonstrate the approach. A paper on this work has been accepted for publication in Nuclear Instruments & Methods in Physics Research (Section A).

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4. A Vector Model for Error Propagation. (D.L. Smith, and L.P. Geraldo*)

This work has been completed and a laboratory report is issued.[1] The abstract reads as follows: "A simple vector model for error propagation, which is entirely equivalent to the conventional statistical approach, is discussed. It offers considerable insight into the nature of error propagation while, at the same time, readily demonstrating the significance of uncertainty correlations. This model is well suited to the analysis of errors for sets of neutron–induced reaction cross sections."

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* Visiting Scientist. Present address: IPEN–CNEN/SP, C.P. 11049–Pinheiros, 01000 Sao Paulo, Brazil.

1 D.L. Smith and L.P. Geraldo, Report ANL/NDM–110, Argonne National Laboratory (1989).

I. INSTRUMENTATION DEVELOPMENT

1. Conversion of the 10–Angle TOF Spectrometer to a 386–Based PC On–Line–Data–Acquisition System. (A. B. Smith, P. T. Guenther, R. Whitman and D. Travis*)

Conversion of the 10–angle TOF spectrometer data–acquisition system involves the redesign of the system logic, construction of custom interfacing circuitry, as well as purchase of off–the–shelf commercial hardware. With the retirement of the CDC–160A on–line–data acquisition computer, a 27–year era will come to a close!

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* Electronics Division, Argonne National Laboratory, Argonne, Illinois.

1. BROOKHAVEN NATIONAL LABORATORY

A. INTRUDER STATES

An important aspect of low energy nuclear structure in near magic regions is the widespread phenomenon of intruder states. In even-even nuclei these are generally thought to involve proton 2p-2h excitations which, in effect, increase the number of valence protons. They therefore have a larger valence N_pN_n product than the normal states in the core nucleus and are both more deformed and descend faster in energy with increasing N_n so that their energies minimize near mid-neutron shell. This picture has been used to explain the Cd and Pb intruder states and systematics.

A critical test of the Cd intruder/vibrational picture involves measurements of absolute B(E2) values for key E2 transitions, that is, level lifetimes. These lifetimes were measured using the picosecond timing techniques that we developed over the past few years. Extensive experiments were carried out for $^{116-120}$Cd this year. The results confirm the basic collective character of the 2^+_1 level, and the 2-phonon triplet levels. They show that in ^{116}Cd it is the 0^+_2, not the 0^+_3 level, that is the intruder. The ^{116}Cd result shows that the 0^+_2-0^+_3 mixing amplitude is ~0.25, in excellent agreement with our earlier estimate of 0.21 for a schematic model. Overall, a nearly constant $B(E2:0^+_1 \rightarrow 2^+_1)$ of about 6 single particle units, reflecting the relatively moderate collectivity of these states, was observed. The absolute values of the B(E2)s for the 0^+ states in ^{118}Cd indicated that there was not enough total $0^+ \rightarrow 2^+$ strength to accommodate the expected vibrational collectivity. One way to recover this strength is to assume that $\tau(0^+_3)$ is much smaller than its upper limit, but this would also reverse the assignments of intruder and normal states in ^{118}Cd and imply that the anharmonicities are larger than previously thought. The impact of this will be pursued with lifetime measurements of ^{120,122}Cd when the HFBR restarts, and with complementary studies on ^{114}Cd employing the Gamma Ray Induced Doppler-broadening (GRID) technique at the ILL.

B. THE A=100 REGION

This region is one of the most critical testing grounds for nuclear structure models because of the rapid spherical-deformed transitions taking place at N=100 in the neutron rich isotopes of Sr, Zr, and Mo. For years a major TRISTAN effort has focused on these nuclei. Recent studies have aimed at understanding issues of coexistence and the evolution of deformation.

One study of lifetimes in ^{98}Sr and ^{100}Zr led to a revision of earlier ideas. Instead of exhibiting coexisting spherical and deformed structures, these nuclei seem to each have two coexisting bands with different deformations. The mixing of these structures was extracted and found to be weak. These results will surely entail a more sophisticated theoretical approach than currently exists and pose a challenge to recent Hartree Fock calculations.

Other sub-nanosecond lifetime measurements in Y and Sr nuclei showed that there is a sudden saturation of deformation at N=60,62 as soon as the deformed region is entered. This is in sharp contrast to the rare earth region where deformation increases almost to midshell. This phenomenon was explained by simple arguments combining p-n interaction ideas and the Nilsson model. The P-factor criterion demands 8-10 valence neutrons before deformation sets in this region as well as near A=150. In the A=100 region this already places the Fermi surface near flat or upsloping orbitals and hence inhibits further increases in equilibrium deformation.

Lifetime measurements in A=97 nuclei were particularly fruitful. They gave a value (3.5(4)b) for the quadrupole moment of the coexisting deformed band in ^{97}Sr. They showed the simultaneous existence of a nearly spherical ground state configuration, of a spherical vibrational excitation built on it and of the deformed structure and gave, as well, the values for the mixing matrix elements between these configurations. The spherical-deformed mixing matrix element is only about half that in the neighboring even nucleus. Comparison of B(E2) values in ^{97}Sr and ^{97}Y give information on the blocking, by neutrons and protons, of vibrational collective E2 transitions from the phonon excitations.

Lifetime measurements of the 3^- level in ^{96}Zr showed a B(E3) value of 65(10)w.u., which makes this the fastest known. Random Phase Approximation (RPA) calculations suggested important configurations in the wave functions that could account for this, in particular a significant $\nu g_{9/2}\nu h_{11/2}$ component not previously thought to be critical. Other lifetimes for 0^+_2 and 4^+_1 states in lighter Zr isotopes resolved earlier experimental discrepancies and were interpreted with shell model calculations.

C. <u>REFLECTION ASYMMETRIC NUCLEI</u>

An outstanding problem of high current interest in nuclear structure concerns the existence and properties of stably octupole deformed (reflection asymmetric) nuclei. These nuclei exhibit interesting features such as nearly degenerate parity doublet bands and large dipole moments. Examples of such nuclei are known in the actinide region and have been suggested near A=140-150. A key question is whether reflection asymmetric shapes occur as dynamic fluctuations or as stable distortions. The Ba isotopes are particularly central to this issue. Recent measurements with our picosecond timing technique gave lifetimes for the 2^+_1, 4^+_1, 0^+_2, 1^-_1, and 3^-_1 levels in ^{142,144,146}Ba. The E1 transition rates turn out to be large in ^{144}Ba and much smaller in ^{146}Ba. Previous calculations with an expanded Interacting Boson Model (IBM) including negative parity bosons and a vibrational "core" were unable to account for this. However, reflection asymmetric deformed mean field calculations (carried out in collaboration with W. Nazarewicz) reproduce the data quite well and definitely establish the need for large stable β_3 values in this region and simultaneously accounts for the differences between neighboring isotopes in terms of subtle cancellation effects in the contribution to the dipole moments.

D. <u>NUCLEAR SYMMETRIES</u>

The IBM predicts three basic nuclear symmetries, that is, rotational (SU(3)), vibrational (U(5)), and axially asymmetric rotors (γ soft) or O(6). Recent work in this area has been the completion of an experiment carried out in collaboration with the ILL in Grenoble to measure the lifetime of the 0^+_3

state in ^{196}Pt will provide the most critical test yet of O(6) character in that nucleus.

The measurement of these lifetimes involves a new and highly sophisticated method, the GRID technique, in which the Doppler broadening of a given γ-ray transition is measured, in flight, following recoil from the emission of a γ ray. This requires very high resolution, since the recoil energies are only a few eV in Pt. The experiments use the double flat crystal spectrometers at ILL. The main result from these measurements is a very long lifetime for the 0^+_3 level (>1.86 ps). This is consistent with the expected hindrance of the forbidden O(6) transition and is a factor of 13 slower than predicted by U(5), thus finally and decisively ruling out such a structure. A number of other lifetimes in Pt were also obtained in these experiments. The consequences of these lifetimes continue to be investigated.

A TRISTAN study of ^{96}Y decay, and the assignment of the Y parent as $J^\pi=0^-$, has led to the possibility of studying a fast first-forbidden $0^- \rightarrow 0^+$ β decay in a nearly double-magic nucleus (^{96}Zr). The result, a log _ft_ of 5.6, is one of the fastest known. Since the wave functions of the ground states of ^{96}Y and ^{96}Zr [which has a closed proton shell at Z=40 and a nearly-magic neutron number of N=56 ($d_{5/2}$ subshell)] are rather well known, a comparison of the empirically-measured absolute log _ft_ value with one calculated in the shell model allows a sensitive test of the presence of meson exchange effects in β decay.

First-forbidden decays in the region of doubly-magic ^{208}Pb have been the recent focus of theoretical study. Here those matrix elements which are proportional to Z are enhanced. Thereby, rank 1 matrix elements become comparably enhanced relative to rank zero matrix elements. Both are additionally enhanced due to an extraordinary coherence in the decay matrix elements, i.e., almost all $j_i \rightarrow j_f$ contributions are in phase. This is true for seven $0^+ \leftrightarrow 0^-$ and $1/2^+ \leftrightarrow 1/2^-$ transitions in A=205-209 nuclei. A large-basis shell-model calculation (by far the largest undertaken to date for these decays) was made to obtain the relevant matrix elements and then a least-squares fit was made to obtain the "best" effective operators. It is found that A_0 needs to be enhanced by 100% and the rank 1 operators quenched by a factor 0.52. The latter is in qualitative agreement with previous findings. The 100 percent enhancement of A_0 is considerably larger than predictions (~40 percent) of mesonic enhancements and may signal another effect of the nuclear medium. Interpretation of this interesting result is underway.

The half-life of ^{56}Co was remeasured by using the decay of the 847-keV γ-ray relative to the 662-keV line of ^{137}Cs. A half-life of 77.32(9)d was adopted, resolving a discrepancy in the literature. ^{56}Co is thought to the primary power source determining the long-term light decay rate of supernova stars. Under favorable circumstances, astronomers can measure the slope of the bolometric light curve of a supernova to an accuracy of better than 1%. Thus, resolving the discrepancy in the reported half-life of ^{56}Co is of high interest to certain astrophysical problems.

In the course of measuring the half-life of ^{56}Co a new γ ray was discovered in the decay of ^{56}Co having an energy of 852.78(5) keV and I_γ=0.050(3) relative to I_{847}=100. It was assigned as the 4298.0(4+)→3445.3(3+) transition in ^{56}Fe with a B(M1) value of 6.5(30)x10^{-3} W.u. consistent with the systematics of M1 transitions in A=45-90 nuclei.

Measurements are continuing on the half-lives of the long-lived isotopes ^{44}Ti, ^{207}Bi, and ^{32}Si using an automated proportional counter system at the BNL Chemistry Department. ^{44}Ti is currently the subject of searches in the remnants of supernova 1987A and is of interest because all existing ^{44}Ca is believed to originate from ^{44}Ti decay. Another aspect of this activity is that ^{56}Co and ^{44}Ti are thought to be the only important sources of positrons from explosive nucleosynthesis as observed from a γ-ray peak at 476 keV thought to be associated with the formation of positronium. After three years of counting, the preliminary value for ^{44}Ti is $T_{1/2}$=64.6(12) yr which disagrees with the three previous values including one of 54(2) yr that used the accelerator mass spectroscopy technique. The preliminary value for the half-life of ^{207}Bi is $T_{1/2}$=34.2(4) yr.

E. National Nuclear Data Center

1. Cross Section Evaluation Working Group (CSEWG)

CSEWG held two meetings in 1989, its 23rd year of activity. The major emphasis of these two meetings was the review of evaluations for ENDF/B-VI and the plans for benchmark testing of ENDF/B-VI. It was decided that most of the new evaluations and all carryover evaluations which had been converted to ENDF-6 format and corrected would be released in the first three months of 1990. Ten "tapes" have already been released and five more will be released shortly. The evaluations for ^{235}U, ^{238}U and ^{239}Pu will be released in June after preliminary data testing has been completed as will several material evaluations which still require revision or may be re-evaluated this spring. The entire library is available without restrictions.

In addition, the photon interaction library (LLNL) and a converted thermal scattering law library (LANL) will be ready for release after review. Part of the decay data library has been received with the remainder expected in May. A charged particle library will be completed in May. Two high energy evaluations for Fe^{56} extending to 1 GeV have been distributed (BNL). The last ENDF/B-VI sublibrary released will be the fission product yield data in the Fall of 1990.

The NEANDC/NEACRP sponsored Working Group on International Evaluation Cooperation has been formed and held its first meeting at ANL in October 1989. The group consists of representatives of CSEWG, JEF/EFF and JENDL along with members from the parent committees. The members of the Working Group have agreed on a free exchange of their evaluated data files and supporting information. The group is now in the process of forming several subgroups to coordinate efforts to solve important evaluation problems.

Two other areas of international cooperation exist. CSEWG has been supporting the Fusion Evaluated Nuclear Data Library (FENDL) project of the IAEA. The ENDF/B-VI library is being sent to the IAEA for possible inclusion of its material evaluations. Recent approaches from the BROND community (USSR-East Germany) show promise for additional joint activities. We expect to have two evaluators from the USSR at the next CSEWG meeting.

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.

The Center evaluated A=50, 58, 66, 141 and 142 and submitted them for publication; A=45, 67, 143 and 150 are being evaluated.

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 Federal Republic of Germany, U.S.S.R., France, Japan, Belgium, Kuwait, Sweden, the People's Republic of China and Canada.

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 4 1/2 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).

For users with ANSI-compatible video terminal (such as DEC's VT series) we have added video capability to the overall service control, and to the ENSDF and NSR retrieval programs. In this mode, forms and menus guide the user in generating his retireval. We have also added a general plotting capability for ENSDF and the experimental reaction data file (CSISRS). The user can perform retrievals, plot the information in either PostScript or Tektronix mode and then send the output to his own computer for final plotting.

4. Reaction Data Activities

Insufficient funding has caused the NNDC staff to be further reduced by one senior staff member. This has led to the termination of the CINDA effort (except for experimental data entries) and charged particle data bibliography and evaluation activities. We will continue to give high priority to the compilation of experimental neutron data but we request that measurers take the initiative to inform us of the existence of compilable data and to provide it to us on a computer readable medium.

Table 1

On-line Access Statistics 1986-1989

Year	Runs	Retrievals	NSR	ENSDF	NUDAT	CINDA	CSISRS	ENSDF
1986	648	1621	814	142	536	129	---	---
1987	1275	4263	2521	863	815	60	---	4
1988	2264	8748	5022	1303	1492	285	459	187
1989	3374	8406	3253	850	1841	522	1649	150

COLORADO SCHOOL OF MINES

1. <u>Radiative capture of low energy protons by light nuclei</u>

We have completed the analysis of our measurements of the radiative capture of low energies protons by 6Li, 7Li, 9Be and 11B. From our measurements of the gamma ray to charged particle branching ratios for the ^{6}Li, ^{7}Li and ^{11}B and from the absolute yield of the gamma rays from the ^{9}Be bombardment, we have determined astrophysical S-factors for the (p,γ) reactions between bombarding energies of about 40 to 175 keV. These S-factors are plotted in Figure 1. These S-factors may in turn be integrated over Maxwellian distributions to obtain the corresponding thermonuclear reactivities. Our deduced reactivities are given in Figure 2. For comparison, the reactivities presented by Caughlan and Fowler[1] are plotted in Figure 3. With the exception of ^{7}Li, we find generally good agreement with Caughlan and Fowler. The discrepency in the case of ^{7}Li is due to the fact that Caughlan and Fowler assumed the only contribution to the $^{7}Li(p,\gamma)^{8}Be$ reaction at low energies is the tail of the resonance at 441 keV[2], while our inferred S-factors for the reactions $^{7}Li(p,\gamma_0)^{8}Be$ and $^{7}Li(p,\gamma_1)^{8}Be^*$ (see Fig.1) indicate a direct, non-resonant contribution.

Our measurements have likewise afforded us determinations of the branching ratios of the radiative transitions to the ground and excited states of the final nuclei. These branching ratios are indicated in Figure 4. In the reaction $^{7}Li(p,\gamma)^{8}Be$, for example we find a 16% branch to the ground state and an 84% branch to the ^{8}Be excited state. In the case of the transitions to ^{12}C, we indicate both our measurements of the decay scheme at the well known resonance[3] at 163.1 keV (3.3%, 94%, <0.2%, and 2.5% to the first four levels of ^{12}C respectively) and the extrapolations to zero energy of the S-factors to the ground and first excited states (62% and 38% respectively.)

2. <u>Nuclear reactions of low energy deuterons with the stable isotopes of Lithium.</u> We have completed the initial phase of a study of the nuclear reactions of low energy deuterons with ^{6}Li and ^{7}Li. The specific reactions which we have investigated are:

1) $^6Li(d,p)^7Li$, $^6Li(d,\alpha)^4He$. The reactions were measured in reflection geometry with thick targets of isotopically enriched metallic ^6Li. A typical spectrum is shown in Figure 5. The peak labelled d(d,p)t is the result of deuterium build-up in the target. The yield (reactions/μC) of the $^6Li(d,\alpha)^4He$ reaction is given in Figure 6 and this yield is well fit assuming an S-factor S = (1.8 + 60*E_{cm}) MeV-b, where E_{cm} is given in MeV. The ratio of the yields of the (d,p)/(d,α) reactions is shown in Figue 7 and shows a surprising energy dependence at low energies. The ratios agree with the published results of Elwyn et al.[4] at the higher energies

2) $^6Li(d,\gamma)^4He$. This reaction was studied using techniques similar to those used in our measurements of the proton radiative capture reactions. We did not observe the 22.3 MeV gamma ray to the ^4He ground state but were able to establish an upper limit of 1.4E-6 on the branching ratio $^6Li(d,\gamma)^8Be$ / $^6Li(d,\alpha)^4He$.

3) $^7Li(d,\alpha)^5He$. This reaction was studied with a natural LiF target using the techniques described in reaction 1) above. A typical spectrum is shown in Figure 8. The thick target yield of this reaction is also given in Figure 6 and is seen to be fairly well fit assuming an S-factor of 0.17 MeV-b.

4) $^7Li(d,\gamma)^9Be$. As with reaction 2), we did not observe the 16.7 MeV gamma ray corresponding to the transition to the ^9Be ground state. We did, however, establish an upper limit of 6E-6 on the gamma-to-alpha branching ratio.

References

1. Georgeanne R. Caughlan and William A. Fowler, Atomic Data and Nuclear Data Tables 40, 283 (1988)

2. Georgeanne R. Caughlan, private communication (1989).

3. F. Ajzenberg-Selove, Nuclear Physics A433 1 (1985).

3. A.J. Elwyn et al., Physical Review C16 1744 (1977).

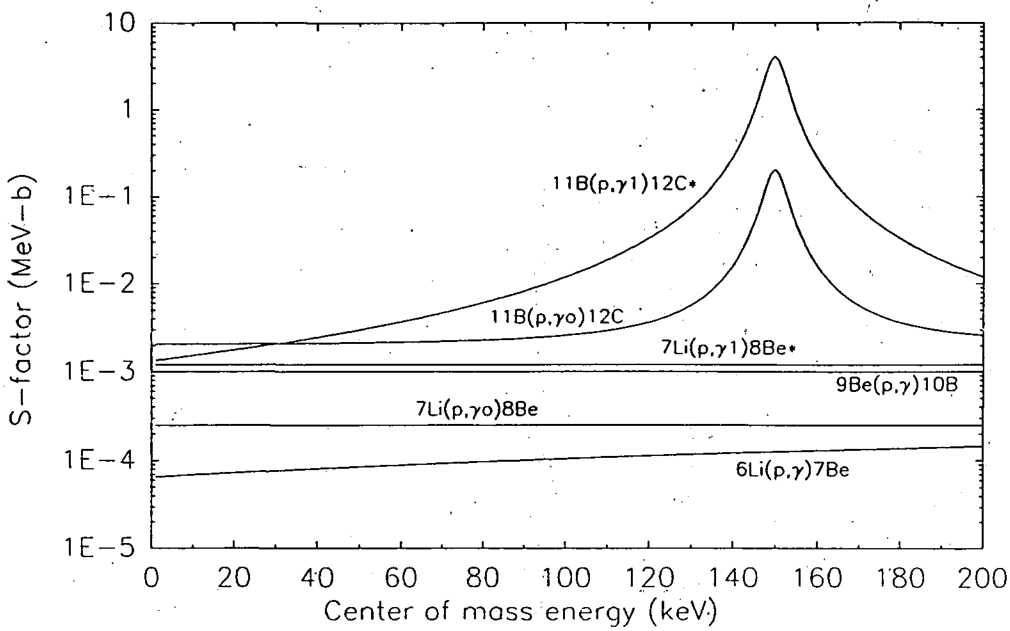

Figure 1. Astrophysical S-factors for the radiative capture of protons by ^{6}Li, ^{7}Li, ^{9}Be and ^{11}B.

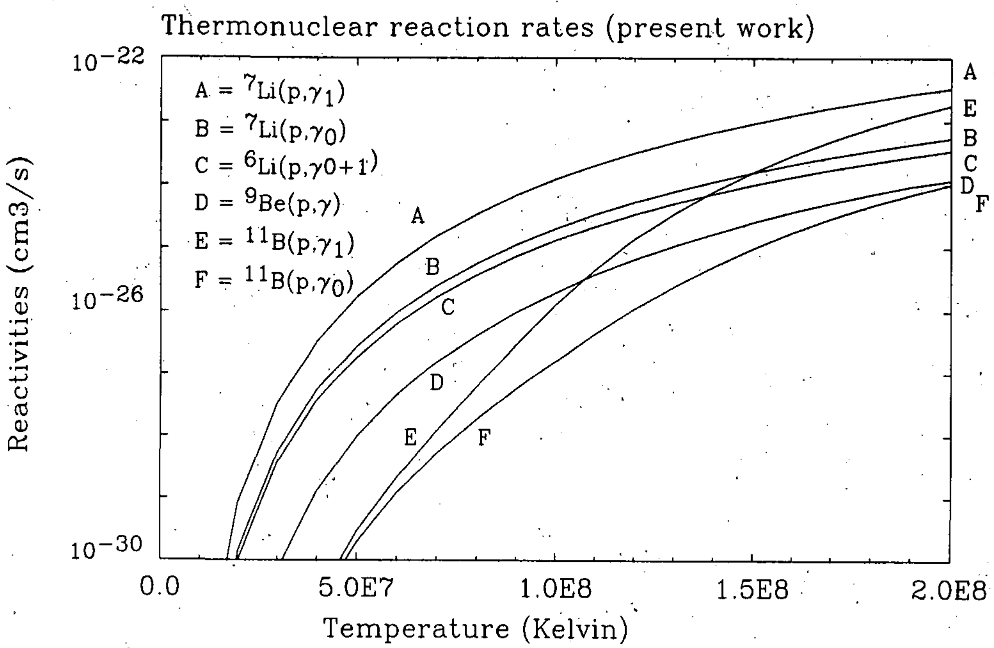

Figure 2. Thermonuclear reactivities deduced from inferred S-factors.

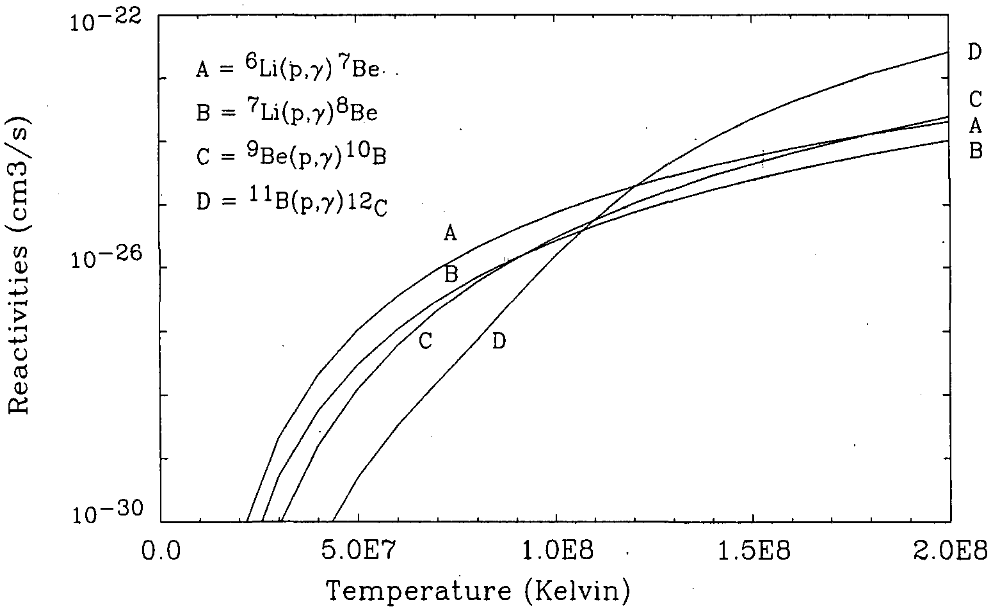

Figure 3. Published reactivities from Caughlan and Fowler for the reactions presented in Figures 1 and 2.

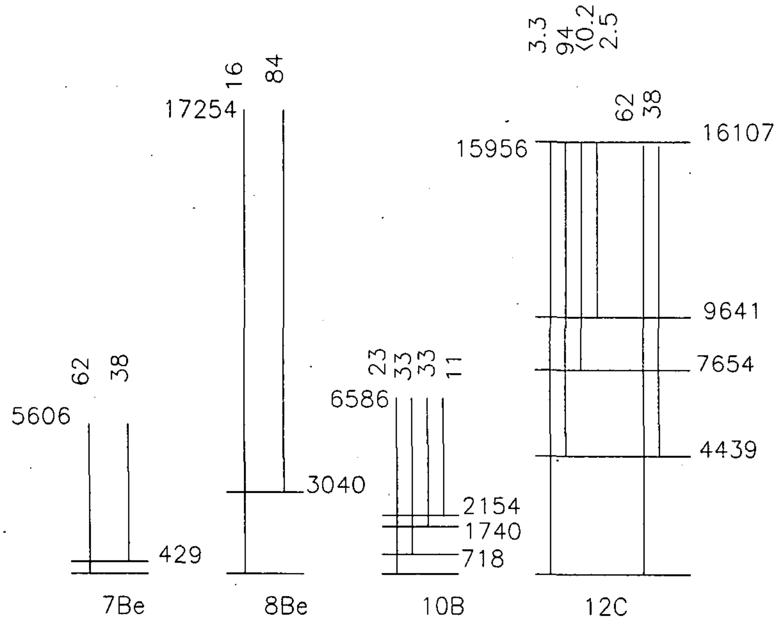

Figure 4. Branching ratios for radiative capture transitions of protons by ^{6}Li, ^{7}Li, ^{9}Be and ^{11}B. The reaction Q-values are given to the left of the diagrams, the branching ratios at the top, and the excitation energies in the final nuclei at the right. For the reaction $^{11}B(p,\gamma)^{12}C$, the branching ratios are given both for the resonance at 163.1 keV and as extrapolated to zero proton energy.

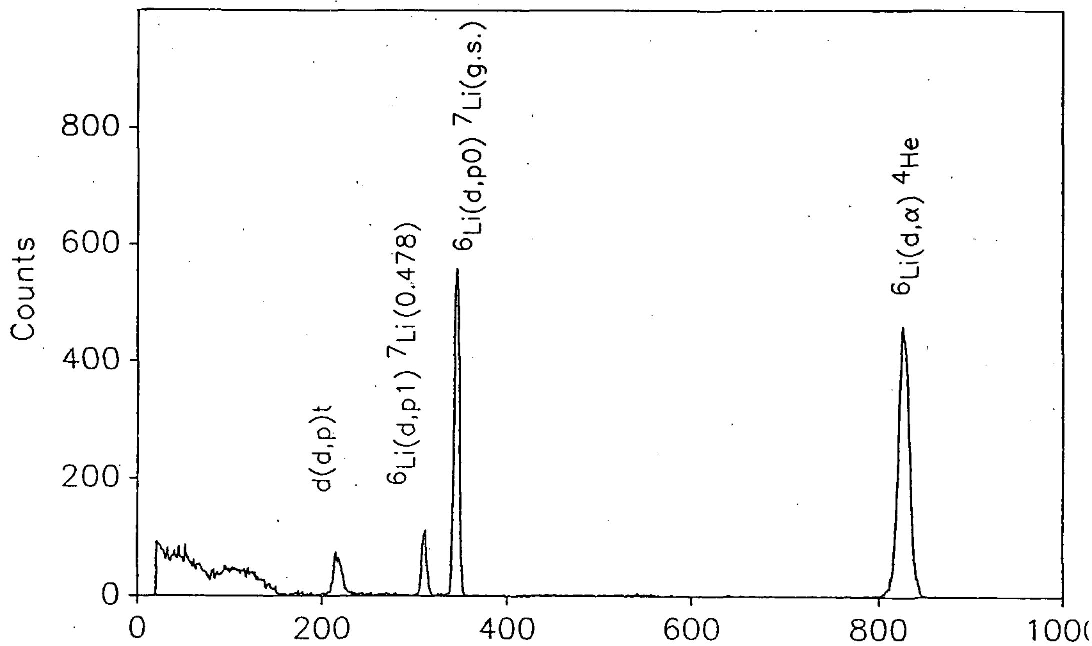

Figure 5. Energy spectrum measured during the bombardment of ^{6}Li with 120 keV deuterons.

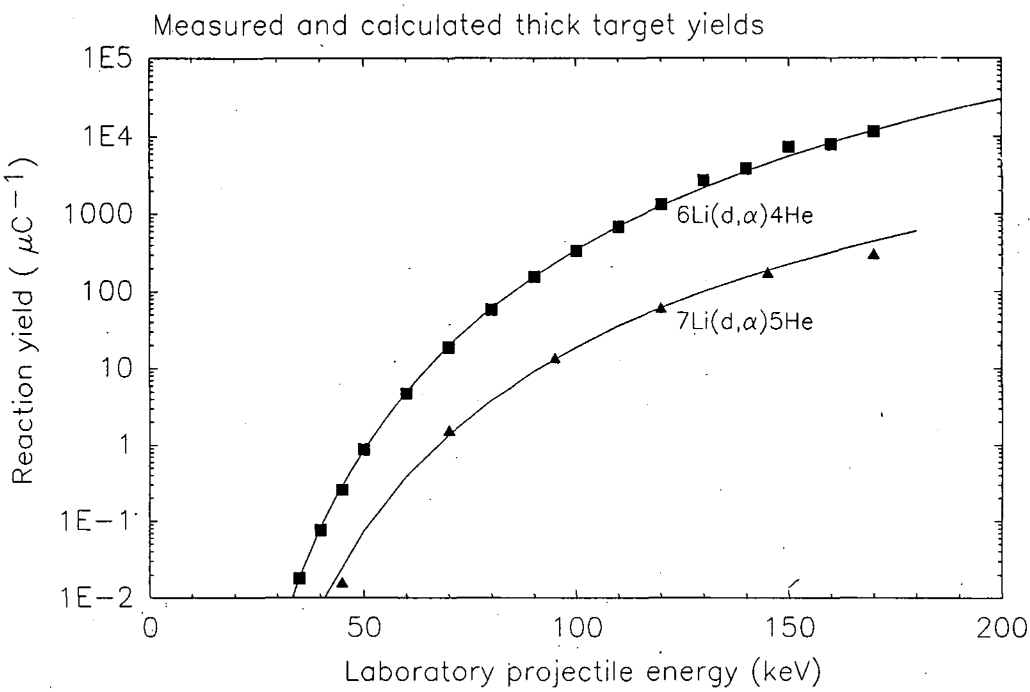

Figure 6. Measured and fit thick target yields for the reactions $^{6}Li(d,\alpha)^{4}He$ and $^{7}Li(d,\alpha)^{5}He$.

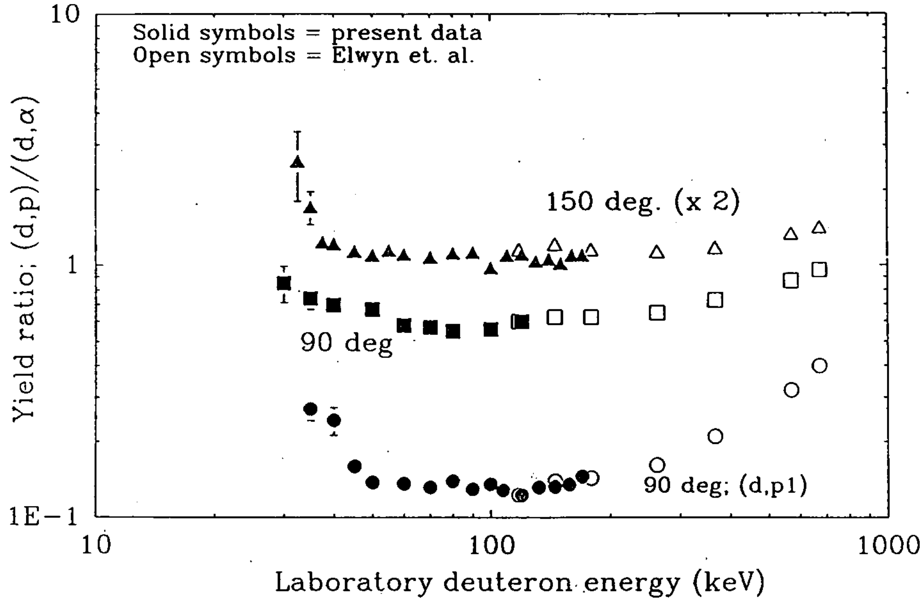

Figure 7. Ratios for the reaction ^{6}Li(d,p)^{7}Li and ^{6}Li(d,α)^{4}He.

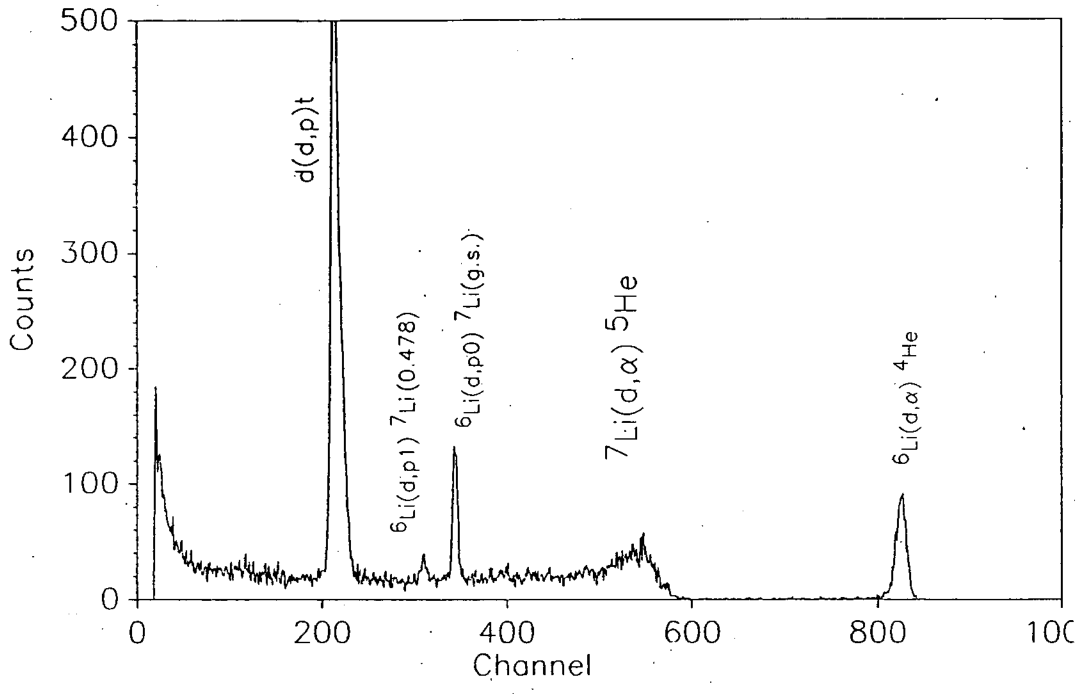

Figure 8. Energy spectrum measured during bombardment of LiF with 120 keV deuterons.

CROCKER NUCLEAR LABORATORY AND DEPARTMENT OF PHYSICS
UNIVERSITY OF CALIFORNIA, DAVIS

A. MEASUREMENTS

1. Neutron Elastic Scattering at 65 MeV on C, Si, Ca, Fe, Sn, Pb.* (E.L. Hjort, F.P. Brady, J.L. Romero, J.R. Drummond, B. McEachern, J.H. Osborne.)

Using a wire chamber based neutron detector[1] neutron elastic scattering cross sections have been obtained for C, Si, Ca, Fe, Sn and Pb at 65 MeV over an angular range of 6.5° to 47°. A CH_2 target was used for absolute normalization to the $^1H(n,n)$ cross section. Two different microscopic optical model potentials were contructed[2] and used to fit the data (Fig. A-1).

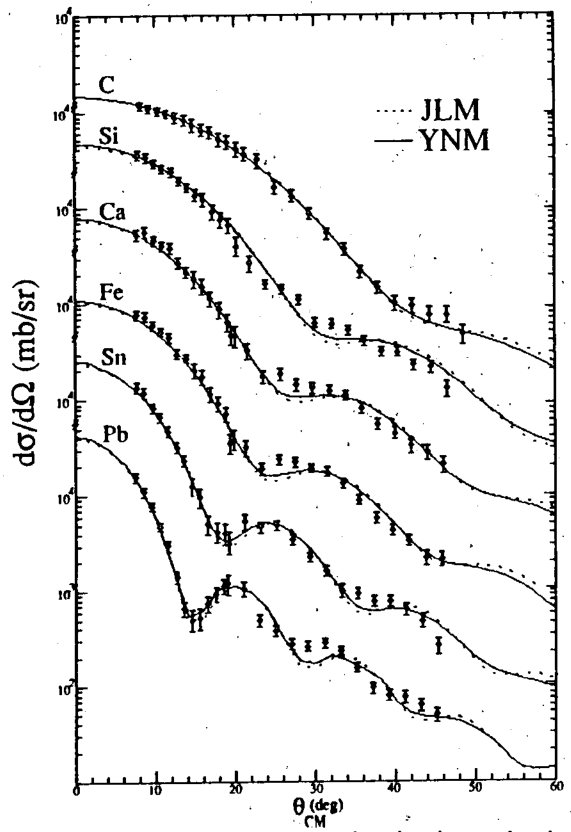

Figure A.1. Fits to the elastic data obtained from the JLM and YNM microscopic optical model potentials for (n,n) scattering at 65 MeV.

* Supported by NSF grant PHY 84-19380.

(1) F.P. Brady et al, Nucl. Instr. and Meth. 228 (1984) 89

(2) L.F. Hansen, private communication, 1990.

2. Double Differential Cross Sections for Fe(n,n'x) at 65 MeV.[$ #] (J.H. Osborne, E.L. Hjort, F.P. Brady, J.L. Romero, J.R. Drummond, B. McEachern, H.H.K. Tang,[♡] G.R. Srinivasan[♡])

Using a wire chamber based neutron detector[(1)] Fe(n,n'x) spectra have been obtained at angles from 10° to 30°. The spectra have been normalized to the elastic cross section of Fe which was obtained simultaneously. Comparisons are made with (p, p'x) and with the Cascade-Statistical Model. Attempts are made to separate the contributions of quasi-elastic scattering from the evaporation part of the reaction.

3. Pb (n,n'x) at 65 MeV and the Isospin Structure of the Giant Quadrupole Resonance Region.[* †] (E.L. Hjort, F.P. Brady, J.L. Romero, J.R. Drummond, M.A. Hamilton and B. McEachern; R.D. Smith,[**] V.R. Brown,[♮] F. Petrovich[‡] and V.A. Madsen[§])

The first Pb (n,n'x) data (at 65 MeV) are compared to earlier (61-66 MeV) (p,p'x) data. The isovector sensitivity of these nucleon probes is used to determine $M_n/M_p \simeq N/Z = 1.54$ for the giant quadrupole resonance (GQR). This result is consistent with other direct GQR measurements, 2_1^+ data connected through core polarization, and several microscopic random-phase-approximation calculations, but in disagreement with a π^-/π^+ study which gives $M_n/M_p = 3.8 \pm 1.2$.

$ Abstract Submitted for the Spring Meeting of the American Physical Society, May 1-4, 1989.

Supported by NSF grants PHY81-21003 and 84-19380.

♡ IBM, East Fishkill, NY.

(1) F.P. Brady et al, Nucl. Instr. and Meth. 228 (1984) 89

* Published in Physical Review Letters 62, 87, 1989.

† We gratefully acknowledge the support of the National Science Foundation under Grant No. NSF 84–19380 and the Associated Western Universities. Part of this work was done under the auspices of the U.S. Department of Energy under Contract No. W-74 05-ENG-48 at LLNL.

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4. The Gamow-Teller Transition Strength for $^{12,13}C(n,p)$ in the Neutron Energy Range 65 MeV - 230 MeV.* # (D.S. Sorenson,(1) X. Aslanoglou,(3) F.P. Brady,(1) J.R. Drummond,(1) R.W. Finlay,(3) R.C. Haight,(2) C. R. Howell,(4) N.S.P. King,(2) A. Ling,(2) P.W. Lisowski,(2) C.L. Morris,(2) B. Park,(3) J. Rapaport,(3) J.L. Romero,(1) W. Tornow,(4) J.L. Ullmann.(2))

Cross Sections have been extracted for the Gamow-Teller transition in $^{12}C(n,p)$ and $^{13}C(n,p)$. The cross sections were obtained simultaneously from 65 to 230 MeV using the Los Alamos National Laboratory white neutron source. Comparisons are made to (p,n) and (p,p′) in this energy range.

5. Gamow-Teller Strength in ^{54}Fe (n,p) and ^{56}Fe (n,p) at 65 MeV.** (B. McEachern, F.P. Brady, J.R. Drummond, G.P. Grim, E.L. Hjort,♡ J.H. Osborne, M.D. Partlan, J.L. Romero.)

To determine the amount of missing GT strength, one compares with the non-energy-weighted sum rule, $S_- - S_+ = 3(N-Z)$, where S_- is the GT strength in the τ_- (β_-) direction and S_+ is in the τ_+ (β_+) direction. Large uncertainties in measured S values impact sum rule verification and hinder answers about GT quenching due to RPA correlations.† Recent measurement‡ of ^{54}Fe(p,n) yields an improved S_- value, providing motivation to better determine S_+ using a more precise measurement of ^{54}Fe(n,p). In addition, the GT matrix elements from ^{54}Fe(n,p), coupled with those from ^{54}Cr(p,n), are important in calculations involving $\beta\beta$-decay: processes significant in the late stages of stellar evolution.§ The CNL (n,p) detector facility was used to measure ^{54}Fe and ^{56}Fe(n,px), $0 \leq \epsilon < 45$ MeV, $0 \leq \alpha < 60°$; differential cross-sections for the Gamow-Teller giant resonance have been extracted and will be presented.

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* Supported by the U.S. DOE, DOD, and NSF.
# Abstract Submitted for the Spring Meeting of the American Physical Society, May 1-4, 1989.
(1) Univ. of California, Davis, CA 95616.
(3) Ohio Univ., Athens, OH 45701.
(2) Los Alamos National Laboratory, Los Alamos, NM 87545.
(4) Duke Univ., Durham, NC 27707.
** Supported in part by NSF Grant PHY87-22008.
♡ Associated Western Universities Graduate Fellow.
† N. Auerbach, Phys. Rev. C36 (1987) 2694.
‡ B.D. Anderson, Private Communication.
§ H.A. Bethe, et al., Nucl. Phys. A234 (1978) 487.

6. Gamow Teller and Spin-Dipole Strength in ^{90}Zr(n,p) at 65 MeV.[$] [♮] (F.P. Brady, T.D. Ford,[†] J.L. Romero, C.M. Castaneda, J.R. Drummond, E.L. Hjort, N.S.P. King;[‡] B. McEachern, D.S. Sorenson, Zin Aung, Amir Klein,[♡] W.G. Love[♡] and J.K. Wambach.[§])

The ^{90}Zr(n,p) reaction at 65 MeV has been studied over a wide range of angles down to 0°. At low excitations the main strength appears to be in three concentrations of spin-dipole strength. Within certain limits Gamow Teller β^+ strength is not evident in the spectra. Together with the earlier analysis of β^- strength ^{90}Zr(p,n) these (n,p) results suggest either (i) that Gamow-Teller quenching due to Δ(isobar)-hole mixing in nuclear particle-hole excitations is relatively small ($\lesssim$ 15%), or (ii) that Δ-hole quenching is percentagewise much larger ($\times$5) for β^+ than for β^- transitions.

$ Published in Physical Review C, 40, R475, 1989.

♮ We acknowledge the support of Natinal Science Foundation Grants No. PHY84-19380 (University of California at Davis) and No. 86-07684 University of Georgia), Associated Western universities, Inc. (T.D.F., B.M., and E.L.H.), and a Fulbright Scholarship (Z.A.).

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IDAHO NATIONAL ENGINEERING LABORATORY

A. EXPERIMENTAL STUDIES

1. Beta-Strength Functions for Fission Isotopes

(R. C. Greenwood, R. G. Helmer, M. A. Lee, M. A. Oates, M. H. Putnam, C. W. Reich, K. D. Watts)

With the recent implementation of the total absorption gamma-ray spectrometer, located on the ^{252}Cf-based INEL ISOL facility, a program of systematic measurement of beta strength-function distributions of short-lived fission-product nuclides is currently underway.

As presently configured, this spectrometer consists of a large NaI(Tl) scintillator, with dimensions of 25.4-cm diameter X 30.5-cm length and having a 5.1 cm diameter X 20.3-cm long axial well. A shielded 300-mm^2 diameter X 1.0-mm thick Si charged-particle detector is located in a thin-walled tape-transport line inside the well of the NaI(Tl) crystal. The Si detector is oriented to view the bottom end of the well, with the source transport tape passing in front of the Si detector at a distance of ~20 mm. With this arrangement, extraneous coincident effects, resulting from beta backscattering or the detection of internal conversion electrons or gammas in the Si beta detector are estimated to be, at most, a few percent each. In actual operation, useful information on the distribution of beta-feeding intensities is obtained both from the gamma-singles data as well as from the gamma-distributions measured in coincidence with the decay betas.

Initial studies with this spectrometer have concentrated on fission products with complex but reasonably well understood decay schemes, to serve as "validation cases" for the technique. Specifically, because of their ease of mass separation in the INEL ISOL facility, these initial studies have concentrated on selected fission-product-isotopes of Cs and Ba together with ^{106}Rh, which is available commercially as a long-lived ^{106}Ru-^{106}Rh source. Of particular interest in these initial studies, in addition to "validating" the measured beta-feeding intensities in comparison to the "known" level scheme information, has been the use of the spectrometer to obtain direct measurements of absolute ground-state beta-branching intensities from a simple ratio of the beta-gamma coincidence to beta singles count-rate. Since this ground-state branching information is crucial to the conversion of relative beta feeding intensities (to excited states) to absolute intensities, modifications to the data acquisition system and program were made to more straightforwardly obtain this ratio from the concurrent singles and beta-gamma coincident list-mode data. These modifications were: (1) to add a clock time to the coincidence beta-gamma list-mode data in order to allow the coincidence data to be multiscaled into time bins identical to the time-multiscaled singles data; (2) to add a synchronized start and stop command so that the singles and coincidence data can be acquired over identical time periods; and (3) to provide anticoincidence veto pulses to the singles ADCs (analogue-to-digital converters) whenever the event handler is busy processing coincidence data.

In parallel with this activity to utilize the total absorption gamma-ray spectrometer to obtain beta strength-function distributions, there has been a commensurate effort to implement the computer codes necessary to analyze the measured spectra to determine these distributions. Because of the paucity of suitable monoenergetic gamma-ray sources above 3 MeV, it was decided to use gamma-ray response functions computed with the CYCLTRAN Monte-Carlo photon and electron transport code (obtained from Sandia National Laboratory). This code has been used to compute response functions for gamma rays from 30 to 5370 keV, along with the associated total detector efficiencies, using the physical description of the total-absorption spectrometer as input. Comparison of these computed response functions with measured response functions for radioactive sources with simple one- or two-gamma-ray spectra shows excellent agreement.

Rather than decompose the measured spectra, it was decided that it would be more useful to calculate simulated spectra and compare these with the measured spectra. This method has the advantage that one portion of the analysis (usually the low-energy end) is not biased irretrievably by another part of the analysis (usually the high-energy end). Thus, a series of calculational codes were developed which (1) compute the detector response for coincident gamma rays with from 2 to 7 gamma rays in the cascade; (2) compute for N gammas in cascade all of the spectral contributions that occur for all combinations of 0, 1, 2,...N-1 of these gamma rays not interacting in the detector; and (3) compute the total spectral response for a complete decay scheme.

The spectra from this computational process agree quite well for the simple test cases such as ^{60}Co and ^{24}Na as well as for the more complex test case of ^{110m}Ag. The latter case is interesting in that the beta feeding is only to levels at 2480 and 2927 keV. The simulation of this spectrum is sensitive enough to the multiplicity of the gamma cascades from these two levels to show that the dominant cascades cannot be of multiplicity 1 or 2, but must be 3 or higher, in agreement with the known decay scheme.

Beta strength distribution measurements, including ground-state beta feeding measurements, have been completed for the fission-product isotopes ^{106}Rh, ^{138m}Cs, ^{139}Cs, ^{140}Cs, ^{141}Cs and ^{141}Ba. Since each of these decay schemes has been studied in some detail using conventional nuclear spectroscopic methods, it has been of interest to compare the distributions of beta feeding intensities obtained in these earlier investigations to the direct measurements obtained in this work. In general these comparisons indicate a reasonable qualitative agreement. However, there is a systematic trend for the present total absorption measurements to indicate more beta feeding to higher lying states, close to the decay energy, than the decay scheme studies had indicated. This observation is in fact consistent with the "Pandemonium" problem known to be inherent in the conventional nuclear decay spectroscopic studies. The ground state beta-feeding intensities obtained from a simple ratio of the beta-gamma coincidence rate to singles beta rate are also, in general, in quite good agreement with those reported in the literature (e.g., Nuclear Data Sheets), as illustrated in Table A-1.

TABLE A-1. Preliminary values of ground-state beta-branching intensities obtained from the total absorption gamma-ray spectrometry data.

Fission Isotope	Ratio $\frac{\beta\text{-}\gamma}{\gamma}$,	Estimated Correction Factor[a]	Ground-state β-branch (%) Measured	Ground-state β-branch (%) Nuclear Data Sheets
^{106}Rh	0.267	1.028	73	78.6±0.7
^{138}Cs	0.912	1.056	4	0
^{138m}Cs	~0.93	1.03	4	0
^{139}Cs	0.185	1.167	78	82±7
^{140}Cs	0.627	1.042	35	40±4
^{141}Cs	0.594	1.078	36[b]	57
^{141}Ba	0.780	1.041	19[c]	17

a Correction factors include estimates for γ escape from the NaI(Tl) detector and missed betas below the β discriminator level.
b The ground state is defined here to include the 48.5 and 55.0 keV excited states.
c. Branching intensity to the ground state plus the 190.3 keV first-excited state in ^{141}La.

In the case of ^{141}Cs the measured branching intensity value of 36% (to all levels below 100 keV) is significantly lower than the literature value of 57%. Since the latter value is based upon transition intensity balances, and involves highly internally converted transitions with energies of 6.5, 48.5 and 55.0 keV it might not be unreasonable to propose that the literature value in fact is in error.

2. A Closely Spaced Doublet at the ^{229}Th Ground State (C. W. Reich, R. G. Helmer)

Precisely measured energy values[1] for a number of the gamma rays from the decay of ^{233}U have provided interesting new information regarding the energy difference between the first excited state (3/2+[631]) and the ground state of (5/2+[633]) of ^{229}Th. Some years ago, based on work at this laboratory, it was postulated[2] that this first excited state, although not directly observed, had to lie quite close to the ground state. The precision of those earlier data permitted only an upper limit of ~0.1 keV to be placed on this energy separation. In this new work, the more precise values obtained for the gamma-ray energies reveal that the energy separation of the two states must be less than a few electron volts. The actual value obtained is

$$E(3/2+[631]) - E(5/2+[633]) = -1 \pm 4 \text{ electron volts.}$$

Even though there is still only an upper limit on its value, this energy spacing must be unprecedentedly small - the smallest by far reported among bound states in nuclei. Moreover, since it lies at, or below, "optical-like" energy spacings, this finding has important applications in other areas, such as fundamental atomic physics and lasers. A paper describing these results has been published[3].

3. IUPAP Task Group on Gamma-Ray Energies (R. G. Helmer)

The task of the Task Group on Gamma-Ray Energies of the Commission on Atomic Masses and Fundamental Constants of the International Union of Pure and Applied Physics is the recommendation and publication of a consistent set of calibration energies for use in gamma-ray spectrometry, especially for use on semiconductor detectors. This group has felt that it is particularly useful if precise energies are available for gamma rays from radionuclides that are used for the calibration of detector efficiencies. Therefore, measurements were made of the energies of the strong gamma rays from the decay of ^{125}Sb and ^{154}Eu, which appear on the list of nuclides involved in a current IAEA Coordinated Research Program (see item A.4 following). This work has been published in Applied Radiation and Isotopes 41, 75 (1990).

4. IAEA Coordinated Research Program on Decay Data for Ge Detector Efficiency Calibration: Measurement (R. G. Helmer)

A Coordinated Research Program (CRP) was convened in June, 1987 at Rome and again in May, 1989 at Braunschweig, FRG by the International

1. C. W. Reich, R. G. Helmer, J. D. Baker and R. J. Gehrke, Int. J. Appl. Radiat. Isot. 35, 185 (1984).
2. L. A. Kroger and C. W. Reich, Nucl. Phys. A259, 29 (1976).
3. C. W. Reich and R. G. Helmer, Phys. Rev. Letters 64, 271 (1990).

Atomic Energy Agency (IAEA) to discuss the quality of the decay data for the nuclides commonly used for the efficiency calibration of Ge detectors for gamma- and x-ray spectrometry. The participants in the meeting were from nine laboratories in seven countries, including R. G. Helmer from the INEL.

A goal of this group is to get subsequent evaluators to use the values it recommends and, thereby, generate one internationally adopted set of values. The quantities evaluated are the nuclide half-life and the emission probabilities of the gamma and x-rays that can be used for Ge detector efficiency calibrations. It was also the purpose of the group to identify cases for which new measurements were needed, that is, where the data were poor or discrepant.

At an advisory group meeting in 1985, it was decided that this CRP work would include 33 radionuclides. In response to the needs expressed at the first CRP meeting, in Rome in 1987, we have measured the relative emission probabilities for the stronger gamma rays from the decay of ^{125}Sb and ^{154}Eu. The results of these measurements have been published in Applied Radiation and Isotopes 41, 75 (1990).

In addition, in response to a need expressed at the June, 1989, meeting of this CRP, we have measured the relative emission probabilities of the two strongest gamma rays from the ^{207}Bi decay. A paper describing the results of this measurement has been accepted for publication in Applied Radiation and Isotopes.

5. Gamma-Ray Emission Probabilities for ^{181}Hf (R. G. Helmer)

Recent measurements in the Radiation Measurements Laboratory at the INEL suggested that the generally accepted emission probabilities for the gamma rays from the decay of ^{181}Hf were inaccurate. Therefore, these quantities have been re-measured. From the relative gamma-ray emission rates and the decay scheme it is possible to normalize these relative rates and determine the emission probabilities. For our measured relative rates it was possible to determine the emission probability of the strong 482-keV gamma ray to be 80.52(11)%. The results of these measurements have been published in Applied Radiation and Isotopes 41, 101 (1990).

6. Half-Life and Relative Gamma-Ray Intensities of ^{176}Lu (R. J. Gehrke, C. Casey, R. K. Murray)

A process for using the ^{176}Lu/^{176}Hf couple for age dating of rocks which contain a sufficient amount of Lu and not too much Hf has been developed; and ^{176}Lu has been used to determine the age of the s-process nuclei. Results from these techniques depend on the value used for the ^{176}Lu half-life. Unfortunately, the reported values have varied from 2.1 to 7.3 X 10^{10} years; and even those more recently measured vary from 3.27 to 4.56 X 10^{10} years.

In order to obtain an accurately measured half-life with an uncertainty that has been propagated from all components, we remeasured the half-life of ^{176}Lu from a sample of Lu_2O_3 enriched to (44.23 ± 0.23)% in ^{176}Lu. The sample was obtained from Isotope Sales at Oak Ridge National Laboratory. The sample, including impurities, had a measured mass of 33.8 mg with an uncertainty of ± 1%. The mass of the chemical impurities, as listed on the sample identification and analysis sheet from ORNL, was subtracted and the Lu_2O_3 mass was converted to the number of ^{176}Lu atoms: $(4.42 \pm 0.05) \times 10^{19}$.

An intrinsic Ge gamma-ray spectrometer with an active volume of 160 cm^3 was used to count the sample. The efficiency of the detector was measured using the same geometry as used to count the sample. The efficiency was measured with a mixed radionuclide source containing ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{203}Hg, ^{113m}Sn, ^{85}Sr, ^{137}Cs, ^{88}Y, and ^{60}Co. A ^{182}Ta source was also counted and the resulting relative efficiencies were fitted to the mixed radionuclide efficiency curve so the shape of the efficiency curve could be better defined in the energy region required for the ^{176}Lu gamma rays. The uncertainty in the efficiency curve was split into to parts: an uncorrelated (± 1.5%) and a correlated (±1.5%) part.

Four 64-hour counts at a 10-cm source-to-detector distance were obtained. Corrections were made for self attenuation in the sample and for cascade coincidence summing. The measured relative gamma-ray intensities are given in Table A-2.

TABLE A-2. Relative intensities for the prominent gamma rays from ^{176}Lu decay.

Gamma-Ray Energy in keV	Total Conversion Coefficient	Relative Intensity
88.4	5.86 ± 0.18	15.5 ± 0.6
201.9	0.281 ± 0.008	83.3 ± 2.2
306.9	0.0746 ± 0.0022	100

^{176}Lu decays by beta decay to the 597- and 998-keV levels of ^{176}Hf. There is no beta feeding to the ^{176}Hf ground state or to the 88- or 290-keVlevels. Therefore, all of the decays pass through the 88-, 202-, and 307-keV transitions so the activity can be determined from the gamma-ray emission rates and the total conversion coefficients (see Table). From the activity and the number of atoms in the sample, the half-life of ^{176}Lu is deduced to be $4.05 \pm 0.09 \times 10^{10}$ years.

A paper presenting these data has been submitted for publication in Phys. Rev. C.

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 have the evaluation responsibility for the ten mass chains in the region $153 \leq A \leq 162$. The plan for the evaluation of these mass chains has been to undertake those most out of date first.

During this past year, our evaluation schedule was interrupted to take on, as a temporary assignment, the evaluation responsibility for the A=206 mass chain. This was done at the request of personnel at the Nuclear Data Project at ORNL in view of the fact that this evaluation was quite out of date (the last published NDS evaluation appeared in 1979) and that they were unlikely to be able to undertake it for at least another year or so. This evaluation has now been completed and is presently in the pre-publication process. Our normal evaluation schedule has been resumed, with the A=160 and 162 mass chains (the two that are the most out of date) being worked on at this time.

The current status of the A-chain evaluations within our area of responsibility (and including the temporary assignment of A=206) is as follows:

A-chain	Status (according to currency)
160	evaluation underway; last published in NDS 46 (1985)
162	evaluation underway; last published in NDS 44 (1985)
206	submitted for publication
153	in review, last published in NDS 37 (1982)
161	Nuclear Data Sheets 59 (1990)
158	Nuclear Data Sheets 56 (1989)
157	Nuclear Data Sheets 55 (1988)
159	Nuclear Data Sheets 53 (1988)
154	Nuclear Data Sheets 52 (1987)
155	Nuclear Data Sheets 50 (1987)
156	Nuclear Data Sheets 49 (1986)

As is evident from this listing the current status of our mass-chain evaluations satisfies one of the objectives of the international evaluation network, namely currency of < 5 years.

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

Within the framework of the Cross Sections Evaluation Working Group, we have the responsibility for the evaluated experimental decay data in ENDF/B. At present, we are involved in preparing the evaluated decay-data sets for Version VI of ENDF/B. This involves upgrading the existing data, as well as expanding the number of nuclides for which such information will be available. Three general categories of nuclides are involved, namely, those in the Actinide File, the Activation-Product File and the Fission-Product File. In order to help avoid the proliferation of files of evaluated data--all drawn from the same base of measured information--whose contents differ only trivially from each other, we have adopted ENSDF as the starting point for this evaluation. However, ENDF/B contains important data categories not included in ENSDF which need to be evaluated. In addition, in many instances, data other than those in ENSDF have been used.

At present, with the exception of nine additional nuclides recently requested by CSEWG to be added to the Activation File, the INEL evaluation work for ENDF/B-VI has been completed. The number of nuclides for which INEL-evaluated decay data will be included in the various subfiles of ENDF/B-VI are as follows: the Activation File (158 nuclides, once the additional nine nuclides are evaluated); the Actinide File (108 nuclides); and the Fission-Product File (510 nuclides).

3. IAEA Coordinated Research Program on Decay Data for Ge Detector Efficiency Calibration: Evaluation (R. G. Helmer)

As discussed in item A.4 above, a Coordinated Research Program (CRP) was convened by the International Atomic Energy Agency (IAEA) to discuss the quality of the decay data for the nuclides commonly used for the efficiency calibration of Ge detectors for gamma- and x-ray spectrometry. In response to the assignments made at these meetings we have carried out the evaluation of the gamma-ray emission probabilities for the decay of ^{94}Nb, ^{95}Nb, ^{113}Sn, ^{152}Eu and ^{203}Hg and have prepared a summary of methods used in Ge detector efficiency calibrations above 3 MeV. A draft version of the report of this CRP has been assembled by the IAEA.

4. Participation in One of the Working Groups of the ICRM (R. G. Helmer)

R. G. Helmer of INEL is Coordinator of the Gamma-and Beta-Ray Spectrometry Working Group of the International Committee for Radionuclide Metrology (ICRM), which represents Metrology groups in 23 countries. This Group met in June, 1989 at Braunschweig, FRG and helped organize a symposium entitled "Nuclear Decay Data: Spectrometric Methods, Measurements and Evaluations" that was held June 6-8, 1989 in Braunschweig. The proceedings of this symposium have been published in Nucl. Instrum. and Methods A286, 357 (1990).

STUDIES OF FISSION PRODUCTS WITH THE TRISTAN SEPARATOR

Neutron-rich nuclides far from stability are mass separated using the TRISTAN separator on-line to the High Flux Beam Reactor at Brookhaven National Laboratory. The nuclides are produced by thermal neutron fission of ^{235}U and their decay studied via γ-ray spectroscopy, $\gamma\gamma$ coincidences, perturbed (and unperturbed) angular correlations and lifetime measurements of nuclear excited states using triple coincidences with fast BaF_2 detectors. The research at TRISTAN is carried out by a Participating Research Team consisting of the Ames group at Iowa State University and scientists from Brookhaven and Clark University.

1. Decay of ^{74}Cu to Levels in Even-Even ^{74}Zn (Winger et al.)

It has been possible to study the decay of low-yield Cu fission products using the TRISTAN high-temperature plasma ion source. The ^{74}Cu half-life was measured to be 1.59 ± 0.05 s. A total of 22 γ rays were assigned to ^{74}Cu decay and 19 were placed in a level scheme for ^{74}Zn containing 10 excited states up to 2969 keV. This work has been published in *Phys. Rev. C.*[1]

2. Decay of ^{74}Zn to Levels in ^{74}Ga (Winger et al.)

In the process of studying the decay of ^{74}Cu, information was also obtained on the decay of the ^{74}Zn daughter to levels in ^{74}Ga. A total of 39 γ rays were placed deexciting 11 states in ^{74}Ga up to 1085 keV. This work has been published in *Phys. Rev. C.*[2]

3. Decay of ^{76}Cu to Levels in ^{76}Zn (Winger et al.)

In a study of the decay of ^{76}Cu to levels in ^{76}Zn, the first information on excited states in neutron-rich ^{76}Zn was obtained. Two isomers of ^{76}Cu were postulated with half-lives of 0.57 s (high-spin) and 1.27 s (low-spin), respectively. The half-lives are to some extent decay-scheme dependent. A total of 12 γ rays were attributed to ^{76}Cu decay with energies ranging from 180 to 1783 keV. Of those, 11 were placed in a level scheme for ^{76}Zn with 8 excited states ranging in energy from 598 to 2974 keV. The low-lying states are fairly well reproduced by a shell-model calculation employing a model space involving active protons in orbitals between Z=28 and 50 and neutrons in orbitals filling the subshell between N=38 and 50. This work has been submitted for publication to *Phys. Rev. C.*

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[1]Winger, Hill, Wohn, Warburton, Gill, Piotrowski, and Brenner, *Phys. Rev. C* 39, 1976 (1989).

[2]Winger, Hill, Wohn, and Brenner, *Phys. Rev. C* 40, 1061 (1989).

4. Monopole Strength and Shape Coexistence in the A≈100 Mass Region (Wohn et al.)

The strength $\rho^2(E0)$ of electric monopole transitions between 0^+ states has been investigated as a criterion for shape coexistence in the neutron-rich A≈100 nuclei. In order to study this phenomena the half-lives for the 0_2^+ levels in ^{100}Zr and ^{100}Mo were measured using a $\beta\gamma\gamma$ fast-timing method. The level half-life was determined by $\beta\gamma$ coincidences using a NE111A plastic scintillator for β rays and a BaF_2 crystal for γ rays. A Ge detector was used to select the desired decay branch. The half-lives for the 0_2^+ levels were measured to be 5.60 ± 0.15 and 1.58 ± 0.04 ns, respectively, for ^{100}Zr and ^{100}Mo. The resulting values for $\rho^2(E0)$ are substantially different from earlier data and confirm our idea that high values of $\rho^2(E0)$ do not necessarily mean strong configuration mixing. An important point is that knowledge of the difference between the two deformations is required in order to use $\rho^2(E0)$ values as a viable indicator of the strength of configuration mixing between two coexisting shapes. This work has been published in *Phys. Rev. C.*[3]

5. Subnanosecond Lifetime Measurements in Y and Sr Nuclei and the Saturation of Deformation Near A≈100 (Wohn et al.)

Absolute transition rates provide essential information on the valence nucleon states in deformed A≈100 nuclei. The $\beta\gamma\gamma$ timing method explained above was used to determine half-lives for the 125-keV $7/2^+$ level in ^{99}Y and the 76-keV 1^+ level in ^{100}Y. The measured half-lives were 47±6, and 72±7 ps, respectively. In the odd-A cases it was possible to determine the M1 strengths only because the $\beta\gamma\gamma$ fast-timing technique developed at TRISTAN permits measurements of half-lives shorter than 100 ps. The intrinsic g factors indicate a constant core deformation. The rapid saturation of deformation in the A≈100 region is explained by simple arguments based on the slope of the valence Nilsson orbitals at the onset of deformation.[4] This work has been published in *Phys. Rev. C.*[5]

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[3]Mach, Hill, Wohn, Warburton, Gill, Piotrowski, and Brenner, *Phys. Rev. C* 41, 350 (1990).

[4]Wohn, Mach, Moszynski, Gill, and Casten, *Nucl. Phys.* A507 141c (1990).

[5]Mach, Wohn, Moszynski, Gill, and Casten, *Phys. Rev. C* 41, 1141 (1990).

6. <u>Deformation and Shape Coexistence of 0^+ States in ^{98}Sr and ^{100}Zr</u> (Wohn et al.)

Neutron-rich A≈100 nuclei are unusual in that there is an extremely abrupt transition from spherical to deformed behavior as neutrons are added. Strong similarities have been noted between highly deformed ^{99}Sr and ^{100}Zr. We have measured the half-lives of the 2_1^+ states in ^{98}Sr and ^{100}Zr obtaining values of 2.80 ± 0.08 and 0.55 ± 0.02 ns, respectively. A half-life of 80 ± 6 ps was measured for the 4_1^+ level in ^{98}Sr. All of these measurements were carried out using the fast $\beta\gamma\gamma$ coincidences system discussed above. Our analysis of the corresponding B(E2) values shows that both ^{98}Sr and ^{100}Zr have coexisting deformed bands that are weakly admixed.[4] The highly deformed (β~0.4) prolate D bands are similar to yrast bands in ^{100}Sr and ^{102}Zr, and the low-lying S bands have moderate values of β~0.2. This work has been published in *Phys. Lett. B*.[6]

[6]Mach, Moszynski, Gill, Wohn, Winger, Hill, Molnar, and Sistemich, *Phys. Lett.* <u>B230</u>, 21 (1989).

UNIVERSITY OF KENTUCKY

A. NEUTRON SCATTERING

1. Shape-Transitional Region (S.E.Hicks, G.R.Shen, and M.T. McEllistrem)

An extended study of neutron scattering from the Os and Pt isotopes has been completed.[1-3] This study showed that the quadrupole collective excitations of these nuclei behave like those of a γ-soft vibrator. The excitation strengths found with neutrons for the Pt isotopes is 37% stronger than that found through electromagnetic excitation experiments.[1] At the same time, the excitation strengths found in the Os isotopes are not at all probe dependent.[4] Both of these results were obtained consistently from scattering experiments at 2.5, 4.0, and 8.0 MeV.

A study of scattering from the two even-A Pb isotopes, ^{204,206}Pb, shows neutron collective strengths a factor of two stronger than those from electromagnetic excitation; the probe dependencies found from the Pt isotopes are greatly enhanced for these semi-magic Pb nuclei.

2. Scattering from ^{48}Ca (S.F. Hicks, S.E. Hicks, and M.T. McEllistrem)

A special study of neutron scattering from ^{48}Ca has been completed which showed that broad d-wave resonances in scattering from that nucleus, for energies from 0.4 to 3 MeV, are the result of coupling $p_{3/2}$ and $p_{1/2}$ particle states to a 3^- core excitation. The resonances are "bound states in the continuum", which acquire decay widths to the ground state scattering through coupling to that channel. This study showed a new way of fixing coupling strengths for collective excitations through examining the widths of these very special resonances.[5]

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

The analysis of the differential and total neutron cross section data for $^{116-124}$Sn has been brought close to completion. This data set consists of the elastic and inelastic differential scattering cross sections for neutrons from the even-A isotopes of tin at neutron energies of 1.00, 1.63 and 4.0 MeV, as well as the neutron total cross sections for the same isotopes from 300 keV to 5 MeV.[6,7] In the coupled-channels analysis of the inelastic scattering cross sections, it was found that it is important to make the real potential in each scattering channel explicitly dependent on the neutron energy in that channel.

The most recent step in the analysis was the application of dispersion theory corrections to the mean field description of the interaction of neutrons with the five even-A isotopes $^{116-124}$Sn. Included in the analysis were not only the

[1] Hicks, Delaroche, Mirzaa, Hanly, and McEllistrem, Phys. Rev. C36, 73 (1987).

[2] Clegg, Haouat, Delaroche, Lagrange, Chardine, Hicks, Shen, and McEllistrem, Phys. Rev. C40, 2527 (1989).

[3] Mirzaa, Delaroche, Weil, Hanly, and McEllistrem, Phys. Rev. C32, 1488 (1985).

[4] Hicks, Cao, Mirzaa, Weil, Hanly, Sa, and McEllistrem, Phys. Rev. C40, 2509 (1989).

[5] Hicks, Hicks, Shen, and McEllistrem, accepted for publication in Phys. Rev. C.

[6] Harper, Weil, and Brandenberger, Phys. Rev. C30, 1454, (1984).

[7] Harper, Godfrey, and Weil, Phys. Rev. C26, 1432 (1982).

coupled channel potentials for neutron scattering from the measurements at the University of Kentucky, but also potentials which fit neutron scattering measurements made at Ohio University[8] at 11 and 24 MeV bombarding energies. We also required a fit to the neutron single-hole and single-particle bound state energies from various particle transfer experiments. The results are very encouraging, in that with the dispersion correction there is good agreement between the calculated and inferred values of the volume integral per nucleon, J/A, for the real potential over all neutron energies. This potential also gives good agreement with the bound state energies.

We also did a spherical optical model (SOM) analysis of the three sets of elastic differential scattering cross sections as well as the total cross section data, resulting in an energy dependent potential that gives a satisfactory fit to all this data. All that remains to be done is to obtain the SOM potentials for the 11 and 24 MeV data sets from Ohio University and do the SOM dispersion theory corrections.

4. Projected Work in Neutron Scattering

Very recent work on neutron scattering from heavy nuclei has established that neutron, and probably other hadron, excitations of collective quadrupole strengths in nuclei are markedly different than those sensed with electromagnetic methods.[1,2] These differences are clues to core polarizations which are not obtained by other means. Confidence in these unusual results was increased when we discovered[9] that mean scattering fields could be determined for these strongly collective nuclei whose application extends from negative energy bound states to scattering. These neutron-excitation differences are important to examine, and interpret quantitatively.

Complementary to the nuclear structure studies by γ-ray detection following inelastic neutron scattering, discussed below, we also propose to continue our studies of structure-character and coupling strengths through direct detection of scattered neutrons. This may well be the best way to see the enhanced strengths associated with multi-phonon excitations, for example.

a. Sn Scattering Studies (J.L. Weil and M.T. McEllistrem)

As soon as the SOM dispersion theory corrections for Sn isotope potentials are done, a short communication will be submitted for publication. A much longer paper describing the coupled channel analysis of the whole Kentucky data set, including the fits to the inelastically scattered neutron groups will be written up for publication. These fits have been delayed by the need for better knowledge of the level density above 2.5 MeV excitation. The Sn(n,n'γ) studies described below are now far enough along to provide that level density information, so that the analysis of the neutron inelastic cross sections can be completed.

b. Collective Excitation Strengths -- Neutrons vs Electromagnetic (D. Wang, Y. Wang, R. Go and M.T. McEllistrem)

Earlier work in the Pt and Os isotopes showed first of all that their strong quadrupole collective character enabled evaluation of various nuclear models as representing the dynamics of each nucleus. The test of direct coupling between the different scattering channels showed clearly that γ-soft, or soft non-axial E2 excitation models were most realistic in this region. We also learned that the Pt isotopes had neutron coupling strengths much stronger[1,2] than those of electron scattering or Coulomb excitation.[10] On the other hand, the even-A Os isotopes had

[8] J. Rapaport, et al., Nucl. Phys. **A341**, 56 (1980).

[9] S.E. Hicks and M.T. McEllistrem, Phys. Rev. **C37**, 1787 (1988).

[10] Ching-Yen Wu, Ph.D. Dissertation, The University of Rochester (unpublished), 1983; D. Cline, Ann. Rev. Nucl. Part. Sci. **36**, 683 (1986).

neutron coupling strengths the same as those found with Coulomb excitation.[2,4] Earlier experiments had shown that hadronic excitation of quadrupole collective states in *deformed* nuclei showed no such probe dependence;[11] this suggests that the Os isotopes are stably deformed, but apparently the Pt isotopes show little deformation-stability.

Our current work on scattering from $^{204,206}Pb$ shows that the neutron excitation enhancements in those isotopes are much larger than previously found[1] for ^{194}Pt. We think it will be important to discover whether these enhanced coupling strengths for neutrons, now confirmed in experiments at several energies in two different laboratories, are systematic large departures from electromagnetic strengths, or special cases. Thus neutron scattering from ^{142}Nd and ^{144}Sm, which are neutron magic but have many valence protons, will be studied. This is complementary to the information we are obtaining in the study of the Pb isotopes, since these nuclei are also semi-magic, but with few valence holes.

An indication of possible two-phonon strength is the 1^- level with strong E1 decay near 3 MeV excitation energy.[12] The only way that proton excitations could form a 1^- state would be through the $\pi(h_{11/2}g_{9/2}^{-1})$ configuration, which would require about 6 MeV of excitation energy. Although we would not expect this 1^- level to be strongly excited in neutron scattering, it might indicate the importance of the multiplet $2^+ \times 3^-$. Other states of that multiplet might have special scattering strength.

Another interesting property we were not able to examine completely in the Pt and Os nuclei was the extent to which the 3^- collective strength was split by coupling to E2 deformation amplitudes. The shift of E3 strength between the Pt and Os isotopes was reported and interpreted by Cottle *et al.*[13] They found that the proton inelastic scattering to E3 excitations in ^{194}Pt was much stronger than that to the lowest E3 level in the even-A Os isotopes, which they interpreted in terms of quadrupole splitting of the E3 strength in the deformed Os nuclei. Although we expect little such splitting in these two nuclei, comparing the E3 excitation strengths for neutrons with those from Coulomb excitation for both will provide an interesting test of the degree of mixing which can occur between those two different collective excitations; the spreading of the E3 strength may be another way to sense quadrupole-collectivity differences between them.

c. Neutron Scattering Studies from ^{140}Ce (Y. Wang, S.F. Hicks, J.F. Vanhoy, S.W. Yates, and M.T. McEllistrem)

A collaboration between the U. S. Naval Academy, University of Dallas, and Kentucky will begin the study of scattering from ^{140}Ce in the summer of 1990. We plan to have a separated isotope metal sample available for these measurements. The issues for this nucleus are similar in many respects to those for ^{142}Nd and ^{144}Sm. To our knowledge, no 1^- level has been reported at low excitation energies, in contrast to the situation in ^{144}Sm. However two-phonon strengths could be expected here, and the E3 strength splitting may be significantly different than for the Sm and Nd nuclei. The question of the distribution of low-lying quadrupole collective strength in these nuclei is one which neutron scattering is eminently suited to address.[1] Very little information about collective strengths is available for these three nuclei at the present time; only the 2_1^+ coupling amplitude has been measured.

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[11] Lagrange, Lachkar, Haouat, Shamu, and McEllistrem, Nucl. Phys. **A345**, 193 (1980).

[12] R.A. Gatenby and S.W. Yates, Conference of Nuclear Chemistry Division of the ACS, Miami Beach, Sept. 15, 1989; R.A. Gatenby, private communication.

[13] Cottle, Stuckey, and Kemper, Phys. Rev. C38, 2843 (1988).

B. NUCLEAR STRUCTURE STUDIES

1. **^{96}Zr** (S.W. Yates, R.A. Gatenby, E.M. Baum, E.L. Johnson, and G. Molnár)

The ^{96}Zr nucleus is one of the few to exhibit a doubly closed subshell structure, and it is certainly the most amenable for study since it is stable. In our collaborative experiments, we have performed an extensive series of measurements[14-17] on ^{96}Zr, including inelastic neutron scattering spectroscopic measurements with fast reactor neutrons and accelerator-produced neutrons, inelastic proton scattering with γ-ray detection, and β-decay measurements which included γ-γ angular correlations at the TRISTAN facility at Brookhaven National Laboratory. Additional measurements by Dr. Molnár and his colleagues at the Kernforschungsanlage Julich, West Germany include inelastic proton and deuteron scattering.[18] Here we briefly note the highlights of our findings.

Probable two phonon vibrational states of the quadrupole-octupole type and also of the double quadrupole type have been identified. This has led Kuznetsov of Michigan State and Meyer of LLNL to calculate[19] such structures for ^{96}Zr, with quite good success on level placements and transition probabilities.

Our initial discovery[16] was that a band of states could be associated with the first excited 0^+ excitation in ^{96}Zr which could be understood as a four-particle, four-hole state having quadrupole deformation--i.e., a shape isomer. In more recent experiments,[14] we have clearly demonstrated that these states form a collective vibrational structure. Coexisting spherical shell model states have also been identified. The extent of mixing between the spherical and deformed configuration was determined[17] to be small by an assessment of the interband transition rates. Additional observations include possible two-phonon vibrational states of the double octupole type. These results, combined with observations from neighboring nuclei, permitted us to understand better the influence of the double subshell closure on the delayed onset of deformation in the mass-100 region.

2. **^{146}Gd** (S.W. Yates)

Three studies of semi-magic ^{146}Gd have been made[20-22] to attempt an understanding of the collective properties of this nucleus through the use of various experimental probes. Double phonon states have been tentatively identified in ^{146}Gd, but our search for two-phonon octupole states proved inconclusive; however, the new information from the

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

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

[16] Molnár, Yates and Meyer, Phys. Rev. C**33**, 1843 (1986).

[17] Mach, Molnár, Yates, Gill, Aprahamanian, and Meyer, Phys. Rev. C**37**, 254 (1988).

[18] G. Molnár *et al.*, IKP Annual Report, 1988, KFA Julich.

[19] Kuznetsov, Henry, and Meyer, Phys. Lett, submitted.

[20] Yates, Julin, Kleinheinz, Rubio, Mann, Henry, Stoffl, Decman, and Blomqvist, Z. Phys. **A234**, 417 (1986).

[21] Kleinheinz, Styczen, Piiparinen, Blomqvist, and Kortelahti, Phys. Rev. Lett. **48**, 1457 (1982).

[22] Mann, Lanier, Struble, Yates, Naumann, and Kouzes, Phys. Rev. C**39**, 2180 (1989).

(p,t) and α,2nγe$^-$) reaction studies has helped greatly in understanding the single-particle and other collective structures of this important nucleus.

3. ^{116}Sn (J.L. Weil, R.Go, and Z. Gácsi)

The decay scheme for ^{116}Sn based on our (n,n$'\gamma$) and the (n,γ) results of S. Raman of ORNL is now in final form, and a paper describing the results is has been drafted. Many significant advances in the analysis of this very large data set have been made during this the past year. The low energy part of the decay scheme, up to 4.5 MeV, is based on the (n,n$'\gamma$) results and contains approximately 100 levels. Unique spins and parities have been assigned to over half of these, and the spins are limited to 2-3 possibilities for most of the rest.

The major advances of this recent period have come as a result of a very careful analysis of the γ-ray production cross sections, and their comparison to very accurate statistical model calculations. Many of the γ-ray excitation functions show anomalous behavior, such as sharp increases in yield as a function of increasing neutron energy, or a monotonic rise that is very unusual. The anomalies can be ascribed either to feeding from higher excited levels or to γ-decays from two or more levels with coincidentally the same decay energy. Also, many of the single escape and double escape peaks showed anomalously large yields. As a result of the analysis of these yield anomalies, 9 - 10 new levels have been added to the decay scheme. A detailed comparison of the experimental cross sections for populating each level with statistical model calculations[23] were helpful in determining the spin-parities of the levels.

A satisfying comparison with theory that we are able to make is with the level scheme calculated by Bonsignori and Allaart using their two-broken pair shell model.[24] This model only gives the neutron excitations that can arise from the $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ shells. Earlier results of theirs were already in fairly good agreement with the low-lying levels of ^{116}Sn, and more recent calculations show very good agreement with the level scheme determined in the present work up to an energy of 3.7 MeV, verifying that the low-lying levels of ^{116}Sn are primarily neutron excitations. The low-lying two-particle, two-hole intruder states described by Heyde are also observed; we are examining our data for evidence of higher-lying members of other intruder bands.[25]

Because of the completeness of the level structure determined for ^{116}Sn up to an excitation of almost 4 MeV, it has been possible to do a statistical analysis of the level densities. This is perhaps the first time that reliable and extensive information has been obtained on the statistics of bound-state level densities for such a heavy nucleus, whereas much more information is in the literature on level densities in the neutron resonance region several MeV higher in excitation. When we use any of the extant level density models to extrapolate from our bound state densities to known resonance region densities for Sn, it is found that the extrapolation fails by approximately an order of magnitude. Clearly, these results call for more theoretical work on level densities.

The data reduction for the extraction of Doppler shifts from the angular distributions of the 160 γ-rays seen in this study is almost complete. A preliminary review of the results shows that measurable shifts are seen for approximately 35 γ-rays. This should lead to lifetime values for about 20 levels.

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[23] Tepel, Hofman, and Herman, Proceeding on the International Conference on Nuclear Cross Sections for Technology, Nat. Bur. Stand. (U.S.) Special Publ. **594**, 762 (1980).

[24] Bonsignori, Savoia, Allaart, van Egmond, and Te Velde, Nucl. Phys. **A432**, 389, (1985).

[25] Wenes, Van Isacker, Waroquier, Heyde, and Van Maldegham, Phy. Lett. **98B**, 398 (1981).

4. **^{204}Pb and ^{206}Pb** (J. Hanly, S.E. Hicks, D. Wang, and M.T. McEllistrem)

The levels of ^{204}Pb have been extensively studied, to reveal much of the structure of the odd-parity and unnatural parity levels. The even-spin, even-parity levels were once again shown to correspond well to those of a two boson model, in which ^{206}Pb excitations are the bosons. The odd-parity and unnatural parity excitations of ^{206}Pb and ^{204}Pb have been carefully identified up to about 2.5 MeV excitation energy, with level schemes for these nuclei that are now substantially complete.[26]

Following these experimental studies, shell model calculations have been done with several well known effective interactions.[27] One set of these calculations[27] provided remarkably good agreement for all observed levels, including even many E2 transition rates and level lifetimes. The detailed correspondences between theory and measurements is quite unprecedented, using a very simple effective two body interaction. The study of the odd-parity levels helps confirm the evidence from the study of the 0^+ levels in support of the strong role played by the $i_{13/2}$ configuration. This role is much stronger than previously expected or calculated in earlier models.

5. **Projected Work in Nuclear Structure**

a. **M1 Excitation & Lifetimes via DSAM in Neutron Scattering** (S.W. Yates, E.M. Baum, E.L. Johnson and D. DiPrete)

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-flip type. Measurements with the (n,n′γ) reaction are complementary to other methods and can contribute significantly to our understanding of both of these types of M1 excitations.

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. The lowest-lying states of this type are expected to have isoscalar character -- i.e., the protons and neutrons move in phase -- and the isoscalar M1 strength can be concentrated[28] in a single low-lying 1^+ state, e.g., the 5846-keV state in ^{208}Pb contains much of the isoscalar strength. The isovector mode, the so-called magnetic dipole resonance, is spread over a wide energy range. The fragmentation and quenching of the M1 and Gamow-Teller strength has been observed in many nuclei and various suggestions -- e.g., the influence of the Δ resonance, one-meson exchange, 2p-2h configurations -- have been offered to account for these features. In addition to the difficulties encountered in understanding the dipole M1 resonance theoretically, a long-standing problem has been the paucity of experimental information on low-lying 1^+ states.

A 1^+ state at 3487 keV in ^{88}Sr is strongly excited from the ground state in the nuclear resonance fluorescence reaction.[29] Calculations[30] also predict a second 1^+ state at 8.82 MeV, i.e., in the region of the giant M1 resonance

[26] Hanly, Hicks, McEllistrem, and Yates, Phys. Rev. C**37**, 1840 (1988).

[27] D. Wang and M.T. McEllistrem, submitted to The Phys. Rev. C.

[28] Wienhard, Ackermann, Bangert, Berg, Blasing, Naatz, Ruckelshausen, Ruck, Schneider, and Stock, Phys. Rev. Lett. **49**, 18 (1982).

[29] F.R. Metzger, Nucl. Phys. **A173**, 141 (1971).

[30] Cecil, Kuo and Tsai, Phys. Lett. **45B**, 217 (1973).

(GMR),[31] with the principal configuration of $\nu(g_{7/2},g_{9/2}^{-1})$. A low-lying 1^+ proton spin-flip state in ^{90}Zr is not expected (and none has been observed), but there is evidence for widely distributed M1 strength in the 8 - 10 MeV range of excitation energies.[32] 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,[33] and is not fully understood.

In our preliminary (n,n′γ) reaction experiments on ^{90}Zr, we have indications of a large number of heretofore unobserved states at 4 to 6 MeV excitation energies that decay to the ground state. Since only spin 1 or spin 2 states are expected to exhibit observable ground state decay branches, it is possible to identify M1 excitations through γ-ray angular distribution and DSAM measurements.

We plan to perform a detailed search for candidates for spin-flip 1^+ states in the N = 50 nuclei ^{88}Sr and ^{90}Zr with the (n,n′γ) reaction. The complementary (γ,γ′) scattering experiments, to verify parity assignments, can be done with the same target materials in collaboration with other laboratories, e.g., the University of Giessen, FRG.

Collective M1 Scissors Mode States. Considerable interest has been generated by the discovery[34] of a new class of collective $J^\pi = 1^+$ states that have been observed in inelastic electron and photon scattering experiments (see the review by Richter[35]). This M1 mode has been observed in deformed nuclei from ^{46}Ti to ^{238}U and their excitation energies scale as $E_x = 66\delta A^{-1/3}$ MeV, where δ is the nuclear deformation parameter. Clearly, these are bound states and, in heavy nuclei, the excitation energies range from 2 to 3 MeV; the B(M1) values are of the order of 1 to 3 μ_N^2.

This new magnetic dipole mode, the so-called "M1 scissors mode," which can be viewed as the angular analogue of the giant dipole resonance, was first characterized[36] in the two rotor model as scissors like oscillations of the axially deformed proton portion of the nucleus against the similarly deformed neutron fluid around an axis perpendicular to the z axis of the intrinsic frame. Lo Iudice and Palumbo[36] first noted that this mode should be excited strongly by magnetic dipole radiation through the coupling with the proton convection current.

The heavy stable Dy nuclei have been studied by inelastic electron and photon scattering and the locations and M1 strengths of the scissors mode states are supposedly well established. In our initial (n,n′γ) measurements on ^{162,164}Dy, we observed *all* of the excited 1^+ states suggested as scissors mode states. With the DSAM method, we plan to measure the lifetimes of these states and to assess their collectivity independently. At the energies of our measurements the maximum shifts in the γ-ray energies we can anticipate is about 1.5 keV, so a premium will be placed on precise energy measurement. The identification of collective M1 transitions will be relatively straightforward, even if we are not able to determine the lifetime with high precision. A survey of known M1 transition rates in the deformed rare earth nuclei indicates that even the fastest transitions from low-lying states are

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[31] A. Bohr and B.R. Mottelson, Nuclear Structure, Vol. 2 (Addison-Wesley, Reading, MA, 1975).

[32] Laszewski, Alarcon and Hoblit, Phys. Rev. Lett. **59,** 431 (1987).

[33] S.P. Kamerdzhiev and Y.N. Tkachev, Phys. Lett. **142B**, 225 (1984) and references therein.

[34] Bohle, Richter, Steffen, Dieperink, Lo Iudice, Palumbo, and Scholten, Phys. Lett. **B137**, 27 (1984).

[35] A. Richter, Contemporary Topics in Nuclear Structure Physics (World Scientific, Singapore, 1988) pp. 127-164.

[36] N. Lo Iudice and F. Palumbo, Phys. Rev. Lett. **41**, 1532 (1978)

retarded by about a factor of thirty, and, from the calculated F(τ) curve for $^{164}Dy_2O_3$, these transitions would fall in the most sensitive region--i.e., F(τ) values near 0.5. Faster transitions would have larger values of F(τ) and would lead to the largest Doppler shifts of the γ-rays and a clearcut identification of collective M1 transitions.

In addition to measuring the lifetimes of these states following the (n,n'γ) reaction, we anticipate that we should be able to observe transitions (beyond the known decays to the ground and first 2^+ states) from these states. These γ-rays have lower energies than the ground state transitions and are typically obscured in nuclear resonance fluorescence measurements by the intense low-energy bremsstrahlung. We believe that our measurements hold the best possibility for observing the complete γ-ray branchings from these isovector M1 excitations.

b. Multiphonon Octupole Excitations (S.W. Yates, E.M. Baum, R.A. Gatenby, and D. DiPrete)

Low-energy octupole vibrations are coherent superpositions of 1 hω particle-hole excitations and are especially strong in closed shell regions. In particular, non-spinflip stretched E3 couplings like the $2p_{3/2} - 1g_{9/2}$ and the $2d_{5/2} - 1h_{11/2}$ excitations across shell or subshell gaps can produce large octupole collectivity.[31] In closed shell nuclei, the octupole vibrations often occur at relatively low excitation energies and compete successfully with the quadrupole mode. Data on multi-phonon states involving octupole excitations are rare.

In two heavy nuclei, ^{146}Gd and ^{208}Pb, the 3^- state actually lies lower than the quadrupole phonon and is the first excited level. These states decay with large, similar E3 transition probabilities of 37 and 34 Weisskopf units,[37] respectively, suggesting that they are indeed collective octupole excitations. The unusual properties of these two nuclei have led to a number of searches[38,39] for the expected $3^- \times 3^-$ quartet of states with spins and parities of 0^+, 2^+, 4^+, and 6^+ at about twice the energy of the 3_1^- state. No clear-cut identification of the members of the two-phonon quartet has emerged in either nucleus.

Stretch-coupled states of the two-phonon type have been established[21,40] in the neighboring nuclei ^{147}Gd and ^{148}Gd. The identification of these states by the characteristic cascades of two E3 transitions was possible because, serendipitously, 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 two neutrons to the two-phonon octupole excitation ($\nu f_{7/2} \times (3^- \times 3^-)$ in ^{147}Gd and $\nu^2 \times (3^- \times 3^-)$ in ^{148}Gd), their descriptions are not as straightforward as would be the case in a doubly closed-shell nucleus. In view of these ambiguities, the identification of two-phonon octupole multiplets in even-even nuclei remains an important goal in our understanding of the octupole mode.

Stable ^{144}Sm is only two protons removed from ^{146}Gd, and $B(E3;3^- \rightarrow 0^+)$ has recently been measured[41] to be 38 ± 3 W.u. Furthermore, the low energy of the one-phonon state suggests that exciting and observing two-phonon excitations is practical. We have begun studies of this nucleus and ^{142}Nd, another N = 82 nucleus, with the (n,n'γ) reaction, and candidates for two-phonon states have been identified. Measurements of the level lifetimes with the DSAM technique, primarily to search for the expected fast E1 transitions to the one-phonon state, are in progress.

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[37] R.H. Spear, Atom. Data and Nucl. Data Tables **42**, 55 (1989).

[38] Yates, Mann, Henry, Decman, Meyer, Estep, Julin, Passoja, Kantele, and Trzaska, Phys. Rev. C**36**, 2143 (1987).

[39] Curutchet, Blomqvist, Liotta, Dussel, Pomar, and Reich, Phys. Lett. **208B**, 331 (1988).

[40] Lunardi, Kleinheinz, Piiparinen, Ogawa, Lach, and Blomqvist, Phys. Rev. Lett

[41] Barfield, von Brentano, Dewald, Zell, Zamfir, Bucurescu, Ivascu, and Scholten, Z. Phys. **A332**, 29 (1989).

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 phonon modes.[42] 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[41] have recently measured $B(E1; 3_1^- \rightarrow 2_1^+) = (2.8 \pm 0.4) \times 10^{-3}$ 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,[43] supports the interpretation the 1^- state in this nucleus as a two-phonon $2^+ \times 3^-$ excitation. However, even our preliminary data from $(n,n'\gamma)$ on this nucleus indicates that the expected $1^- \rightarrow 2^+$ transition from a member of the quadrupole-octupole multiplet in ^{144}Sm is absent, thus casting doubts on their conclusions. This example points to one of the many advantages of $(n,n'\gamma)$ spectroscopy where we are able to observe low-energy branches that are obscured by the intense bremsstrahlung present in the resonance fluorescence measurements.

c. Phonon and Shell Model States in Sn and Fe Isotopes (J.L. Weil, Z. Gácsi and J. Boone)

The analysis of the ^{116}Sn$(n,n'\gamma)$ Doppler shifts will be continued to completion, and the lifetimes extracted. The second paper on the structure of ^{116}Sn, describing the assignment of spins and parities, should be completed in the coming year.

Because of the serious lack of agreement between current level density theories and our experimental bound state level densities for ^{116}Sn, we have been searching for a theoretician who would be interested in working on this problem. Dr. A.V. Ignatyuk from Obninsk is a theoretician with world-recognized competence in level density theory, and has said he would be interested in visiting us to work on this problem.

The search for weak transitions between the ^{124}Sn multi-phonon states will be completed, allowing us to complete the evaluation of the present evidence for this multi-phonon structure. It is anticipated that a paper will be submitted on the results to one of the letter journals.

Once the $(n,n'\gamma)$ studies on ^{116,124}Sn have been published, work will be resumed on the ^{120}Sn$(n,n'\gamma)$ data set, which was taken at about the same time. Although the basic data reduction has been completed and a preliminary decay scheme has been constructed, it still remains to do the analysis of the excitation functions to check on the placement of all the feeding and to search for additional γ-rays needed to give a reasonable net excitation function. Peak overlap with single- and double-escape lines in the spectrum also needs to be checked.

Now that a suspected problem in the Doppler shift lifetime analysis code has been found to be non-existent it is possible to go ahead and publish our results from the ^{56}Fe$(n,n'\gamma)$ study. This publication will report several new γ-ray transitions and levels in ^{56}Fe, as well as newly determined lifetimes for eight levels.

d. Shell Model Calculations near A = 140 (D. Wang and M.T. McEllistrem)

Extensive shell model calculations for the $N = 82$ nuclei of this mass region were made twenty years ago, with a rather successful description of the low-lying even-parity levels and electromagnetic transition rates.[44] However, even less was then known about possible collective excitations than is known now. As noted above, extensive γ-ray studies of ^{144}Sm and ^{142}Nd are already under way in our laboratory, to explore the region where

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[42] P. Vogel and L. Kocbach, Nucl. Phys. **A176**, 33 (1971).

[43] F.R. Metzger, Phys. Rev. **C14**, 543 (1976).

[44] B.H. Wildenthal and D. Larson, Phys. Lett. **37B**, 266 (1971).

dipole collective excitations can be felt. We expect to make new shell model calculations, using the presently more extensive experimental information from recent experiments,[45,46] as well as the results to be developed in the proposed experiments.

We have already begun some calculations, using methods similar to those highly successful in our ^{204}Pb and ^{206}Pb calculations.[27] As in the Pb calculations, we will use the shell-model code OXBASH82. We will particularly attempt to fix odd-parity levels, since none have been reported in the earlier experimental studies of this nucleus. Promoting protons into the $h_{11/2}$ orbit should give several such levels; they do not seem to be observed. Noting valence excitations, and understanding their properties, will assist us to identify and appreciate the collective levels outside our model.

C. NUCLEAR ASTROPHYSICS

1. The Alpha Capture Strength Function in Carbon (J. Trice, J.L. Weil, M.Z. Wang, and M.A. Kovash)

The carefully detailed $^{12}C(\alpha,\gamma)^{16}O$ reaction studies include angular distributions on the well known 1^- and 2^+ resonances as well as many other complete angular distributions, covering the center-of-mass (c.m.) energy region of 2.0 – 3.1 MeV. These γ-ray differential cross sections span the broad 1^- state at 2.4 MeV c.m. energy and hence enable high confidence separation of the E2 and E1 contributions to the low energy α-particle strength function. This permits extrapolation to the energies of astrophysical interest, in the several hundred keV region. These measurements are the dissertation work of Mr. James Trice, soon to be written up for publication.

2. Synthesis of ^{187}Os and Nucleochronology (M.T. McEllistrem, R.R. Winters, R.L. Hershberger, and R.L. Macklin)

The role of capture from the 9.76-keV excited level of ^{187}Os in the nucleosynthetic equilibrium quantity of that nuclide in massive stars has been a controversial topic related to using the Re/Os nucleochronology to date the galaxy. This topic was addressed in an earlier elastic and inelastic neutron scattering study from ^{187}Os, which enabled determination of the neutron penetration probabilities for neutrons incident on both the ground state and excited state of that nucleus.[47] However, doubt about the validity of extrapolating this result to capture cross section determinations could linger, since a model must intervene (the statistical model) to relate the cross sections to each other.

Extending the elastic and inelastic scattering study to ^{189}Os enabled us to study scattering and capture from a nucleus in which the roles of ground and excited levels were reversed; the $1/2^-$ ground state of ^{187}Os became an excited level of ^{189}Os, whereas the $3/2^-$ excited level became the ground level. Measuring total, differential inelastic scattering, and capture cross sections from the latter nucleus was useful to show that the same model which worked so well for ^{187}Os would also work just as well for ^{189}Os. This work has now been published.[48]

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[45] Diószegi, Veres, Enghardt, and Prade, J. Phys. G. **11**, 853 (1985).

[46] Enghardt, Kaubler, Prade, Keller and Stary, Nucl. Phys. **A449**, 417 (1986).

[47] Hershberger, Macklin, Balakrishnan, Hill, and McEllistrem, Phys. Rev. C**28**, 2249 (1983).

[48] McEllistrem, Winters, Hershberger, Cao, Macklin, and Hill, Phys. Rev. C**40**, 591 (1989).

3. **Halflife of ^{56}Co** (K.L. Liu and M.K. Kovash)

Light emissions from the supernova 1987A show an exponential diminution of strength with an indicated half-life of about 77 days. This provides direct evidence for the production of ^{56}Co during the collapse of the star, but efforts to observe additional products of the collapse are hampered by the uncertainty in the knowledge of the exact half-life of ^{56}Co.

We have remeasured this half-life using a source produced with the UK Van de Graaff accelerator. Gamma-rays were observed in a Ge(Li) spectrometer continuously over a period of 110 days. Yields from transitions at 846, 1039, 1238, 2034, and 2598 keV were analyzed, along with a ^{137}Cs calibration line at 662 keV. The resulting yields were fit to a time-dependent function of the form of a double-exponential plus time-independent and linear time-dependent background terms. Only the data from the 2034 keV transition were well described with a single exponential decay component, while fits to the other transitions revealed statistically significant background contributions in the measured yields. The half-life determined from the analysis of the 2034 keV transition is 77.02 ± 0.28 days.

4. **Solar Neutrino Detector-related Projects**

a. **^{81}Br - ^{81}Kr Mass Difference** (Y. Wang, D. Wang, and M.T. McEllistrem)

The $^{81}Br(p,n)^{81}Kr$ reaction is being studied to determine the Q-value of this reaction to within $\pm$ 1 keV or slightly less. All data taking should be concluded for this project by the end of March, 1990. However, the careful analysis of sources of errors will take some time beyond that point. Existing Q-values and values[49] for the ^{81}Br - ^{81}Kr mass difference have uncertainties of $\pm$ 6 keV, rather larger than would be useful when and if a bromine solar neutrino detector would be developed in this country.[49] That possible detection scheme had been retarded by the difficulty of detecting the resulting ^{81}Kr, but the development over the last five years of single krypton atom detection by G. S. Hurst and colleagues with resonance ionization techniques (RIS)[50] has removed that obstacle.

The accelerator energy scale is calibrated with the $^{7}Li(p,n)$ reaction using both proton and HH^+ ions, and also the $^{19}F(p,n)^{19}Ne$ reactions. Careful attention will be paid to the energy shift of the HH^+ threshold caused by the "Coulomb explosion" of the dissociating ion. We are using the $^{51}V(p,n)$, the $^{55}Mn(p,n)$, and the $^{41}K(p,n)$ reactions to standardize our time-of-flight scale for neutron energies. All of these reactions have Q-value uncertainties of well under 1 keV, typically $\pm$ 0.4 keV. These reactions also have Q-values similar to that of bromine. The $^{41}K(p,n)$ reaction is particularly useful, since it is internal to the KBr target. We have already achieved a result with an uncertainty of about 2 keV.

Knowledge of the Q-value to within better than $\pm$ 1 keV would be particularly important were a prototype bromine detector to be calibrated using ^{51}Cr as a laboratory source of neutrinos. The role of the $5/2^-$ excited level in the calibration would be sensitive to that Q-value.

b. **$^{127}I(p,n)^{127}Xe$ and the ^{127}I Detector** (J.F. Vanhoy, D. Wang, and M.T. McEllistrem)

Prof. Haxton of the University of Washington has proposed that ν-capture on ^{127}I to ^{127}Xe could be a very sensitive and effective solar neutrino detector, should the Gamow-Teller capture strength to several low-lying states

[49] Burks, Anderson, Aoki, Karp, Ludwig, Thompson, and Varner, Phys. Rev. C30, 742 (1984).

[50] Hurst, Chen, Kramer, Cleveland, Davis, Rowley, Gabbard, and Schima, Phys. Rev. Lett. 53, 1116, (1984).

of ^{127}Xe be as large as expected.[51] Like Br or Cl, I compounds are readily available in large quantities, it is monoisotopic, and the decay product is a noble gas with a quite reasonable half-life of 36.4 days. In this respect, it is similar to the ^{37}Ar produced in the ^{37}Cl detector; similar counting techniques would work, and the more complex RIS methods would not be needed to detect the capture products. However, the spectroscopy of the low energy levels of ^{127}Xe is poorly known.

This spectroscopy is proposed to be studied using the $^{127}I(p,n)^{127}Xe$ reaction. We propose to use triple correlations in the reaction $^{127}I(p,n\gamma\gamma)$ reaction to probe the level scheme and clarify spin assignments, branching ratios, and mixing ratios. Often the angular distributions of γ-rays from the $(p,n\gamma)$ reactions provide unique spin assignments, and a well determined decay scheme. However, the relatively high ground-state spin of ^{127}I, $5/2^+$, means that γ-ray singles will contain very little information for levels of spin 5/2 or less. Thus the proposal is to study triple angular correlations, using both (n,γ) and (γ,γ) correlations to resolve ambiguities.

Such triple correlation experiments with neutron detection are difficult at our accelerator energies. We have done careful studies of beam-handling and target chamber design, and believe we have the sensitivity to obtain adequate counting rates with low background conditions. The measurements will require days of running time per point, but such running conditions are quite realistic at our accelerator. We have done several test runs both of singles γ-ray detection and γ-γ and n-γ correlations. The signal to background rates are quite promising, and the counting rates even for the n-γ correlations are adequate. The γ-γ correlation rates are substantially larger than the n-γ ones, and good background conditions can be attained for both correlations.

5. <u>Optical Potential Studies</u> (C.E. Laird, D. Sousa, G. Calkin, T. Hooper, S. Qiang, and S. Rucker)

During the last year the Eastern Kentucky University group experimentally studied proton induced reactions on ^{52}Cr and natural Cu targets. For elastic scattering of protons from ^{52}Cr, yields were measured at angles of 165 and 225 degrees and proton energies from 2 MeV to 5.8 MeV. $^{52}Cr(p,n)$ measurements were made from below threshold to 6.5 MeV, and $^{52}Cr(p,\gamma)$ yields were measured from 1.5 MeV to 5.3 MeV. Also, measurements have been made on a natural copper target of the Cu(p,n) yields from 2 to 5.8 MeV and of Cu(p,γ) yields from 2 to 4.5 MeV. These will complement the previous ^{65}Cu measurements[52] of Hershberger and Gabbard and will be used to determine the (p,n) cross sections for ^{63}Cu as well as the radiative and inelastic scattering cross sections for both copper isotopes. These measurements will be analyzed to determine optical model parameters for these nuclei complementing previous such determinations in the mass 40-90 region.

[51] W.C. Haxton, Phys. Rev. Lett. **60**, 768 (1988).

[52] R.L. Hershberger and F. Gabbard (private communication).

A. NUCLEAR DATA EVALUATION

1. Mass-Chain Evaluation (E. Browne, R.B. Firestone, A.O. Macchiavelli, V.S. Shirley, and B. Singh)

The LBL Isotopes Project is responsible for evaluating 28 mass chains with 167≤A≤194 and for converting 21≤A≤44 to ENSDF format. Responsibility for mass chain A=177 has been temporarily reassigned to Japan. A summary of the current evaluation status of LBL mass chains is given in the table below:

Status of LBL Mass-Chain Assignments

Mass Chain	Publication Year	Status
33-44[a]	1978	Sent to BNL 1987 (LBL)
167	1989	Published (LBL)
168	1988	Published (LBL)
169[b]	1982	Published (LBL)
170	1987	Published (China)
171	1984	Published (LBL)
172	1987	Published (China)
173	1988	Published (LBL)
174	1984	Submitted 12-89 (LBL)
175[b]	1976	(5-90) (LBL)
176	1976	Submitted 5-89 (LBL)
177	1975	(Japan)
178	1988	Published (LBL)
179	1988	Published (LBL)
180	1987	Published (LBL)
181	1984	Submitted 12-89 (LBL)
182	1988	Published (LBL)
183	1987	Published (LBL)
184	1989	Published (LBL)
185	1989	Published (LBL)
186	1988	Published (LBL)
187	1982	Submitted 9-89 (LBL)
188	1981	In press (LBL)
189	1981	In press (LBL)
190	1982	Submitted 12-89 (LBL)
191	1989	Published (LBL)
192[b]	1983	Published (LBL)
193	1981	Submitted 9-89 (LBL)
194	1989	Published (LBL)

[a] A=21-44 is in press and will be entered into ENSDF in 1990.

[b] To be evaluated in 1990.

The Isotopes Project contributed approximately 2.5 full-time equivalent (FTE) effort into mass-chain evaluation in 1989. This includes Dr. Balraj Singh who has been dividing his time between the LBL and the McMaster evaluation groups. The group has achieved a stable production rate of more than 2 mass-chain evaluations per FTE/year. Seven evaluations (compared to five produced last year) were completed in 1989. One LBL evaluator, Virginia Shirley, is spending a year at the Free University of Berlin, starting October 1989 where she will continue evaluating mass chains for the Isotopes Project while on professional leave. A new evaluator, Dr. Augusto O. Macchiavelli, joined the Isotopes Project as of September, 1989. His experience in the study of high-spin states in nuclei, and involvement with the early stages of the Gammasphere proposal, will bring a new area of expertise to the Isotopes Project.

2. Major Horizontal Evaluations

a. Table of Radioactive Isotopes (E. Browne, R.B. Firestone, and V.S. Shirley)

This book, tailored to the needs of applied users in industry, biology, medicine, and other fields, but also serving as an indispensable reference for nuclear physicists and chemists, contains 1056 pages and sells for $59.95. Sales through August, 1989 were 2104 volumes, and sales for the past year were 235 volumes.

b. Table of Isotopes, 7th edition Shirley, editors; E. Browne, J.M. Dairiki, and R.E. Doebler, principal authors)

This 1630-page book, which contains nuclear structure data not presented in the "Table of Radioactive Isotopes", is an excellent complement to the latter. The "Table of Isotopes" was reprinted in 1986 and currently sells for $48.50. 10,190 volumes were sold through August 1989, and sales for the past year were 272 volumes.

c. Table of Isotopes, 8th Edition (R.B. Firestone, E. Browne)

The Isotopes Project has submitted proposals to the IAEA Nuclear Structure and Decay Data (NSDD) Advisory Group and to the National Academy of Sciences Panel on Basic Nuclear Data Compilations for production of a new edition of the "Table of Isotopes". Preliminary approval has been received from the NSDD, and we await the comments of the NAS Panel. Our goal is to complete the book in three years with existing operating funds. No adverse effect on the mass-chain production rate is expected because of increased evaluation efficiency. The new edition will emphasize nuclear structure data and will be based on the ENSDF file. It is anticipated that the book will be a single volume and maintain the high production standards of previous editions.

d. Electronic Table of Isotopes (R.B. Firestone, C.A. Stone, and E. Browne)

The Isotopes Project proposed an electronic "Table of Isotopes" to the NAS Panel in 1989. Subsequently, a collaboration was formed between LBL and NIST to develop this concept. The initial version of the electronic "Table of Isotopes" is being developed on a Macintosh II personal computer. It will contain a searchable, full-color 'wall chart' derived from the "Table of Radioactive Isotopes". Basic isotope and isomer properties including half-lives, decay modes, spins, parities, masses, and limited radiation data will be included. In addition, physics utility functions for calculating Clebsch-Gordan and Racah coefficients, $\gamma\gamma$-angular correlations, interaction of radiation with matter, conversion coefficients, and reduced transition probabilities will be included. Specially tailored application programs for neutron activation, decay heat, and nuclear theory are under development. The first distribution of the electronic "Table of Isotopes" is expected in 1991. We welcome suggestions for additional features and data to be included in this system.

3. Evaluation Methodology

The Isotopes Project has a continuing interest in developing methods for evaluating nuclear data in order to improve efficiency and the quality of the evaluations. The group's contributions to the mass-chain evaluation effort are described below:

a. Analysis of α-, β-, and γ-Ray Emission Probabilities (R.B. Firestone)

This paper in Nucl. Instr. Meth. Phys. Res. A286 , 584 (1990) presents a self-consistent analysis of radiation intensities, which includes physical constraints, for normalizing decay schemes. This paper was originally given at the International Committee for Radionuclide Metrology (ICRM) Meetings and International Symposium,

b. Computer Codes (Isotopes Project)

The Isotopes Project develops computer codes for implementing new or revised methods and procedures, and maintains a library of codes for evaluating nuclear data for ENSDF. These codes are available in the Berkeley ENSDF Evaluation Program Library (BEEP).

B. SPECTROSCOPY STUDIES

1. ^{56}Ni Decay Revisited (B. Sur, E.B. Norman, K.T. Lesko, E. Browne, and R.-M. Larimer)

In a series of experiments we have reinvestigated the decay of the doubly magic nucleus ^{56}Ni which is believed to be copiously produced in supernovae. We have confirmed its previously known decay scheme and half-life, and have searched for several rare decay modes. We establish an upper limit of 5.8×10^{-7} for the branching ratio of the second forbidden unique β^+

decay to the 158-keV level in ^{56}Co, leading to a lower limit of 2.9×10^4 years for the half-life of fully ionized ^{56}Ni nuclei in cosmic rays. We also establish an upper limit of 1.5×10^{-3} for the branching ratio of the isospin forbidden Fermi electron capture transition to the 1451-keV level in ^{56}Co, which in turn leads to an upper limit of 66 keV for the isospin mixing Coulomb matrix element of the ^{56}Ni ground state.

2. Gamma-ray Strength Function for EC/β^+ Decay Near N=82 (R.B. Firestone)

Nuclei far from stability may beta decay to high-lying daughter levels which emit intense, unresolved γ rays. The intensity of these γ rays is needed to calculate beta-delayed particle emission probability and decay heat. Calculation of the gamma-strength function typically involves standard level-density assumptions and average gamma widths. This prescription is successful in describing average neutron resonance capture γ-ray intensities, but has not been confirmed for nuclear beta decay. The decays of the neutron deficient N=81 isotopes ^{145}Gd(1/2+)[1] and ^{149}Er(11/2−)[2] have been thoroughly studied and offer insight into the gamma strength. These decays show considerable structure in the beta-strength function, and this structure is repeated in the gamma strength. In ^{145}Gd(1/2+) decay M1 strengths are found to be strongly retarded with respect to E2 strengths, and considerable energy dependence exists in the M1 strength. Conversely, for ^{149}Er(11/2−) decay the gamma strength is dominated by M1 transitions to the 11/2− ground-state.

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[1]R.B. Firestone, et. al., Phys. Rev. C25, 527 (1982).
[2]R.B. Firestone, et. al., Phys. Rev. C39, 219 (1989).

3. Nuclear Decay Studies Far-from-Stability (R.B. Firestone, J.M. Nitschke, R.M. Chasteler, J. Gilat, A.A. Shihab-Eldin, K.S. Vierinen, and P.A. Wilmarth)

The decays of rare-earth nuclei in the region near N=82 and Z=64 and extending towards the proton drip line have been studied with the OASIS mass-separation facility on-line at the Lawrence Berkeley Laboratory SuperHILAC. Spectra of x-rays, gamma rays, and beta-delayed protons and alpha particles have been measured in both singles and coincidence mode. Decay schemes have been derived, in many instances, with absolute branching intensities for electron capture, positron emission, and beta-delayed particle decay. In favorable cases, Q(EC) values have been determined from the measured electron capture and positron decay branchings. Nuclear structure near the closed shells has been qualitatively explained by a simple weak-coupling model, and the disappearance of Z=64 shell effects near N=78 has been explored. The systematics of Gamow-Teller spin-flip transitions have been investigated and are compared with Shell-Model predictions.

LAWRENCE LIVERMORE NATIONAL LABORATORY

A. NUCLEAR DATA CALCULATIONS AND EVALUATIONS

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

Last year we reported that we had initiated major reevaluations of charged-particle reaction cross sections important to fusion applications, including angular distributions of secondary particles, Maxwellian-averaged reaction rates, etc., for the Livermore Evaluated Charged Particle Library (ECPL). Our initial effort included using previous evaluations as well as recently reported results for ^{2}H(d,n)^{3}He, ^{2}H(d,p)^{3}H and ^{3}H(d,n)^{4}He. This year we have included the ^{3}He(d,p)^{4}He reaction. Because of differences in recently reported measurements of these reactions and because the ^{3}He(d,p)^{4}He data base, although extensive at low energies, is actually poor, we have undertaken a major reevaluation effort of all these reactions. The last complete effort of several of these reactions was the work of Liskien and Paulsen.[1] We expect our effort to yield reaction cross section evaluations with quantifiable uncertainties over the energy range from threshold ($\approx$300 eV) to 20 MeV.

a. ^{2}H(d,p)^{3}H Data Base and Evaluation

We have assembled experimental cross section data from 19 individual references for ^{2}H(d,p)^{3}H. Included in this data base are 153 integrated reaction cross section points and 126 angular distributions. Figure 1 shows the present low energy ^{2}H(d,p)^{3}H reaction data base and evaluation plotted in terms of the astrophysical s-factor as a function of laboratory deuteron energy. The evaluation is indicated with $\pm$3% limits. Not all reference data are yet included in this evaluation. Figure 2 shows the present data base and evaluation in terms of cross section vs. laboratory deuteron energy to 20 MeV. The evaluation is represented as energy-cross section pairs ($\approx$750 points) which can be interpolated using linear-linear interpolation to an accuracy of 0.1% over the entire energy range.

b. ^{2}H(d,n)^{3}He Data Base and Evaluation

An experimental cross section data base has been assembled from 22 individual references for ^{2}H(d,n)^{3}He. Included in this data base are 166 integrated reaction cross section points and 95 angular distributions. Figure 3 shows the low energy ^{2}H(d,n)^{3}He reaction data base and evaluation plotted the same as in Fig. 1. Not all reference data are yet included in this evaluation. Figure 4 shows the present data base and evaluation in terms of cross section vs. laboratory deuteron energy to 20 MeV with $\pm$3% limits indicated.

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[1] H. Liskien and A. Paulsen, Nuclear Data Tables **11**, 569 (1973).

Fig. 1 The present low energy $^2H(d,p)^3H$ reaction data base and evaluation plotted in terms of the astrophysical s-factor as a function of laboratory deuteron energy. The evaluation is indicated with ±3% limits. Not all reference data are yet included in this evaluation.

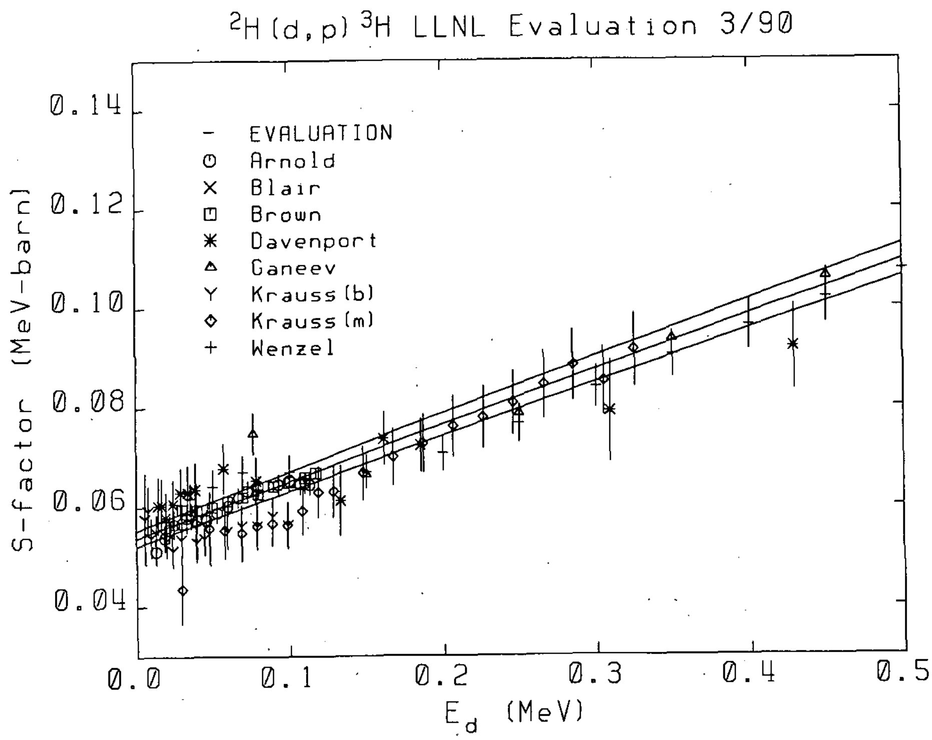
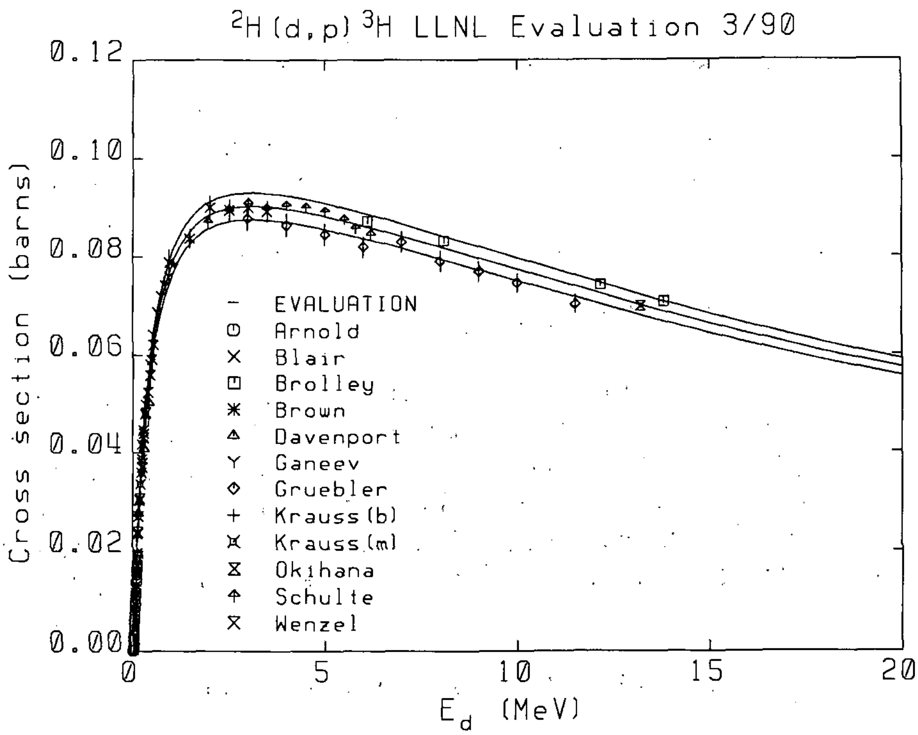


Fig. 2 The present data base and evaluation for $^2H(d,p)^3H$ in terms of cross section vs. laboratory deuteron energy to 20 MeV.



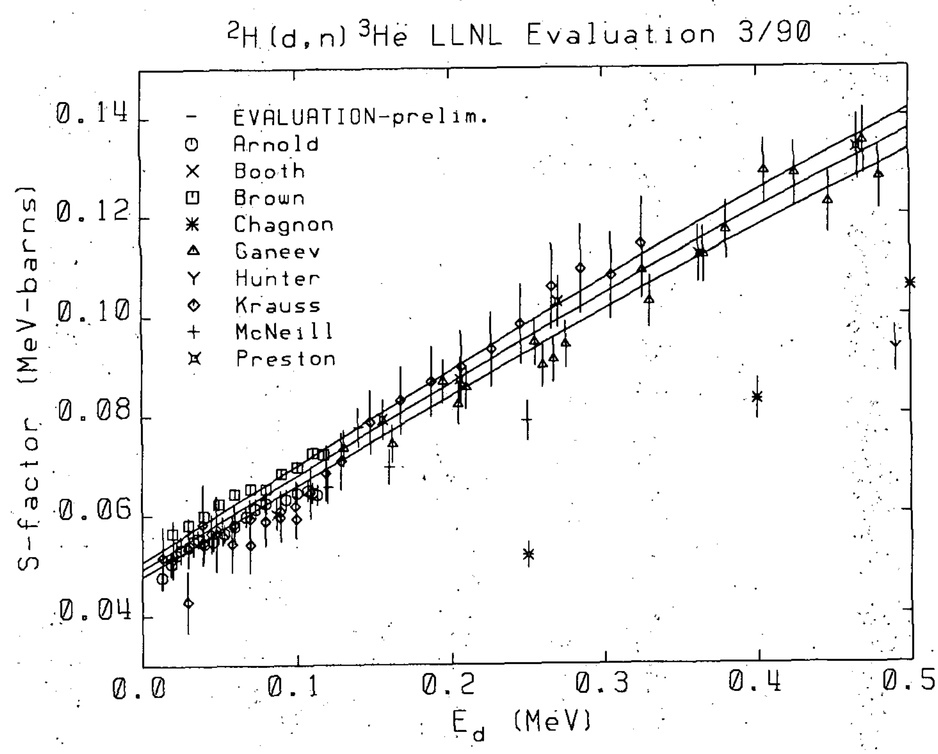


Fig. 3 The low energy $^2H(d,n)^3He$ reaction data base and evaluation plotted the same as in Fig. 1. Not all reference data are yet included in this evaluation.

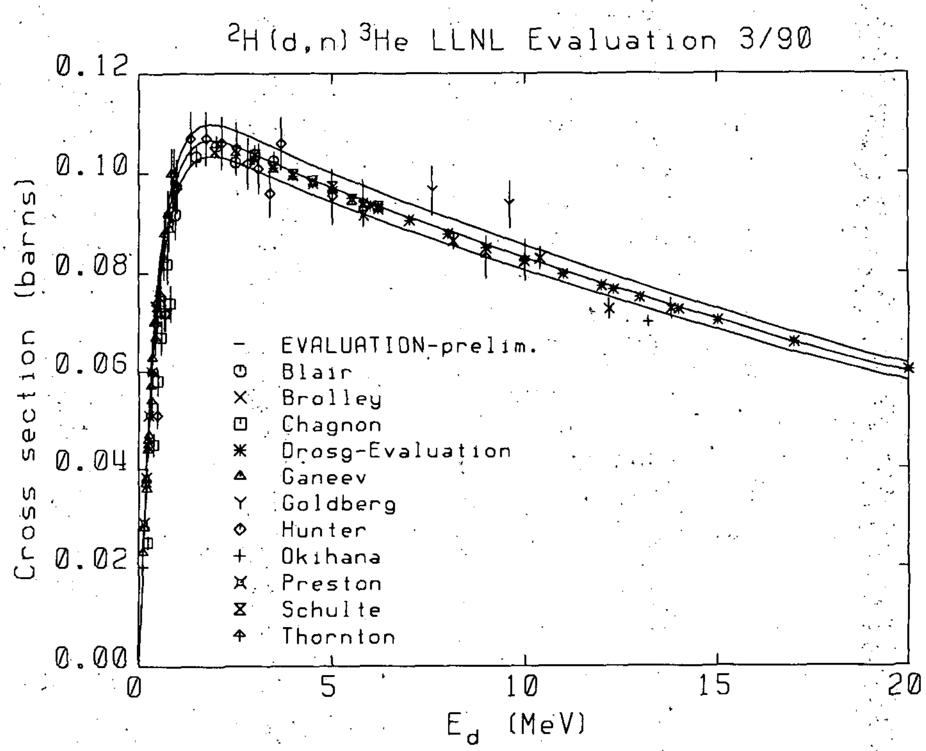


Fig. 4 The present data base and evaluation for $^2H(d,n)^3He$ in terms of cross section vs. laboratory deuteron energy to 20 MeV with ±3% limits indicated.

c. ^{3}H(d,n)^{4}He Data Base and Evaluation

While the ^{3}H(d,n)^{4}He evaluation extends to 20 MeV, we concentrate here on the important low-energy region. The low-energy portion of the ^{3}H(d,n)^{4}He reaction data base has been fitted using an R-matrix analysis. This region is dominated by a large resonance which corresponds to the E_x=16.8 MeV excited J^π=3/2$^+$ state in the compound ^{5}He system. In the simplest description, five parameters are required for the R-matrix analysis. The excitation energy of the compound state, the entrance channel reduced-width amplitude $\gamma_{d+t}^{l=0}$, the entrance channel radius r_{d+t}, the exit channel reduced-width amplitude $\gamma_{n+\alpha}^{l=2}$, and the exit channel radius $r_{n+\alpha}$. The boundary conditions were chosen to correspond to the channel shift functions evaluated at the resonance energy.

Many attempts were made to fit the cross section data using different assumptions about how much of the data base should be included in the fitting process. Also, in some cases, some of the parameters were given fixed values and were not allowed to vary. The final method used in this evaluation was also used in the analysis of the ^{3}He(d,p)^{4}He data base (see next section). For this evaluation, all of the available data were used up to an energy of E_d=0.2 MeV. The channel radii were fixed at r_{d+t}=5.0 fm and $r_{n+\alpha}$=3.0 fm. These values are the same as used by Jarmie, *et al.*[2] Allowing the channel radii to vary yielded little improvement in the fit and resulted in parameters which were less physical. Some variations in the channel radii, e.g., setting $r_{n+\alpha}$=5.0 fm, still resulted in comparable fits and physical parameters since one or both of the reduced-width amplitudes could change slightly to make up the difference.

In order to account for normalization inconsistencies between data sets, the overall normalization of each data set was allowed to vary provided that the average change of all data used was zero. Weighting the changes by the author's estimate of the normalization uncertainties was not considered. For the data sets of this reaction, the normalization changes were small (see Fig. 6). More complete details of the fitting process and a listing of the resulting parameters will be presented in a forthcoming report. The current R-matrix fit is displayed in Figs. 5-8. Shown in Figs. 5 and 6 is the integrated cross section and in Figs. 7 and 8, the astrophysical s-factor. The data displayed in Figs. 5 and 7 use the original normalizations as given in the references. The data displayed in Figs. 6 and 8 show the renormalized experimental data as described previously. Figs. 9 and 10 show the ratio of the original data and renormalized data to the evaluation. The present evaluation differs by no more than 1.5% from the one- and two-level R-matrix fits of Jarmie, *et al.*[2] and Brown, *et al.*[3] in the energy range E_d<0.2 MeV.

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[2] N. Jarmie, R. E. Brown, and R. A. Hardekopf, Phys. Rev. C **29**, 2031 (1984).

[3] R. E. Brown, N. Jarmie, and G. M. Hale, Phys. Rev. C **35**, 1999 (1987).

Fig. 5 Shown are the integrated cross sections for six of the presently used $^3H(d,n)^4He$ data sets and the preliminary evaluation (line) based on the R-matrix fit described in the text.

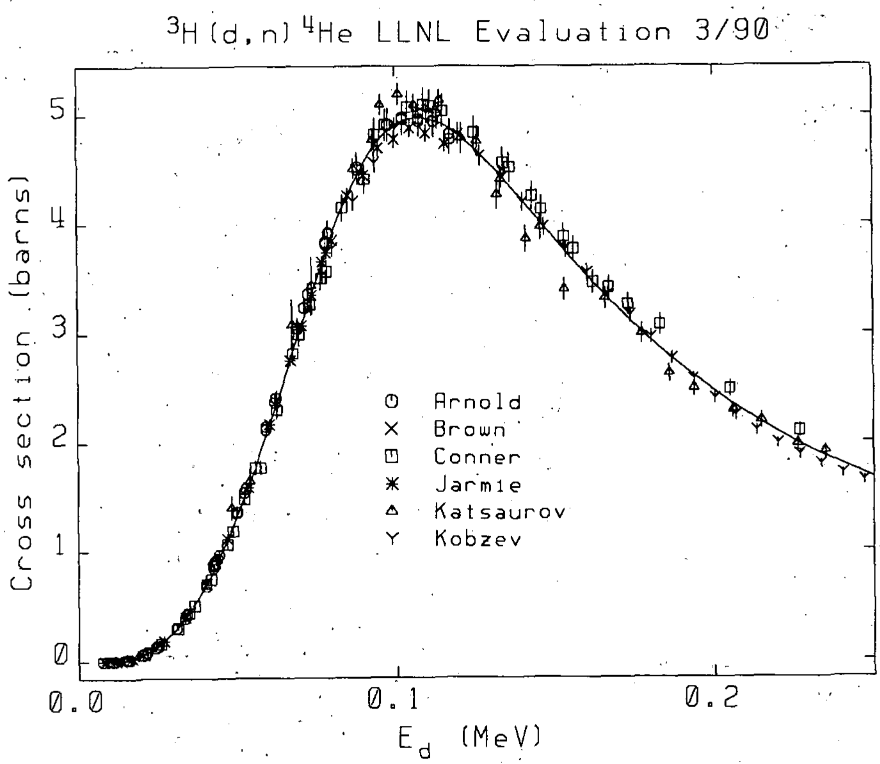


Fig. 6 Same as Fig. 5 except that the data sets are plotted with the new normalizations determined by the R-matrix fitting procedure. The average renormalization of all the data sets was required to be zero. Data are only shown up to the highest energy considered in the R-matrix analysis.

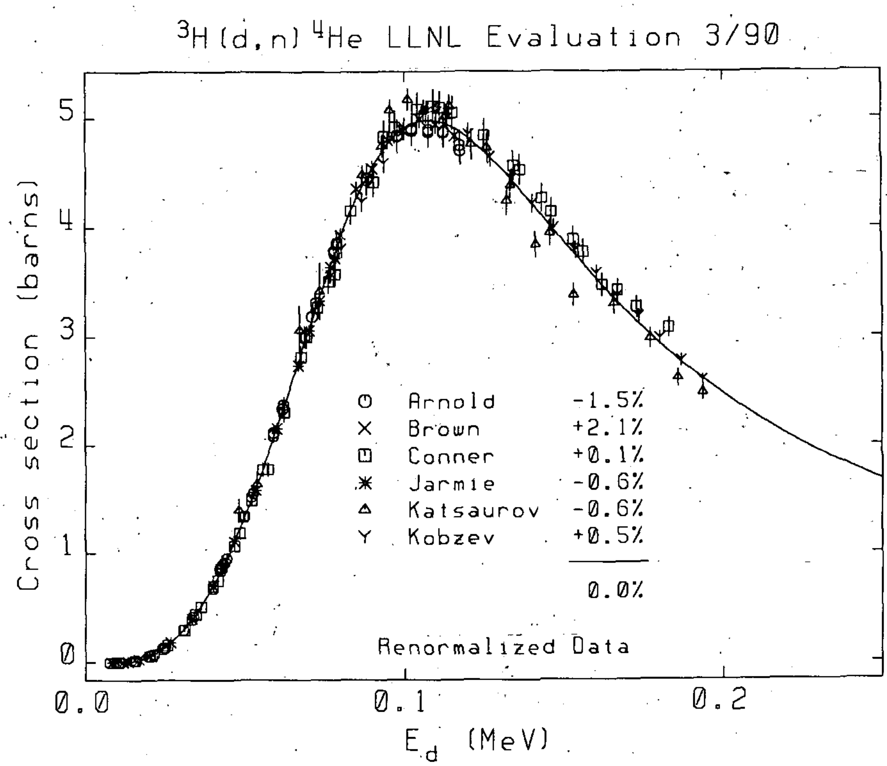


Fig. 7 Shown are the six $^3H(d,n)^4He$ data sets represented as astrophysical s-factors and the preliminary evaluation (line) based on the R-matrix fit described in the text.

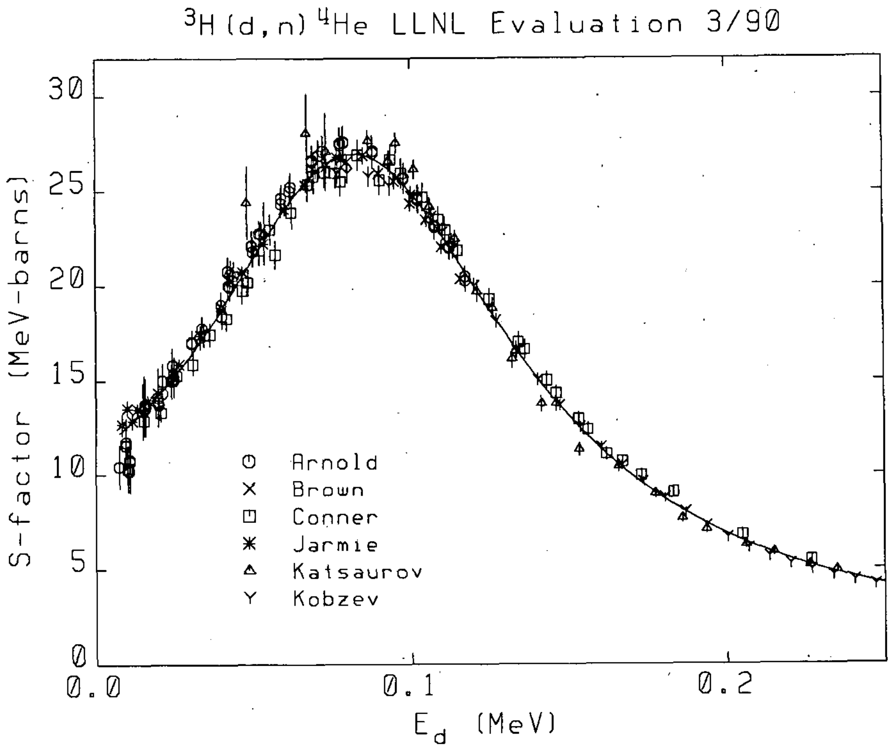


Fig. 8 Same as Fig. 7 except that the data sets are plotted with the new normalizations determined by the R-matrix fitting procedure. The average renormalization of all data sets was required to be zero. Data are only shown up to the highest energy considered in the R-matrix analysis.

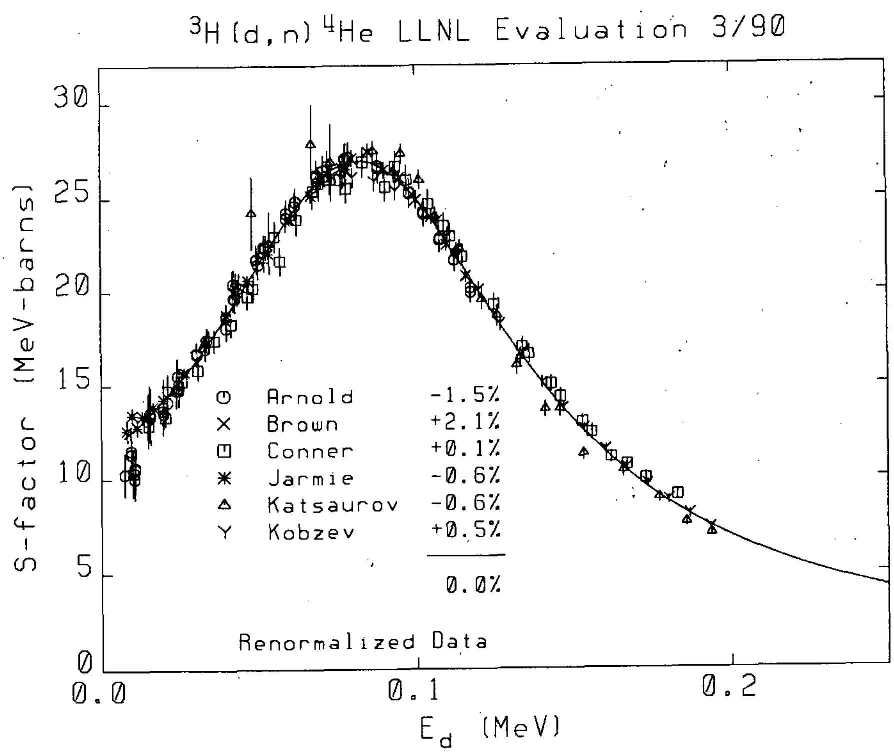


Fig. 9 Shown are the ratios of the six $^3H(d,n)^4He$ data sets to the preliminary evaluation based on the R-matrix fit described in the text. The symbols are the same as used in the previous four figures.

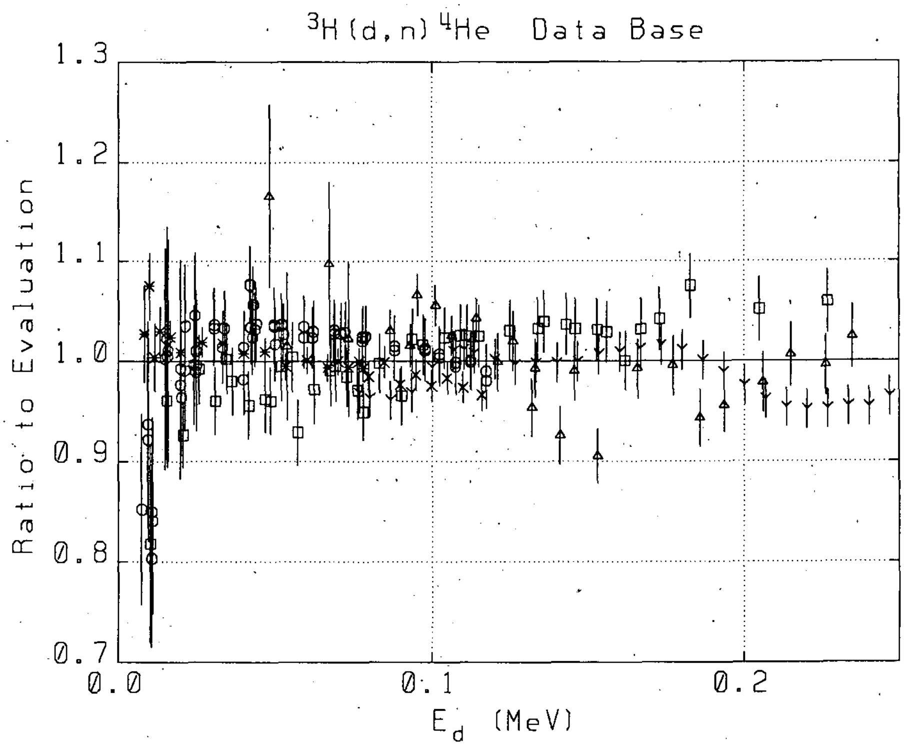
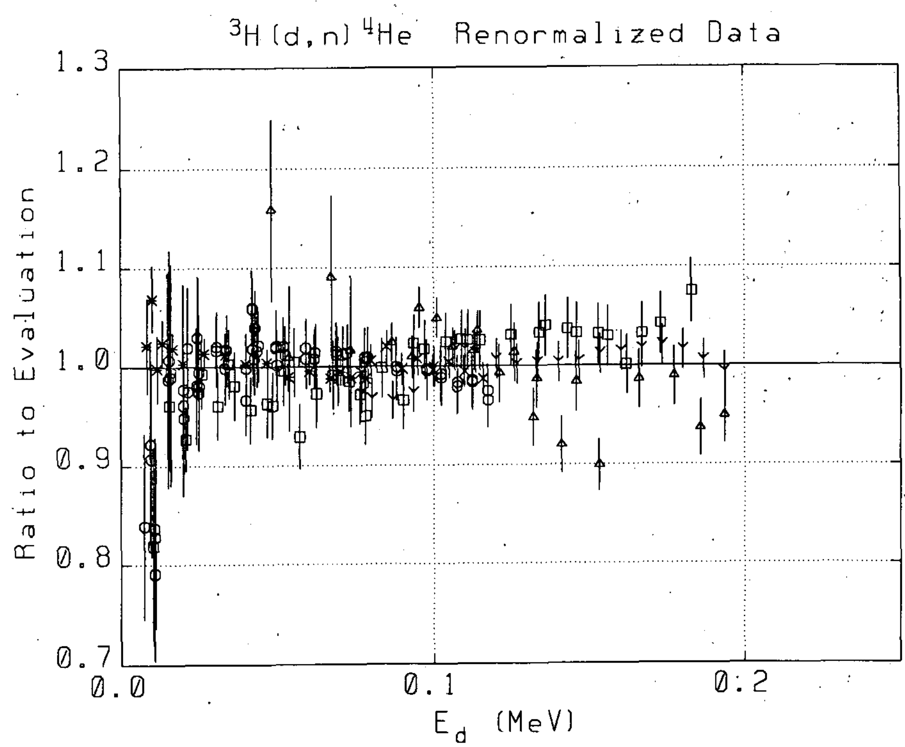


Fig. 10 Same as Fig. 9 except that the data sets are plotted with the new normalizations determined by the R-matrix fitting procedure. The average renormalization of all data sets was required to be zero. Data are only shown up to the highest energy considered in the R-matrix analysis.



d. $^3He(d,p)^4He$ Data Base and Evaluation

As with the low-energy portion of the $^3H(d,n)^4He$ reaction, the mirror reaction $^3He(d,p)^4He$ has been fit using an R-matrix analysis. This region is dominated by a large resonance which corresponds to the E_x=16.8 MeV excited J^π=3/2$^+$ state in the compound ^5Li system. Because of the mirror symmetry involved, the assumptions that went into the R-matrix analysis of this reaction were the same as those used in the $^3H(d,n)^4He$ reaction. The experimental information for this reaction is very discrepant as can be seen in Figs. 11 and 13. Because of the discrepancies in this data base and because of the mirror symmetry with the $^3H(d,n)^4He$ reaction, the first R-matrix analyses we attempted assumed that the corresponding reduced-width amplitudes would be equal. Under the assumptions of a charge-symmetric nuclear force and no Coulomb differences in the internal wavefunctions, that should have been the case. However, satisfactory fits under these assumptions could not be obtained implying that the Coulomb differences cannot be neglected. Hence, the data bases for each reaction were fit independently.

In the process of the R-matrix analyses, we concluded that two of the data sets, Bonner, *et al.*[4] and Jarvis and Roaf[5] should be omitted completely. Bonner's data do not have the same shape as the other data sets and Jarvis's data are off in magnitude by about a factor of 2. Also, some of the low-energy points of Carlton[6] and Kliucharev[7] were omitted because they also possessed what we believe to be the wrong shape. The remaining data basically have consistent shapes but very different normalizations. In order to account for the normalization inconsistencies, the overall normalizations of the data sets were allowed to vary provided that the average change for all data sets was zero. Weighting the changes by the authors' estimates of the normalization uncertainties was not considered since many of the data sets were more discrepant than the quoted errors would allow. It became apparent that treating the normalizations as completely free parameters with the one constraint of requiring the average normalization of all data sets to be zero was the most reasonable way to proceed. The current R-matrix fit is shown in Figs. 11-14. Shown in Figs. 11 and 12 is the integrated cross section and in Figs. 13 and 14 the astrophysical s-factor. The data displayed in Figs. 11 and 13 use the original normalization as given in the references. The data shown in Figs. 12 and 14 show the renormalized experimental data as described previously. Figures 15 and 16 show the ratio of the original data and renormalized data to the R-matrix fit.

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4 T. W. Bonner, J. P. Conner, and A. B. Lillie, Phys. Rev. **88**, 473 (1952).

5 R. G. Jarvis and D. Roaf, Proc. Roy. Soc. **A218**, 432 (1953).

6 R. F. Carlton, private communication from Nelson Jarmie, Los Alamos National Laboratory.

7 A. P. Kliucharev, B. N. Esel'son and A. K. Val'ter, Sov. Phys. Dokl. **1**, 475 (1956).

Fig. 11 Shown are the integrated cross sections for the twelve $^3He(d,p)^4He$ data sets and the present evaluation (line) based on the R-matrix fit described in the text.

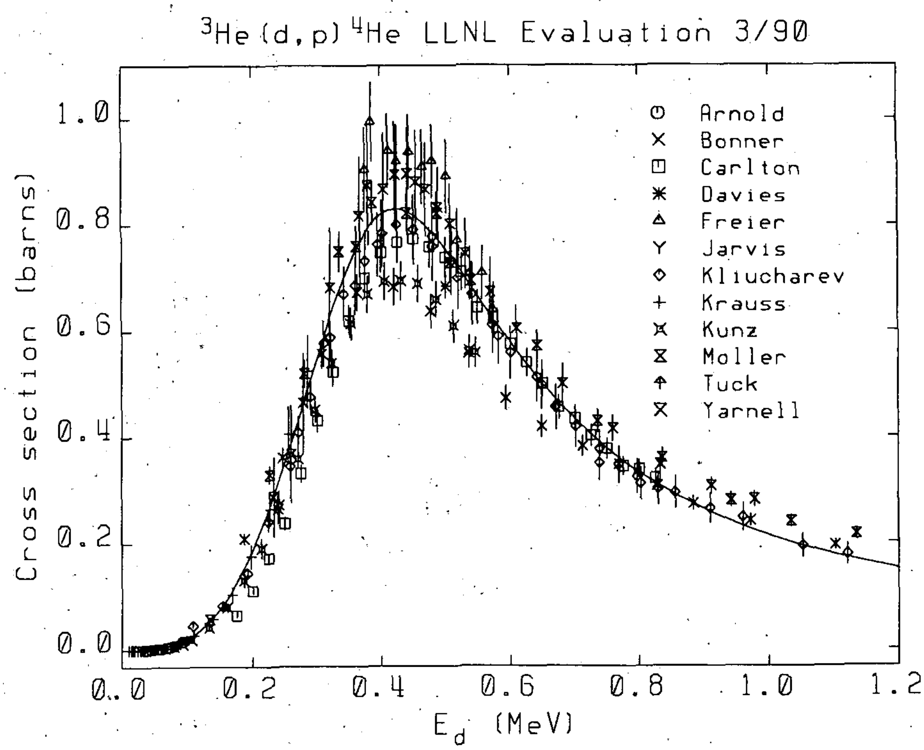


Fig. 12 Same as Fig. 11 except that the data sets are plotted with the new normalizations determined by the R-matrix fitting procedure. The average renormalization of all data sets was required to be zero. Data are only shown up to the highest energy considered in the R-matrix analysis.

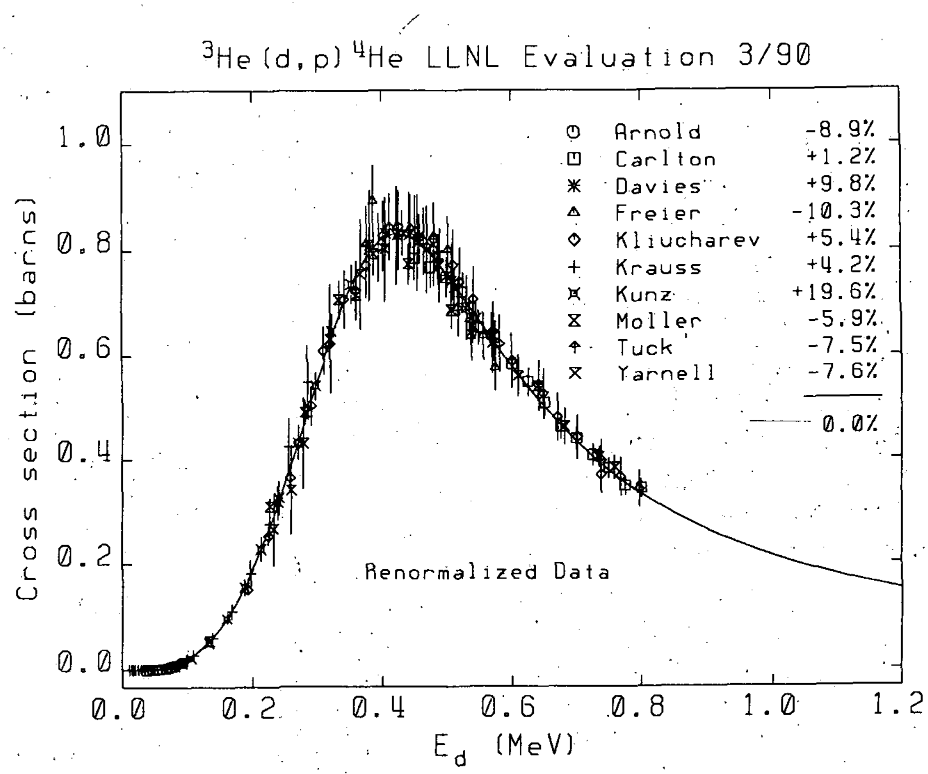


Fig. 13 Shown are the astrophysical s-factors for the twelve $^3He(d,p)^4He$ data sets and the present evaluation (line) based on the R-matrix fit described in the text.

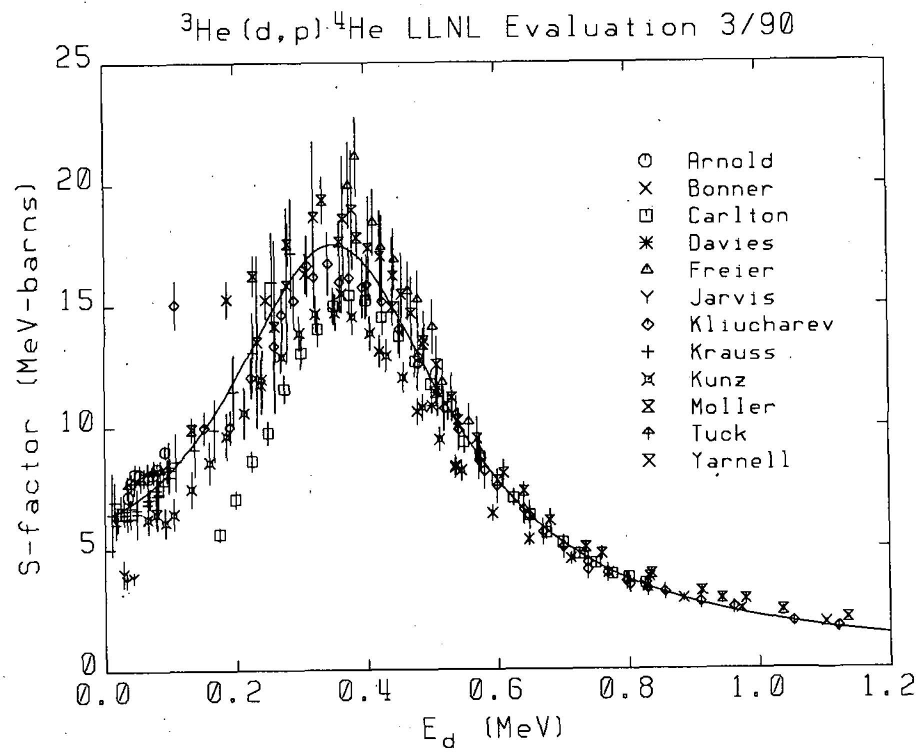


Fig. 14 Same as Fig. 13 except that the data sets are plotted with the new normalizations determined by the R-matrix fitting procedure. The average renormalization of all the data sets was required to be zero. Data are only shown up to the highest energy considered in the R-matrix analysis.

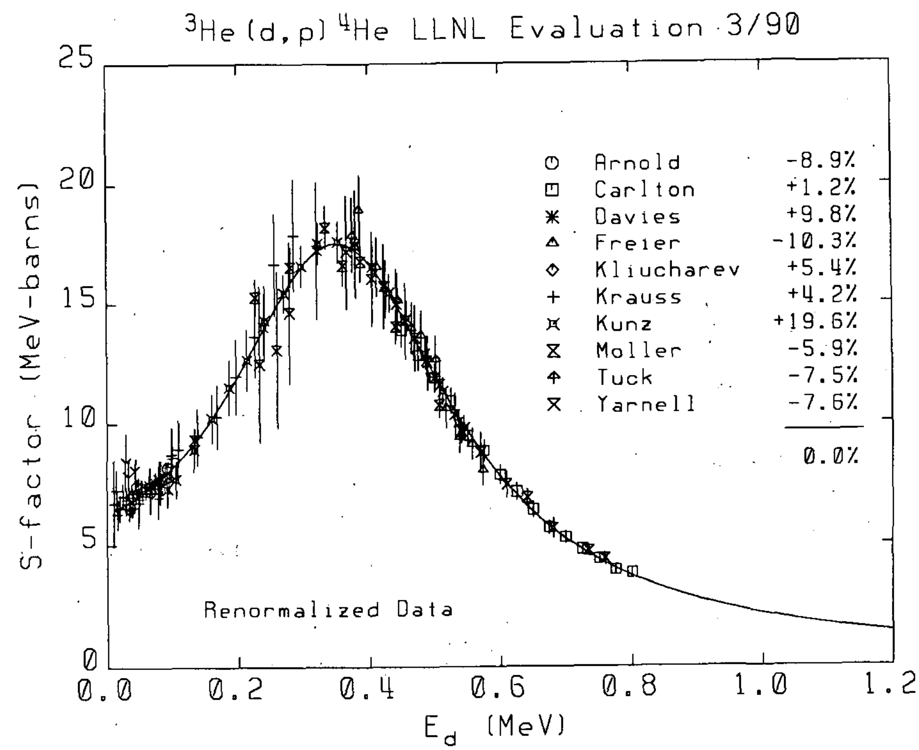


Fig. 15 Shown are the ratios for the twelve $^3He(d,p)^4He$ data sets to the evaluation based on the R-matrix fit described in the text. The symbols are the same as used in the previous four figures.

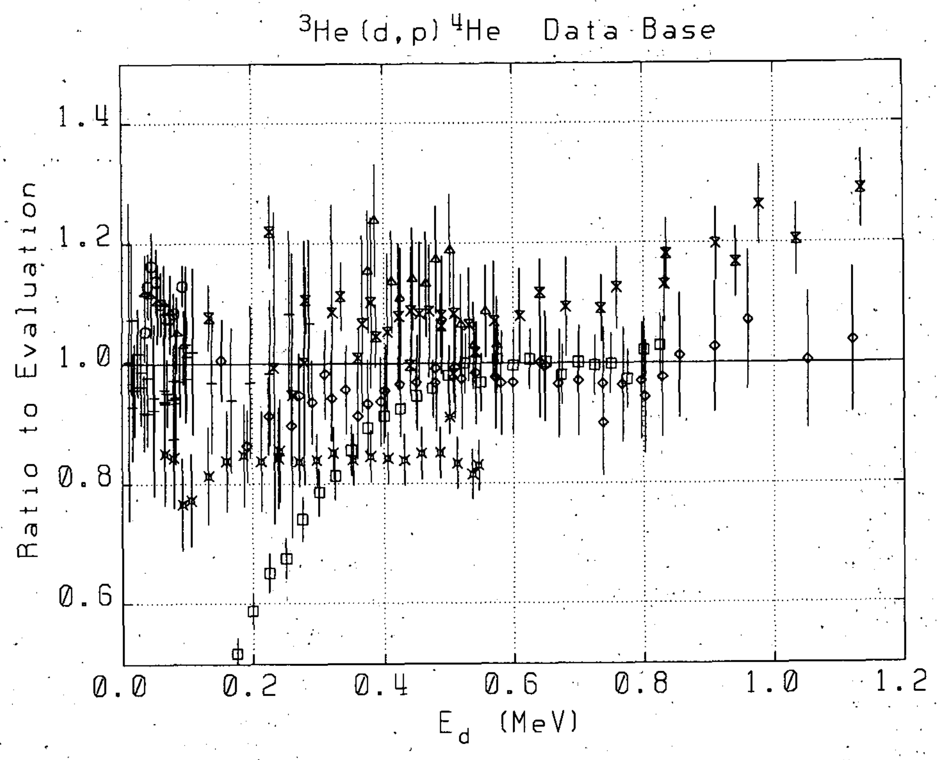
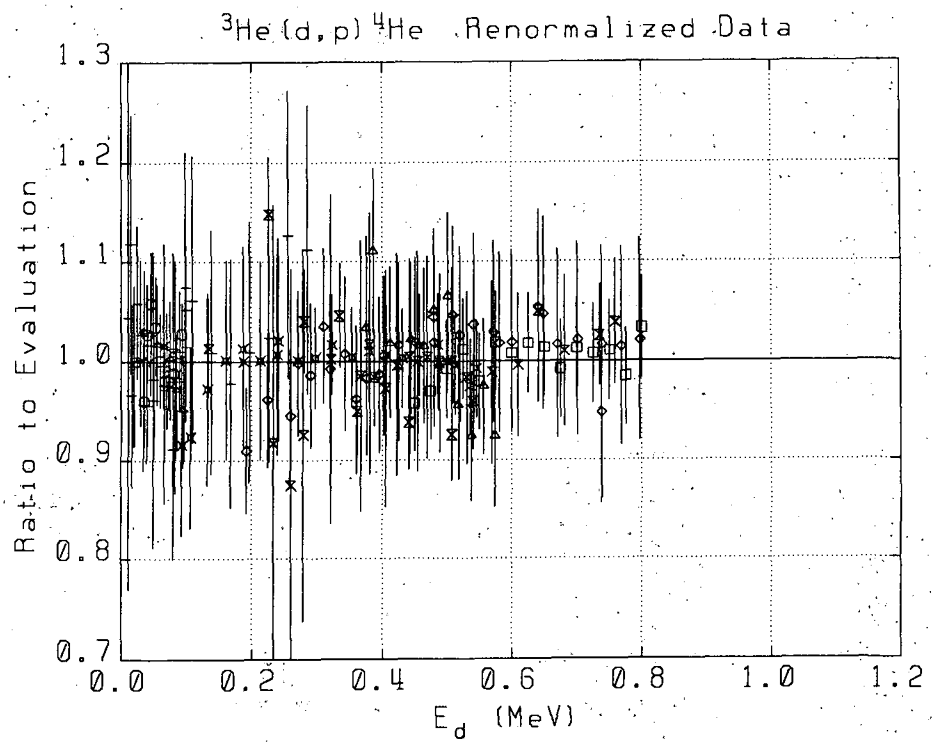


Fig. 16 Same as Fig. 15 except that the data sets are plotted with the new normalizations determined by the R-matrix fitting procedure. The average renormalization of all data sets was required to be zero. Data are only shown up to the highest energy considered in the R-matrix analysis.



2. Advanced Modeling of Thermonuclear Reaction Cross Sections (D. A. Resler, S. D. Bloom and S. Moszkowski†)

We have developed a unique computational modeling capability which allows the calculation of thermonuclear reaction cross sections from a fundamental nucleon-nucleon interaction (nuclear force). Our motivation for this modeling is twofold: (1) To improve the nuclear reaction data on which the more macroscopic calculations of complex phenomena are based since there is a need for more cross section information than can be measured, and (2) To further our understanding of the fundamental nuclear force by using the existing experimental nuclear data base to constrain our model.

In this research we are investigating a nucleon-nucleon interaction which satisfies certain key "global" or "bulk" properties of matter. For example, our interaction is constrained to have the correct saturation properties for infinite nuclear matter and finite (light) nuclei simultaneously. By using a harmonic oscillator basis for the wavefunctions and gaussian form-factors for interactions which include density-dependence and non-locality, we are able to obtain closed-form expressions for binding energies and compressibilities for ^{4}He, ^{16}O, and nuclear matter. With this interaction we perform large-scale structure calculations for light nuclei using the nuclear shell model code CRUNCHER.[8]

Unique to this code is our formulation of generalized multinucleon spectroscopic amplitudes which are required to describe typical thermonuclear reactions such as d+t going to n+α+17.59 MeV or d+^{3}He going to p+α+18.35 MeV. Using these spectroscopic amplitudes, we employ a multilevel-multichannel R-matrix reaction formalism[9] to calculate the desired nuclear cross sections. An important feature of our approach which connects an effective nuclear force to actual reaction cross sections through nuclear structure (shell model) calculations is the ease with which the user can implement an effective interaction to calculate specific reaction cross sections. We are developing an effective interaction to accurately describe well-known thermonuclear reactions such as d+t and d+^{3}He. This interaction will be used to calculate other reactions such as d+^{6}Li where limited experimental measurements exist.

3. New Data Evaluation Tools for Sun Workstations (D. A. Resler)

Our reliance on the use of powerful desktop workstations has increased over the past year. These machines are well-suited for the interactive manipulations and displaying of data that occur in data evaluation work. They are also powerful enough for many of the

† UCLA

[8] D. A. Resler and S. M. Grimes, Computers in Physics 2, 65 (1988).

[9] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958).

complicated nuclear modeling calculations which we undertake. During the past year we have added three Sun Sparc-1 Workstations to our computer network. Two are used extensively in direct data evaluation work and the development of tools relevant to data evaluations. The third machine is used extensively in the IDA modeling effort. A set of codes has been developed for use with the Sun Workstations to make the task of evaluating data easier. The code THINER is used to remove (x,y) pairs of points from an input file under the conditions that, with the proper interpolation scheme between the remaining points, the old curve defined by the original points is duplicated within a given tolerance by a new curve defined by a smaller set of points. The code CSPLINE is used to generate a smooth curve by using cubic spline interpolation between an input set of points. The code QP for ''Quick Plot'' is used to graphically display data on a Sun Workstation. Included in QP is the ability to rapidly place a smooth curve through experimental data by use of a ''mouse''.

4. Program to Derive Information from Atomic Mass Tables (D. A. Resler)

An interactive code, MASS, has been developed which gives abundance information, atomic weights, binding energies, atomic mass excesses, atomic masses, nuclear masses, separation energies, Q-values, and thresholds in a user-friendly way. Uncertainties are given for all appropriate quantities. Calculations are based on the atomic mass excess table of Wapstra and Audi[10] and the natural abundances given in the 7th Edition of the Table of Isotopes.[11] The code is written in ANSI FORTRAN-77, has been tested on a Sun workstation, and is available to the nuclear data community. Subprograms used in this code can be easily placed in application codes for obtaining the same information as is available interactively. Such usage is advantageous for ensuring that consistent values are being used in all our application codes.

5. SuperCRUNCHER (D. A. Resler)

Because of the computational complexities of combining shell model calculations with R-matrix calculations, the development of an interactive controller code SC (SuperCRUNCHER) has been started. The setup of previous calculations sometimes took several days. SC now allows the setup of the shell model part of the calculations to be done interactively in a matter of minutes. As part of this development, a library of shell model effective interactions has been assembled. The user can choose one of the library interactions or can set up a new one when doing the shell model calculations. Work is continuing on streamlining the remainder of the calculational processes in the shell model/R-matrix technique.

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[10] ''Atomic Mass Table'', A. H. Wapstra and G. Audi, Nucl. Phys. A432, 1 (1985)

[11] *Table of Isotopes, 7th Ed.*, edited by C. Michael Lederer and Virginia S. Shirley, John Wiley, New York, 1978.

6. New Resonance Parameter File For Use With The IDA Code ESTIMA (D. A. Resler)

In the IDA set of nuclear modeling codes,[12] ESTIMA is one of two codes used to obtain accurate level density information by performing statistical analyses of neutron resonance parameters. The resonance parameter information based on the 1981 compilation of S. Mughabghab, M. Divadeenam, and N. Holden for Z=1-60 and the 1984 compilation of S. Mughabghab for Z=61-100 was obtained from Brookhaven National Laboratory and has been prepared for use in the ESTIMA code.

7. Some Neutron and Photon Reactions on the Ground and Isomeric States of $^{236,237}Np$ (D. G. Gardner and M. A. Gardner)

We calculated neutron- and photon-induced reactions on the 1.1×10^5-year ground state and 22.5-hour isomer of ^{236}Np and on the 2.1×10^6-year ground state and 68-ns isomer of ^{237}Np. Of primary concern are the isomeric ratios produced, although some photon absorption and photoneutron results are given. We investigated the production of the short-lived isomer of ^{236}Np, via the (n,2n) and (γ,n) reactions on ^{237}Np, leading eventually to the high-energy γ-ray emitter ^{208}Pb; the photoproduction and destruction of the 60 keV, 68-ns isomer of ^{237}Np, a possible γ-ray laser candidate; and the use of photoexcitation and destruction of nuclear isomers in the field of nuclear waste disposal. We show here a sample of our results—those that concern some the the photon-induced reactions on $^{236,237}Np$. Figure 17 shows our calculated production of the 1^+ isomer of ^{236}Np via the (n,2n) and the (γ,n) reactions on ^{237}Np. Although our version of the STAPRE code does not now include fission competition, and therefore our results may not be accurate near threshold, when we apply a constant factor, Γ_n/Γ_f, to roughly correct for fission competition, we obtain the results shown. Our calculated excitation function for the production of the 1^+ isomer in ^{236}Np, compared with several sets of experimental data for the (n,2n) reaction, shows surprisingly good agreement. We found the (γ,n) reaction favors the 1^+ isomer in ^{236}Np, where between 90% and 98% of the (γ,n) reaction populates the isomer, as opposed to the (n,2n) reaction where only 45% to 82% feeds the isomer.

If the reactor conditions are such that the production of the ^{236}Np isomer by γ-rays is important, then it is also important to know how efficiently the 6^- gs and the 1^+ isomeric state are interconverted by photons. We have made these calculations for incident photons in the energy range 2 to 10 MeV. Our results appear in Fig. 18(a), where the 6^- gs is the target, and in Fig. 18(b), where the target state is the 1^+ isomer. If the desire is to minimize the ^{236m}Np production, our results are not encouraging. Figure 18(a) shows that the irradition of the gas tends to produce primarily the isomer, with a $\sigma(1^+)/\sigma(6^-)$ ratio of about 3, whereas photons hardly destroy the isomer at all, as Fig. 18(b) shows. However, from the viewpoint of reactor waste disposal, photons can pump up the ^{236}Np gs to

[12] G. Reffo, ENEA, Bologna, Italy.

Fig. 17 Production of the 1^+ isomer of ^{236}Np via the (n,2n) and the (γ,n) reactions. The (n,2n) calculation is compared with data.

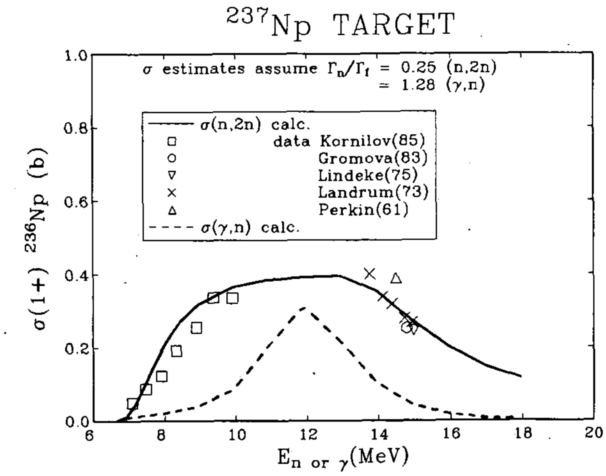
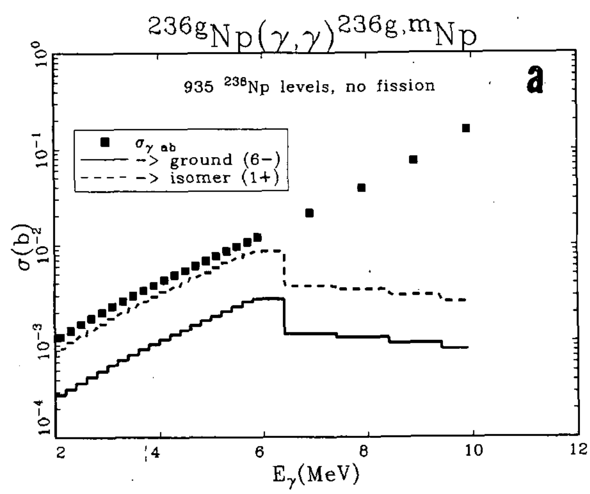
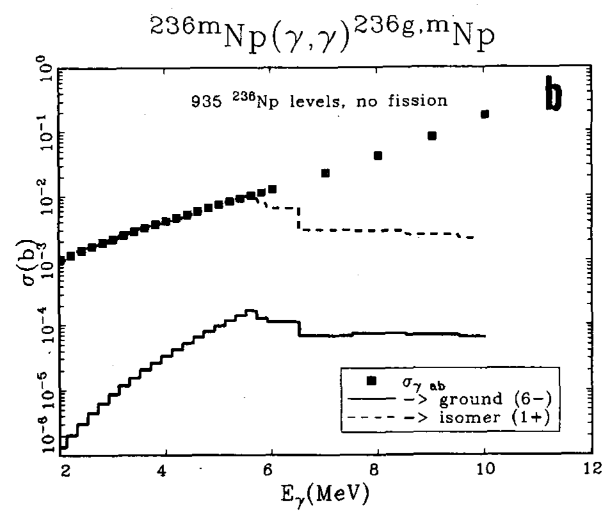


Fig. 18 Interconversion of the ground and isomeric states of ^{236}Np when (a) the 6^- ground state, or (b) th 1^+ isomeric state, is the target.





the isomer, and eventually destroy it. This particular example is probably not a major concern of the reactor community, but it illustrates how γ-radiation may play a role in nuclear waste disposal, particularly in nuclei with one or more isomeric states. A full report of this work appears in the Proceedings of a Specialists Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications, Argonne National Laboratory, 13th-15th September, 1989, NEANDC-259 'U', p. 217.

8. Development of a PC Code for Nuclear Structure and Radiative Transition Analyses and Supplementation—NUSTART (G. L. Larsen, D. G. Gardner, and M. A. Gardner)

NUSTART is a computer program for the IBM PC/AT. It was designed to be used with the nuclear reaction cross section code STAPLUS, a CRAY computer code under development at LLNL that is based on the STAPRE[13] code. The NUSTART code was developed to handle large sets of discrete nuclear levels and the multipole transitions among these levels, and operates in three modes. The Data File Error Analysis mode analyzes an existing STAPLUS input file containing the levels and their multipole transition branches for a number of physics and/or typographical errors. The Interactive Data File Generation mode allows the user to create input files of discrete levels and their branching fractions in the format required by STAPLUS, even though the user enters the information in the (different) format used by many people in the nuclear structure field. In the Branching Fractions Calculations mode, the discrete nuclear level set is read, and the multipole transitions among the levels are computed under one of two possible assumptions: (1) the levels have no collective character, or (2) the levels are all rotational band heads. Only E1, M1, and E2 transitions are considered, and the respective strength functions may be constants or, in the case of E1 transitions, the strength function may be energy dependent. The first option is used for nuclei near closed shells while the band head option may be used to vary the E1, M1, and E2 strengths for interband transitions. K-quantum number selection rules may be invoked if desired.

9. Evaluated Neutron-Induced Nuclear Data for Natural Zinc (M. H. MacGregor and R. J. Howerton)

A similar evaluation effort to that reported for ^{20}Ne last year was undertaken for ^{Nat}Zn. The evaluation was based, where possible, on experimental data, but for the most part was based on the IDA set of coding[14] for incident neutron energies from 500 keV to 30 MeV. The four principal isotopes of zinc were each evaluated separately and compared to experiment. Then, using the post-processing code ALPHA, the cross sections were

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[13] M. Uhl and B. Strohmaier, "A Computer Code for Particle-Induced Activation Cross Sections and Related Quantities", Institut fur Radiumforschung und Kernphysik Report IRK 76/01 with "Addenda" (1976).

[14] G. Reffo, ENEA, Bologna, Italy.

checked for unitarity and the particle and gamma-ray spectrum were checked for energy conservation. Finally, the evaluated data were combined together via the post-processing code BETA to form natural zinc. Data for lower energies were obtained by expanding the resonance parameters given by Mughabghab and Dunford.[15]

10. Evaluated Activation Cross Sections (R. J. Howerton)

Evaluated neutron activation cross sections were entered into the LLNL ACTL data file for ^{10}Be, ^{15}N, ^{18}O, ^{20}Ne and $^{78,80,82,83,84,86}Kr$. Insofar as possible, the new evaluations were based on experiment, but most of the evaluated data were obtained from systematics.

11. Conversion of the ENDL Data File to 300 °K (R. J. Howerton)

In recent years, there has been an increasing use of the ENDL data for calculations where low-energy neutrons have a high importance factor. To provide a better set of basic data, the entire ENDL data file has been Doppler broadened to 300 °K.

B. MEASUREMENTS

1. Limits on Neutron Emission From "Cold Fusion" in Metal Hydrides (B. Balke, L. Cox, O. Fackler, M. Mugge, P. C. Souers, R. T. Tsugawa, and R. M. White)

We have investigated possible neutron emission from cells containing titanium and palladium under D_2, DT or HD gas at pressures near 10 and 50 atm and at temperatures between -197 °C and room temperature. Spurious backgrounds were eliminated from the data by means of coincidence counting, and through analysis of the energy and temporal distribution of the detected pulses. After 1500 hours of observation, we have seen no evidence for either steady-state neutron production or short (< 100 μs) neutron bursts. The limits we obtain, scaled for sample size, are in conflict with all present reports of neutron emission in metal hydrides under high gas pressure and thermal stress.

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[15] S. F. Mughabghab, M. Divadeenam, and N. E. Holden, *Neutron Cross Sections Vol.1 Part A*, Academic Press, New York (1981) and private communication.

LOS ALAMOS NATIONAL LABORATORY

A. NUCLEAR DATA MEASUREMENTS

1. Low-Energy Fusion Cross Sections: Charged Particle Reactions
(Nelson Jarmie and Ronald E. Brown)

The goal of this project is to determine cross sections for interactions among the hydrogen isotopes in the bombarding-energy range 10-120 keV. Such cross sections are fundamental to the operation of future controlled-fusion reactors. Experimental work with the facility constructed for this purpose (LEFCS: Low-Energy Fusion Cross Sections) is complete. Analysis and publication are continuing.

Our D+T data[1,2] helped lead to the to the discovery[3] (first in nuclear physics) of a so-called *shadow pole* in the S-Matrix for the $^2H(t,\alpha)n$ reaction. Knowledge of this pole has improved the understanding of the mass-5 system, and has already been used by other physicists[4]. G. Hale of Los Alamos has also used our accurate data to better understand charge symmetry in light-nuclear mirror systems[5].

In addition to the the $^2H(t,\alpha)n$ reaction being complete and published[1,2,3], the final $^2H(d,p)^3H$ and $^2H(d,n)^3He$ reactions paper has now been published[6]. A complete set of numerical differential cross-section data will be published in the A.I.P. Data Repository[6], as well as being available from the authors. We have measured differential cross sections for both reactions at 11 deuteron bombarding energies from 20 to 117 keV. The differential data are accurate to 2.0% over most of the energy range, with a scale error of 1.3%. Integrated cross sections are derived with total errors generally about 1.5% which greatly improves the accuracy over previous measurements. Specific examples were given in last year's report. See also Refs. 7 and 8.

Having the best low-energy D+D data, and reasonably good understanding of the low-energy behavior of the mass-4 system; we found ourselves in the midst of the "cold fusion" furor; being asked repeatedly about the possibility of a resonance or other behavior near zero bombarding energy, and about the effect of screening by atomic electrons: both items discussed in our paper[6]. (New screening calculations are available[9].)

Analysis of the $T(t,\alpha)nn$ reaction data continues: difficult because of the 3-body continuous spectrum, as well as the small cross section and interference by the $^3H(d,\alpha)n$ contaminant reaction. Calculations by G. Hale of Los Alamos extending R-Matrix phenomenology to handle 3-body breakup continue[10]. This development is of great interest to us to help analyze the three-body breakup alpha spectra of the $T(t,\alpha)nn$ reaction; and, in particular, to be able to estimate the shape of the neutron spectrum, which we have found impossible to measure experimentally. We are exploring other models for the reaction also.

Production of a standard "handbook" of the best evaluated fuel-cycle cross sections and reactivities was under consideration last year. Some fusion-reactor designers are still using old and sometimes grossly inaccurate data, and there exists no world standard collection of charged-particle data such as exists for neutron data. We have given up the attempt to produce such a handbook because of the lack of interest in funding the project.

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[4]J. B.J. M. Lanen et al., Phys. Rev. Lett., **63**, 2793 (1989).

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2. Low-Energy (n,charged particle) Cross Sections: The $^{35}Cl(n,p)^{35}S$ Cross Section from 25 meV to Approximately 100 keV (P.E. Koehler and H.A. O'Brien)

We have measured the $^{35}Cl(n,p)^{35}S$ cross section from 25 meV to approximately 100 keV. The measurements were made at LANSCE employing our "standard" (n,charged particle) setup[1] with a 10 mm thick solid state detector. Measurements were also made (at about 10 times the counting rate) with our new ionization chamber. However, due to problems with the LANSCE "time-zero" pulse during these measurements, the resolution of the ionization chamber measurements was about four times worse than the data taken with the solid state detector setup. The data are shown in fig. 1 together with the data of Dubna group[2] which were taken with a lead slowing-down spectrometer. This reaction may play a role in the nucleosynthesis of light elements in the s process[3]. We are currently converting the cross sections into astrophysical reaction rates. The experimental rate will be compared to the rate used[4] in previous calculations to ascertain any change on the resulting calculated isotopic abundances.

We have measured the $^{35}Cl(n,p)^{35}S$ cross section from 25 meV to approximately 100 keV. The measurements were made at LANSCE employing our "standard" (n,charged particle).

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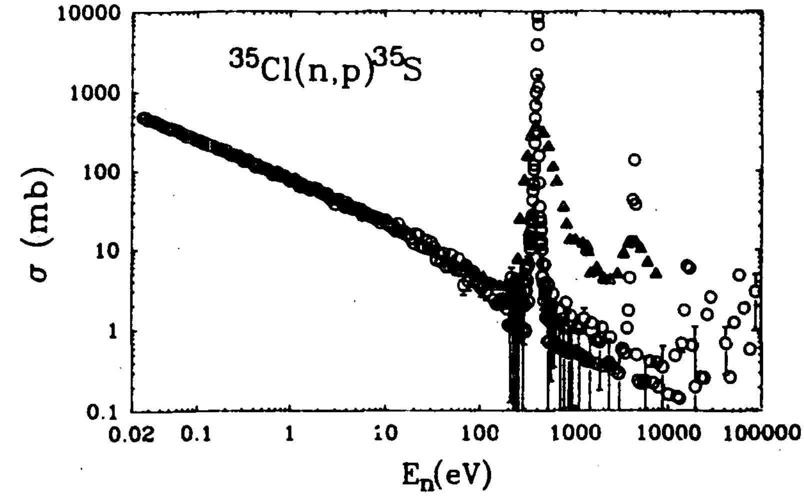

Fig. A-1. The $^{35}Cl(n,p)^{35}S$ cross section from 25 meV to 100 keV. The open circles are the results of our recent measurements whereas the solid triangles are the data from ref. 2. The data of ref. 2 have been renormalized to the presently accepted thermal cross section.

3. Direct Mass Measurements Using the TOFI Spectrometer: The Neutron-Rich Isotopes of Chlorine Through Iron (X. L. Tu , X. G. Zhou, V. G. Lind (Utah State University, Logan, Utah 843222), D. J. Vieira, J.M. Wouters, Z.Y. Zhou (Nanjing Unersity, Nanjing, PRC), and H.L. Seifert(University of Giessen, D-6300 Giessen, FRG)

Nuclear masses have been of fundamental importance to nuclear science ever since J.J. Thompson used them to reveal the exixtence of multiple isotopes for a given element in 1913. In present day experiments nuclear masses are used: (1) to examine the basic properties of nuclei such as pairing interactions, Coulmb effects, and changes in nuclear structure, (2) to probe new regions of nuclei where large-scale changes occur in shape, and (3) as input parameters in a variety of theoretical calculations including astrophysical models. This greatly expanded role has arisen naturally because the mass of a nucleus directly reflects the sum of the forces that hold a nucleus together. The key to using masses as described above is to measure them in a systematic fashion and to look for global as well as local variations in the mass surface. These measurements are especially important far from the vally of β–stability where the mass is often the first piece of quantitaative information to be determined - thus leading to new insight into the nature of such nuclei with extreme neutron-to-proton ratios. Such was the case for our recent measurements in the ^{24}O region where a dramatic confirmation of shell model wavefunctions and two-body interaction strengths was shown.[1]

The advent of the recoil mass spectrometer has greatly facilitated experiments to measure masses on the neuton-rich side of the valley of β-stability. Such systems have distinct advantages because they are: universal, fast, and require little or no excited state level information about the nucleus being studied. During the last few years the experiments of our group and that of a French group have used recoil mass spectrometers to determine the masses of approximately 30 neutron-rich isotopes ranging from ^{11}Li to ^{38}P[1,2,3]. In this report, we present our most recent experimental results on the masses of several neutron-rich isotopes of chlorine through iron. Our motivation for performing this experiment was to use the large number of new masses, made available, to investigate: (1) the systematic behavior behavior of the pairing energy, (2) locate a new region of enhanced binding, and (3) check the validity or failure of a variety of mass models.

Our ability to make direct mass measurements of exotic neutron-rich nuclei relies on the use of a unique Time-of-flight Isochronous (TOFI) recoil spectrometer. This spectrometer can measure the masses of fast recoiling nuclei that are produced at the Los Alamos Meson Physics Facility through interaction of 800-MeV, 1-mA proton beam with a thin (1 mg/cm^2) natTh target. TOFI's unique feature is its isochronous design which requires that ions with the same mass-to-charge ratio (a typical resolution for this experiment was $\Delta(m/q)/(m/q) = 2.3 \times 10^{-4}$ (*FWHM*)). The state and atomic number of each recoil mass spectrometer in general include: (1) the need to measure only one parameter with high precision, and (2) the distributions of the knowns and unknowns are largely intermixed in the mass-to-charge spectrum such that no extrapolators of the calibration are needed.

We have measured the masses of over 35 neutron-rich nuclei ranging from ^{45}Cl to ^{66}Fe. Given these new measurements, we have extended the mass surface by as many as 5 neutrons for a given element and compared the shape to theory; the differences lead to several new insights.

Several groups have suggested that there is an isospin dependence in the neutron and proton pairing energies[4,5]. Our data enabled us to examine this dependence in a region where sudden changes in the nuclear struture from one nucleus to the next are expected to be minimal. Although additional measurements are needed, our work leads to a confusing result where we observe some isospin dependence in the neutron pairing energies, but little or no dependence in the proton pairing energies.

A plot of the two-neutron separation energies (S_{2n} = M (A,Z)) derived from our mass measurements is shown in Fig. A-2.

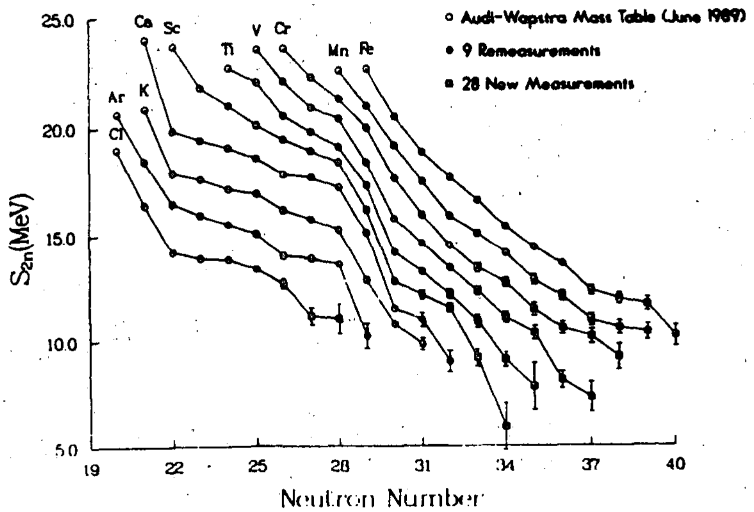

Fig. A-2. Plot of two-neutron separation energies S_{2n} verses neutron number. The open circles represent previous measurements, the solid circles indicate nuclei which have been remeasured, and the solid squares are for nuclei where first time measurements are reported herein

Two neutron separation energies enable one to highlight (model independently) local structural changes without the odd-even effects caused by nuclear pairing. The most striking feature in Fig. 1 is the sudden decrease in S_{2n} just after the N = 28 closed shell. Of further interest is the leveling off of both the calcium and scandium S_{2n} lines at N = 31 (i.e. ^{51}Ca and ^{52}Sc). This Trend continues out to ^{53}Sc, N = 32, but is not as evident in

^{52}Ca. Such a change in slope is reminiscent of the S_{2n} upturn observed at N = 20 for neutron-rich sodium isotopes that indicated the onset of prolate deformation. Another, but less likely explanation, is the occurrence of a neutron subshell closure at N = 32. We would expect ^{52}Ca to show the largest effect from such a subshell closure since it would be supported by Z = 20 shell closure, however, we do not observe this effect.

Finally, we have compared our data to several mass models (see Fig. A-3). On the whole the agreement between our data and theory is good. One area of discrepancy occurs for the calcium and scandium isotopes near N = 32 where theory consistently predicts too little binding. Again this effect is more pronounced in the scandium isotopes and suggests that a local deformation is occurring in these nuclei. Another discrepancy worth noting is the tendency for most theories to over predict the binding of neutron-rich nuclei above titanium. This discrepancy tends to grow with increasing atomic number as well as with neutron-excess although the deviations between theory and experiment rarely exceed 3σ experimental standard deviations.

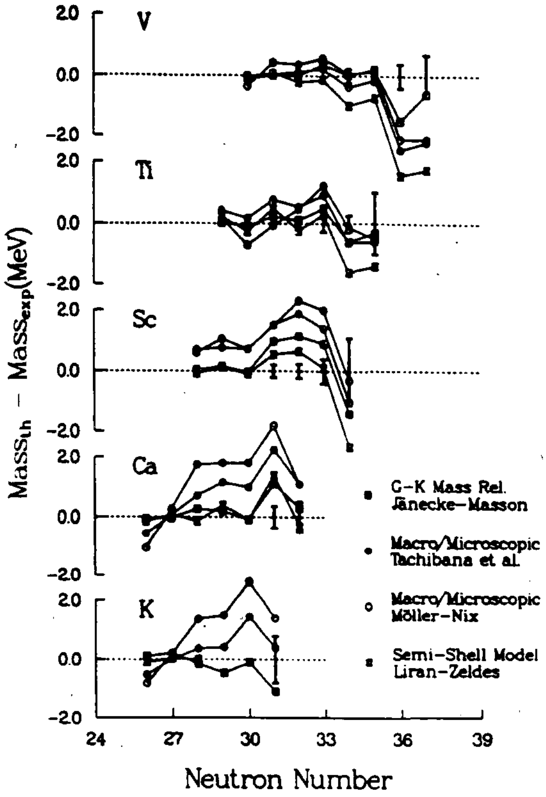

Fig. A-3. Comparison of experimental masses with the mass predictions (Ref. 6) of Janecke-Masson (using the Garvey-Kelson mass relationships), Tachibana et al., Moller-Nix, and Lirean-Zeldes.

Nuclear masses continue to be an important source of information about the interplay of forces within a nucleus and the resulting nuclear structure effects they elicit. In this annual report, we have shown how mass measurements of the very neutron-rich isotopes of chlorine through iron have been used to specifically study pairing energy systematics, define a new region of enhancing binding due to changes in nuclear structure/shape, and evaluate several mass models. Improvements to TOFI and the detection system are Planned in order to extend our measurements to both higher Z elements and to more neutron-rich nuclei. With more extensive measurements and refined theoretical models we will continue to advance our knowledge of the atomic mass surface.

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4. High Resolution (n,xγ) Measurements (R. O. Nelson, S. A. Wender, C. M. Laymon, H. A. O'Brien, D. M. Drake, R. C. Haight, G. L. Morgan, P. G. Young, W. Feldman, R. Reedy (LANL), D. C. Larson (ORNL), H. Vonach, M. Drosg, A. Pavlik (IRK, Vienna), W. Amian (KFA, Juelich), J. Brueckner (Max Planck Institut fur Chemie, Mainz), P. Englert (San Jose State University)

Measurements of (n,xγ) reaction data in the range $< E_n < 200$ MeV have been performed using two HPGe detectors at 90 and 125 degrees for samples including $^{204,206,207,208}Pb$, ^{89}Y, ^{56}Fe, and BN. A study of the stronger transitions was also made on samples of B_4C, C, Mg, Al, Si, SiO_2, S, Ca, Ti, Cr, Mn, Fe, ^{232}Th, and ^{238}U. Samples of Be and Ta were used to determine backgrounds from scattered neutrons. Gamma rays from product nuclei were measured in the range $0.2 < E_\gamma < 7$ MeV. The beam was obtained from the WNR spallation neutron source facility on an 18.5 m neutron flight path at 15 degrees with respect to the incident 800 MeV proton beam from LAMPF.

Results from a preliminary run last year on ^{56}Fe have been presented[1]. This year absolute cross sections have been obtained for six transitions from $^{14}N(n,x\gamma)$ in the range $2 < E_n < 20$ MeV. The results for ^{14}N agree well with previous measurements and provide better neutron energy resolution and a greater neutron energy range than the earlier data. This data is being used in a re-evaluation of the ^{14}N cross sections. Analyses to determine absolute cross sections from the other data are in progress. Model calculations will be performed and compared with the data. Additional data will be taken during the 1990 run cycles.

[1]"High Resolution Measurement of $^{nat}Fe(n,xgamma)$ at the WNR", R.O. Nelson, S.A. Wender, G.L. Morgan, Bull. Am. Phys. Soc. 34, (1989) 1233

5. Neutron Capture Gamma Ray Measurements (C. M. Laymon, R. Nelson, S. Wender)

During the past year as part of the WNR program to investigate giant multipole resonances through neutron capture, we designed and constructed a gamma ray spectrometer for detecting high energy photons. It consists of a 4"x6" BGO crystal inside an active plastic scintillator which is used to veto cosmic ray and escape radiation. The device is encased in passive shielding consisting of lead, polyethylene, boron, and cadmium. We have found that the plastic shield rejects approximately 98% of the cosmic ray events that survive the passive shielding. In the last days of the 1989 LAMPF run cycle we used the detector to acquire some preliminary $^{40}Ca(n,\gamma)$ data at 90 degrees from which we were able to extract gamma yields to the ground and first excited states of ^{41}Ca in the giant resonance region. Currently, we are building a platform for the detector and shielding which can be rotated about the sample position so that we can measure angular distributions.

6. The (n,p) reaction from 50 to 250 MeV as a Probe of Gamow-Teller Strength (J. L. Ullmann, R. C. Haight, D. S. Sorenson, A. G. Ling, P. W. Lisowski, N.S.P. King (Los Alamos), F.P. Brady, J.R. Romero, J. Osborne (Univ. Cal. Davis), B. K. Park, J. Rapaport, R. W. Finlay, X. Aslanoglou, V. Mishra, (Ohio University), C. Howell, W. Tornow (Duke University)

During the LAMPF running period of 1989 the 15 degree left flight path at WNR was used to acquire (n,p) data on the following isotopes: ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{13}C, ^{nat}S, ^{40}Ca, ^{58}Ni, ^{60}Ni, ^{62}Ni, ^{64}Ni. Two hardware upgrades were made for the 1989 run cycle. A Hytec list processor was used to read the data from the Camac crate instead of the MBD as was done in 1988. This resulted in a factor of 2 increase in data read speed and brought the live time up to about 70%. Secondly, new target chambers were constructed to provide a larger active area (6in X 6in) and increased wire spacing (4mm). The larger area ensured that the target chamber frames would not intercept the beam as was the case in 1988. The data taken in 1989 is presently being analyzed. Figure A-4 shows some preliminary results from the 1989 running period.

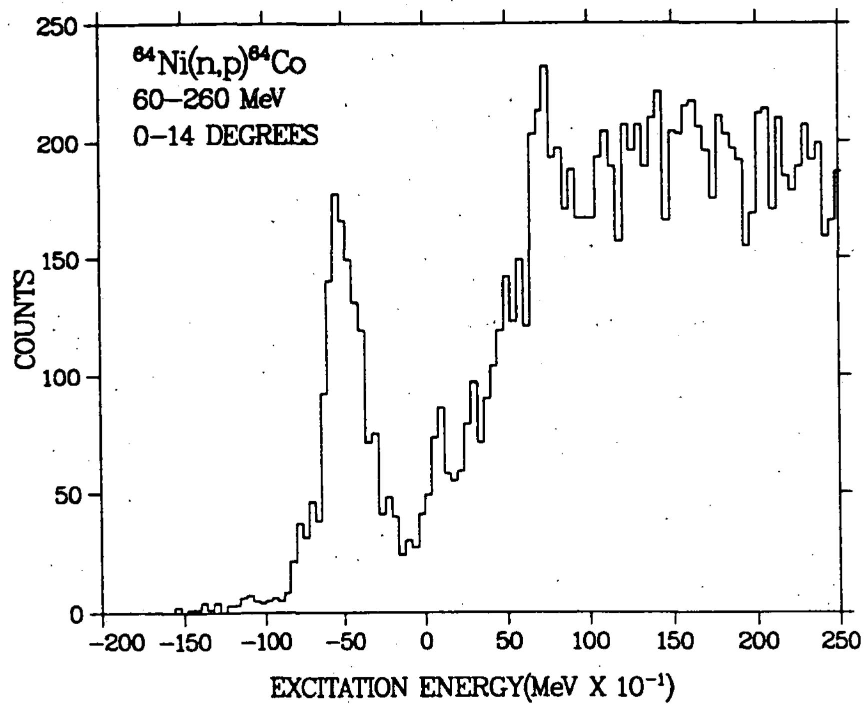

Fig. A-4. Excitation spectrum for the reaction $^{64}Ni(n,p)^{64}Co$. The large peak at -5 MeV is hydrogen background.

7. (n,charged particle) Measurements Below 50 MeV at WNR in the Study of Nuclear Level Densities (R. C. Haight (Los Alamos), S. M. Grimes, V. Mishra, R. S. Pedroni, N. Boukharouba, and K. Doctor (Ohio University))

Nuclear level densities can be studied in three ways though (n,p) and (n,alpha) reactions at MeV energies. Information on the level density in the compound nucleus can be obtained by analyzing the Ericson fluctuations for individual channels. In the last year we have taken data with good energy resolution for these reactions on ^{28}Si (to give ^{29}Si as the compound system) by putting a detector in the 90-meter beam at WNR. Time-of-flight was used to separate the neutron energies. For the residual nucleus, the shape of the continuous evaporation spectrum of charged particles can give information on the nuclear level density. Using the 9-meter flight path at 90 degrees, we have recently obtained data on the $^{27}Al(n,\alpha)$ reaction up to about 30 MeV neutron energy to indicate level densities in Na. Finally, the excitation function of the cross section to a region of low excitation in the residual nucleus can yield information on the level density of the target nucleus which is the residual nucleus in the most important competing channel, namely that produced by neutron evaporation from the compound system. The aluminum data already mentioned will therefore give information also on the level density of ^{27}Al. These data are all being analyzed at the present time.

8. Neutron Induced Fission Cross Section For ^{235}U and Fission Cross Section Ratios for ^{232}Th, $^{233,234,235,236,238}U$, ^{237}Np, and ^{239}Pu from 1 to 400 MeV (P. W. Lisowski, J.L. Ullmann, S. J. Balestrini, A. Gavron)

During the 1989 running period at the Weapons Neutron Research Facility (WNR), we concentrated on determining the neutron flux over the range from 2 to 400 MeV to complete our analysis of the $^{235}U(n,f)$ cross section. Additional fission cross section ratio data were taken on ^{232}Th, ^{238}U, ^{237}Np, and ^{239}Pu. New data were taken for $^{233,234,236}U$.

For fission measurements during the next running period, we have substantially enlarged our collaboration to include members from T-Division, Darmstadt, West Germany, and the University of Georgia. We are developing a novel pin diode detector array to allow us to measure fission fragment mass and kinetic energy distributions in the same energy range as reported above. Neutrons will also be detected in coincidence with proton recoil scintillation detectors. Using the characteristic focussing of neutrons by the fission fragments, we will attempt to separate contributions from neutrons preceeding fission from neutrons emitted by the fragments. This information, coupled with mass and kinetic energy distributions should enable us to separate the contribution of the different 'chances' of fission at excitation energies between 7 and 100 MeV

9. Low-Energy (n,charged particle) Cross Sections: Measurement of the LANSCE Neutron Flux from 25 meV to 100 keV (P. E. Koehler)

Using the $^{6}Li(n,\alpha)^{3}H$ reaction as a standard, the LANSCE neutron flux was measured from 0.025 eV to 100 keV. The flux at 1 eV was measured to be 2.3 x 10^6 neutrons/(s cm^2 eV) with the Proton Storage Ring (PSR) delivering 57 mA of current to the neutron production target. This translates to an anticipated flux of 4 x 10^6 neutrons/(s cm^2 eV) when the PSR reaches its design intensity of 100 mA. A manuscript describing the results of these measurements has been accepted for publication in Nuclear Instruments and Methods.

There have been no published measurements of the energy dependence of the neutron flux at LANSCE. The present measurements of the absolute magnitude and energy dependence of the flux help to fill this void and should be useful for planning future experiments at LANSCE. Also, the measurements should provide a valuable benchmark for Monte Carlo calculations.

The measured flux was converted to neutron leakage at the moderator for comparison to a Monte Carlo calculation[1]. The energy dependence of the calculation was found to be in good agreement with the measurements. The absolute size of the calculated flux was found to be in reasonable agreement with the measurements, although there appears to be room for improvement.

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[1] G. J. Russell, J. S. Gilmore, H. Robinson, G. L. Legate, A. Bridge, R. J. Sanchez, R. J Brewton, R. Woods, and H. G. Hughes, III, in the Proceedings of the 10th Meeting of theNational Collaboration on Advanced Neutron Sources, Institue of Physics Conf.

10. <u>Status of the Los Alamos Weapons Neutron Research Facility and Nuclear Physics Research at LANSCE</u> (P. W. Lisowski)

During the period from October 1988 through May 1989, all of the neutron beamline collimation systems at WNR were redesigned and massively shielded to reduce backgrounds from neutron 'skyshine' on LANSCE instruments. That work was shown to be effective during tests conducted in November 1989. At WNR during the operating period from May 1989 through October 1989, 90% of the scheduled beam time was used to simultaneously operate five flight paths at the Target-4 white source. Experiments studying nuclear level densities; medium energy charged particle production; neutron induced pion production, fission, and gamma ray production, were all conducted. Measurements taking about 10% of the beam time were supported at the WNR Target-2 Facility, including research in support of the Mars Mission and studies of strategic system vulnerabilities to advanced threats. At LANSCE, WNR/P-3 scientists participated in studies of parity violation using polarized neutron beams, measurements of neutron reactions with radioactive samples and development of innovative techniques for determining materials properties under dynamic conditions. A total of 83 scientists participated in nuclear physics research supported by P-3 at the the WNR Facility or on the three flight paths used by P-3 at LANSCE.

11. <u>Measurement of the Polarization of Neutrons from the WNR Source</u> (R. C. Haight (Los Alamos), V. Mishra, N. Boukharouba, K. Doctor, R. S. Pedroni, and S. M. Grimes (Ohio University))

Because neutrons produced by the WNR source can in principle be polarized, we have measured the polarization at the 90-degree flight path for neutron energies up to 30 MeV. The approach is to scatter the neutrons from a helium-gas cell and measure the left-right asymmetry of the recoiling alpha particles. The analyzing power of this scattering is large (>90%) at alpha-recoil angles of 25 degrees for all neutron energies in this range except for a small interval near the 22.155 MeV resonance. Recoiling alpha particles were detected by symmetrically placed delta-E - E detectors that consisted of a low pressure delta-E proportional counter and a silicon surface-barrier E detector. Our preliminary result is that the polarization in this beam line is less than 10% for neutron energies up to 30 MeV

B. NUCLEAR DATA EVALUATION

1. Heavy-Element Fission Half-Lives (P. Möller and J. R. Nix)

Experimental studies of fission properties of nuclei close to Fm sometimes show two components in the kinetic-energy distribution and rapid changes in mass distributions and spontaneous-fission half-lives with a change of only one or two neutrons or protons. Particularly striking is the experimental result that for Fm the spontaneous-fission half-life varies by 13 orders of magnitude with a change in neutron number from N = 152 to N = 158.

A theoretical description of these data requires a description of the fission barrier in terms of several shape coordinates. Multi-dimensional calculations of potential-energy surfaces for the heaviest actinides show several paths from the ground-state to different scission configurations. In Fig. B-1 we compare experimental spontaneous-fission half-lives with calculated ones along two different paths for even nuclei from Z = 100 to Z = 106. The notation old path corresponds to shapes leading to elongated scission shapes, new path to shapes leading to a compact scission configuration of two touching spheres. The old path is present in the calculated potential energy surfaces for all nuclei studied. The new path only exists for nuclei close to ^{264}Fm. It is clear from the figure that from about N = 156 the new path becomes the dominating one and explains the rapidly decreasing half-lives in this region of large N values. As the new path is fully developed, the calculated half-lives become approximately constant with increasing neutron number, in agreement with experiment. When analyzing the discrepancies between calculations and experiment one should recall that a change in the calculated ground-state energy by one MeV affects the calculated half-life by about 6 orders of magnitude.

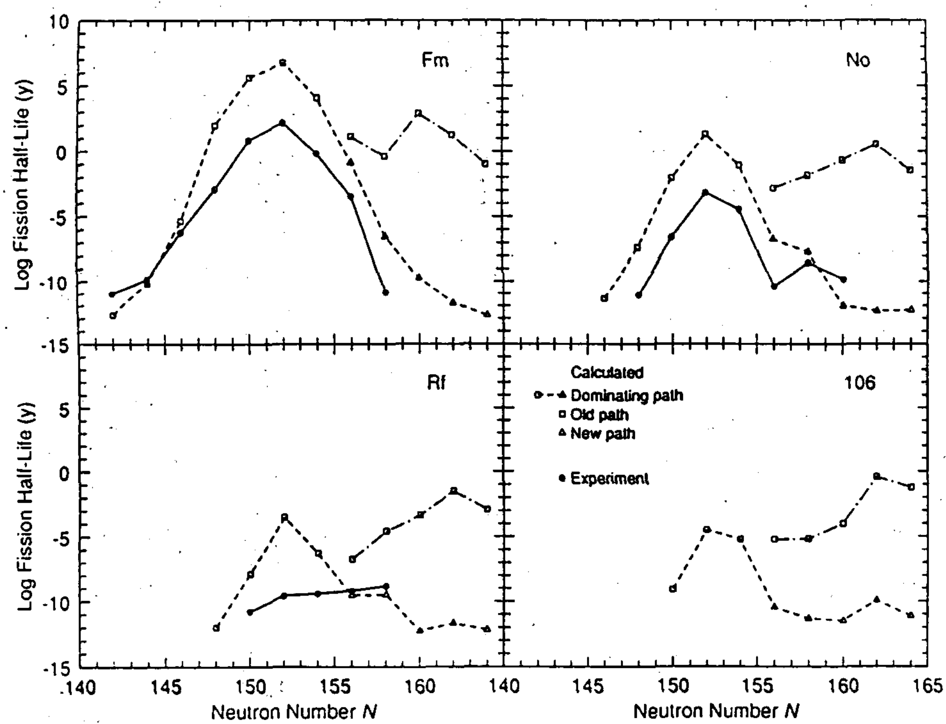


Fig. B-1. Calculated spontaneous-fission half-lives compared with experimental data.

2. Heavy-Element Fission Barriers (P. Möller and J. R. Nix)

Experimental studies of fission properties of nuclei close to ^{258}Fm sometimes show two components in the kinetic-energy distribution and rapid changes in mass distributions and spontaneous-fission half-lives with a change of only one or two neutrons or protons. These results led to the speculation that the two modes of fission were the result of two different valleys, or paths, from the single nuclear ground state to two different scission configurations. The scission configuration yielding low kinetic energies would correspond to elongated shapes and the configuration resulting in high fission-fragment kinetic energies was thought to correspond to two approximately spherical fragments.

In the top part of Fig. B-2 we show a family of shapes leading from the ground state to these two different scission configurations. Corresponding potential-energy surfaces have been calculated for several hundred heavy elements. Two examples are shown in the lower part of the figures. For ^{258}Fm the results show three fission paths indicated by arrows. The lower path, sometimes called the new path, leads to compact, spherical scission shapes with high kinetic energies, and the upper path to very elongated shapes with low final kinetic energies. Thus, one finds that the structure of the calculated potential-energy surface agrees well with what was expected from experiment. However, to explain the similar spontaneous-fission half-lives for the high and low kinetic-energy modes, the paths corresponding to these two different modes cannot be very different. Therefore, it is our contention that it is a third path, the switchback path, indicated by a long-dashed line that leads to elongated scission configurations. This path differs from the new path only in the very outermost part of the fission barrier, and one can show that the spontaneous fission half-lives are of the same magnitude along the two lower paths even if the two outer barrier heights are somewhat different. Investigations of the stability of the potential energy in the shaded region with respect to mass-asymmetric shape degrees of freedom have shown that the saddle on the switchback path is lowered by about two MeV due to mass asymmetry, but that the lower saddle leading to spherical, compact shapes is unaffected by mass-asymmetric shape degrees of freedom.

For ^{252}Cf, seen in the middle part of the figure, access to the compact fission valley is blocked by a ridge at 8 MeV (about 10 MeV above the ground state).

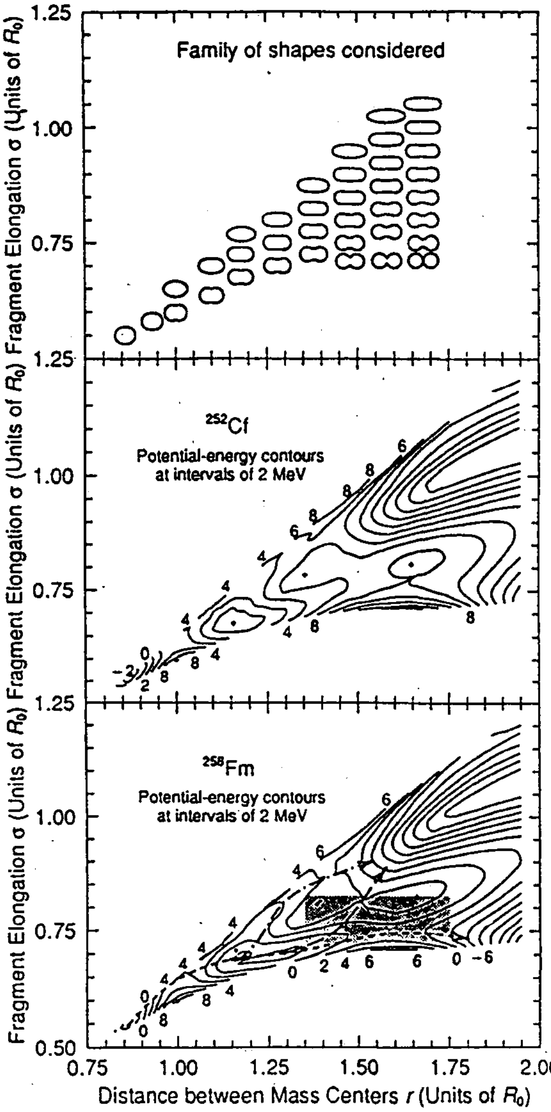


Fig. B-2. Nuclear shapes and potential energy surfaces for the fission of two heavy elements.

3. Prediction of Intermediate-Energy Neutron Scattering Observables from a Dirac Optical Potential (D. G. Madland and R. Kozack)

Using a Dirac scalar-vector global optical potential for nucleon + ^{208}Pb scattering,[1] we have performed calculations of unmeasured neutron + ^{208}Pb scattering observables. These show remarkable differences when compared with the corresponding proton + ^{208}Pb scattering observables, which have been measured. Examples for the differential cross section and spin observables at 100 MeV are shown in Figs. B-3 and B-4. The origins of the differences have been determined by performing calculations for a "gedanken" projectile with a proton isovector interaction and a neutron Coulomb interaction. These differences have stimulated proposals within the experimental neutron physics community for measurements testing our findings. This work has been accepted for publication.[2]

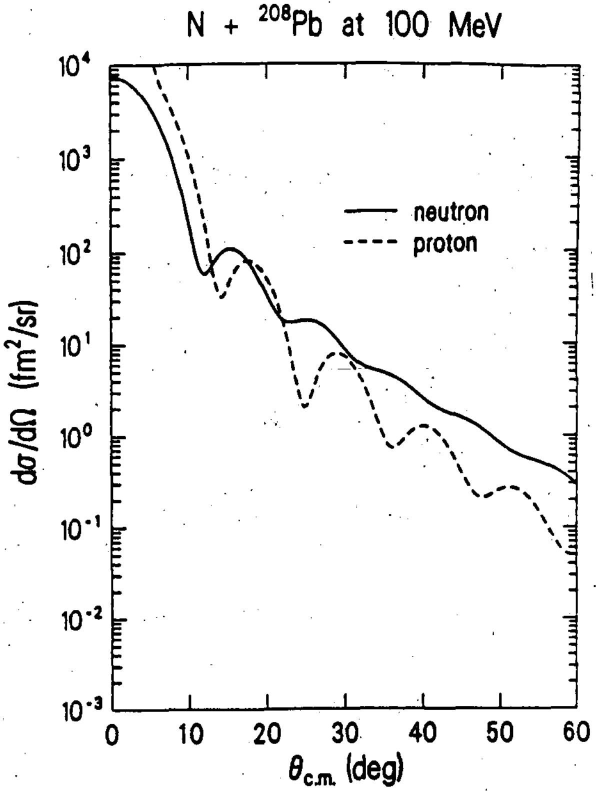


Fig. B-3. Differential cross sections for nucleon plus ^{208}Pb elastic scattering at 100 MeV. The solid curve is the prediction obtained for neutron scattering, while the dashed curve is the prediction obtained for proton scattering. A Dirac scalar-vector global potential with a logarithmic energy dependence has been used for both predictions.

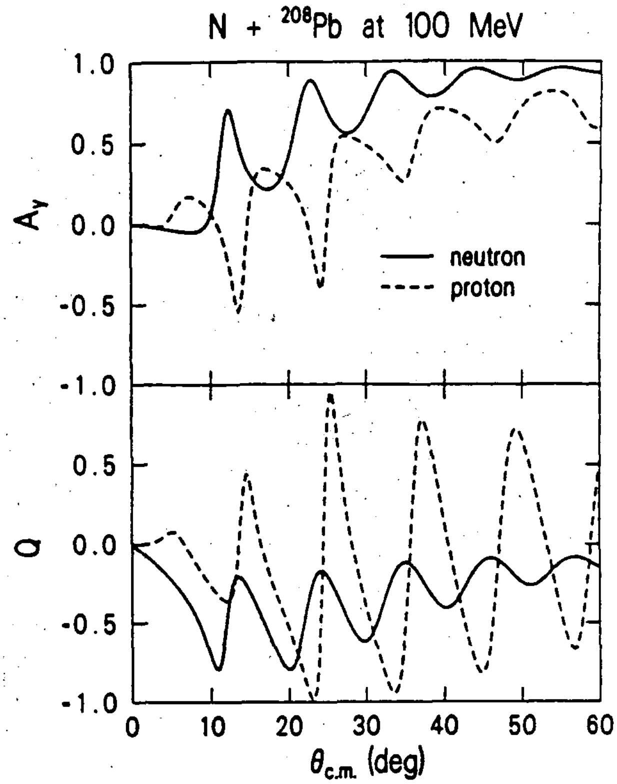


Fig. B-4. Spin observables for nucleon plus ^{208}Pb elastic scattering at 100 MeV. The solid and dashed curves have the same meaning as in Fig. B-3.

[1] R. Kozack and D. G. Madland, "Dirac Optical Potentials for Nucleon Scattering by ^{208}Pb at Intermediate Energies," Phys. Rev. C 39, 1461 (1990).

[2] R. Kozack and D. G. Madland, "Prediction of Intermediate-Energy Neutron Scattering Observables from a Dirac Optical Potential," accepted for publication in Nucl. Phys. (Nov. 1989).

4. Theory of Neutron Emission in Fission (D. G. Madland)

Following a summary of the observables in neutron emission in fission, a brief history has been given of the theoretical representations of the prompt fission neutron spectrum N(E) and average prompt neutron multiplicity $\bar{\nu}_p$. This was followed by descriptions, together with examples of modern approaches to the calculation of these quantities including recent advancements. Emphasis was placed upon the predictability and accuracy of the modern approaches. In particular, the dependence of N(E) and $\bar{\nu}_p$ on the fissioning nucleus and its excitation energy was discussed, as was the effects of and competition between first-, second-, and third-chance fission in circumstances of high excitation energy. Finally, properties of neutron-rich (fission-fragment) nuclei were discussed that must be better known to calculate N(E) and $\bar{\nu}_p$ with higher accuracy than is currently possible. This work has been published.[1]

[1] D. G. Madland, "Theory of Neutron Emission in Fission," Proc. Conf. on 50 Years with Nuclear Fission, Washington DC/Gaithersburg, MD, 1989 (Am. Nuclear Soc., La Grange Park, Ill., 1989), Vol. 1, p. 429.

5. Fission Neutron Spectra for ^{240}Pu, ^{238}Pu, and ^{242}Pu [D. G. Madland, R. L. Walsh (ANSTO, Lucas Heights, New South Wales, Australia), and G. Chircu (Univ. of New South Wales, New South Wales, Australia)]

We have calculated the prompt fission neutron spectra for the spontaneous fission of ^{240}Pu, ^{238}Pu, and ^{242}Pu using the Los Alamos model[1] and incorporating center-of-mass anisotropy effects.[2] Our calculations agree well with the trends of the (somewhat scarce) experimental data for these three fissioning systems and they are currently being used in plutonium assay work for nuclear safeguards. This work has been published.[3]

[1] D. G. Madland and J. R. Nix, "New Calculation of Prompt Fission Neutron Spectra and Average Prompt Neutron Multiplicities," Nucl. Sci. Eng. 81, 213 (1982).

[2] R. L. Walsh, "Spin-Dependent Calculation of Fission Neutron Spectra and Fission Spectrum Integrals for Six Fissioning Systems," Nucl. Sci. Eng. 102, 119 (1989).

[3] R. L. Walsh, G. Chircu, and D. G. Madland, "Fission Neutron Spectra for ^{240}Pu, ^{238}Pu, and ^{242}Pu," Proc. Conf. on 50 Years with Nuclear Fission, Washington DC/Gaithersburg, MD, 1989 (Am. Nuclear Soc., La Grange Park, Ill., 1989), Vol. 1, p. 274.

6. R-matrix Analysis of the ^{17}O System [G. M. Hale, P. G. Young, and Z. P. Chen (Univ. of Beijing, PRC)]

We have updated our previous analysis[1] of the ^{17}O reactions with more recent experimental data and level structure information at excitation energies below 10 MeV. New measurements of the n+^{16}O total cross section by Larson,[2] Cierjacks,[3] and Okubo,[4] were included at neutron energies from 1 keV to 6.5 MeV. We also included new measurements in the 2-4 MeV energy range of elastic scattering differential cross sections and polarizations by Drigo.[5]

The channel configuration and data summary for the analysis are given in Table B-I. R-matrix parameters for 45 levels were varied in order to fit the more than 3500 data points included for the three reactions considered. The level structure found agrees for the most part with the recommended data,[6] but with different parity assignments for some of the resonances and minor differences in positions and widths for the others. The resulting fit is a good representation of the data for all reactions. As an example, we show in Fig. 1 the n+^{16}O total and reaction cross sections at energies below 6 MeV. One sees that all the details of the considerable structure in the cross sections are well described by the fit.

The neutron cross sections from this analysis are being used up to about 6 MeV in a new ENDF evaluation for ^{16}O. Revisions of the higher-energy cross sections that reflect the new measurements in that region are currently in progress. The new evaluation is scheduled to be included in version VI of the ENDF/B file.

Table B-I. Channel configuration and data summary for the ^{17}O system R-matrix analysis.

Channel	l_{max}	a_c (fm)
n-^{16}O	4	4.44
α-^{13}C	4	5.69

Reaction	Energy Range	Observable Types	# Data Points
^{16}O(n,n)^{16}O	E_n=0-6.5 MeV	σ_T, $\sigma_{nn}(\theta)$, $A(\theta)$	2421
^{16}O(n,α)^{13}C	E_n=0-6.0 MeV	σ_{reac}, $\sigma_{n\alpha}(\theta)$, $A(\theta)$	904
^{13}C(α,α)^{13}C	E_α=0-4.6 MeV	$\sigma_{\alpha\alpha}(\theta)$	207
	Totals:	7 obs.	3532

[1]G. M. Hale, P. G. Young, and D. G. Foster, Bull. Am. Phys. Soc. XX, xxx (1972).

[2]D. C. Larson, "ORELA Measurements to Meet Fusion Energy Neutron Cross Section Needs", Proc Symp. on Neutron Cross Sections from 10 to 50 MeV (BNL-NCS-51245), 277 (1980).

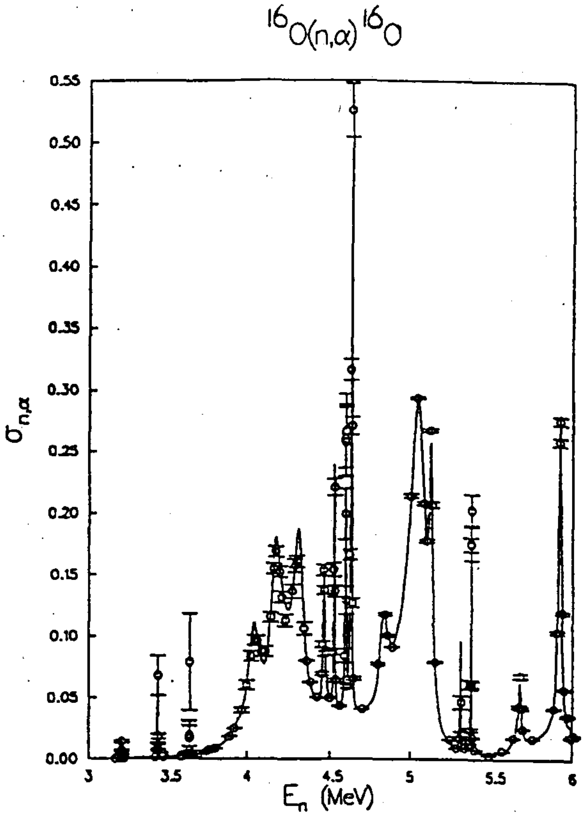
[3]S. Cierjacks et al., J. Nucl. Inst. Meth. 169, 185 (1980).

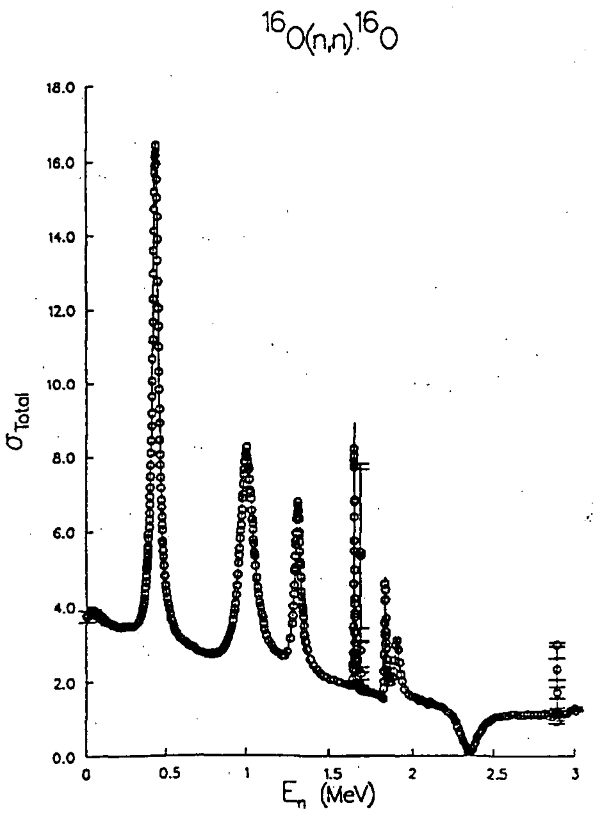
[4]W. Okubo (JAERI), private communication (1984).

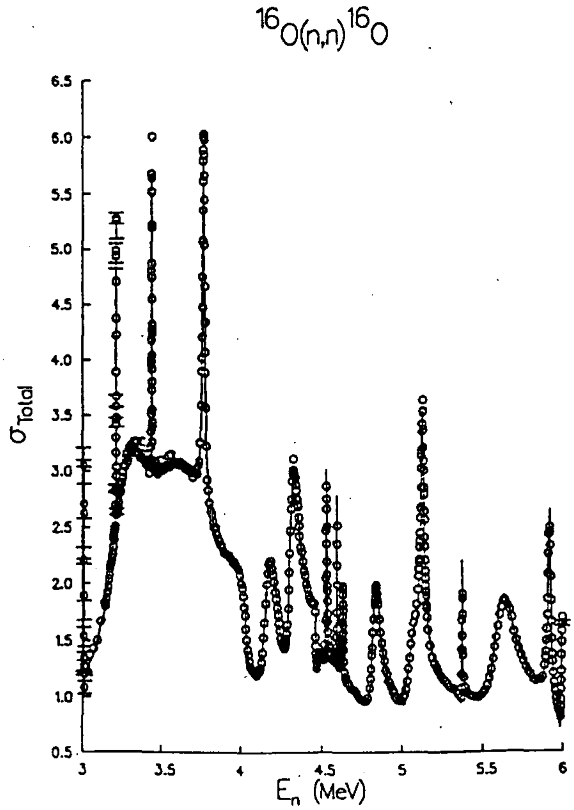
[5]L. Drigo, G. Tornielli, and G. Zannoni, Nuov. Cim. 31, 1 (1976).

[6]F. Ajzenberg-Selove, Nucl. Phys. A460, 77 (1986).

Fig. B-5. Total (bottom) and reaction (top) cross sections for n+^{16}O at energies up to 6 MeV. The curves are the R-matrix calculation and the data are those of Refs. 2-4.







7. ENDF/B-VI Radioactive Decay and Yield Libraries [T. R. England, C. W. Reich (Idaho Enational Engineering Lab.), F. M. Mann, R. E. Schenter (Hanford Engineering Development Lab.), J. Katakura (Japan Atomic Energy Research Inst.), and M. C. Brady (Oak Ridge National Lab.)]

Decay Data

ENDF/B-VI will contain sub-libraries of all radioactive decay data and fission product yields. These libraries will continue to contain error files. Reaction cross sections (neutrons and charged-particle) for materials and individual nuclides will be contained in other libraries.[1]

As this summary was being prepared, the evaluated experimental decay data for ENDF/B-VI are contained in three separate files, namely, the Activation File (149 nuclides), the Actinide File (108 nuclides),[2] and the Fission Product File (510 nuclides), the latter being incomplete at this point.

The number of nuclides in the Fission Product File for which experimental information is given has increased considerable (from 318 in Version V to 510 in Version VI) and now includes essentially all such nuclides for which information other than simply a half-life is known.[2] Additional categories of data have also been included, and the previous data have been upgraded and expanded. For example, delayed-neutron spectra of 271 individual precursor nuclides are given for the first time.[3] The results of recent specialized evaluations of P_n and Q_B values have been included. Where the decay schemes are believed to be essentially complete, the average energies have been, as in the past, computed directly from this information. Where this is not the case, extensive use has been made of both directly measured average-decay energies and the results of nuclear-model calculations to obtain the <E> values. Model calculations will be used for unmeasured spectra and will supplement some incomplete measurements.

The six-group abundances, half-lives, and spectra for delayed neutrons,[3] using the new 271 precursor data base and ENDF/B-V decay parameters and yields have been completed for 28 fissioning nuclides. The following table briefly summarizes the content in the actinide activation and expected content in the fission-product decay files.

Fission-Product Yields

The fission-product yields sub-library[4,5] includes 50 sets (each containing ~ 1200 fission products of direct and cumulative yields for 34 fissioning nuclides). It incorporates the delayed neutron branchings for the cumulative yields; direct or independent yields are values before delayed neutron emission. Table B-III lists the current fissioning nuclides having yields. Each set incorporates all data through 1988 and some in 1989. There are approximately 1200 nuclides having yields in each set.

Final evaluations are expected to include all data through 1989. The decay and yields files represent an increase in the amount of data by a minimum factor of 2 and up to a factor of 5 over ENDF/B-V.

TABLE B-II. ENDF/B-VI Decay Data in Activation, Actinide, and Fission-Product Files*

Data Type	Activation	Actinide	Fission-Product
Total Nuclides	149	108	>891
Isomeric states	22	5	168
Stable	0	0	127
Delayed Neutron Precursors	0	0	271
Nuclides with Spectra	149	108	755
Gamma and/or x-ray	119	98	736
Beta and/or discrete elec.	119	96	677
positron and/or <e.c>	61	0	40
Alpha	12	71	3

(File: Activation, Actinide, Fission-Product)

*Activation and Actinide decay files are complete with limited tests.

Fission-Product files are not complete as of 11/7/89 and numbers are approximate. The number of fission products having some measured spectra or average energies is 510; theoretical values will be given for most sremaining unstable nuclides, and will supplement the discrete, but incomplete spectra in 115 nuclides of the 510 sets.

TABLE B-III. Evaluated yield sets for ENDF/B-VI

Fiss. Nuc.	Fiss. Nuc.	Fiss. Nuc.
^{227}Th(T)	^{238}Np(F)	^{248}Cm(S)
^{229}Th(T)	^{238}Pu(F)	^{249}Cf(T)
^{232}Th(F,H)	^{239}Pu(T,F,H)	^{250}Cf(S)
^{231}Pa(F)	^{240}Pu(F,H)	^{251}Cf(T)
^{232}U(T)	^{241}Pu(T,F)	^{252}Cf(S)
^{233}U(T,F,H)	^{242}Pu(F)	^{253}Es(S)
^{234}U(F,H)	^{241}Am(T,F,H)	^{254}Es(T)
^{235}U(T,F,H)	^{42M}Am(T)	^{254}Fm(S)
^{236}U(F,H)	^{243}Am(F)	^{255}Fm(T)
^{237}U(F)	^{242}Cm(F)	^{256}Fm(S)
^{238}U(S,F,H)	^{244}Cm(S)	
^{237}Np(F,H)	^{245}Cm(T)	

S=Spon., T=Therm., F=Pooled Fast, H=14 meV

[1]F. M. Mann, "Status of Dosimetry and Activation Data," Proc. Int. Conf. Nuclear Data for Sci. and Tech., May 30-June 3, 1988, Mito, Japan, p. 1013.

[2]C. W. Reich, "Review of Nuclear Data of Relevance for the Decay Heat Problem," Proc. Spec. Mtg. on Data for Decay Heat Predicitions, Studsvik, Sweden, 7-10 Sept. 1987 [NEANDC-245 'U" (1987)], p. 21.

[3]M. C. Brady and T. R. England, "Delayed Neutron Data and Group Parameters for 43 Fissioning Systems," to be published in Nucl. Sci. Eng.

[4]B. F. Rider and T. R. England, "Evaluation of Fission-Product Yields for the US National Nuclear Data Files," Proc. Spec. Mtg. Data for Decay Heat Predictions, Studsvik, Sweden, 7-10 Sept. 1987 [NEANDC-245 'U' (1987)], P. 21.

[5]T. R. England and J. Blachot, "Status of Fission Yield Data," Proc. Int. Conf. Nucl. Data for Sci. and Tech., Mito, Japan, 30 May-3 June 1988, p. 943.

8. Theoretical Analyses of Neutron-Induced Reactions on Actinides for ENDF/B-VI: ^{235}U, ^{238}U, ^{237}Np, and ^{239}Pu (P. G. Young and E. D. Arthur)

In addition to the ^{235}U analysis described previously,[1] we have completed theoretical analyses of neutron-induced reactions on ^{238}U, ^{237}Np, and ^{239}Pu over the incident energy range 0.01-20 MeV in support of the ENDF/B-VI evaluation effort. The primary purpose for performing the analyses is to provide data on the reactions and energy ranges where little or no experimental data exist, especially for neutron emission reactions, with particular emphasis on the odd-A actinides. Therefore, depending on the specific nuclide involved, the main function of the theoretical analyses is to provide total, elastic, inelastic, (n,2n), and (n,3n) cross sections, and in all cases, the angular and energy distributions of secondary neutrons.

To summarize the analyses briefly, coupled-channel deformed optical model calculations were performed with the ECIS code[2] over the incident neutron energy range from approximately 0.001 to 20 MeV. The role of the coupled-channel calculations is to provide total, elastic, and ground-state rotational-band (n,n') cross sections, as well as neutron transmission coefficients for Hauser-Feshbach statistical theory calculations. The Hauser-Feshbach statistical calculations were performed with the COMNUC[3] and GNASH[4] reaction theory codes. Both codes include a double-humped fission barrier model, using uncoupled oscillators for the barrier representation in GNASH and coupled or uncoupled oscillators in COMNUC. Fission transition state spectra were calculated from inputted bandhead parameters or were constructed by taking known (or calculated) energy levels and compressing their spacing by a factor of 2. Phenomenological level density functions were used to represent continuum levels at ground-state deformations, appropriately matched to available experimental level data. Multiplicative factors were applied to the level density functions to account for enhancements in the fission transition-state densities at barriers due to increased asymmetry conditions. The fits to measured fission cross sections achieved in the analysis are compared with experimental data in Fig. B-6.

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[1]P. G. Young and E. D. Arthur, "Calculation of ^{235}U(n,n') Cross Sections for ENDF/B-VI," Int. Conf. on *Nucl. Data for Science and Technology*, Mito, Japan, May 30 - June 3, 1988 (Ed. S. Igarasi, Saikon Publ. Co., Ltd., 1988) p. 603.

[2]J. Raynal, "Optical-Model and Coupled-Channel Calculations in Nuclear Physics," IAEA SMR-9/8, Int. At. En. Agency (1970).

[3]C. L. Dunford, "A Unified Model for Analysis of Compound Nucleus Reactions,"AI-AEC-12931, Atomics Int. (1970).

[4]P. G. Young and E. D. Arthur, 'GNASH: A Preequilibrium Statistical Nuclear-Model Code for Calculation of Cross Sections and Emission Spectra," Los Alamos Scientific Laboratory report LA-6947 (Nov. 1977); E. D. Arthur, "The GNASH Preequilibrium-Statistical Model Code," LA-UR-88-382 (1988).

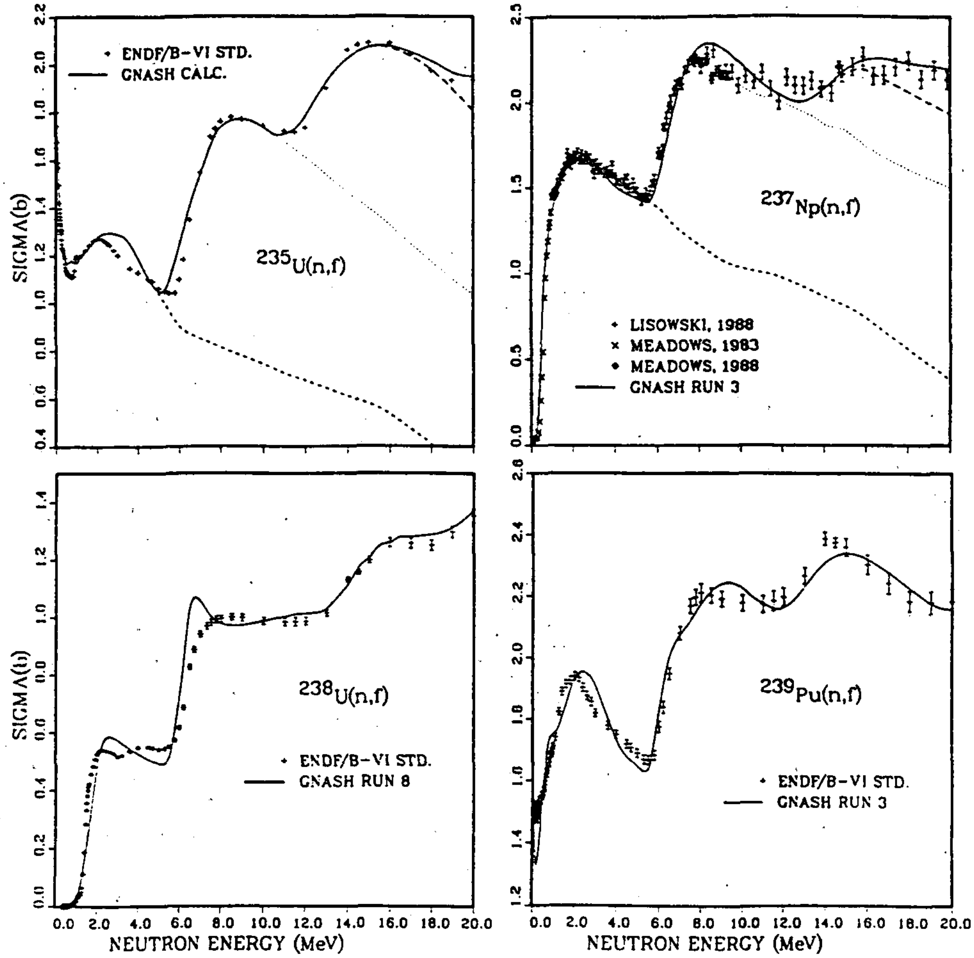

Fig. B-6. Calculated and measured neutron-induced fission cross sections for ^{235}U, ^{238}U, ^{237}Np, and ^{239}Pu from ~50 keV to 20 MeV. The dashed and dotted curves shown for ^{235}U and ^{237}Np represent the calculated contributions from 1st, 2nd, and 3rd-chance fission.

9. <u>Transport Data Libraries for Incident Proton and Neutron Energies to 100 MeV</u> (P. Young, E. Arthur, M. Bozoian, T.England, G. Hale, R. Little, R. LaBauve, R. MacFarlane, D. Madland, R. T. Perry, and W. Wilson)

New nuclear data evaluations for n + W and p + ^{1}H, ^{28}Si, and W reactions have been completed for our 100-MeV transport data library. The evaluations are in ENDF/B-VI format and include specification of cross sections, energy and angular distributions of emitted neutrons, gamma rays, protons, deuterons, and alpha particles. The incident neutron libraries are matched below 20 MeV with more detailed ENDF/B-V evaluations. At present, the 100-MeV library includes neutron- and proton-induced data for ^{1}H, ^{9}Be, ^{12}C, ^{16}O, ^{27}Al, ^{28}Si, ^{56}Fe, W, and ^{238}U. The data have been processed with the NJOY code for use in the multigroup version of the MCNP Monte Carlo transport code. The necessary interfaces and code patches for use of the data in MCNP have been completed. A report describing the transport data libraries has been prepared.[1]

[1]P. G. Young *et al.*,"Transport Data Libraries for Incident Proton and Neutron Energies to 100 MeV," Los Alamos National Laboratory report LA-11753-MS , to be issued in 1990.

10. New Evaluation of the n+^{14}N Reactions [G. M. Hale, P. G. Young, and M. Chadwick (U. Oxford)]

We have undertaken a new ENDF/B evaluation of the neutron cross sections for ^{14}N, which is based at neutron energies below 2.5 MeV on an R-matrix analysis of reactions in the ^{15}N system. This analysis includes total cross sections and elastic scattering differential cross sections for n+^{14}N, as well as integrated and differential data (with some polarizations) for the ^{14}N(n,p)^{14}C , ^{14}C(p,n)^{14}N, and ^{11}B(α,p)^{14}C reactions. The fits to the data are generally good, as the comparison to the ^{14}N(n,p) relative cross section measurement of Koehler and O'Brian[1] at low energies shows in Fig.B-7. Our thermal cross-section values and scattering lengths are somewhat different from the accepted ones, however, and we find that new S-wave levels are necessary to account for the energy dependence of the cross sections, especially near the neutron threshold.

Above an incident energy of 2.5 MeV (threshold for inelastic neutron scattering), the evaluation for ENDF/B-VI is based mainly on the experimental data base, taking advantage of several new measurements made available since the previous ENDF/B evaluation was completed in the early 1970's. The new experimental data result in considerable modification of some of the evaluated data, particularly due to new elastic and inelastic neutron angular distributions measurements by Chardine et al.[2] and inelastic gamma-ray measurements by Nelson et al.[3]

[1] P. E. Koehler and H. A. O'Brian, Phys. Rev. C 39, 1655 (1989).

[2] J. Chardine, G. Haouat, S. Seguin, and C. Humeau, "Diffusion Elastique et Inelastique de Neutrons sur 14N Entre 7.7 et 13.5 MeV," Commissariat à l'Energie Atomique report CEA-N-2506 (1986).

[3] R. O. Nelson *et al.*, "Studies of Higher-Order (n,xγ) Reactions at the WNR Spallation Neutron Source," to be presented at the Washington meeting of the American Physical Society, 16-19 April 1990.

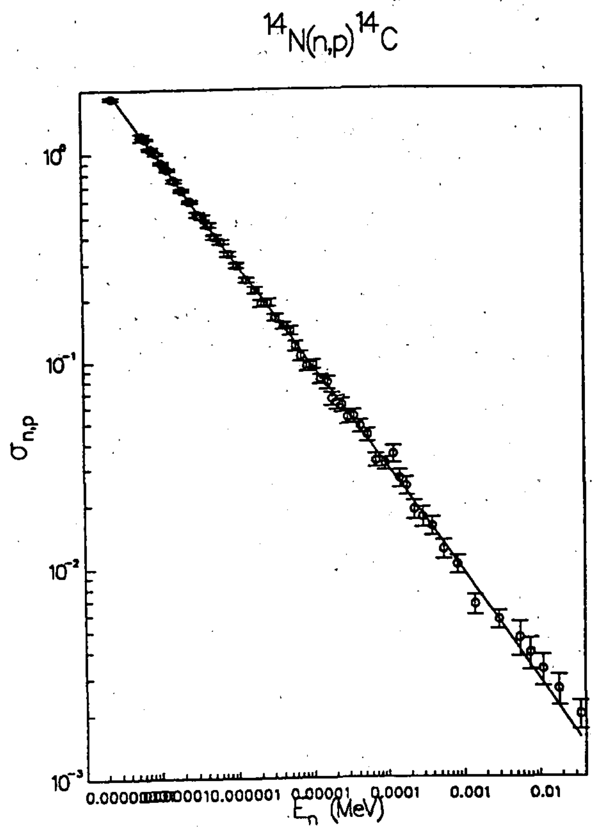

Fig. B-7. Calculated ^{14}N(n,p)^{14}C cross section (solid line) compared with the data of Ref. 1. The first experimental point is the absolute thermal value to which the relative data in Ref. 1 were normalized.

11. Nuclear Level Density Sensitivity Studies (E. D. Arthur)

A series of calculations[1] were performed to examine the sensitivity of calculated particle emission spectra to the level density determined using one of the following models - Gilbert Cameron[2], Back Shifted Fermi Gas[3], and the more modern phenemonological model of Ignatyuk[4]. These calculations also examined the issue of the sensitivity of new IAEA-sponsored experiments[5] that are underway to provide level density information through measurement of (p,n) and (n,n') emission spectra. Particle emission spectra offer a significant opportunity for determining level densities of the residual systems produced, as well as the validation of specific level density models. However questions pertaining to data types, or more specifically, which reaction channels are most sensitive to level density effects must be addressed to achieve maximum benefits from such experimental data. In our study, we found that channels (such as those involving neutron and proton emission) which dominate the Hauser-Feshbach calculation of both partial and total widths are relatively insensitive to large changes in actual level density values that may be used. Alpha emission spectra indicate a sensitivity arising from the fact that they are often minor reaction processes. The level density used affects decay widths and therefore competition with other channels. Discrete level data also show sensitivities to level density effects (in competing channels) for similar channel strength and channel competition arguments.

We also examined the differences in calculated results obtained using the Gilbert Cameron model and that of Ignatyuk for higher energy reaction data around shell closures. The Ignatyuk model incorporates an energy dependent Fermi gas parameter which has the effect of damping out shell effects at higher excitation energies. The Gilbert Cameron model does not. We therefore chose to calculate reactions on n + ^{207}Pb up to incident energies of 50 MeV using these two models. Figure B-8(a) illustrates the large differences existing between ^{208}Pb level densities predicted by these two models.These are indicative of difference obtained for other nearby nuclei. Figure B-8(b) shows the actual impact upon calculated neutron production and (n,xn) cross sections. The large level density difference that occurs at high excitation energies is mitigated in several ways. The first pertains to the normalization of partial decay widths to the total width to produce Hauser Feshbach results where the relative shape of the level density is the dominant factor in the cross section calculation. Secondly, preequilibrium emission can mask much of the high excitation energy behavior of these level density models. Finally, as each multiple neutron emission channel opens, the greatest sensitivity occurs near excitation energies of 10-15 MeV in the preceding compound system that decays into the residual (n,xn) system of interest. In these excitation energy regimes, orders of magnitude differences do not exist between level densities of the two models, and this accounts for the magnitude similarities of the calculated cross sections.

[1]E. D. Arthur, P. T. Guenther, A. B. Smith, and D. L. Smith, " Applied Uses of Level Density Models", Invited Presentation at the IAEA Specialists' Meeting on Nuclear Level Densities, Bologna, Italy, November, 1989.

[2]A Gilbert and A. G. W. Cameron, Can. Journal of Physics 43 , 1446 (1965).

[3]W. Dilg, Nucl Phys A217, 269 (1973).

[4]A. V. Ignatyuk, Sov. J. Nucl. Phys. 21, 450 (1979).

[5]For example, the IAEA Coordinated Research Proposal (CRP) on Nuclear Level Densities begun in 1988.

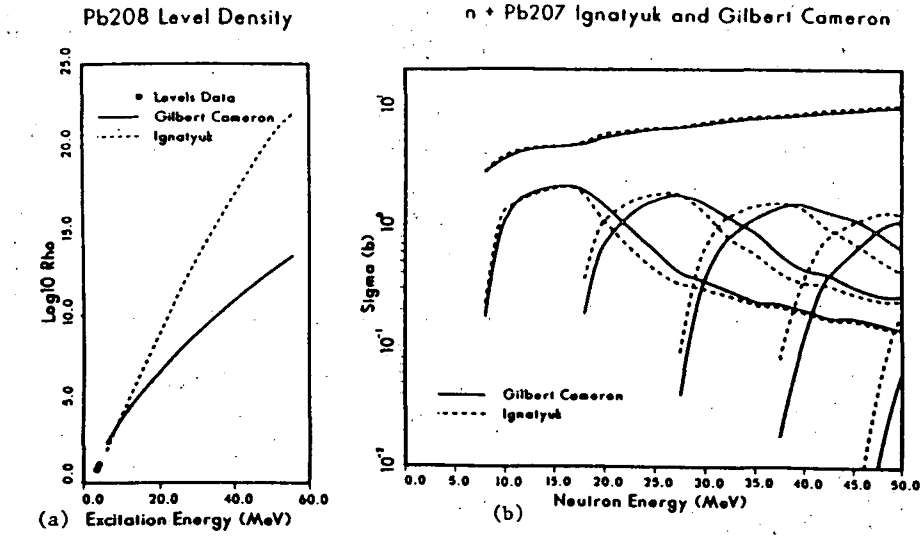

Fig. B-8. Comparison of Ignatyuk (dashed line) and Gilbert Cameron (solid line) formalism results. a) Level densities for ^{208}Pb. b) Comparison of cross sections for total neutron production, (n,xn) reactions (x=2-6).

12. Calculation of Medium Energy Nucleon-Nucleus Fission Cross Sections (E. D. Arthur and P. G. Young)

An intensive effort has been underway to develop and apply models appropriate for realistic description of nucleon-induced fission up to incident energies of 100 MeV. Results are discussed in detail in Ref. 1. Most of the effort has concentrated on models that provide more physics insight to higher energy fission processes that do those that are generally utilized in intranuclear cascade evaporation code calculations. The present calculations employ fission penetrabilities as well as explicit calculation of fission transition state spectra and densities occurring at the fission saddle point. Although we still must determine the barrier parameters empirically, we are interested in the determination of the systematics of barrier parameters as more compound systems are reached at higher energies. We are also pursuing a preliminary investigation of fission dynamics for fission occurring at high excitation energies in a given compound system. At higher excitation energies, situations may occur where the assumption of statistical equilibrium is not valid, and particle emission can occur before the fissioning system can reach the scission point. We have approximated these effects and have investigated their impact on total calculated fission cross sections as well as on cross sections associated with specific multichance fission components. We chose calculation of ^{237}Np(n,f) cross sections up incident energies of 100 MeV to examine these phenomena. To summarize our results thus far, we find that while dramatic changes may occur for individual fissioning systems comprising multichance fission, the effect on the total (n,f) cross section is small. This occurs mainly because of compensating effects that offset the decreased fission probabilities associated with compound systems occurring early in the chain, with increased populations of later stage systems that lead to increased fission contributions. We thus see little effect upon our calculations at high energies using this approximation but caution that these investigations are still in a preliminary form.

[1]E. D. Arthur and P. G. Young, "Calculation of Medium Energy Fission Cross Sections," Proc. Int. Conf. on the 50th Anniversary of Fission, James Behrens and Allan D. Carlson, Ed, American Nuclear Society publication, p971 (1989).

13. Transmutation of Defense High Level Nuclear Wastes Using High Current Accelerators (E. D. Arthur, P. W. Lisowski and C. D. Bowman)

Significant advances in the technology associated with high current, high energy linear accelerators offer attractive possibilities for new applications. One may exist in the possible transmutation of defense high level nuclear waste using an intense accelerator-produced source of neutrons. Investigation of this technology application to defense-generated nuclear wastes is of particular appeal for several reasons:

1. The Department of Energy has identified production complex cleanup as a priority item.
2. Significant amounts of high level wastes composed of short-lived and long-lived fission products, along with higher transuranics , exist in a partitioned form.
3. The present approach for dealing with such wastes promises to be expensive and may be open to technical criticism.
4. Long lived fission products such as ^{99}Tc and ^{129}I dominate long-term scenarios because of their mobility and their potential impact on the biosphere.
5. New technical advances, particularly in the area of accelerator development, offer real and implementable options for creating neutron fluxes high enough to transmute short-lived radionuclides having low interaction cross sections.
6. There is a growing national and international interest in transmutation concepts as evidenced by the Japanese OMEGA project, and study efforts such as the CURE (Clean Use of Reactor Energy) concept under development at Westinghouse Hanford Laboratory.

We have completed preliminary scoping arguments that indicate the desirability of a pursing a more detailed investigation of an accelerator transmutation approach. We have published a recent paper outlining the nuclear data needs for accelerator-based radionuclide transmutation[1]. Accelerator-based transmutation of defense high level nuclear wastes would concentrate on a relatively few radionuclides which exists in significant quantities in defense wastes. Candidate species include neptunium, americium, curium isotopes as well as fission products such as ^{90}Sr,^{137}Cs, ^{99}Tc, and ^{129}I. Higher order transuranics would be transmuted through fission to products having much shorter half lives, while fission products would be transmuted using low-energy neutron capture to stable by-product nuclei. An indication of the possible effectiveness of transmutation is indicated in Fig. B-9. There effective half lives achieved for the cross section curves shown and for an assumed neutron flux of 5×10^{15} n/cm^2/sec are compared with natural decay half lives for three of the candidate species listed above. Such flux considerations indicate a reduction in effective time scales associated with such radionuclides of 1 to 8 orders of magnitude.

Neutron economy arguments, based upon the isotopes and reaction processes involved as well as the neutron fluxes expected from such an accelerator neutron source (> 10^{27} neutrons produced per year), indicate that defense waste amounts on the order of one to two thousand kilograms could be transmuted within decade-like time scales. In order to improve upon such estimates, we have developed, and are now testing, simple models that include burnup and cycle times associated with target removal, fabrication, and repartitioning.

[1]C. D. Bowman, P. W. Lisowski, and E. D. Arthur, "Spallation-Based Science and Technology Associated Nuclear Data Requirements", to be published in the Proc. of Int Symp. on Advanced Nuclear Energy Research, Jan. 22-26, 1990, Mito City, Japan.

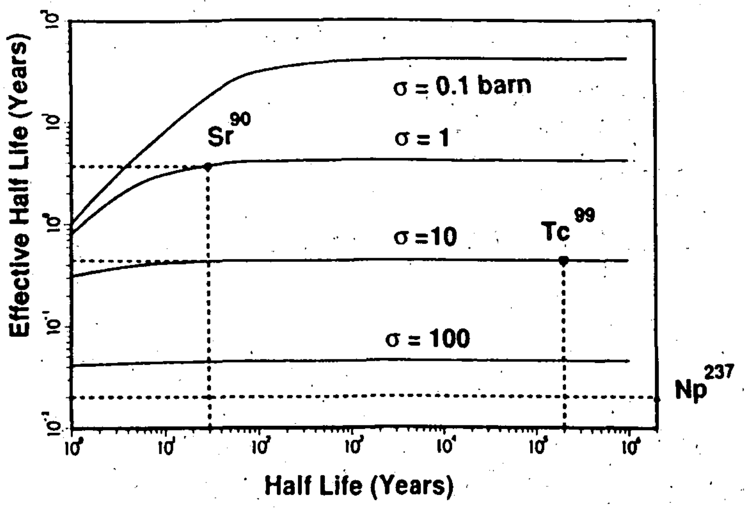

Fig B-9. Effective half lives of radionuclides that occur in a neutron flux level of 5 x 10^{15} n/cm^2/sec.

UNIVERSITY OF LOWELL

A. NEUTRON SCATTERING STUDIES

(L.E. Beghian, G.H.R. Kegel, J.J. Egan, A. Mittler, C.A. Horton, C. Jen, D.J. DeSimone, P.A. Staples and G. Yue)

1. Inelastic Neutron Scattering from Nitrogen-14

The inelastic scattering cross section for the first excited state of N-14 at 2.313 MeV has been obtained from (n,n'γ) measurements for incident neutrons in the range 2.650 to 3.550 MeV. A gamma-ray production excitation function at 125° was measured in 100-keV steps. In addition an angular distribution was measured at 3.450 MeV. Figs. A-1 and A-2 show these data.

Neutrons were produced by the $^7Li(p,n)^7Be$ reaction. The scattering sample was a cylinder of boron nitride 6.3 cm in height with a 2.34-cm radius. The measurements were made by using a 40-cm^3 Ge(Li) detector surrounded by a NaI(Tl) anti-Compton annulus housed in a massive shield of lead and paraffin loaded with lithium carbonate. The pulsed beam time-of-flight technique was used to further reduce background due to room scattered neutrons. The absolute neutron fluence was determined by comparison to a calibrated fission chamber.

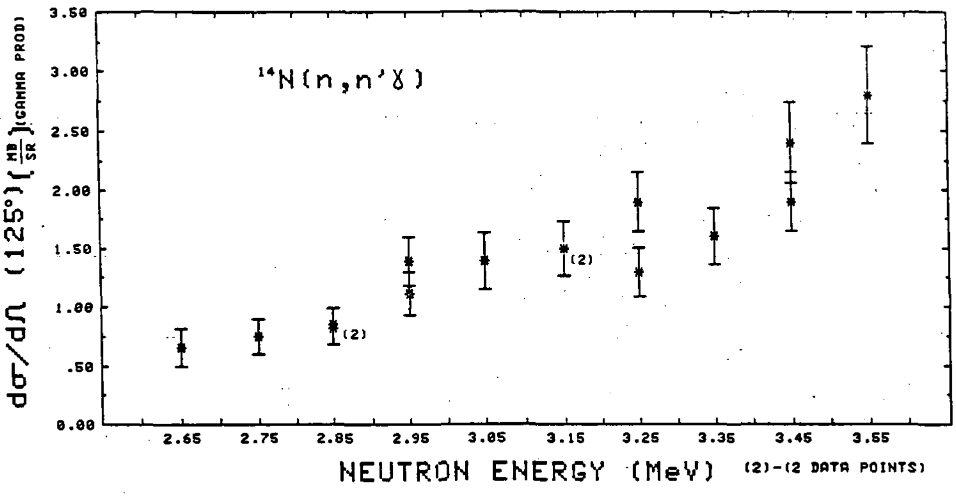

Fig. A-1 Gamma-ray production excitation function at 125°

Figure A-3 shows the neutron scattering cross section inferred from the (n,n'γ) measurements. These results were obtained by multiplying the 125° excitation function data by 4π, a reasonable approach in light of the near isotropy of the angular distribution.

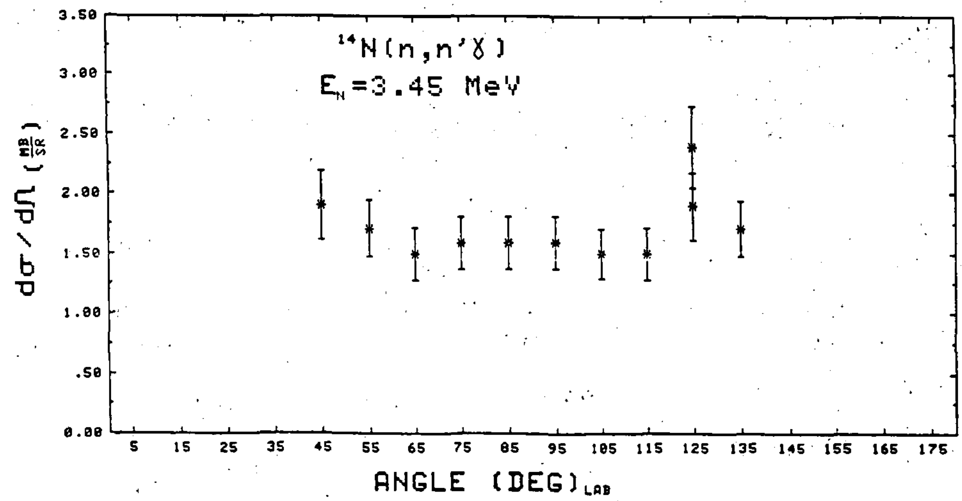

Fig. A-2 Gamma-ray production angular distribution at 3.45 MeV.

The earlier work of Bostrom et al.[1] and that of Day[2] are shown for comparison. These earlier measurements do not extend below 3.40 MeV. Shown also for comparison is the ENDF/B-V evaluation which underestimates the cross section.

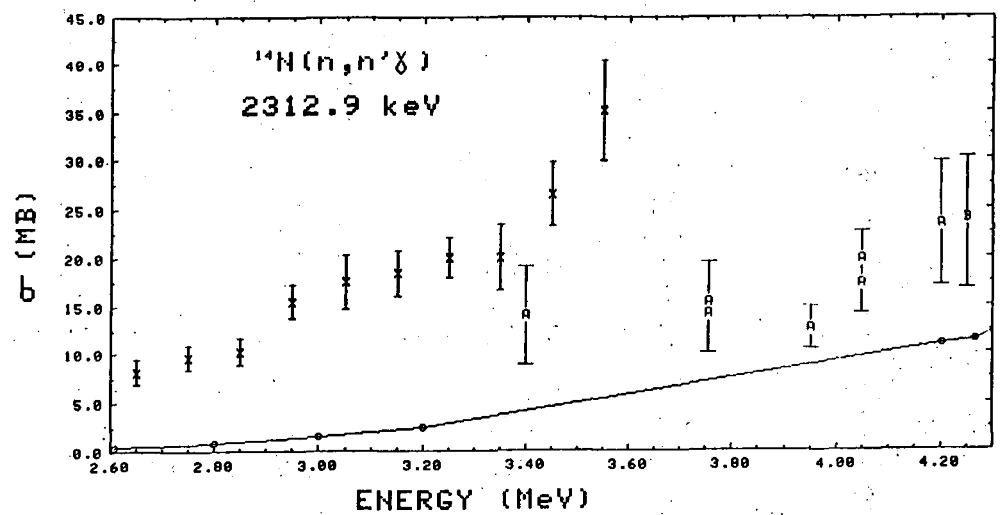

Fig. A-3 Neutron scattering cross section inferred from the (n,n'γ) measurements for the 2312.9 keV state in N-14. X- present work. A- Bostrom et al.[1]; B- Day[2]; Line- ENDF/B-V

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[1] N.A. Bostrom, I.L Morgan, J.T. Prudhome, P.L. Okhuysen, A.R. Sattar, in Neutron Cross Sections and Technology: Proceedings of Conference, NBS Special Publ. p. 71 (1959)

[2] R.B. Day, Phys. Rev. 102, 767 (1956).

2. Inelastic Scattering from Th-232 and U-238 at 135 KeV

A series of measurements of the neutron inelastic scattering cross section of the 2+ states of U-238 at 44.9 keV and Th-232 at 49.4 keV were made at an incident energy of 135 keV for six scattering angles: 45°, 55°, 70°, 90°, 110° and 122.5°. A detector consisting of 2 XP-2020 photomultipliers, described in last year's report, was used.

Very thin (13 keV) targets were made by depositing lithium on tantalum in situ, and repeated short runs with Th, U and Bi scatters were added to produce spectra. The Bi spectrum was fitted to the U-238 and Th-232 spectra to simulate the elastic spectrum and subtracted from them to strip the inelastic spectrum.

Figure A-4 shows a typical U-238 spectrum (solid line) with a normalized superimposed Bi spectrum (dotted line). The contribution from the 2+ excited state is clearly evident.

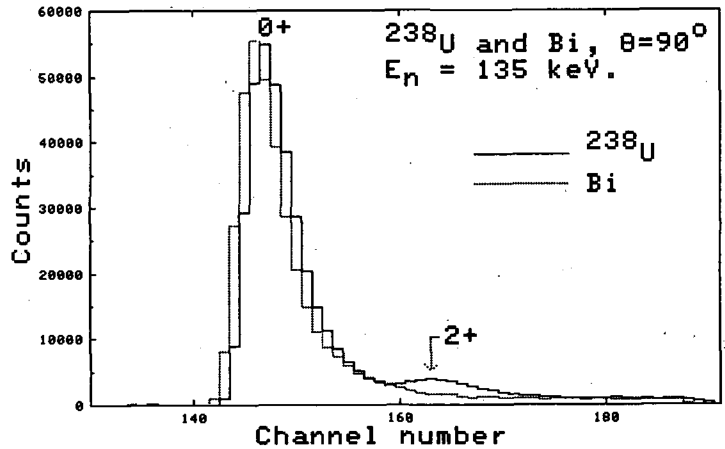


Fig. A-4 U-238 (solid line) and Bi (dotted line) time-of-flight spectra 135 keV

Detector efficiency was measured using a U-235 fission chamber normalized to a BF_3 counter. Analysis of these measurements is still in progress. Preliminary results are consistent with the inelastic scattering differential cross section being symmetric about 90°.

B. DECAY HEAT AND DELAYED NEUTRON STUDIES
(G.P. Couchell, D.J. Pullen, W.A. Schier, P.R. Bennett, E.S. Jacobs and M.F. Villani)

1. Decay Heat Study at Short Delay Times

A feasibility study was begun this past summer for the measurement of beta and gamma-ray spectra of premium quality from the fission of U-235 at delay times ranging from 0.1 to 1000 s using our helium jet/tape transport system. The study has already included:

1) measurement of gamma-ray spectra with NaI(Tl) (for decay heat) and with Ge(Li) (for individual precursor gamma lines) from the neutron fission of U-235;
2) good progress on the development of a gamma-ray unfolding program to analyze NaI(Tl) spectra for their energy content;

3) construction and preliminary calibration of a beta spectrometer;

4) preliminary measurement of the beta count rate as a function of delay time.

The program's goal would be to provide decay heat information from the fission of Th-232,U-233, U-235, U-238 and Pu-239 for delay times down to 0.1 s after fission where no aggregate measurements exist, to provide hundreds of tests with individual gamma line intensities as a function of delay time for ENDF data bases generated mainly from individual precursor measurements, and to test statistical model predictions for the shape and hardness of aggregate beta spectra immediately after fission, a study very sensitive to the energy variation of the beta strength function.

a. Delay Gamma-Ray Spectra of U-235

The fission fragments are rapidly transported from the small hemispherical fission chamber lined with U-235 in the target room to the moving transport tape in the counting room. Beta-gamma coincidence produces premium gamma-ray spectra because a short, well-defined delay-time interval is selected, data is accumulated at one time interval until excellent statistics are obtained, beta and random gamma backgrounds are excluded, and absorption and prompt fission effects (from neutron backgrounds) are absent because no fission foil is transferred to the counting room.

One might expect the complexity of the gamma-ray spectrum to be so great that the measurement of individual gamma lines at short delay times would be nearly impossible. But the benefit of this coincidence technique can be demonstrated in a Ge(Li) spectrum (Fig. B-1) taken in the 0.79-1.25 s delay-time interval. This spectrum displays a large number of measurable lines with tentative identification of precursors whose half-lives are comparable to the delay times selected. Activities that are both shorter and longer lived are strongly suppressed thus dramatically reducing the complexity of the aggregate spectrum.

Entire new sets of lines emerge at delay times considerably removed from one another. Thus Ge(Li) measurements of lines from isotopes whose production probability in fission and whose decay rates are well known can be used to obtain absolute fission rates for each aggregate NaI measurement. The measurements can also serve as a check on production probabilities and decay rates for many individual isotopes having large uncertainties in one or more of these parameters.

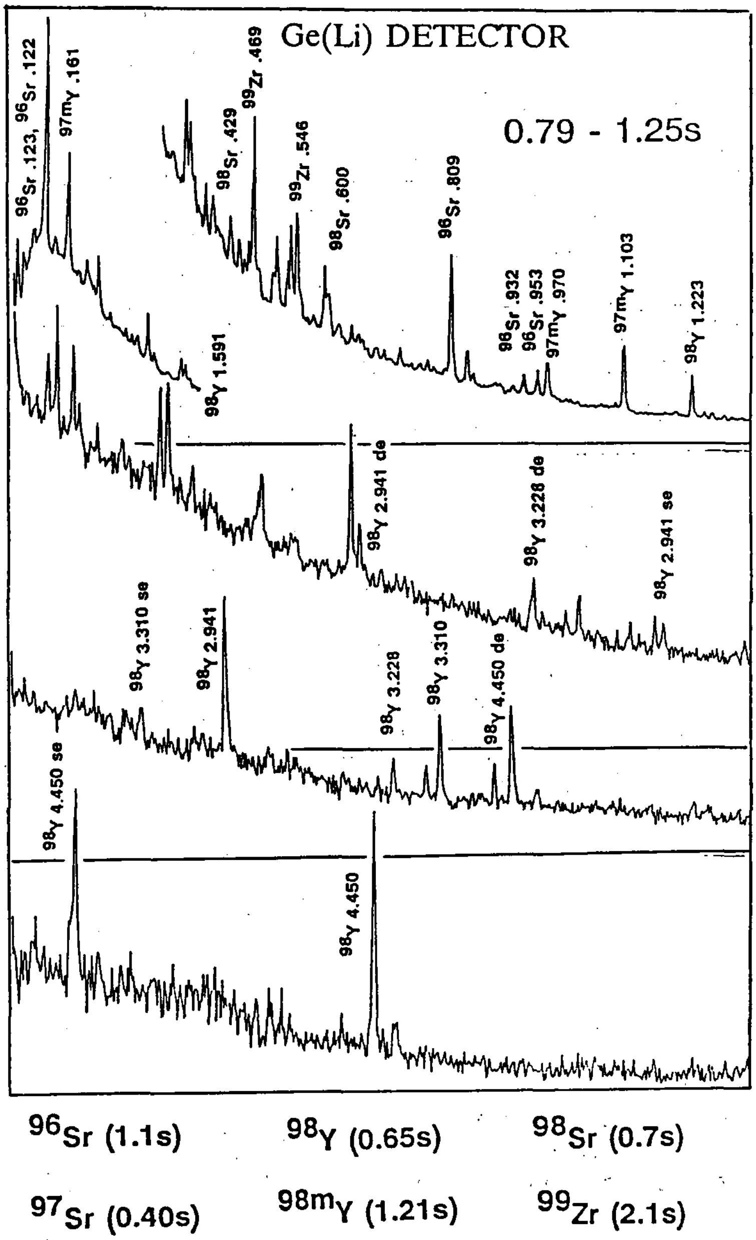


Fig. B-1 Delayed gamma spectrum measured in beta-gamma coincident for neutron fission of 235U in the delay time interval 0.79-1.25 s

b. Analysis Program to Extract Energy Content of NaI(Tl) Spectra

In order to determine an average photon energy from a composite NaI gamma spectrum, one must remove all typical response function characteristics other than full energy peaks. A typical response function may be viewed as comprised of four components: 1) a photopeak, 2) a single and a double escape peak, 3) a backscatter peak and 4) a Compton band. Any method of stripping any or all of these components requires the ability to create a complete response function at any energy from a collection of experimentally obtained ones. Each component is treated separately due to varying dependencies on photopeak energy; thus, four separate interpolations (or extrapolations) must be performed. Initially, experimental response functions are decomposed into the four components using a graphical interactive program that employs linear background to remove peak shapes from the Compton band.The shape of each component is directly interpolated as opposed to interpolating the parameters of least- squares fits which make the procedure dependent on the quality of fitting functions. For each component, a channel-by-channel interpolation to a desired photopeak energy is performed, after it has been compressed (or expanded) to line-up chosen characteristics along common channels. After proper normalization, any or all of the components may be added together to produce a desired response function.

With this capability, stripping a composite gamma spectrum is now reduced to properly identifying all full energy peaks and subtracting out the unwanted response function components. For a complicated spectrum possessing overlapping photopeaks this proves to be a difficult task. However, two possible methods can be applied which do not rely on direct identification of each peak. First by starting at the high energy end of the spectrum, each channel can be viewed as being a photopeak and a stepwise progression can be made to the low end, subtracting out a scaled response function with each step. A second approach is to represent each measured spectrum in a least-squares fashion as a superposition of response functions spaced approximately a FWHM apart. Each of the two methods will be investigated for decomposition reliability using complex spectra constructed by the addition of known spectra.

c. Beta Spectrometer Development and Calibration

Considerable effort has been made in developing a beta spectrometer suitable for decay heat measurements and in performing a preliminary calibration. The spectrometer that is operational consists of a plastic scintillator (3.6 cm diameter x 5 cm long) and a disk (2.5 cm diameter x 0.025 cm thick) on its face optically isolated by a thin aluminum foil. The cylinder is coupled directly to the phototube whereas the disk is viewed off at an angle by two phototubes.

The cylinder by itself has considerable gamma-ray sensitivity but when the coincidence requirement is added, gamma rays are very effectively discriminated. Also by excluding betas detected near the cylinder walls, edge effects are greatly diminished. Comparisons between measured and calculated beta spectra for Na-24 (E =1.37 MeV) and Cl-38 (1.11, 2.77, 4.81 MeV) are presented in Fig. B-2 and B-3. Excellent agreement is observed even though these sources are also gamma-ray emitters. P-31 (1.71 MeV), Mn-56 (0.7, 1.04, 2.81 MeV), and Zn-69 (0.91 MeV) are other suitable calibration sources we produce on our reactor.

Aggregate beta spectra from neutron fission of U-235 will soon be measured. These should be of premium quality because a short, well-defined delay time interval is again selected by viewing a small portion of the moving tape and shielding the remainder, the gamma background is well discriminated by the spectrometer, and no self absorption or prompt fission effects are present since the fission foil is not transferred to the counting room.

Fig. B-2 Comparison between measured and calculated ^{24}Na (E_β=1.37 MeV) beta spectrum.

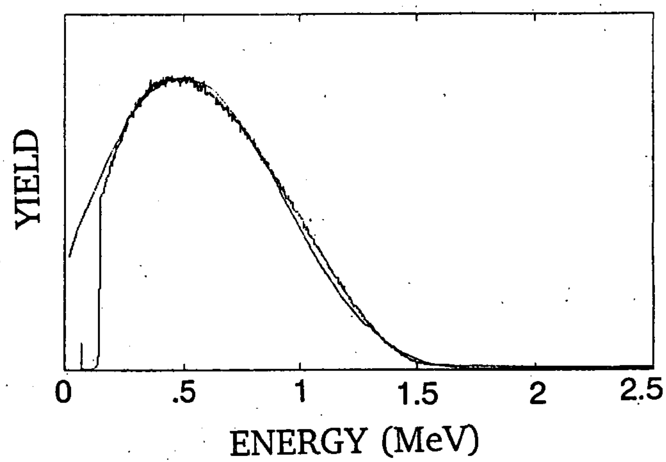
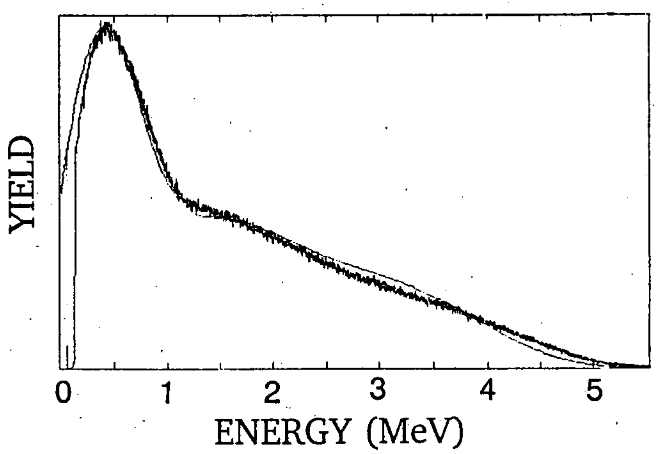


Fig. B-3 Comparison between measured and calculated ^{38}Cl (E_β=1.11, 2.77, 4.81 MeV) composite beta spectrum.



d. Beta Count Rate as Function of Delay Time

Beta count rate verses delay time is one means of normalizing decay heat data. Its measurement is quite rudimentary with the tape transport system since it just requires the positioning of a movable beta detector at various distances from the spray point and normalizing to a fixed beta detector. Again delay time is well-defined and gamma-ray sensitivity is minimized by choosing thin plastic scintillators. Multiscaling allows one to select corresponding measurements for the two detectors. Again the movable detector dwells long enough to give excellent statistics. If a very wide range of delay times must be spanned, more than one tape speed is chosen with considerable overlap among measurements for normalization purposes.

2. Six-Group Decomposition of Composite Delayed-Neutron Spectra

Our measurements of composite (aggregate) delayed neutron (DN) spectra as a function of time following fission of ^{235}Pu were reported earlier. An important goal of this study is the extraction of representative Keepin Six-Group spectra from the measured spectra, and a number of improvements have been made during the past year in the analytical techniques used in decomposing the measured spectra.

Measured delayed-neutron energy spectra, $F_i(E_\mu)$ i=1, ..., M delay-time intervals, can be transformed into a set of Keepin Six-Group spectral bases of the form,

$$F_i(E_\mu) = \sum_{j=1}^{6} A_{ij}\chi_j(E_\mu)$$

where μ=1, ..., 200 energy bins. For $M \geq 6$, the spectral bases, $\chi_j(E_\mu)$, can be obtained in a least-squares fashion by inverting the matrix of coefficients. It was previously reported that initial attempts produced solutions that were highly oscillatory and often negative. Improved solutions were obtained by using an iterative procedure damping the spectral solutions with an initial guess spectrum. The iteration was terminated when the solutions yielded acceptable spectral shapes, a rather subjective criterion. Due to the complex nature of the iteration method and subsequent spectrum re-normalization, the propagation of error due to the iterative least-squares technique was calculated utilizing Monte-Carlo methods. However, the results yielded unrealistically (small) uncertainties.

The iterative technique was studied for a range of values for the damping coefficient using Maxwellian generated spectra as first guess spectra. It was found that equally acceptable solutions could be obtained for a much smaller damping constraint and only one iteration, thus elimination of the subjectivity of the earlier method. With no longer the need to iterate, the variances for the six-group solutions were rapidly calculated from the covariant matrix. The results were much more realistic than those produced by the Monte-Carlo method.

An alternative least-squares technique, solutions editing, was developed that did not require initial guess spectra. The solution editing technique applies a full singular value decomposition (SVD) to the matrix of coefficients before matrix inversion. The SVD process identifies any singularities, to within any precision, and excludes them from the solution. The resultant six-group compare well to the preliminary ENDF/B-VI DN spectra provided to us by T. England. They are also very similar to the solutions obtained in the iterative method. In addition, the solution editing method readily produces associated uncertainties.

THE UNIVERSITY OF MICHIGAN
DEPARTMENT OF NUCLEAR ENGINEERING

A. PULSED 14 MeV NEUTRON FACILITY (J. Yang, N. Tsirliganis, E. Christodoulou, V. Rotberg, R. Spears, D. Wehe, G. Knoll)

1. Facility Development

The major part of our effort has been spent on the continuing development of our nanosecond pulsed 14 MeV neutron facility. Located in a large-volume heavily shielded laboratory, the facility has been designed to promote low-scatter conditions in the vicinity of the target in keeping with our objectives to carry out secondary neutron measurements under conditions that are as clean as possible. The system consists of a 150 kV Cockcroft-Walton accelerator, a quadrupole doublet, a sweeper, a pulser, a mass analysis magnet, a two-gap klystron buncher, a quadrupole triplet, the associated vacuum system and electronics . To create a low scattering environment near the target, the beam line is positioned midway between the floor and the ceiling of the laboratory, about 4 meters above floor level. Beams and posts from floor level support the beam line and detector rails, and a low-mass grid floor provides personnel access. A liquid nitrogen vapor jet is used to cool the Ti-T neutron generating target to minimize mass and keep the measurements relatively free of influence from neutrons that are scattered before reaching the sample.

All the design and most of the fabrication of components for this system have been carried out in our own laboratories, largely through graduate student efforts. This undertaking was culminated over the past year with achievement of 1.6 ns overall time resolution in our first neutron time of flight measurements. Several remaining components of the system, including the pre-bunching beam pulser and a large-mass shield for the detector are near completion. The facility will be the only one of its type in the country, and we expect to begin exploiting its unique capabilities in our initial cross section measurements over the next year.

2. Initial Testing

During the development phase of the bunching system, we have carried out a series of time resolution tests to measure its performance. In these tests, we have used an aluminum blank in place of the tritium target, and 2.5 MeV D-D neutrons were generated from the self-implanted deuterium in the blank. The "zero time" signal was derived from a capacitive beam pickoff tube near the neutron-producing target. In order to minimize the contribution of the detector to the overall timing resolution, a 3 mm thick plastic scintillator mounted on a EMI 2887B photomultiplier tube was used to detect the neutrons after a flight path of less than a meter. Under these circumstances, the largest contribution to the measured time resolution is expected to be the inherent width of the beam pulse itself.

This system was used to find the optimum operating conditions for the buncher by measuring the observed timing resolution as the bunching parameters were varied. The best time focusing for 3.45 m drift length, 150 keV deuteron energy, and 6 MHz buncher RF frequency was obtained at a 10 kV peak-to-peak buncher voltage. This result is in close agreement with the predictions of the computer code used in the initial buncher design. The FWHM of the peak in the measured time spectrum corresponds to a timing resolution of 1.6 ns. Considering the finite time resolution of the detector itself, we estimate that the time width of the beam pulse alone is approximately 1.0 - 1.2 ns. This buncher performance is likely to be more than adequate for our neutron energy measurements in view of the additional time spread that will be introduced by finite neutron flight time through the larger detector that we have fabricated for the actual time-of-flight experiments.

B. MEASUREMENTS IN THE PHOTONEUTRON LABORATORY

1. Measurement of the Fast Neutron Capture Cross Section of U-238 (E. Quang, G. Knoll)

This series of experiments was described in the progress report of a year ago. Several subsequent measurements have been carried to to check several correction factors used in the cross section calculations. Additional experiments were conducted to demonstrate that the possible escape of recoils from our ^{243}Am gamma ray calibration foil did not constitute a significant systematic error. Additional checks were also made of the counting rate stability of the manganese bath counting system. All experimental and analytical work is now complete, and will be presented in a paper accepted for the program of the American Nuclear Society Meeting in June 1990. Final cross section values obtained were 494 ± 11 and 138 ± 5 mb at 23 and 967 keV, respectively.

The measurements are based on experimental techniques that emphasize direct absolute determinations. Adjustments that are needed to the data are straightforward and amount to no more than a few percent in any case. The absolute values of the cross sections are directly dependent on the absolute neutron emission rate of the U. S. national standard neutron source NBS-1, but are largely free of reliance on any reference cross section values. Our methods rely on the ability to accurately calculate the average neutron flux from a spherically symmetric neutron source in the simple cylindrical geometry of the experiments. The absolute basis of the gamma ray counting used in the measurements was established for the ^{243}Am calibration source with the proven technique of absolute alpha counting in limited solid angle geometry. As a benefit of the chemical separations that were carried out, all gamma ray counting was accomplished as ratio measurements between samples of similar physical form and activity level to minimize additional corrections. Under these conditions, these somewhat infrequent examples of absolute measurements of this technologically important cross section should be of significant value in future data evaluations.

2. Absolute Measurements of the Fast Neutron Capture Cross Section of Au-197 (S. Sakamoto*, E. Quang, G. Knoll)

Because of its application as a capture cross section standard, the neutron capture cross section in gold is of considerable interest. We have therefore carried out a series of experiments using absolute techniques that have led to measured values at 23 and 967 keV, the median energies of the Sb-Be and Na-Be photoneutron sources used in this work. These sources were activated in the Ford Nuclear Reactor and transferred to our low-albedo laboratory for irradiation of the gold target foils. The influence of room-return neutrons was measured through a series of activations performed with foils at varying distances from the center of the source. The neutron emission rates of the sources were subsequently measured using our manganese bath. The absolute efficiency of the bath is known from a prior calibration traceable to NBS-I. The absolute scalar neutron flux at the irradiation positions is then calculated from knowledge of the irradiation geometry.

The gamma rays from the decay of the induced ^{198}Au activity were measured absolutely using a pair of cylindrical NaI(Tl) detectors in near 4π geometry. Through the use of an intermediate calibration foil, the absolute detection efficiency was determined using $4\pi\beta$-γ coincidence counting techniques. In calculating the experimental cross section values, corrections were made to account for the contributions of room returned neutrons and scattering from the experiment support structures. The resulting values were then adjusted for the small energy spread of the source neutrons by assuming the relative shape of the cross section from ENDF/B-V. All experimental and analysis work is now completed, and will be described in a paper to be submitted for publication. The final measured values are 618 $\pm$ 11 and 99.7 $\pm$ 2.8 mb at 23.3 and 967 keV, respectively.

C. ACTIVATION CROSS SECTION MEASUREMENTS IN COOPERATION WITH ARGONNE NATIONAL LABORATORY (G. Piccard, D. Smith[ANL], J. Meadows [ANL])

A cooperative measurement program has been established to determine activation cross sections using facilities both at Michigan and Argonne National Laboratory. Initial efforts are underway using targets of natural yttrium. Irradiations have been carried out at the ANL Fast Neutron Generator facility, and samples transported to our laboratories for activity measurements now in progress. Measurement objectives are the determination of the ^{89}Y(n,p) and ^{89}Y(n,α) cross sections at neutron energies between 5 and 10 MeV.

*On leave from Tokai University, Japan

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
(formerly the National Bureau of Standards)

A. NUCLEAR DATA MEASUREMENTS

1. ^{235}U Fission Cross Section Measurements (A. D. Carlson and O. A. Wasson, NIST; P. W. Lisowski, J. L. Ullmann and A. Gavron, LANL; N. W. Hill, ORNL)

Further measurements and analysis have been done on this experiment. The measurements are being performed on the 20 m fission flight path of the target 4 neutron facility at the Los Alamos Meson Physics Facility. A large amount of the data obtained earlier with an IBM-PC acquisition system has been analyzed for the ^{235}U fission cross section. These data and some of the recent data obtained with the MICROVAX-XSYS computer-data acquisition system were reported in April at the conference "Fifty Years With Nuclear Fission." The neutron fluence was measured below 30 MeV with the NIST Annular Proton Telescope (APT). At high neutron energies for these data it was not possible to accurately resolve background from the foreground, partly due to the geometry of the detector. Some fluence measurements above 30 MeV were also made with a small scintillator. These measurements provided valuable information where data had not been obtained previously. However, the data could not be determined with the high accuracy which was desired. These complications with the APT and scintillator fluence measurements led to the design of two separate detectors which overlap in their useful neutron energy ranges and allow data to be obtained from about 3 to above a hundred MeV. The Low Energy Telescope (LET) uses a thin polyethylene film and Si(Li) detector in a vacuum enclosure at 15 degrees from the neutron beam line. The geometry allows very good proton recoil pulse height resolution. The detector will stop proton recoils from ~25 MeV neutrons. A separate higher energy telescope, the Medium Energy Telescope (MET) is also at an angle of 15 degrees from the beam but is operated in air downstream from the LET. The MET is composed of a polyethylene disk and three proton recoil scintillator detectors. The detectors consist of 0.16 cm and 0.6 cm thick plastic scintillators and a 15.2 cm thick CsI scintillator. The MET is used in a coincidence mode in order to reduce the neutron background. For both the LET and MET detectors, the contribution from neutrons interacting with carbon in the polyethylene can be evaluated with a run made with a carbon sample. Cross section measurements with these detectors have been made and the data analysis is nearly complete. Measurements of the masses of the fission deposits used in these experiments are being determined by alpha counting.

2. <u>The $^{10}B(n,\alpha\gamma)$ Cross Section from 100 keV to 3 MeV</u> (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 standard cross section was initiated last year in collaboration with Oak Ridge National Laboratory to improve the accuracy of the cross section in the neutron energy region above 100 keV. A shape measurement is being undertaken using the NIST Black Detector at 150 m on ORELA flight path 6 to provide flux normalization. Preliminary runs indicate that the desired neutron energy range can be covered by using two overlapping runs to cover the factor of approximately 100 in range of detector pulse height. A beryllium target neutron source is used to provide adequate neutron flux at the high end of the neutron energy range. A high purity germanium photon detector having 30% efficiency is used to measure the reaction gamma ray from the boron sample. Both are placed at 19 m on the flight path. The detector is enclosed in neutron and gamma-ray shielding. The system is enclosed in electrical interference shielding to minimize interference with the detector signal. Preliminary runs indicate that measurements over the desired energy range are possible with good precision. The first measurements were completed in the fall of 1989. The most recent measurements beginning in March of 1990 have utilized the new ORELA data taking system based on a microcomputer. Data analysis programs have been largely completed at NIST and have been tested on the preliminary data. These results show promise of a significant improvement in the accuracy of this important standard in the neutron energy region above 100 keV.

3. <u>Measurement of the ^{235}U (n,f) Cross Section at 2.5 MeV Neutron Energy</u> (K. C. Duvall)

A measurement of the $^{235}U(n,f)$ cross section at 2.5 MeV using the $D(d,n)^3He$ reaction and the time-correlated associated-particle (TCAP) method is in progress. The deuteron beam is supplied by the 100 kV Ion Accelerator. A fission chamber containing six uranium tetrafluoride deposits, 5 cm in diameter, and ranging in thickness from 230-300 $\mu g/cm^2$ has been installed. Typical sources of background and their contribution to the uncertainty in the cross section have been evaluated. The data is being collected in two parameters: pulse height and time-of-flight, at a rate of 35 counts per hour with an associated particle rate of 3000 counts per second. Optimal rates using fresh targets are about three times higher. The accidental background is 15%. Although the data collection rate is slow, the measurements are being conducted around the clock as a result of the stable, unattended operation of the accelerator. Data has been collected thus far with a statistical accuracy of 4% (1 std).

B. NEUTRON DETECTOR DEVELOPMENT AND FACILITIES FOR NUCLEAR DATA MEASUREMENTS

1. A 2.5 MeV Neutron Source for Neutron Cross Section Measurements (K. C. Duvall)

A 2.5 MeV neutron source is operational at the 100-kV, 0.5-mA ion generator at NIST. Neutrons are produced by the $D(d,n)^3He$ reaction with a yield of 3×10^6 s^{-1}. The time-correlated Associated-Particle method is used for neutron fluence determination and for background elimination. A fission chamber containing six UF_4 deposits is in operation for use in the $^{235}U(n,f)$ cross section measurement at 2.5 MeV.

2. Absolute Thermal Neutron Counter Development (D. M. Gilliam, G. L. Greene and G. P. Lamaze)

An accurate neutron fluence monitor for the measurement of cold and thermal neutrons is being developed. A gamma-alpha coincidence technique is employed to make an accurate calibration of a totally-absorbing ^{10}B capture gamma detector system. This neutron detector is being developed as part of a neutron lifetime experiment, but it also has potential applications for improved thermal neutron cross section measurements, improved calibration of the NIST manganous bath, and possible implications for ^{252}Cf nubar data.

One important feature of the absolute calibration of this system is that the alpha-gamma coincidence method can be checked by intercomparisons with standard alpha-particle sources. The combination of these two methods is expected to permit uncertainties of less than 0.1%. Encouraging preliminary results have been reported.[1] A much more elaborate experimental arrangement is now operational.[2] This new arrangement includes two germanium detectors to greatly reduce gamma-ray detector efficiency dependence on neutron beam position, two alpha-particle detectors to permit optimization of calibrations by both the coincidence and standard source methods, and much better boron target positioning precision. The new apparatus will be operated at the NIST Reactor in a thermal beam, and then moved to the new Cold Neutron Guide Hall as one of the first experiments to use that new facility.

3. Remote Data Acquisition (R. A. Schrack)

The transmission of experimental data acquired under remote operating conditions has undergone rapid improvement in the

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[1] J. Radioanalytical and Nucl. Chem., 123 (1988) 551-559).

[2] Nucl. Instr. and Meth. in Phys. Res., A284, No.1 (1989) 220-222.

past year. The acquisition of a compression program has allowed ASCII programs to be reduced in size by about a factor of ten. It has also become feasible to transmit binary files directly to our local microcomputers. We have installed an Ethernet local area network that allows direct transmission without the need for a local host computer. The transmission of the experimental results that took several hours last year can now be accomplished in about thirty seconds. While data transmission problems have been effectively solved we are looking into the possibility of real time remote monitoring of experiments that would allow the detection of experimental difficulties in a timely manner.

4. <u>Search for Neutron Emission during Electrolysis</u> (O. A. Wasson, R. A. Schrack, A. D. Carlson, K. C. Duvall, D. M. Gilliam, D. S. Lashmore, and C. E. Johnson)

The announcement in late March,1989, by scientists in Utah of excessive heat emission and neutron production during electrolysis using Pd electrodes and heavy water-based electrolytes provided an excellent opportunity to apply our neutron detector expertise to timely measurements of a possibly important energy source. We immediately began a collaboration with the scientists in the Electro-Deposition Group at NIST who were experts in the field of electrolysis. We supplied the neutron detectors and associated electronics while they supplied the electrolytic cells and associated materials. We rapidly verified that there were no neutrons produced at the high rate of approximately 10^4 s^{-1} as reported by Pons and Fleishmann. We then changed to lower background neutron detectors to search for weaker neutron production rates of 0.1 s^{-1} as was reported by Jones and colleagues. No neutrons exceeding the cosmic-ray background rate were observed in any of our experiments during a five month interval.

The neutron energy calibration for both the large plastic scintillator and the liquid scintillator was done using the 2.5 MeV neutrons produced by the $D(d,n)^3He$ reaction at the 100-kV ion generator. This was one of the unique calibration tools available at our laboratory.

5. <u>Search for Cold Fusion in a Gas Cell</u> (K. C. Duvall)

An experiment was setup to explore the possibility of producing cold fusion with deuterium ions from a gaseous discharge. This approach to cold fusion is analogous to the method that has received widespread attention using an electrochemical cell. However, a rather novel approach is used to measure the cold fusion yield in the gas cell by detecting charged particles from the competing D(d,p)T fusion reaction. The charged particles are energetic enough to transverse the gaseous medium and to be detected with high efficiency in a silicon surface barrier detector mounted within the chamber. The cathode material used consisted of either Pd or Ti. The brass anode contains an opening that allows a deuteron beam from the 100-kV accelerator to be incident onto the cathode and therefore providing a convenient means of calibrating the charged particle detector. No evidence of cold fusion occurring in the gas cell was found in these measurements for either Pd or preloaded Ti cathodes, at hot and cold cathode temperatures, with ion currents up to 150 mA. The charged particle data indicated that cold fusion was not occurring at a rate above 5 fusions per second.

C. NUCLEAR DATA COMPILATIONS, EVALUATIONS AND MEETINGS

1. Conference entitled "Fifty Years with Nuclear Fission" (J. W. Behrens, A. D. Carlson, S. D. Carpenter, W. A. Cassatt, R. S. Caswell, J. A. Grundl, E. V. Hayward, R. A. Schrack, and O. A. Wasson)

The NIST and the American Nuclear Society sponsored a three-day meeting to celebrate this historic event at NIST on April 25-28, 1989. The honorary co-chairmen were John Wheeler and Edoardo Amaldi while the general co-chairmen were Glenn Seaborg and Emilio Segrè. The 400 attendees were saddened by the death of Professor Segrè just prior to the conference. Mr. Raymond Kammer represented NIST and Ms. Gail de Planque represented the American Nuclear Society at the opening reception on Tuesday evening, April 25 in Gaithersburg. The following day plenary sessions were held at the National Academy of Sciences. Distinguished speakers, all pioneers in the nuclear revolution, reviewed the "Prelude to the First Chain Reaction - 1932 to 1942" in the morning and "Fission Research and Development-Since 1939" in the afternoon. The meeting continued at NIST on Thursday and Friday with presentations by approximately 130 distinguished scientists on the important developments in nuclear science. A banquet honoring the pioneers in this momentous discovery and subsequent development was held on Thursday evening, during which the pioneers recalled the significant events in their careers. The proceedings have been published by the American Nuclear Society under the editorship of A. D. Carlson and J. W. Behrens. Video tapes of selected sessions of the conference are also available from the American Nuclear Society.

2. NEANDC Endorsed Working Group on the $^{10}B(n,\alpha)$ Cross Section Standards (A. D. Carlson, Chairman)

The $^{10}B(n,\alpha)$ cross sections are important 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 it caused in the ENDF/B-VI standards evaluation process.

An Inter-Laboratory working group was recently formed in order to provide a mechanism for improving these cross sections. The working group was endorsed by the NEANDC. Representatives from the measurement, evaluation and user communities met at NIST for the first meeting. It was noted at this meeting how successful these NEANDC working groups or task forces have been in the past. The extensive collaborative work on the parameters of the 1.15 keV resonance in ^{56}Fe is a good example. The objective of the present working group is to have many laboratories collaborate in programs to improve the data base for the cross sections of neutron induced reactions on ^{10}B.

Some of the problems with the data base were highlighted. 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. Some unified effort to produce well characterized samples for these measurements is required.

Information learned from Benchmark integral measurements was discussed. Generally in the past integral data have indicated that the boron differential data are too low in the higher neutron energy region. One recent analysis of integral data does not necessarily support any increases in the ENDF/B-VI evaluation, however.

There were a number of presentations and discussions on boron measurements which have been just recently completed, are now being made or are under consideration. These presentations relate to work at ORNL, NIST, CBNM, and LANL. Active programs are underway at ORNL, NIST and LANL. CBNM has programs under consideration.

3. <u>The Evaluation of The Standards for ENDF/B-VI</u> (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 evaluation of the standard neutron cross sections for ENDF/B-VI has been completed. These standards have been accepted for use in ENDF/B-VI by the Cross Section Evaluators Working Group (CSEWG). The uncertainties for these standard cross sections obtained from the combination of the simultaneous and R-matrix evaluations are still being investigated. The rather small values of some of these uncertainties were a concern expressed in the phase I review of these standards. It should be noted that the uncertainties for the output from the simultaneous and R-matrix evaluations had been increased by the square root of chi squared per degree of freedom before these results were combined in order to take into account the spread of the experimental input values and thus produce more realistic uncertainties. This is a step in the right direction but the assumption is too simplistic. For example, for a cross section, most of the contribution to chi squared may be from one small region in energy, but the chi squared per degree of freedom factor will be applied to all energies. A general method to properly handle this is very difficult. For the subset of the boron and lithium cross sections it may be possible to solve this problem. An effort is now underway towards this end. It may be necessary to attach a statement to the standards cautioning the user that the uncertainties obtained from the evaluation process may be underestimated due to effects such as unrecognized correlations between data sets having high weight. It has been suggested that in addition to the uncertainties obtained from the evaluation process, the standards subcommittee should provide another set of uncertainties, with generally more acceptable values which may have been obtained by a less rigorous process. Work is now underway to provide those uncertainties.

The documentation of the standards evaluation process is nearly completed.

After the acceptance of the cross section standards by CSEWG, a revision by C. Y. Fu to the carbon scattering standard became available which takes into account the two small resonances in ^{13}C. It should be noted that the standard is the natural carbon scattering cross section. This revision was phase I reviewed and accepted for use in ENDF/B-VI.

A suitably accurate representation of the ^{252}Cf spontaneous fission neutron spectrum to be used for ENDF/B-VI is now under investigation.

4. <u>Photon and Charged-Particle Data Center</u> (S. M. Seltzer, M. J. Berger, J. H. Hubbell, A. Schechter)

a. Electron and Positron Stopping Powers and Ranges

An easy-to-use PC program EPSTAR has been developed to calculate the stopping powers (collision and radiative), csda ranges and radiation yields of electrons and positrons in the energy region from 1 keV to 10 GeV (NIST Standard Reference Database 7). The code incorporates the basic cross-section data (with minor improvements) and algorithms used in preparing the tables for ICRU Report 37 "Stopping Powers for Electrons and Positrons", so will allow the user to reproduce those results and to extend the calculations to any material and energy-list of choice.

b. 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.

c. Photon Energy-Absorption Coefficients

A program is underway to prepare a new compilation of photon energy-absorption coefficients, based on our current database of photon interaction cross sections and auxiliary data. A critical review and tabulation of the x-ray fluorescence yields for the K, L, and M shells of all elements Z=1 to 100 has been completed (NBSIR 89-4144, "Bibliography and current status of K, L, and higher shell fluorescence yields for computations of photon energy-absorption coefficients", J.H. Hubbell), and the bremsstrahlung yields of electrons and positrons slowing down are being imported from our EPSTAR calculations. In a collaborative effort with P.D. Higgins, C.H. Sibata and F.H. Attix, results have been prepared for 29 elements and 14 compounds of dosimetric interest for photons with energies from 10 keV to 100 MeV. More extensive compilations are planned.

d. Bremmstrahlung Production Cross Sections

A PC database and code has been developed for the calculation of bremsstrahlung production cross sections, differential in emitted photon energy, for electrons with kinetic energies from 1 keV to 10 GeV for any material specified by the user. The code handles a variety of input for the composition of the material, including chemical formulas.

e. Electron and Positron Elastic-Scattering Cross Sections

A database of elastic-scattering cross sections is being prepared from the results of recently completed exact phase-shift calculations, using Hartree-Fock potentials. The results 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).

1. OAK RIDGE NATIONAL LABORATORY

This past year has seen the winding down of our ENDF/B-VI responsibilities (24 evaluations plus Standards), as well as initiation of several new experimental efforts. These include a measurement of the electric polarizability of the neutron (with Schmiedmayer and Riehs of the Technical University, Vienna), a measurement of the $^{10}B(n,\alpha\gamma)$ reaction as part of an effort to improve and extend the energy range of this standard (with Wasson and Schrack of NIST), a measurement of η of ^{235}U from 1 meV to 0.5 eV (with Moxon of Harwell), a measurement of the neutron emission from iron at three angles from 1 to 20 MeV, and a measurement of the capture widths of ^{56}Fe resonances, including the 1.15 keV, with a newly constructed capture gamma ray system. In addition, the ORELA data acquisition system is being replaced by a new system based on personal computers and an ORELA designed interface. The first two of these systems are operational on the neutron emission and $^{10}B(n,\alpha\gamma)$ measurements, and work very well. As a consequence of the evaluation effort at ORELA, there are more papers listed under heading B (theory and evaluation) than normal.

A. CROSS SECTION MEASUREMENTS

1. Capture, Total and Reaction

a. $^{53}Cr(n,n'\gamma)$ Reactions and the Level Structure of ^{53}Cr[1] (D. C. Larson and J. K. Dickens)

b. Neutron Capture by ^{12}C at Stellar Temperatures[2] (R. L. Macklin)

Prompt gamma-ray detector measurements with graphite samples were examined to establish their limit of sensitivity to weak resonance in the keV neutron energy range. For $kT = 30$ keV the cross section is estimated to be no larger than 14 μb. A lower limit of 3.2 μb is based on 1/v extrapolation of the measured thermal cross-section.

c. Neutron Capture of ^{122}Te, ^{123}Te, ^{124}Te, ^{125}Te, and ^{126}Te[3] (R. L. Macklin and R. R. Winters[4])

Isotopically enriched samples of the tellurium isotopes from mass 122 to mass 126 were used to measure neutron capture in the energy range 2.6 keV to 600 keV at the Oak Ridge Electron Linear Accelerator pulsed neutron source. Starting at 2.6 keV, over 200 Breit-Wigner resonances for each isotope were used to describe the capture data. Least-squares adjustment gave parameters and their uncertainties for a total of 1659 resonances.

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[1] Physical Review C 39, 1736 (1989).

[2] Accepted for publication in Astro. J. (November 1989).

[3] ORNL-6561 (July 1989).

[4] Department of Physics, Denison University, Granville, OH 43023.

Capture cross sections averaged over Maxwellian neutron distributions with temperatures ranging from $kT = 5$ keV to $kT = 100$ keV were derived for comparison with stellar nucleosynthesis calculations. For the three isotopes shielded from the astrophysical r-process, ^{122}Te, ^{123}Te and ^{124}Te at $kT = 30$ keV the respective values were (280 ± 10) mb, (819 ± 30) mb and (154 ± 6) mb. The corresponding products of cross section and solar system abundance are nearly equal in close agreement with s-process nucleosynthesis calculations.

d. Measurement of the ^{85}Rb and ^{87}Rb Capture Cross Sections for s-process Studies[1] (H. Beer[2] and R. L. Macklin)

e. Preliminary Cross Sections for Gamma Rays Produced by Interaction of 1 to 40 MeV Neutrons with ^{59}Co[3] (T. E. Slusarchyk[4])

Data for 46 distinct gamma rays previously obtained at the 20-meter station of the Oak Ridge Electron Linear Accelerator (ORELA) were studied to determine cross sections for 1.0–40.0 MeV neutron interactions with ^{59}Co. Data reduction methods and preliminary cross sections are given in this report.

f. Neutron Scattering in ^{189}Os for Nucleosynthesis Rates of the Odd-A Os Isotopes and Nucleochronology[5] (M. T. McEllistrem,[6] R. R. Winters,[7] R. L. Hershberger,[8] Z. Cao,[9] R. L. Macklin, and N. W. Hill)

g. Resonance Neutron Capture by Argon-40[10] (R. L. Macklin, R. R. Winters,[7] and D. M. Schmidt[11])

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[1] Astrophysical Journal 339, 962-977 (1989).

[2] Kernforschungszentrum Karlsruhe, Institute für Kernphysik III, D-7500 Karlsruhe, Federal Republic of Germany.

[3] ORNL/TM-11404 (October 1989).

[4] Consultant, U.S. Navy.

[5] Physical Review C 40, 591 (1989).

[6] Department of Physics, University of Kentucky, Lexington, KY.

[7] Department of Physics, Denison University, Granville, OH 43023.

[8] Nichols Research Corporation, Huntsville, AL.

[9] Institute of Atomic Physics, Beijing, Peoples Republic of China.

[10] Astronomy and Astrophysics 216, 109 (1989).

[11] Department of Physics, University of California at Santa Barbara, Santa Barbara, CA 93106.

h. Tests for 'Cold Fusion' in the Pd-D2 and Ti-D2 Systems at 40 to 380 Mpa and −196 to 27°C[1] (J. G. Blencoe, M. T. Naney, D. J. Wesolowski, and F. G. Perey)

Experiments have been conducted on the Pd-D_2 and Te-D_2 systems at 40 to 380 MPa and −196 to 27°C to investigate the possibility that "cold fusion" occurs in palladium and titanium deuterides generated by reaction with high-pressure D_2 gas. The experiments were performed using a 4.8 mm i.d. stainless steel pressure vessel that can be operated routinely at pressures as high as 400 MPa.

Experimental results obtained so far range from negative to potentially significant. No sustained heat production has been observed in any experiment. Thermal pulses that persist briefly after pressurizing Pd with D_2 gas are attributable to small amounts of chemical heat released when Pd and D_2 react to form palladium deuteride. No sustained neutron flux above background was observed in any Pd-D_2 experiment.

On the other hand, in a Ti-D_2 experiment just completed, potentially significant results were obtained. During this experiment, there was a period of five consecutive hours when count rates rose to approximately 60 counts/hour above the average background rate. This detector count rate corresponds nominally to 1000 neutrons/hour emitted from the Ti-D_2 sample. However, due to several deficiencies in our neutron detection methods and equipment, we cannot demonstrate conclusively that our experimental data are valid. Consequently, we are upgrading our neutron detection equipment in preparation for a second, improved Ti-D_2 experiment.

i. A Search for Cold Fusion Neutrons at ORELA[2] (D. P. Hutchinson, R. K. Richards, C. A. Bennett, C. C. Havener, C. H. Ma, F. G. Perey, R. R. Spencer, J. K. Dickens, B. D. Rooney, J. Bullock, IV, and G. L. Powell)

A number of experiments were begun on March 29, 1989 to look for neutron emission from a palladium cathode in an electrolytic cell using a deutrated electrolyte. Several different electrode configurations were tried. The fast neutron detector utilized a pair of NE213 scintillator/photomultiplier pairs in a shielded enclosure. This neutron detector has an efficiency of 13% and records a background count rate of 200 events per hour. At present no neutron counts above the background level have been detected.

j. Lack of Evidence for Cold Fusion Neutrons in a Titanium-Deuterium Experiment[3] (F. G. Perey, M. T. Naney, J. G. Blencoe, and D. J. Wesolowski)

In a previous paper we reported potentially significant results from a "cold fusion" experiment on a titanium-deuterium sample. A follow-up experiment with a much-improved neutron detection system has failed to indicate that neutrons were emitted from a similar Ti-D_2 sample.

[1] Submitted to Journal of Fusion Energy (July 1989).

[2] Bull. Am. Phys. Soc. 34, 1860 (1989).

[3] Submitted to Journal of Fusion Energy (September 1989).

2. Actinides

a. High Resolution Fission Cross Section Measurements at ORELA[1] (L. W. Weston and J. H. Todd)

b. Subthreshold and Near-Subthreshold Fission Physics Measurements at the Oak Ridge Electron Linear Accelerator Facility[2] (L. W. Weston and J. A. Harvey)

c. Neutron Absorption Cross Section of Uranium-236[3] (R. L. Macklin and C. W. Alexander)

d. Statistical Properties of the ^{235}U Resonance Parameters up to 300 eV[4] (L. C. Leal,[5] G. de Saussure, R. R. Winters,[6] and R. B. Perez[7])

e. Resonance Structure in the Fission of (^{235}U + n)[8] (M. S. Moore,[9] L. C. Leal,[5] G. de Saussure, R. B. Perez,[7] and N. M. Larson)

f. Resonance Structure in the Fission of (^{235}U + n)[10] (M. S. Moore,[9] G. de Saussure, L. C. Leal,[5] R. B. Perez,[7] and N. M. Larson)

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[1] Proceedings of ANS Conference on Fifty Years with Nuclear Fission, Gaithersburg, MD, April 25–28, 1989, Vol. 1, p. 957.

[2] Proceedings of ANS Conference on Fifty Years with Nuclear Fission, Gaithersburg, MD, April 25–28, 1989, Vol. 2, p. 368.

[3] Nucl. Sci. and Eng. 104, 258 (1990).

[4] Trans. Am. Nucl. Soc. 59, 341 (1989).

[5] University of Tennessee, Knoxville, TN.

[6] Department of Physics, Denison University, Granville, OH, 43023

[7] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

[8] Nucl. Phys. A 502, 443c (1989).

[9] Los Alamos National Laboratory, P-15, Los Alamos, NM 87545.

[10] Presented at the International Conference Fifty Years of Research in Nuclear Fission, Berlin, West Germany, April 3–7, 1989.

3. Experimental Techniques

a. Procedures Manual for the Oak Ridge Electron Linear Accelerator[1] (J. A. Harvey, O. W. Christian, T. A. Lewis, and R. W. Peelle)

Work at the Oak Ridge Electron Linear Accelerator (ORELA) is covered by regulations and procedures that relate to employee and public safety, the safeguarding of sensitive materials, and the security for the federal property within the ORELA building. The goal of this manual is to make the procedures of particular concern conveniently available to persons working at ORELA. However, this manual does not cover procedures for optimization of accelerator performance or research projects.

This manual is a major update of one issued in March 1969 and reissued in 1979 as ORNL/TM-6801. The changes reflect the availability of the Safety Study (SS) report and the Operational Safety Guideline (OSG) report, and the modified research environment. Following the accepted practice for other ORNL procedure manuals, we have chosen a loose-leaf format to facilitate revisions. A new Table of Contents will be issued with each revision giving the publication date of each section. An up-to-date copy of the text may also be seen by typing HELP ORELA PROCEDURES on the ORELA VAX computer.

In the area of safety, the SS and OSG reports were prepared to support the acceptability of the risk associated with continued opeation of the ORELA facility. These documents are attached as Appendices A and C are frequently referenced in the text. Since the language in these documents has official status, paraphrasing of material included there is avoided in this manual. Except for emergencies, this document does not include procedures common to industrial and laboratory environments. It is assumed that technical workers are trained in their disciplines.

b. The NE-110 Scintillator Response to 10- to 100-MeV Carbon Ions[2] (J. K. Dickens and J. W. McConnell)

Measurements of the response of NE-110 organic scintillator to 13-, 34-, 44-, 70-, and 95-MeV incident carbon ions are reported.

c. Electron Linear Accelerators for Fast Neutron Data Measurements in Support of Fusion Energy Applications[3] (K. H. Bockhoff,[4] A. D. Carlson,[5] O. A. Wasson,[5] J. A. Harvey, and D. C. Larson)

The interest in neutron data for energy applications has moved over the past 40 years from thermal/epithermal data to data in the eV/keV range (following or anticipating the general trend of technological development from thermal to fast fission reactors) to the MeV energy range to include fusion reactors. While the support for further improvement of data for fission reactors has weakened, the interest in neutron data for the development

[1] Expected publication date, April 1990.

[2] Nucl. Inst. Meth. in Phys. Res. A281, 577 (1989).

[3] Accepted by Nucl. Sci. Eng.

[4] Geel, Belgium.

[5] National Institute of Standards and Technology.

of terrestrial fusion power sources is rising, irrespective of the uncertain time schedule for the successful realization of such reactors. For this application, neutron data are mainly wanted from the keV region to about 14 MeV, which implies an extension of the energy region intensively investigated for fission reactor interests to substantially higher energies.

d. Calculation of the ORELA Neutron Moderator Spectrum and Resolution Function[1] (F. G. Perey and S. N. Cramer)

The yield, spectrum, and delay-time distributions (resolution function) of escape neutrons from the ORELA water-moderated and water-cooled tantalum target assembly are calculated using time-dependent, three-dimensional Monte Carlo techniques. Results are obtained for three different areas of the target that are frequently used in high resolution experiments: the full moderator, a small area of the moderator close to the tantalum target, and the tantalum target itself. The resulting spectra and delay-time distributions are compared with measured values and presented in a form suitable for use in the resonance parameter analysis code SAMMY.

e. ORELA's Personal Data Acquisition Work Station[2] (B. D. Rooney, J. H. Todd, R. R. Spencer, and L. W. Weston)

A new multiparameter data acquisition system has been developed and fabricated at the Oak Ridge Electron Linear Accelerator (ORELA) which utilizes an IBM PS/2 model 80 personal computer and data handler with a 2048 word buffer. The acquisition system can simultaneously acquire data from one, two, or three digitizers, multiplex up to four detectors, read and control up to sixteen scalers, and output 32 DC logic signals which can be used to control external instrumentation. Software has been developed for the OS/2 operating system, supporting multiparameter data storage up to three million channels and has the capability of collecting data. The system also supports multiparameter biasing and can collect, crunch, and store data at rates as high as 30,000 events per second.

B. DATA ANALYSIS

1. Theoretical

a. Pairing Interaction Effects in Exciton Level Densities[3] (C. Y. Fu)

Pairing corrections in particle-hole (exciton) state-density formulas commonly used in precompound nuclear theories are, strictly speaking, dependent on the nuclear excitation energy U and the exciton number n. A general (but simple) formula for (U, n)-dependent pairing corrections has been derived, based on the BCS pairing equations for constant single-particle spacing, for the exciton state-density formula for one kind of Fermion. It is shown that the constant-pairing-energy correction used in standard state-density formulas, such as Gilbert and Cameron, is a limiting case of the present

[1] In preparation for ORNL/TM.

[2] ORNL/TM-11454 (in review).

[3] NEANDC Specialists' Meeting on Level Densities, Bologna, Italy, November 15–17, 1989.

(U, n)-dependent results. Spin cutoff factors with pairing effects are obtained in the same derivations, thereby defining the exciton level-density formula for applications in quantum mechanical precompound theories. Preliminary results from extending the pairing interaction effects to level-density formulas for two kinds of Fermions are summarized. The results show that the ratios in the exciton level densities in the one-Fermion and two-Fermion approaches depend on both U and n, thus likely leading to differences in calculated compound to precompound ratios. However, the changes in the spin cutoff factors in the two cases are rather small.

b. Maxwellian Cascade Model[1] (R. L. Macklin)

A model for gamma-ray cascade de-excitation of a nucleus derived from the Maxwellian energy distribution function but imposing energy conservation was investigated. Energy distributions and multiplicities and their averages were found over a range of nuclear temperatures and excitation energies appropriate to neutron capture. The model was compared to existing measurements for tantalum, a case where the level density was high and thus a good approximation to the model.

c. Use of Monte Carlo Techniques to Derive Yields for $n + {}^{12}C$ Multibody Breakup Reactions: Programming the Computer to Simulate Collisions by Fast Neutrons[2] (J. K. Dickens)

A computer "experiment" using Monte Carlo sampling methods has been designed to simulate the breaking up of ${}^{12}C$ by medium-energy neutrons into final reaction channels having 2, 3, or 4 outgoing charged particles. The calculational nuclear physics concept used in the "experiment" is one of a sequentially decaying highly-excited compound nucleus. Two methods of Monte Carlo sampling, the rejection method and the cumulative-distribution method, are discussed as applied to probability functions developed in the program.

d. Analysis of the ${}^{235}U$ Neutron Cross Sections in the Resolved Resonance Range[3] (L. C. Leal,[4] G. de Saussure, and R. B. Perez[5])

e. R-Matrix Analysis of the ${}^{241}Pu$ Neutron Cross Sections in the Energy Range Thermal to 300 eV[6] (H. Derrien[7] and G. de Saussure)

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[1] ORNL/TM-11372 (November 1989).

[2] Comp. in Phys. 3, 62 (1989).

[3] Proceedings of ANS Conference on Fifty Years with Nuclear Fission, Gaithersburg, MD, April 25–28, 1989, Vol. 1, p. 939.

[4] University of Tennessee, Knoxville, TN.

[5] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

[6] ORNL/TM-11123 (April 1989).

[7] Centre d'Etudes Nucleaires de Cadarache, Saint-Paul-Lez-Durance, France.

f. Calculation of Resonance Self Shielding in ^{235}U[1] (L. C. Leal,[2] G. de Saussure, and R. B. Perez[3])

The self-shielded fission rates for ^{235}U measured by Czirr have been computed, in the range 0.464 to 464 eV, with the ^{235}U resolved resonance parameters of the present version of ENDF/B-VI.

The good agreement between computed and measured relative shielded fission rates over most energies and for uranium absorber thicknesses varying from 0.5 to 19 g/cm^2 suggests that the ENDF/B-VI resolved resonance parameters for ^{235}U provide a good description of resonance self-shielding; the discrepancies between calculations and measurements in the range 4.64 to 21.5 eV are not understood and suggest that additional measurements of self indication ratios might still be desirable.

g. A New Resonance Region Evaluation of Neutron Cross Sections for ^{235}U[4] (G. de Saussure, L. C. Leal,[2] R. B. Perez,[3] N. M. Larson, and M. S. Moore[5])

h. R-Matrix Analysis of the ^{241}Pu Neutron Cross Sections in the Energy Range Thermal to 300 eV[6] (H. Derrien[7] and G. de Saussure)

The report is a description of the analysis of the ^{241}Pu neutron cross sections in the resolved resonance region at Oak Ridge National Laboratory (ORNL) using the multilevel-multichannel Reich-Moore code SAMMY. The resonance parameters were obtained in the energy range 0 to 300 eV. The statistical properties of the parameters are discussed. Tabulated and graphical comparison between the experimental data and the calculated cross sections are given. The results are available in ENDF/B-V format and will be proposed for the evaluated data library JEF2 and ENDF/B-VI.

i. Status of Theories Used for Calculations of Production Cross Sections of Long-Lived Radionuclides[8] (C. Y. Fu)

The theories discussed in this paper are confined to those currently being used or considered for the calculation of activation cross sections. The theories are the same regardless of whether the activation product is long lived or short lived. However, the cross sections for the generation of long-lived radionuclides are more difficult or expensive

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[1] American Nuclear Society Annual Meeting, Nashville, TN, June 10-14, 1990.

[2] University of Tennessee, Knoxville, TN.

[3] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

[4] Nucl. Sci. Eng. 103, 109 (1989).

[5] Los Alamos National Laboratory, P-15, Los Alamos, NM 87545.

[6] Submitted to Nucl. Sci. Eng. (June 1989).

[7] Centre d'Etudes Nucleaires de Cadarache, Saint-Paul-Lez-Durance, France.

[8] IAEA Consultants' Meeting on Cross Sections for the Generation of Long-Lived Radionuclides, Argonne, IL, September 13–14, 1989.

to measure, hence there are fewer data available and the requirement on the predictive capability of the theories used is more stringent.

Topics included in this paper are the optical model, gamma-ray strength function, total and exciton level-density theories, and the pre-compound model. In each subject, we describe the most commonly used theories first, followed by relatively new developments that are used in at least one model code or the promising theories that do not appear to require a large effort for incorporation into existing H-F codes.

j. Maxwellian Cascade Model[1] (R. L. Macklin)

A model for gamma-ray cascade de-excitation of a nucleus derived from the Maxwellian energy distribution function but imposing energy conservation was investigated. Energy distributions and multiplicities and their averages were found over a range of nuclear temperatures and excitation energies appropriate to neutron capture. The model was compared to existing measurements for tantalum, a case where the level density was high and thus a good approximation to the model.

k. Updated Users' Guide for SAMMY: Multilevel R-Matrix Fits to Neutron Data Using Bayes' Equations[2] (N. M. Larson)

l. R-Matrix Analysis of ^{239}Pu Neutron Cross Sections in the Energy Range Up to 1000 eV[3] (H. Derrien,[4] G. de Saussure, and R. B. Perez[5])

We report the results of a R-matrix analysis of the ^{239}Pu neutron cross sections up to 1 keV neutron energy. The analysis was performed with the multilevel-multichannel Reich-Moore code SAMMY. We describe the method of analysis and discuss the selection of experimental data. Some tabular and graphical comparisons between calculated and measured cross sections and transmissions are presented. The statistical properties of the resonance parameters are examined. More extensive comparisons between calculations and measurements and a table of the resonance parameters in ENDF/B format are available in an ORNL report. The resonance parameters were proposed for the new evaluated data files ENDF/B-VI and JEF2.

[1] Submitted to Nucl. Instrum. Meth. (November 1989).

[2] ORNL/TM-9179/R2 (June 1989).

[3] Submitted to Nucl. Sci. Eng. (September 1989).

[4] Centre d'Etudes Nucleaires de Cadarache, Saint-Paul-Lez-Durance, France.

[5] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

m. Reich-Moore and Adler-Adler Representations of the ^{235}U Cross Sections in the Resolved Resonance Region[1] (G. de Saussure, L. C. Leal,[2] and R. B. Perez[3])

In the first part of this paper, a reevaluation of the low-energy neutron cross sections of ^{235}U is described. This reevaluation was motivated by the discrepancy between the measured and computed temperature coefficients of reactivity and is based on recent measurements of the fission cross section and of η in the thermal and subthermal neutron energy regions. In the second part of the paper, we discuss the conversion of the Reich-Moore resonance parameters, describing the neutron cross sections of ^{235}U in the resolved resonance region, into equivalent Adler-Adler resonance parameters and into equivalent momentum space multipole resonance parameters.

n. Analysis of the ^{239}Pu Neutron Cross Sections from 300 to 2000 eV[4] (H. Derrien[5] and G. de Saussure)

A recent high-resolution measurement of the neutron fission cross section of ^{239}Pu has allowed the extension from 1 to 2 keV of a previously reported resonance analysis of the neutron cross sections, and an improvement of the previous analysis in the range 0.3 to 1 keV.

The results of the ^{239}Pu fission cross-section measurement reported in 1984 by Weston and Todd and recent transmission measurments of Harvey et al. were analyzed up to 1 keV. The resonance parameters obtained in this analysis have been accepted for the present version of ENDF/B-VI. The 1984 fission cross-section measurement of Weston and Todd was done on a 20-m flight path and the instrumental resolution of the measurement was not sufficient to carry the resonance analysis beyond 1 keV. A new fission cross-section measurement, on a 80-m flight path, has recently been completed by Weston and Todd. The resolution of this new measurement is comparable to that of the transmission measurements of Harvey et al. (also done on a 80-m flight path) and allows to extend the resonance analysis to higher energies. The purpose of this report is to describe the results of a consistent multilevel resonance analysis, from 300 eV to 2 keV, of the new fission cross-section measurement of Weston and Todd and of the transmission measurements of Harvey et al.

o. A Re-Evaluation of $^{32}S(n,p)$ Cross Sections From Threshold to 5 MeV[6] (C. Y. Fu)

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[1] To be presented at the International Conference on the Physics of Reactors: Operation, Design, and Computation, Marseille, France, April 23–27, 1990.

[2] University of Tennessee, Knoxville, TN.

[3] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

[4] To be presented at the American Nuclear Society Annual Meeting, Nashville, TN, June 10–14, 1990.

[5] Centre d'Etudes Nucleaires de Cadarache, Saint-Paul-Lez-Durance, France.

[6] Proceedings of the American Nuclear Society Topical Conference on Advanced in Nuclear Computation and Radiation Shielding, Santa Fe, NM, April 9–13, 1989, Vol. 1 p. 17:1 (1989).

p. Background Subtraction in Multiplicity Distributions[1] (F. G. Perey)

We propose an algorithm for substracting background from neutron multiplicity distribution data which dampens the strong oscillations one frequently observes with the conventional method when the average multiplicity in the background is high and the statistics in the counting data are not very high. The algorithm, which is a constrained least-squares algorithm, produces results that converge to those of the conventional method when the statistics are sufficiently high.

2. ENDF/B Related Work

a. Evaluated Cross Sections for Neutron Scattering from Natural Carbon Below 2 MeV Including R-Matrix Fits to ^{13}C Resonances[2] (C. Y. Fu)

The ENDF/B-V differential cross sections for neutron scattering from natural carbon below 2 MeV, recommended as standards for measurements and based on an R-matrix analysis for ^{12}C using natural carbon data, are revised to include ^{13}C resonances for high-resolution applications. The recommended ^{13}C cross sections are also based on an R-matrix analysis of the available data. The 0.1529-MeV and the 1.736-MeV resonances rise above the natural carbon background by 7% and 1%, respectively. The angular distributions of the elastically scattered neutrons from ^{13}C are generated by the R-matrix theory. The final recommended cross sections and Legendre coefficients of angular distributions for natural carbon, adopted for ENDF/B-VI, are tabulated.

b. Structural and Shielding Material Evaluations for ENDF/B-VI[3] (D. C. Larson and P. G. Young[4]

Following completion of ENDF/B-V several problems and shortcomings were apparent in evaluations for important shielding and structural materials. Lack of energy balance was a new problem which arose from use of nonisotopic evaluations and lack of checking by evaluators. Discrepancies between evaluated and measured neutron emission spectra resulted from omission of a precompound component in the theoretical analysis of the data. Difficulties experienced by users in obtaining accurate KERMA and radiation damage function quantities were due primarily to format shortcomings. These problems and potential solutions were discussed by the General Purpose Evaluation Subcommittee of CSEWG in the early 1980's. Improvements in formats and nuclear model codes, and use of isotopic evaluations were some of the techniques implemented to insure improved evaluations for ENDF/B-VI. New developments in experimental techniques provided improved data upon which to benchmark the evaluations. In this paper we outline major improvements and provide a list of materials upgraded for ENDF/B-VI.

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[1] In preparation for ORNL/TM.

[2] Accepted by Nucl. Sci. Eng.

[3] Trans. Am. Nucl. Soc. 60, 606 (1989).

[4] Los Alamos National Laboratory, Los Alamos, NM 87545.

c. A Review of Activation Cross Sections in the ENDF/B-VI General Purpose Files of Cr, Fe, Ni, Cu, and Pb[1] (C. Y. Fu)

Isotopic evaluations for ^{50,52,53,54}Cr, ^{54,56,57,58}Fe, ^{58,60,61,62,64}Ni, ^{63,65}Cu, and ^{206,207,208}Pb are included in ENDF/B-VI for the first time. These general purpose files, all by the ORNL evaluation group, naturally account for many activation cross sections. In this review, we first took the 33 activation reactions for these materials from the high priority CSEWG list for fusion reactor design and checked for their presence in the general purpose files. It was immediately obvious that an evaluation for ^{204}Pb, omitted due to its low abundance, needs to be added as it would contain three high priority activation cross sections, namely, ^{204}Pb(n,γ), (n,p), and (n,2n). Among the three, ^{204}Pb(n,γ)^{205}Pb, having the very long half life of 14 million years, is particularly important for consideration of radioactive waste disposal. Another reaction with long-lived (0.3 million years) daughter, ^{61}Ni(n,2p)^{60}Fe, ignored in the general purpose evaluation because of its small cross section, should also be added. The remainder of the activation cross sections are reviewed in terms of the experimental data base and the evaluation methods. Most of them have been significantly improved over ENDF/B-V through either detailed resonance analysis (e.g., capture cross sections) or least-squares averaging (e.g., dosimetry reactions).

d. Test of the ENDF/B Unresolved Resonance Formalism for ^{235}U[2] (L. C. Leal,[3] G. de Saussure, R. B. Perez,[4] N. M. Larson, and M. S. Moore[5])

It is common practice in ENDF/B to represent neutron cross sections in the unresolved resonance region by specifying the average values and distribution laws of resonance parameters. This formalism allows the calculation of resonance self-shielding and of its variation with temperature. The purpose of this paper is to present a test of the validity of the formalism by comparing self-shielding factors computed with the ENDF/B unresolved formalism, with values computed with the resolved resonance parameters recently evaluated for the neutron cross sections of U-235 up to 500 eV.

e. New Cross Section Evaluations for Reactor Fuel Materials[6] (L. W. Weston, P. G. Young,[7] and W. P. Poenitz[8])

There were major new evaluations for the "Big 3" (U-235, U-238, and Pu-239) and the "Little 2" (Pu-240 and Pu-241) for ENDF/B-VI. New and improved analysis methods

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[1] NEANDC Specialist's Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications, Argonne, IL, September 13–15, 1989.

[2] Trans. Am. Nucl. Soc. 60, 620 (1989).

[3] University of Tennessee, Knoxville, TN.

[4] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

[5] Los Alamos National Laboratory, Los Alamos, NM 87545.

[6] Trans. Am. Nucl. Soc. 60, 606 (1989)

[7] Los Alamos National Laboratory, Los Alamos, NM 87545.

[8] Argonne National Laboratory – West, Idaho Falls, ID 83401.

and models were used for the thermal parameters, the resolved resonance region, the unresolved resonance region and the high-energy neutron region of smooth cross sections. The maturing of evaluation techniques and methods in the eleven years since ENDF/B-V has been most impressive. Appreciable amounts of new nuclear data have also become available.

f. Methods and Formats for ENDF/B-VI[1] (R. W. Roussin)

The formats for ENDF/B-VI have been dramatically revised (though Version V formats had been extremely resistant to change.) These changes are due to the recognition of some inherent limitations in the format in terms of providing a true representation of the physics of interaction of particles with matter.

The format manual, "Data Formats and Procedures for the Evaluated Nuclear Data file, ENDF" has been completely rewritten and the final version is expected to be issued during 1989. Draft copies are available to evaluators and potential processors of ENDF/B-VI. The new format designated ENDF-6, allows higher incident energies, adds more complete descriptions of the distributions of emitted particles, and provides for incident charged particles and photons by partitioning the ENDF library into sublibraries. Decay data, fission product yield data, thermal neutron scattering data, and photo-atomic data have also been formally placed in sublibraries. Representations of the resonance region via R-function and R-matrix have been introduced and emitted-particle-correlated energy-angle distributions are allowed. Covariance formats for secondary distributions and isomer production are provided.

g. Photon Cross Sections for ENDF/B-VI[2] (D. K. Trubey, M. J. Berger,[3] and J. H. Hubbell.[3])

The PHOTX library of the National Institute of Standards and Technology will be used as the basis of File 23 (photon cross sections) for ENDF/B-VI. The PHOTX library is based on an experimental data base consisting of 21,000 data points from 512 literature sources for 82 elements. An important difference from earlier compilations is that renormalization of photo-effect cross sections is not performed.

h. Uncertainties of the ENDF/B-VI ^{238}U Unresolved Resonance Parameters in the Range 4 keV $< E <$ 45.18 keV (MAT = 1398, MF = 2, MT = 251)[4] (G. de Saussure and J. H. Marable[5]

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[1] Trans. Am. Nucl. Soc. 60, 617 (1989).

[2] ANS Topical Meeting on Advances in Nuclear Engineering Computation and Radiation Shielding, Santa Fe, NM, April 9–13, 1989, Proc. Vol. 1, pp. 18:1 (1989).

[3] National Institute of Standards and Technology, Gaithersburg, MD.

[4] Nucl. Sci. Eng. 101, 285 (1989).

[5] Consultant.

i. On the ENDF/B Unresolved Resonance Region Formalism Representation for Pu-239[1] (S. Ono,[2] R. Paviotti-Corcuera,[2] R. B. Perez,[3] and G. de Saussure)

The calculation of self-shielded group cross sections is a main ingredient in determining reactor neutronics. During the past few years, core physicists have shown concern about the reliability of self-shielding factor calculations in the unresolved resonance region. The representation of the neutron cross sections in the UR region is based on the statistical theory of nuclear reactions. In this region the cross sections are specified by the average values and distribution functions of the resonance parameters. There are some severe limitations built into the UR region methodology, as prescribed, for instance, in the ENDF/B files formats and procedures.

The purpose of this work is to compare the performance of several cross-section evaluation files for the calculation of average cross sections in the unresolved resonance region and to test the validity of the ENDF/B methodology for the calculation of self-shielding factors in this region. The ^{239}Pu neutron cross sections were used for this comparison since a multilevel R-matrix analysis was available, which extended the resolved resonance region from its present ENDF/B limit of 300 eV up to 1 keV.

j. Improvements in ENDF/B-VI Silicon, Chromium, Iron, and Nickel Evaluations for Radiation Damage Studies[4] (D. C. Larson, D. M. Hetrick, C. Y. Fu, and S. J. Epperson[5])

For neutron radiation damage studies and KERMA calculations reliable cross-section data and associated spectral distributions are needed for outgoing charged particles, recoil nuclei, gamma rays and neutrons. If information available from the evaluated nuclear data files is incomplete, only approximate calculations can be made for the above quantities of interest. The severity of the approximation depends on the presence and quality of available cross-section data and spectral distributions. A fundamental point is the requirement of energy balance; no more (or less) energy can come out from a reaction in the form of particles and gamma rays than is carried into the reaction by the energy of the neutron plus the Q value ($E + Q$). Unfortunately, for many cross-section evaluations up through ENDF/B-V, energy conservation was only approximately achieved. This point was clearly made following preliminary release of ENDF/B-V, as a result of processing and data testing. A primary cause of this difficulty was the use of elemental evaluations, for which the Q value for a reaction is not well defined; only an average Q can be used.

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[1] To be presented at the American Nuclear Society Annual Meeting, Nashville, TN, June 10–14, 1990.

[2] Centro Tecnico Aeroespacial, Sao Jose dos Campos, Brazil.

[3] Oak Ridge National Laboratory and University of Tennessee, Knoxville, TN.

[4] To be presented at the Seventh ASTM-EURATOM Symposium on Reactor Dosimetry, Strasbourg, France, August 27–31, 1990.

[5] University of Florida, Gainesville, FL.

Use of a sophisticated nuclear model code (TNG) to simultaneously reproduce experimental data in a global manner for all reactions at all incident energies has significantly improved the evaluated results. This method takes advantage of constraints imposed by the measured total cross section and results in smaller uncertainties in the final results than evaluation methods which use several unrelated codes to calculate the various partial cross sections.

k. <u>Contribution to NNDEN Evaluation Newsletter</u>[1] (D. C. Larson)

l. <u>Contribution to Fast Neutron Cross Sections Newsletter</u>[2] (D. C. Larson)

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[1] NNDEN Evaluation Newsletter NNDEN-42, 44 (1990).

[2] Submitted to Fast Neutron Cross Section Newsletter (November 1989).

OHIO UNIVERSITY

A. MEASUREMENTS

1. The (p,n) Reaction on Li Isotopes for E_p = 60–200 MeV (J. Rapaport, C.C. Foster*, C.D. Goodman*, C.A. Goulding**, T.N. Taddeucci**, D.J. Horen†, E.R. Sugarbaker††, C. Gaarde#, J. Larsen#, J.A. Carr##, F. Petrovich## and M.J. Threapleton##)

Differential cross section angular distributions for the ^{6,7}Li(p,n)^{6,7}Be reactions have been measured at energies between 60 and 200 MeV. The experimental angular distributions have been analyzed using a microscopic distorted wave impulse approximation. The results of self–consistent microscopic DW calculations based on a complete set of weak and electromagnetic data for the mass 6 and 7 systems have also been obtained. The measured (p,n) cross section for the ^{7}Be (gs) and ^{7}Be (0.43 MeV) transitions are used to obtain the branching ratio of the ^{7}Be (gs) decay to the gs and 0.478 MeV states in ^{7}Li. The zero degree polarization transfer (D_{nn}) data have also been measured for the ^{6}Li(p,n)^{6}Be (gs) and for the ^{7}Li(p,n)^{7}Be (gs+0.43 MeV) transi– tions. We have studied the energy dependence of total and zero degree differential cross section for the ^{7}Li(p,n)^{7}Be (gs+0.43 MeV) transitions. We have also completed a study for the (n,p), (p,p') and (p,n) reactions in ^{6}Li populating isospin triplets.

2. Zero Degree Cross Sections for the ^{7}Li(p,n)^{7}Be (gs+0.43 MeV) Reaction in the Energy Range 80–790 MeV (T.N. Taddeucci**, R.C. Byrd**, T.A. Carey**, C.A. Goulding**, J.B. McClelland**, L.J. Rybarcyk**, W.C. Sailor**, W.P. Alford@, M. Barlett@@, D.E. Cickowski@@, C.C. Foster*, C.D. Goodman*, W. Huang*, C. Gaarde#, J. Larsen#, E. Gulmez‡, C.A. Whitten, Jr.‡, D. Horen†, D. Marchlenski††, E.R. Sugarbaker†† and J. Rapaport)

Differential cross section distributions for the ^{7}Li(p,n)^{7}Be (gs+0.43 MeV) reaction have been measured for E_p = 80, 120, 160, 200, 494, 644 and 790 MeV. These distributions have been integrated and normalized to independent values for the total

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cross section obtained from parameterizations of ^{7}Li(p,n) activation measurements. Zero degree cross sections obtained from this normalization have been calculated.

3. Gamow–Teller Transition Strengths from the ^{11}B(p,n)^{11}C Reaction in the Energy Range 160–790 MeV (T.N. Taddeucci*, R.C. Byrd*, T.A. Carey*, J.B. McClelland*, L.J. Rybarcyk*, W.C. Sailor*, W.P. Alford**, D.E. Ciskowski†, C.C. Foster††, C.D. Goodman††, W. Huang††, I.J. van Heerden††, C. Gaarde#, J. Larsen#, E. Gulmez##, C.A. Whitten, Jr.##, D.J. Horen@, D. Marchlenski@@, E. Sugarbaker@@, D. Prout‡ and J. Rapaport)

Zero degree cross sections have been measured for the ^{11}B(p,n)^{11}C reaction at bombarding energies of E_p = 160, 200, 494, 644 and 790 MeV. In addition, spectra have been obtained at lab scattering angles of 3° and 5° at 494 MeV, and the transverse spin–slip probability at 0° has been measured for E_p = 160 MeV. These data are used to obtain estimates of the Gamow–Teller transition strength to final states in ^{11}C up to an excitation energy of about 14 MeV. These values are important in the study that proposes ^{11}B as a neutrino detector material that can simultaneously provide distinguishable sensitivity to the electron–neutrino flux and the flavor–inclusive neutrino flux.[1]

4. Pre–Equilibrium Neutron Emission from ^{93}Nb and ^{209}Bi at 20 MeV‡‡ (A. Marcinkowski+, R.W. Finlay and J. Rapaport)

Earlier studies of pre–equilibrium neutron emission induced by neutrons with E_n > 14 MeV have been extended a) in the bombarding energy and b) in the energy range of emitted neutrons that were detected. The present study attempts to explore the transition from pre–equilibrium to equilibrium regions of the spectra.

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‡‡ Supported in part by the National Science Foundation and by the Atomic Energy Agency of Poland.
\+ Permanent address: Soltan Institute for Nuclear Studies, Warsaw, Poland.
1 Raghavan and Pakosa, Phys. Rev. D37, 849 (1988).

5. Spin–Spin Cross Sections of ^{27}Al and ^{93}Nb for Neutrons from 20 to 50 MeV* (W. Heeringa**, H.O. Klages**, Chr. Wölfl** and R.W. Finlay)

Spin–spin cross sections of ^{27}Al and ^{93}Nb have been measured for neutrons between 20 and 50 MeV with high precision. Absolute size and energy dependence of data agree well with existing predictions from folding–model calculations. The data can also be reproduced with phenomenological spin–spin potentials, but do not allow distinction between spherical and tensor interactions. The deduced spin–spin strengths are close to 1 MeV.

6. The n+^{209}Bi Mean Field Between –20 and 60 MeV†1 (R.K. Das†† and R.W. Finlay)

New measurements of differential elastic neutron scattering for ^{209}Bi at energies between 7.5 and 24.0 MeV are presented along with new measurements of σ_T up to 60 MeV. These data, taken together with earlier measurements at lower energy, provide a very large data set for testing and extending the dispersive optical model analysis (DOMA). The dispersion correction to the optical model has been obtained from the scattering and total cross section data. The potential is extrapolated to negative energy for comparison with bound state properties. A very good description of all of the data is obtained from –20 MeV to +60 MeV. The present analysis suggests somewhat less depletion of the Fermi sea in this mass region than has been obtained from electron scattering data and from other recent treatments of the dispersion correction to the optical model.

7. Spectroscopy of ^{24}Mg via $^{23}Na(d,n)^{24}Mg$# (P.M. Egun##, C.E. Brient and S.M. Grimes)

We have measured the angular distribution for $^{23}Na(d,n)^{24}Mg$ at 8 MeV. Comparisons are made to the results of DWBA calculations have yielded absolute spectroscopic factors for 28 states, including a few unresolved doublets, with new spectroscopic factors for six states. The results are compared to spectroscopic factors in the literature.

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1 Submitted to Physical Review

8. Spectra for the (p,xn) Reaction at E_p = 120 and 160 MeV for Targets of ^{27}Al, ^{90}Zr and ^{208}Pb* (W. Scobel**, M. Trabant**, R. Bonetti†, C. Chiesa†, R.C. Byrd††, C.C. Foster#, S.M. Grimes, M. Blann##, B.S. Pohl## and B.A. Remington##)

Measurements of the neutron spectra produced by bombardment of targets of ^{27}Al, ^{90}Zr and ^{208}Pb with 120 and 160 MeV protons have been made. Data have been obtained for angles from 0° and 145° and for neutron energies from 30 MeV to the maximum energy produced. The data have been compared with the predictions of a semi–classical pre–equilibrium model (the geometry dependent hybrid model, GDH) and the multi–step direct model, MSD, of Feshbach, Kerman and Koonin. Good agree– ment in magnitude and relative angular dependence is found with the MSD model, while the GDH model does well in predicting angle–integrated cross sections but fails to predict the angular distributions. All of the neutrons in the region studied $E_n \geq 30$ MeV come from non–equilibrium reactions.

A paper on these results has been submitted to Physical Review C.

9. Neutron Inelastic Scattering from ^{13}C* (E.F. Saito, T.N. Massey, J.E. O'Donnell, R.O. Lane and H.D. Knox@)

The inelastic neutron scattering to levels in ^{13}C from 6.86 and 10 MeV is currently under study to obtain information on the properties of levels in ^{14}C from 15 to 19 MeV. The shell model R–matrix analysis of the scattering data will allow deduction of the level properties in ^{14}C. The measurements in progress are in the incident energy neutron energy region $6.8 < E_n < 13$ MeV, using dynamic pulse shape discrimination and dynamic bias on the time–of–flight. The secondary neutron observed in this energy range[1] should be modeled well by Barker's theory[2] of sequential two–body reactions in the R–matrix formalism.

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* Work supported by the Department of Energy
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1 D.A. Resler, R.O. Lane and H.D. Knox, Phys. Rev. C35, 855 (1987)
2 F.C. Barker, Aust. J. Phys. 42, 35 (1989)

B. MODEL CALCULATIONS AND ANALYSIS

1. Phenomenological Analysis of Dispersion Corrections for Neutron and Proton Scattering from ^{208}Pb* (R.W. Finlay, J. Wierzbicki**, R.K. Das† and F.S. Dietrich††)

Elastic scattering of protons and neutrons from ^{208}Pb in the energy range up to 61.4 MeV is analyzed in order to establish a consistent phenomenology with which to examine the recent results of dispersion theory. The present analysis avoids conventional assumptions about the energy dependences of potential depths or geometrical parameters and attempts to include estimates of the uncertainty in our knowledge of the derived potential parameters. Recently reported evidence for energy–dependent geometrical parameters in the n+^{208}Pb potential is supported by the present analysis, but no comparable effect is observed for phenomenological proton potentials in the range of available data ($E_p > 9$ MeV). The present analysis shows that, unlike the situation for heavy–ion scattering, the Coulomb potential does not cut off the imaginary potential for p+^{208}Pb. Consequently, no rapid excursions in the parameters of the p+^{208}Pb potential are expected to occur until the incident energy is well below the Coulomb barrier where the nuclear potential is essentially unobservable.

2. Analysis of Precise Neutron Total Cross Section in Terms of the Nuclear Ramsauer Effect†† (J.D. Anderson# and S.M. Grimes)

Total cross sections for neutrons incident on targets of ^{139}La, ^{140,142}Ce and ^{141}Pr in the energy range $3 \leq E_n \leq 60$ MeV have recently been measured[1]. These data have previously interested in terms of optical model parameters. The present reanalysis suggests that the general trend of optical model parameters can be seen from a semi–classical Ramsauer effect analysis. In particular, the results from these four nuclei yield results for isovector strength which are inconsistent with previous results. The Ramsauer analysis confirms this result and shows that the problem is caused by variations in isoscalar strength near closed nuclear shells. These variations mask the effects of isovector potentials. Analysis of cross sections of similar precision but on adjacent isotopes farther from closed nuclear shells should be capable of yielding information on isovector potential strengths. The Ramsauer analysis does not replace a more conventional analysis but can provide guidance on regions of energy and mass

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1 H.S. Camarda, J.W. Phillips and R.M. White, Phys. Rev. C29, 2106 (1984).

numbers where measurements would be particularly useful. A series of neutron total cross section measurements for $3 \leq E_n \leq 500$ MeV is planned for 1990.

3. A Study of the ^{9}Be(n,2n) Reaction Cross Section* (H.D. Knox** and T.N. Massey)

We have completed initial study of the ^{9}Be(n,2n) cross section using the shell model R–matrix technique developed at this laboratory. The spectroscopic factors for the R–matrix channels (^{9}Be+n, ^{9}Be*+n, ^{6}He+α, ^{6}He*+α, ^{5}He+^{5}He, ^{5}He*+^{5}He and ^{5}He*+^{5}He*) were calculated in a $1\hbar\omega$ spsd model space. The unmeasured inelastic neutron channels have a predicted maximum cross section of ~ 0.1 barns which is significant when the cross sections of these five states have been added. The predicted inelastic scattering to the 2.429 MeV state has approximately half of the measured cross section. This result is thought to be due to the low number of positive parity states (44 positive parity versus ~ 400 negative parity below 30 MeV excitation energy) for ^{10}Be. Work is in progress to extend the calculations to $2\hbar\omega$ in the spsd model space for the positive parity levels in ^{10}Be and complete the calculation of the spectroscopic factors needed for the R–matrix analysis.

C. TECHNIQUES AND FACILITIES

1. Calibration of the Recoil Energy in the Crystalline Si Detector (P. Zecher, D. Wang, J. Rapaport, C.J. Martoff† and B.A. Young††)

Silicon crystals are being proposed as detectors of dark matter by directly measuring the recoil energy deposited in the crystal, when an incident dark matter particle elastically scatters off a nucleus in the detector. To calibrate this detector, the energy dependence of the ionization produced in this silicon crystal by recoiling silicon atoms was measured in the 4–54 keV energy interval. Monoenergetic neutrons with energy between 1 and 4 MeV were elastically scattered from the silicon crystal and detected at 20° and 35.6° in coincidence with signals from the silicon detector. It is found that the fraction of the recoil energy that is dissipated as ionization follows an $E^{1/2}$ dependence which agrees well with the predictions of the theory of Lindhard et al.[1]

* Work supported by the U.S. Department of Energy.
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† Temple University, Philadelphia, Pennsylvania 19122
†† Stanford University, Stanford, California 94305
1 Lindhard et al., Mat. Fys. Medd. 33, 10 (1963)

2. A Facility for Total Neutron Cross Section Measurements up to 600 MeV at WNR Target 4* (R.W. Finlay, G. Morgan**, P. Lisowski**, J. Rapaport, K. Hicks and W. Abfalterer)

A facility is proposed to measure total neutron cross sections at intermediate energy. The program is motivated by recent developments in relativistic optical models but could be carried out in such a manner as to provide valuable new data below 20 MeV that are of possible interest in applied physics and neutron dosimetry.

3. Determination of the Light Response of BC–404† Plastic Scintillator for ^{3}He and ^{4}He with Energies Between 3 and 13 MeV†† (S.K. Saraf#, N. Al–Niemi##, C.E. Brient, S.M. Grimes and R.S. Pedroni)

The light output of a BC–404 scintillator as a function of energy between 3 and 13 MeV has been measured for ^{3}He and ^{4}He. A slightly lower pulse height is found for ^{4}He than for ^{3}He at the same energy. The data are not consistent with models of the scintillation process by Wright and Birks but agree well with a newer model proposed by Meyer and Murray. They are also in reasonable agreement with earlier data of Becchetti et al., although the present measurements provide better definition of the response curve below 6 MeV.

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* Supported in part by the National Science Foundation

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† Obtained from Bicron, 12345 Kinsman Road, Newbury, Ohio 44045

†† Work supported by the U.S. Department of Energy

Present address: Brookhaven National Laboratory, Upton, New York 11973

Present address: Kent State University, Kent, Ohio 44242

UNIVERSITY OF PENNSYLVANIA

A. INTRODUCTION

The principal thrust of the work deals with the compilation of the information on the energy levels and on the structure of the nuclei with mass numbers A = 5-20. Approximately 1500 papers are published every year on these nuclei.

B. PUBLICATIONS

1. "Energy Levels of Light Nuclei A = 11-12", Nuclear Physics A506 (1990) 1-158

2. "The Light Nuclei" by F. Ajzenberg-Selove, in "Energy in Physics, War and Peace", A Festschrift Celebrating Edward Teller's 80th Birthday, Ed. Hans Mark and Lowell Wood; Kluwer Academic Publishers, Norwell, MA (1988) p. 39-47

3. "The Light Nuclei: What is Known and What is Not" by F. Ajzenberg-Selove, Proceedings of the XX Masurian School, Mikolajki, Poland, September 2-9, 1988, published in "Heavy Ions in Nuclear and Atomic Physics", Editors: Z. Wilhelmi and G. Szeflinska; Adam Hilger, Pubs. (1989), p. 1-20

4. Co-Editor, with H.H. Barschall, of "A Physicist's Desk Reference (The Second Edition of Physics Vade Mecum)", American Institute of Physics, 1989

C. ACCEPTED FOR PUBLICATION

"Nuclear Spectra" by F. Ajzenberg-Selove, to be published in the McGraw-Hill Encyclopedia of Science and Technology, Seventh Edition (1992)

D. COMMITTEE

Member, Physical Sciences Panel, Associateship Programs, National Academy of Sciences, National Research Council, 1988-

E. WORK IN PROGRESS

We prepared preliminary versions of the reviews on A = 13 (sent out as preprint 3-89 in September 1989), A = 14 (sent out as preprint 4-89 in December 1989), and A = 15 (sent out as preprint 1-90 in February 1990).

A final version of A = 13-15 will then be sent to Nuclear Physics in July 1990, exactly on the schedule approved by the Panel some years ago.

Professor Ron Tilley (North Carolina State) and Professor Henry Weller (Duke), working at the Triangle University Nuclear Laboratory (TUNL) have agreed to take over this work, and the Panel on Basic Nuclear Data Compilations has endorsed this transfer. Professors Tilley and Weller have visited Penn to find out how we do the work. They plan to start reviewing A = 16-17 in 1990, while I complete A = 13-15. We have already sent the TUNL group the original vellums of the figures and the reference lists appropriate to A = 16-17. We will continue to send them new information on A = 16-17 through the fall of 1990. During the late summer and fall of 1990, we will go through our voluminous files and we expect to transfer to TUNL any useful reference lists, publications and vellums on the nuclei with A = 5-15 and 18-20. In October 1990 we will also read the proofs for A = 13-15, which takes about one woman-month. During the 1990 calendar year I will be available to the TUNL group for consultation as they work on the review of A = 16-17.

F. Ajzenberg-Selove; with
G. C. Marshall

A. NUCLEAR DATA

1. "Fission Cross Section Measurements of Cm-247, Cf-250 and Es-254 from 0.1 eV to 80 keV"* (Y. Danon,** R.E. Slovacek,** R.C. Block,** R.W. Lougheed,*** R.W. Hoff,*** M.S. Moore****)

Fission cross section measurements were made with the RINS system (1) over the neutron energy range from approximately 0.1 eV to 80 keV upon samples of Cm-247, Cf-250 and Es-254. The Cm-247 measurement was undertaken to complete the RINS fission cross section measurement sequence of the curium isotopes (2-3), Es-254 was measured because it is a very heavy odd-odd nucleus which might show interesting nuclear structure effects in its fission cross section, and Cf-250 was measured to account for its buildup as a daughter product from the 276-day halflife Es-254.

These measurements utilized 3.2±0.2, 0.15±0.01 and 0.21±0.01 microgram samples, respectively, of Cm-247, Cf-250 and Es-254 which were electroplated onto hemispherical fission chamber electrodes (4). The Es-254 sample was chemically separated (primarily to remove its daughter product Cf-250) and RINS measurements commenced approximately 48 hours after separation to minimize Cf-250 buildup. These measurements were made simultaneously in the same fission chamber with a reference sample of U-235, and the fission cross sections were normalized to the ENDF/B-V U-235 cross section in the 0.1-to-10 keV energy region. These are the first reported fission measurements in this energy region for Cf-250 and Es-254 and below 20 eV from Cm-247. The measured fission cross sections are shown in Figures 1, 2 and 3, respectively, for Cm-247, Cf-250 and Es-254. The Cm-247 in our sample was 29% abundant with the other major constituents being Cm-244 and Cm-246. The data in Figure 1 have not been corrected yet for the effect of the other curium isotopes; the major impurities, the even-even species, will provide only minor interferences to the Cm-247 signal. Only 1-sigma counting statistical errors are shown in these figures; an overall systematic error of less than 10% is estimated for all three cross sections.

The smooth curve in Figure 1 is the RINS resolution-broadened cross section for the Cm-247 measurement of Moore & Keyworth (5). The RINS measurement is in excellent agreement with their data over the strong resonance group near 70 eV but is about 30% larger at higher energies; the source of this disagreement is not know but is characteristic of other comparisons of RINS measurements with the higher energy average data from the Moore & Keyworth experiments (2-3). Five low-energy resonances are observed at approximately 1.2, 3.2, 4.5, 9 and 19 eV; all but the 4.5-eV resonance have been reported by Belanova et al. from total cross section measurements (6).

The Cf-250 cross section exhibits a strong resonance at 0.6 eV with a peak cross section of about 200 barns. There also appears to be broad structure near 50 eV with a peak of the order of 3 barns. Assuming a 1/v dependence and extrapolating the cross section from the 2-to-10 eV region, a thermal cross section of about 95 barns is obtained.

The cross section for Es-254 is very different from that obtained from all other nuclei measured by RINS. The cross section shows no resonance structure below 4 eV and only small structure near 6, 18, 60 and 400 eV. This is very surprising because a heavy odd-odd nucleus like Es-254 would be expected to have very strong resonances with a level spacing somewhat less than that of U-235. The lack of structure may be the result of the fission widths exceeding the level spacing, thus producing a continuum with a few weak clusters of strength. An extrapolation of the RINS data to thermal energy is in good agreement with the measured value (shown as the open square).

These measurements demonstrate the power of the RINS method for measuring the fission cross of very small samples of highly active nuclei.

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*Work supported by the U.S. Dept. of Energy and the Lawrence Livermore National Laboratory.

**Rensselaer Polytechnic Institute

***Lawrence Livermore National Laboratory

****Los Alamos National Laboratory

1. R.E. Slovacek, D.S. Cramer, E.B. Bean, J.R. Valentine, R.W. Hockenbury and R.C. Block, "U-238(n,f) Measurements Below 100 keV", Nucl. Sci. & Eng. 62, 455 (1977).

2. H.T. Maguire, Jr., C.R.S. Stopa, R.C. Block, D.R. Harris, R.E. Slovacek, J.W.T. Dabbs, R.J. Dougan, R.W. Hoff and R.W. Lougheed, "Neutron-Induced Fission Cross-Section Measurements of Cm-244, Cm-246 and Cm-248", Nucl. Sci. & Eng. 89, 293 (1985).

3. B. Alam, R.C. Block, R.E. Slovacek and R.W. Hoff, "Measurements of the Neutron-Induced Fission Cross Sections of Cm-242 and Pu-238", Nucl. Sci. & Eng. 99, 267 (1988).

4. J.W.T. Dabbs, N.W. Hill, C.E. Bemis and S. Raman, "Fission Cross Section Measurements on Short-Lived Alpha Emitters", Proc. Conf. Nuclear Cross Section & Technology, Washington, DC, March 3-7, 1975, NBS Spec. Publ. 425, Vol. 1, 81 (1975).

5. M.S. Moore and G.A. Keyworth, "Analysis of the Fission and Capture Cross Sections of the Curium Isotopes", Phys. Rev. C Vol. 3, No. 4, 1656 (1971).

6. T.S. Belanova, A.G. Kolesov, S.N. Nikol'skil, V.A. Poruchikov, V.N. Nefedov, V.S. Artamonov, R.N. Ivanov and S.M. Kalebin, "Neutron Resonances of Cm-247 in the Energy Range of 0.5-20 eV", Sov. At. Energy Vol. 47, No. 3, 206 (1979).

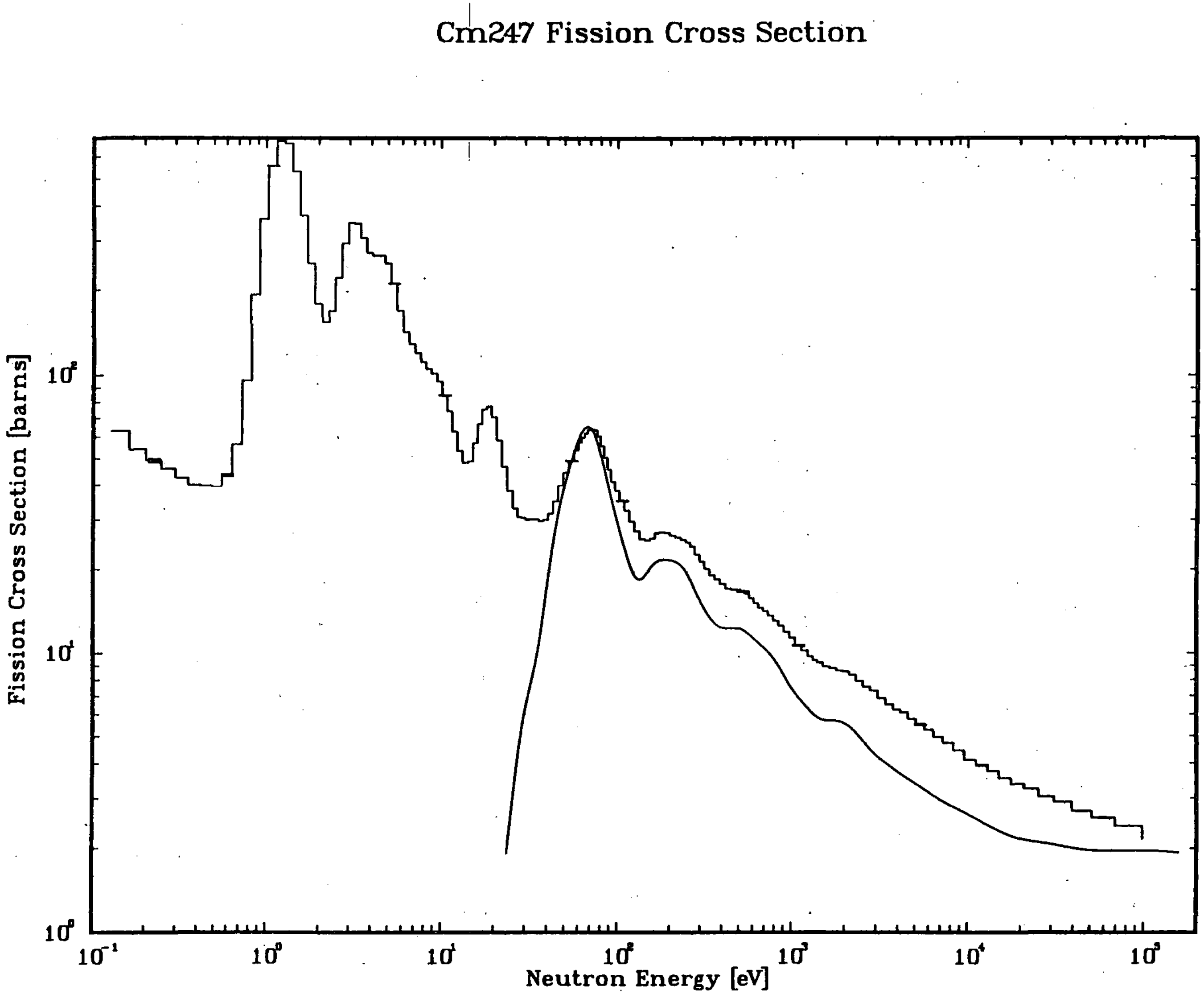

Fig. A1. Fission cross section of Cm-247 over the neutron energy range from approximately 0.1 eV to 80 keV. No corrections have been applied for the effect of the other isotopes in the Cm-247 sample.

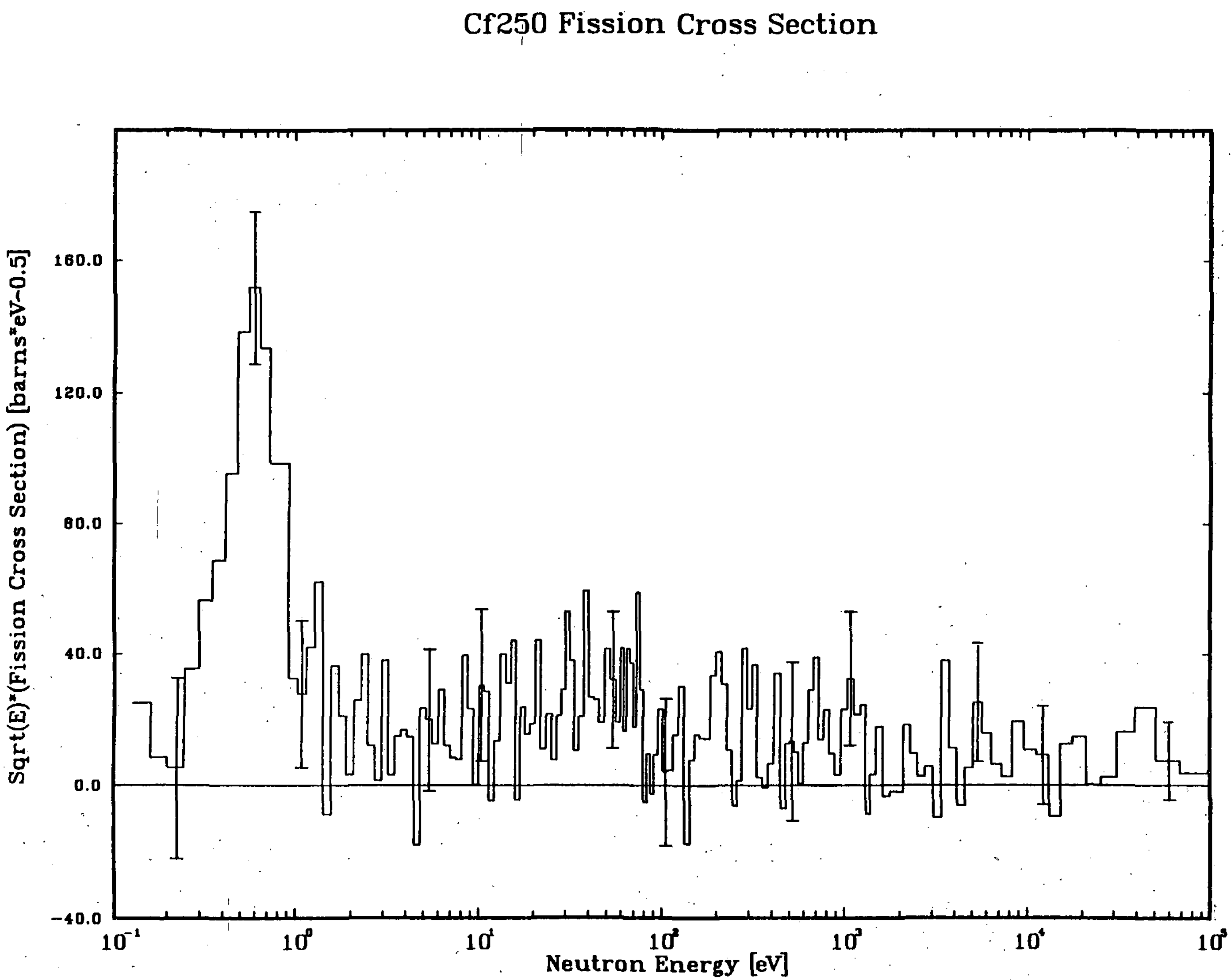

Fig. A2. Fission cross section (times the square root of energy) of Cf-250 over the neutron energy range from approximately 0.1 to 80 keV.

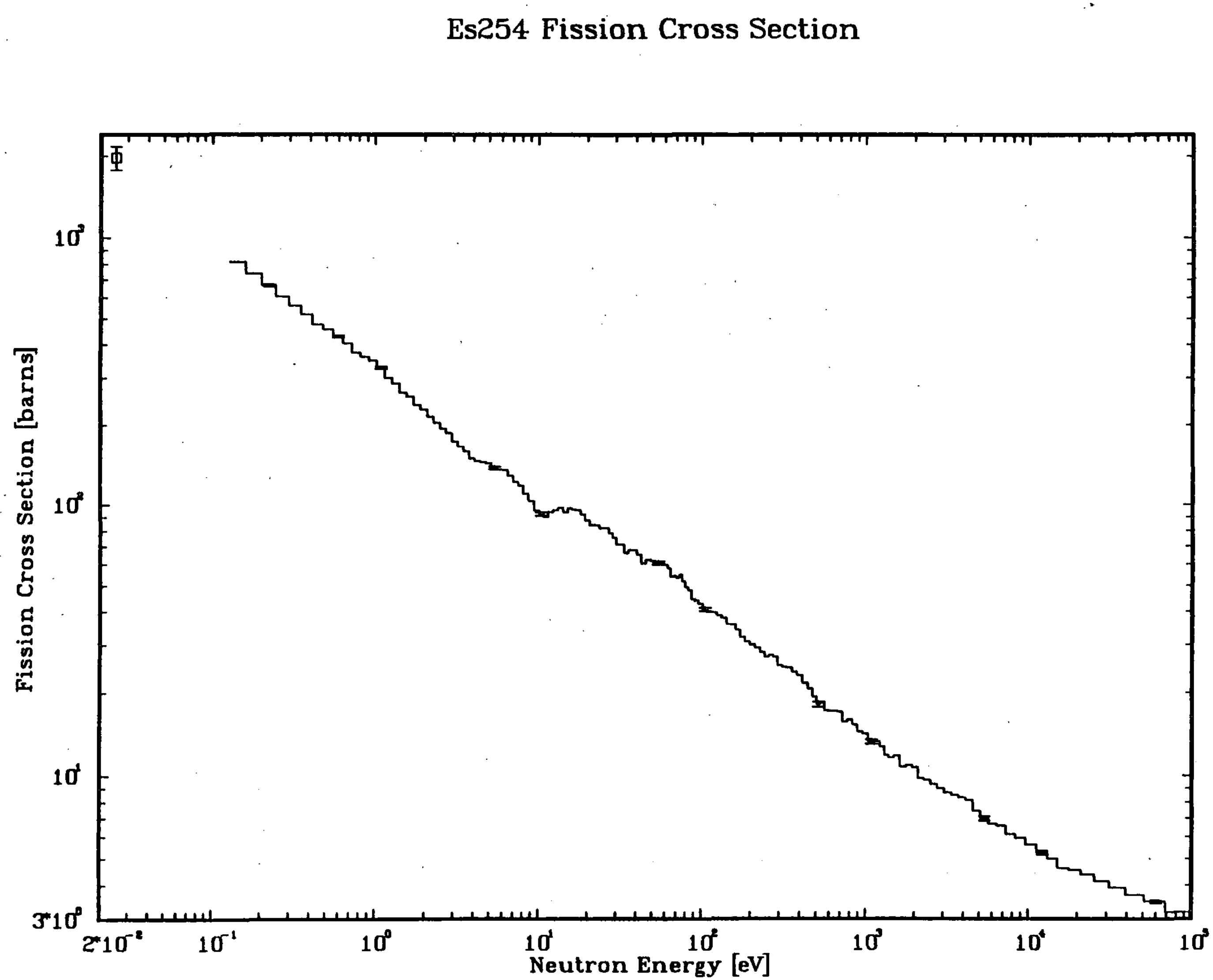

Fig. A3. Fission cross section of Es-254 over the neutron energy range from approximately 0.1*to 80 keV.

B. FISSILE ASSAY

1. "Measurement of Uranium and Plutonium Content in a Fuel Assembly Using the RPI Spent Fuel Assay Device"*(D.R. Harris, F. Rodriguez-Vera, N. Abdurrahman, Y.-D. Lee, R.E. Slovacek, R.C. Block)

It is vitally important for adequate safeguards that the uranium and plutonium fissiles in spent reactor fuel be separately and adequately assayed! Such assays also are important in assigning fissile credits, in taking account of fissile contents in determining criticality for spent fuel, and in testing reactor analysis methods. Specifically, it is essential to distinguish the plutonium fissiles Pu-239 and Pu-241 from the uranium fissile U-235. This is essential because plutonium can be chemically separated from the slightly enriched uranium used in most power reactors, and this plutonium then can be used in a nuclear explosive. The slowing down time (SDT) assay device is the only method that accomplishes this for spent fuel.

The SDT assay method has been under development at Rensselaer Polytechnic Institute (RPI) for more than 10 years. Results have been reported on SDT measurements and calculations of the sensitivity of assay of the various fissiles in small samples, in single fuel pins, and in a depleted U_3O_8 parallelepiped simulating a fuel element (1-8). In this paper we report measurements of the significant parameters, the sensitivities of the slowing-down-time assay device to the fissile contents of a boiling water reactor (BWR) assembly mock-up of fresh fuel. The mock-up contains an 8 x 8 array of 4.81 Wt% enriched high-density UO_2 fuel rods clad in stainless steel, and is referred to as FAFA. The FAFA assembly design and construction have been described earlier (4), as were preliminary results.

The mock-up fuel assembly was placed in the RPI lead pile with a U-238 fission chamber and two Th-232 fission chambers 1" away along one face of the mock-up. As is usual in SDT measurements, the RPI electron linear accelerator (LINAC) was pulsed, and when the time-focused neutron pulse fills the mock-up it causes fissions in the fissile contents. Fast fission neutrons from the fissions in the mock-up are detected at once in the threshold fission chambers, thus providing a time response that follows the energy variation of the fissile cross sections. The latter are distinctively different for the plutonium and uranium nuclides and provide the assay information.

It should be noted that the spent fuel assay device under design at RPI differs from that used in the experiment by using (a) more assay chambers around the actual spent fuel assembly, (b) a different accelerator source at different neutron burst strengths and repetition rates, and (c) a different lead configuration. The purpose of the experiments is to provide design data for the actual device.

Figure 1 shows the normalized assay detector results versus slowing-down time. Also shown are results from two small Pu-239 and U-235 fission chambers referred to as probes; these chambers probe the interrogation neutron flux within the FAFA. From the radical differences between the probe results for the different fissiles, the fissile contents are determined by least-square fitting. Figure 2 illustrates that there is little variation of the interrogation neutron flux inside the fuel assembly, a result consistent with earlier Monte Carlo calculations. The experimental results indicate that Pu-239 assay results accurate to 1% can be obtained for an actual BWR spent fuel assembly in about 5 minutes.

*Work supported by the U.S. Dept. of Energy

1. W.M. Sprecher, "Technical Bases for OCRWM's Policy Decisions on International Safeguards," Trans. Am. Nucl. Soc. 60, 244 (1989).

2. F.W. Bornt, D.R. Harris and R.C. Block, "Fissile Assay Measurements of U-235 in a Lead Slowing Down Time Spectrometer," Trans. Am. Nucl. Soc. 39, 344 (1981).

3. F.W. Bornt, Jr., "Lead Slowing Down Spectrometer Assay Measurements of a Simulated Fuel Bundle," MS Thesis, Rensselaer Polytechnic Institute, Troy, NY (1981).

4. R.C. Little, H.M. Fisher, B. Alam, R.C. Block, D.R. Harris and R.E. Slovacek, "Monte Carlo Modeling of the Neutronics of a Lead Slowing Down Time Assay Device," Trans. Am. Nucl. Soc. 43, 199 (1982).

5. B. Alam, "Plutonium Assay Using a Lead Slowing Down Time Spectrometer," MS Thesis, Rensselaer Polytechnic Institute, Troy, NY (1983).

6. B. Alam, J.W. Wilkinson, E.C. Vanterpool, D.R. Harris and R.C. Block, "Accuracy for Plutonium Assay Using a Lead Slowing Down Spectrometer," Trans. Am. Nucl. Soc. 45, 136 (1983).

7. H.M. Fisher, "Monte Carlo Feasibility Assessment of the Lead Slowing Down Time Spectrometer for Spent Fuel Management," PhD Thesis, Rensselaer Polytechnic Institute, Troy, NY (1985).

8. E.C. Vanterpool, "LWR Fuel Assembly Assay by Pulsed Neutron Interrogation," PhD Thesis, Rensselaer Polytechnic Institute, Troy, NY (1989).

9. R.C. Block, D.R. Harris, R.E. Slovacek, F. Rodriguez-Vera, N. Abdurrahman and S.T. Shin, "Fissile Assay of Spent Fuel Using Slowing Down Time Device," Rensselaer Polytechnic Institute, Troy, NY (1989).

10. R.C. Block, D.R. Harris, F. Rodriguez-Vera, R. Slovacek and N. Absurrahman, "Fissle Assay of Spent Fuel Using a Slowing Down Time Device," Trans. Am. Nucl. Soc. 60, 247 (1989).

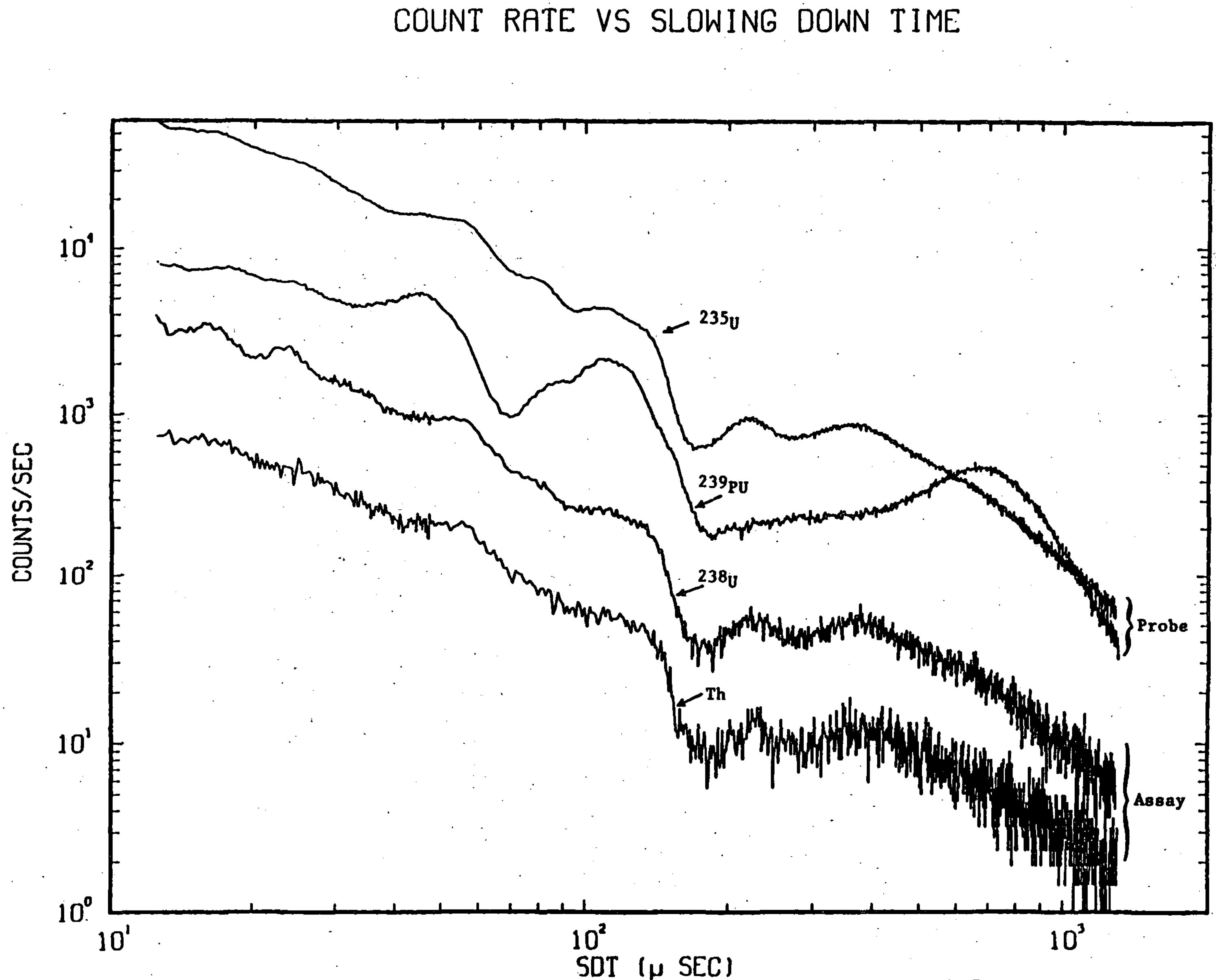

Fig. B1. The counting rate vs slowing down time (SDT) for a 1.0-mg ^{235}U probe detector, a 0.3-mg ^{239}Pu probe detector, a 200-mg ^{238}U assay detector and a 200-mg Th assay detector.

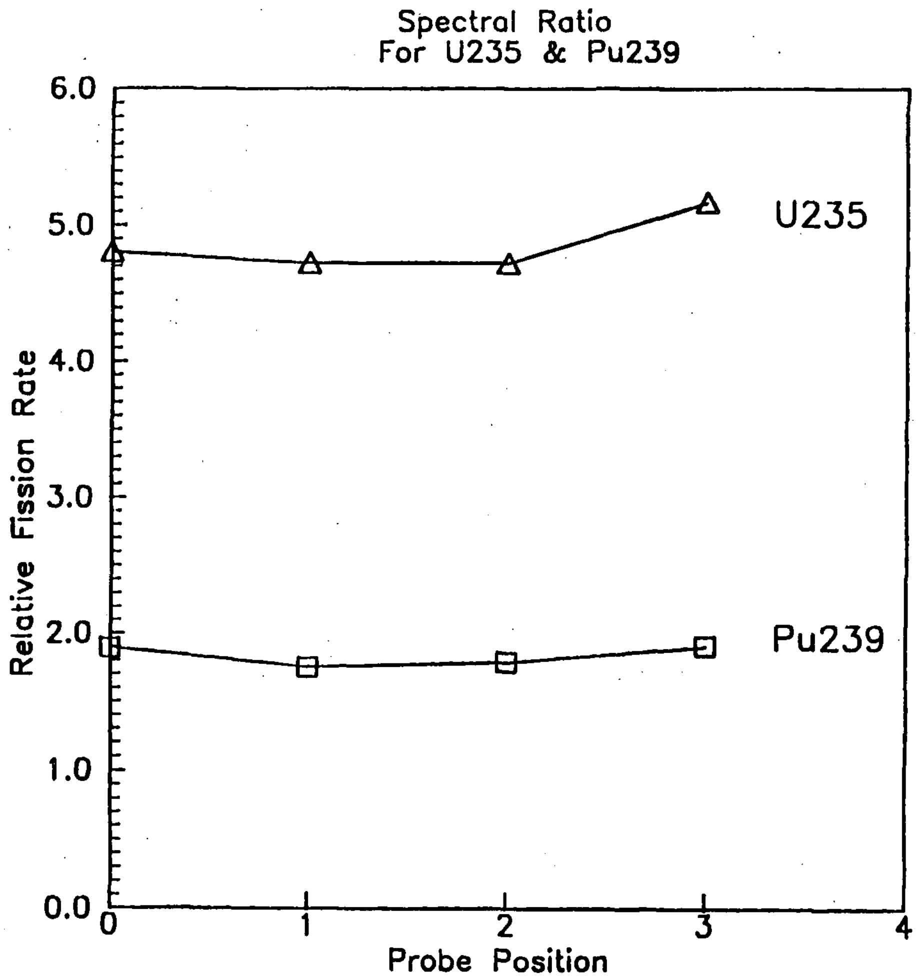

Fig. B2. The relative counting rate in the 0.1-mg ^{235}U and 0.3-mg ^{239}Pu probe detectors as a function of the probe position. Position 0 is at the center of the fuel assembly and position 4 is near the top of the assembly.

ROCKWELL INTERNATIONAL

A. NEUTRON PHYSICS

1. Helium Generation Cross Sections for Fusion Applications
(D. W. Kneff and B. M. Oliver)

Neutron-induced helium generation is a major consideration in the development of materials for fusion reactor environments. Rockwell International is engaged in the measurement of helium production in fusion-energy neutron environments and in other neutron environments used for fusion-reactor materials testing, including mixed-spectrum fission reactors. Current emphasis is on the measurement of the cross sections of pure elements and separated isotopes for fast (~8-15 MeV) monoenergetic neutrons. Most of this work is being performed as a collaborative effort with Argonne National Laboratory (ANL), and includes cooperative experiments with Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL). It is sponsored by the Department of Energy's Office of Fusion Energy.

Current work includes the helium analysis of several materials irradiated in various fast-neutron irradiation experiments. These materials include C (diamond, graphite), Be, Mg, Ca, Nd, TiN, ZrN, and PbS irradiated by ~14.8-MeV neutrons from a T(d,n) source, and beryllium samples irradiated with Be(d,n) neutrons. The T(d,n)-irradiated compounds are under investigation to determine cross sections for their non-metallic constituent elements (N, S). The Be(d,n) irradiation is a joint experiment with D. L. Smith, J. W. Meadows, and L. R. Greenwood of ANL. The beryllium results will be combined with a detailed neutron environment characterization by ANL for an accurate determination of the spectrum-averaged $^{9}Be(n,2n)^{8}Be$ cross section.

Future near-term activities include the completion of the beryllium helium analyses and the continuation of helium generation measurements for several materials irradiated in T(d,n) neutron environments. Fluence mapping will be completed for these irradiations and the results combined with the helium measurements to derive total helium production cross sections.

TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

1. Introduction

Triangle Universities Nuclear Laboratory (TUNL) is involved with a large variety of measurements and analyses. Many of the measurements use polarized incoming charged particle or neutron beams to probe details of nuclei, nuclear structure or nuclear interactions.

Knowledge about nucleon-nucleon scattering is important for developing more precise knowledge about the nucleon-nucleon (NN) interaction potential. Such knowledge is important for understanding and predicting low-mass fusion reactions, as well as for the more fundamental purpose of understanding the basic force underlying nuclear reactions. This NN interaction is also fundamental to formulating microscopic models of nuclear reactions involving medium-weight and heavy nuclear targets.

Another program deals with scattering processes and interactions where the projectile and target are light nuclei, i.e., $A \leq 4$. Measurements for these reactions lead to a further understanding of the NN interaction (off-the-energy-shell part), the three-nucleon force 3NF, the d+d fusion reaction and D-state effects in the low-mass region.

For nuclei heavier than $A \geq 28$, we are mainly attempting to produce models for nucleon-nucleus scattering. We develop phenomenological spherical and deformed optical model (OM) potentials to describe elastic scattering and deformed OM potentials to describe inelastic scattering. The spherical optical model (SOM) potentials are of three types: i) simple energy dependencies on the potential strengths and geometries, ii) complicated energy dependencies on the strengths that are a result of the dispersion-relation constraint that connects the real potential to the imaginary potential through an integral relationship, and iii) a microscopic folding-model. The deformed potentials are developed through coupled-channels calculations.

All of the models we are investigating are constrained by measurements of analyzing powers (for polarized beams), as well as cross sections. Such data bases permit definite conclusions about spin-sensitive parts of the interaction or spin-sensitive nuclear structure determinations. To a large extent the material reported below has been excerpted from the 1989 annual progress report XXVIII; more details can be obtained therein or directly from the underlined contributor. This summary has been prepared by Richard L. Walter.

2. Neutron-Proton $A_y(\theta)$ Data at Low Energies and the ^3P NN Interactions
(G. J. Weisel, M. AlOhali, Z. P. Chen, P. D. Felsher, J. M. Hanly, C. R. Howell, J. M. Lambert,* W. Tornow, P. A. Treado,*+ R. L. Walter)

*Department of Physics, Georgetown University, Washington, D.C.
+ Deceased

Recent low-energy n-p $A_y(\theta)$ data, some of which were obtained at TUNL, led to a more accurate determination of the ωNN coupling constant in the Bonn-I potential.[1] An increase of its value by about 10% brought the Bonn-I predictions into agreement with the data. This newest version of the potential, incorporating the new ωNN coupling constant, is called 'Bonn II'.

Since the magnitude of the analyzing power $A_y(\theta)$ in low-energy n-p scattering depends primarily on the $^3P_{0,1,2}$ NN interactions, high accuracy $A_y(\theta)$ data are of particular importance. In the past, the $^3P_{0,1,2}$ NN interactions were determined mainly from p-p scattering data alone. In order to place stronger constraints on these interactions, we have completed a measurement of $A_y(\theta)$ for n-p scattering at 7.6, 12.0, 14.1, 16.0 and 18.5 MeV. The data, carefully corrected for finite geometry and multiple scattering effects, are shown in Fig. 1 in comparison to the Bonn II predictions. Since the magnitude of $A_y(\theta)$ is very small, high-accuracy data are required: the statistical uncertainty of the present data is typically below ±0.001.

The 12-MeV data were compared to the predictions of four models. The prediction using the global NN phase-shift analysis of Arndt gives too large $A_y(\theta)$ values for angles beyond 100°. The Nijmegen phase-shift analysis prediction is slightly higher in magnitude than the data. The Bonn II and the Paris NN potential model predictions give good overall representation of the data.

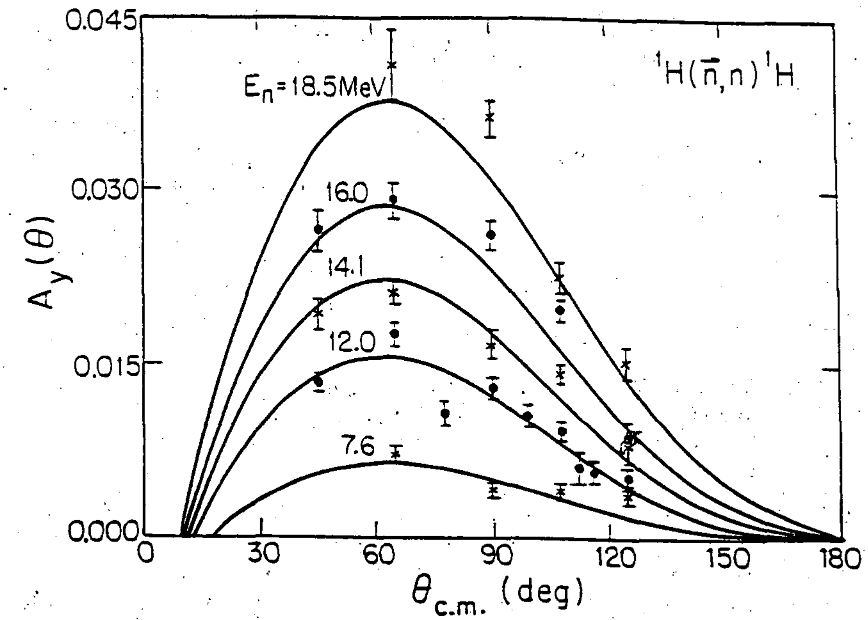

Fig. 1 Data for $A_y(\theta)$ for n-p elastic scattering at 7.6, 12.0, 14.1, 16.0, and 18.5 MeV, bottom to top, compared to Bonn II predictions.

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

At energies above 14 MeV, the Nijmegen, Bonn II, and Paris predictions become virtually indistinguishable. Therefore, in our future work, we will concentrate on improving the 7.6 and 12 MeV data. To this end we are constructing a new experimental area which includes a shielded neutron source. This will make it possible to obtain data at four angles simultaneously.

3. Discrepancies between Rigorous Calculations and n-d $A_y(\theta)$ Data (W. Tornow, M. Al Ohali, Z. P. Chen, P. D. Felsher, J. M. Hanly, C. R. Howell, G. Mertens,* I. Slaus,** R. L. Walter, G. J. Weisel)

Recently, the first results of rigorous three-nucleon Faddeev calculations for the n-d continuum using meson-exchange based two-nucleon interactions became available.[2] In these calculations all partial-wave components of the Paris and new Bonn nucleon-nucleon (NN) potentials with two-body angular momenta $J \leq 2$ were included. Definite discrepancies between calculations and elastic n-d analyzing power $A_y(\theta)$ data at 10, 12, 13 and 14.1 MeV were found in near the maximum of $A_y(\theta)$; here, the calculations yield $A_y(\theta)$ values which are about 25% smaller than the data. The angular range around the maximum of $A_y(\theta)$ depends strongly on the values for the $^3P_{0,1,2}$ partial-wave NN interactions. Ignoring the effects of three-body forces, a substantial modification of the two-body ^3P_J interactions is needed to bring the n-d calculations in closer agreement with the data.[2] The problem of charge independence breaking (CIB) of the ^3P NN interaction also surfaces in these comparisons.

In order to reduce the influence of higher partial-wave interactions, we extended our previous elastic $^2H(n,n)^2H$ measurements of $A_y(\theta)$ to lower energies, namely, 5.0, 6.5 and 8.5 MeV. These new data are also considerably higher in magnitude than the predictions. The present measurements support our previous findings at higher incident energies that the Paris and new Bonn nonrelativistic NN potentials fail to describe elastic n-d analyzing powers. The discrepancies are so severe that on-shell properties of the NN interaction probably cannot account completely for the observed effects. An overview of this work is given in Nucl. Instr. and Meth. in Physics Research B40/41, 470 (1989).

4. Three-Nucleon-Force and Off-Shell Effects in $^2H(n,nnp)$ Breakup (C. R. Howell, M. Al-Ohali, P. D. Felsher, G. Mertens,* W. Tornow, R. L. Walter, G. J. Weisel)

Because a quantitative description of the nuclear force by QCD seems to be in the distant future, we use the next most fundamental theory, the meson-exchange model of the nucleon-nucleon (N-N) interaction, to study few-nucleon systems ($A \geq 3$). The availability of supercomputers has enabled major advances in the calculation of three-nucleon (3N) scattering observables. For

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* Physikalisches Institut, Universität Tübingen, FRG
** Ruder Boskovic Institute, Zagreb, Yugoslavia
[2] H. Witala, W. Glöckle and T. Cornelius, Nucl. Phys. **A491** (1989) 157

the first time, 3N scattering observables can be calculated using the exact forms of the Bonn[3] potential as input for the basic N-N force.

Recent cross-section measurements by Strate *et al.*[4] for the ^{2}H(n,nnp) breakup reaction show sizeable disagreement with 3N calculations. The implications are strong enough to warrant an independent remeasurement. We have constructed a massively-shielded neutron source which uses the ^{2}H(d,n)^{3}He reaction in order to repeat the measurements of Strate *et al.* at 13.0 MeV for the space-star and colinear configurations.

For such 3-body breakup reactions the experimental determination of 5 kinematic variables is sufficient to define completely the kinematics of the reaction. In our setup the momenta of the two outgoing neutrons and the energy of the recoil proton are measured, thereby determining 7 kinematic variables. The overdetermination of the kinematics puts constraints on the data that help minimize effects of experimental backgrounds. Based on the yields obtained in a test run, we estimate a measurement to an accuracy of 5% will require 30 days. A paper on the previous unshielded arrangement for breakup studies has been submitted to Nucl. Instr. and Meth.

5. Analyzing Powers of the $\vec{d}$+d→d+p+n Breakup Reaction. (P.D. Felsher, M. Al Ohali, J.M. Hanly, C.R. Howell, Y. Koike*, J.M. Lambert,** G. Mertens,+ M.L. Roberts, I. Slaus,++ W. Tornow, P.A. Treado,**+++ R.L. Walter, G. Weisel)

The four-nucleon (4N) system has received much theoretical attention in the past two years (in part due to the cold-fusion controversy). Our interest in this project is at energies above the cold-fusion arena. Recent advances in realistic microscopic theories have led to calculations for the 4N bound-state problem,[5] as well as for some 4N scattering systems.[6] However, compared to the 3N situation, the 4N calculations are still quite rudimentary due to the increased complexity of the 4N system.

In the present study we measured of polarization observables for deuteron-proton (d-p) and deuteron-neutron (d-n) quasifree scattering (QFS), to the extent that QFS can be investigated through the $\vec{d}$+d→d+p+n breakup reaction. This breakup reaction is well suited for investigating aspects of the 4N scattering problem since contamination from nucleon-nucleon (N-N) final-state interactions (FSI) is known to be small, and, to within the validity of the impulse approximation, the d-p and d-n QFS data should resemble d-p and d-n free scattering. Furthermore, a comparison between d-p QFS and d-n QFS should

[3] R. Machleidt, K. Holinde and Ch. Elster, Phys. Report **149** (1987) 1

[4] J. Strate *et al.*, J. Phys. G: Nucl. Phys. **14** (1988) L229

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+++ Deceased

[5] J. Carlson, Proceedings of Few Body XII (1989)

[6] A.C. Fonseca *et al.*, Contributed Papers from Few Body XII (1989) B18

give some insight into the role of the short-range component of the Coulomb force on 3N and 4N scattering observables.

Vector and tensor analyzing powers A_y, A_{yy}, and A_{zz} were measured for the $\vec{d}+d \rightarrow d+p+n$ breakup reaction at an E_d = 12 MeV. Two of the three outgoing particles were detected in coincidence, and by measuring their momenta, the kinematics of the reaction was completely defined. The detectors were positioned at angles suitable for investigating d-n and d-p QFS. A computer code, based on this modified PWIA formalism, has been developed. This code uses the T matrices for d-N free scattering. At the present time, the calculations do not include Coulomb forces. Plans call for calculations using both the initial- and final-energy prescriptions to test the influence of the Coulomb force. It is anticipated that realistic four-nucleon calculations will be made in the near future using the new Cray Y-MP supercomputer facility of the state of North Carolina.

6. <u>The $^2H(\vec{d},\gamma)^4He$ Reaction at 30 to 50 MeV</u> (R. M. Whitton, <u>H. R. Weller</u>, S. Kuhn, E. Hayward, W. R. Dodge, S. Van der Werf)

Measurements were reported last year for tensor and vector analyzing powers for $^2H(\vec{d},\gamma)^4He$ at E = 30 and 50 MeV. The polarized-beam data were obtained at the 88-inch Cyclotron at LBL, and the unpolarized $\sigma(\theta)$ at E = 30 MeV was obtained at the KVI in Groningen. These data augment an extensive set of data obtained at TUNL and Wisconsin at E < 15 MeV and at IUCF at 95 MeV. Within the pure E2 approximation, a tensor analyzing power can only arise from a tensor force effect. The observed values are large, suggesting that a significant fraction of the capture cross section arises as capture to the D-state of ^4He. Below 15 MeV significant p-wave capture strength complicates the analysis, while at 95 MeV the long-wavelength approximation may be invalid. The best determination of the D-state in ^4He using capture reactions may be in the unprobed energy region of 30 to 50 MeV.

A direct-capture calculation was performed assuming a pure E2 transition. The predicted value of A_{yy} is proportional to the amount of D-state included in the ground state of ^4He. We found that a 3.2% admixture best fit the data at 30 MeV. The 50-MeV data could be more fully analyzed since both $T_{20}(\theta)$ and $A_{yy}(\theta)$ data were taken. The $A_{yy}(\theta)$ data indicate a $^5D_2$ strength of 6.0%. The $T_{20}(\theta)$ require a 12% $^5S_2$(E2) capture strength. Our analysis indicates that at 50 MeV, 18.0% of the capture cross section arises from E2 capture to the D-state of ^4He. Once again, the $A_y(\theta)$ data can be accounted for by introducing E1 radiation. In the case of 50 MeV the results of the T-Matrix analysis indicate a $^3P_1$(E1) strength of 3.0 ± 1.0%, compared to 17.9% from the RGM model.

7. <u>The $^3H(p,\gamma)^4He$ Reaction and the $(\gamma,p)/(\gamma,n)$ Ratio in ^4He</u> (<u>G. Feldman</u>, M.J. Balbes, L.H. Kramer, J. Z. Williams, H. R. Weller, D. R. Tilley)

In the absence of strong isospin mixing, the ratio of the photoproton to photoneutron cross sections for ^4He is expected to be near unity below E_g ~ 35 MeV. However, there has been considerable debate about the experimental value of this ratio, and deviations as large as a factor of two were reported in 1983. Recently, a new measurement[7] of photoproton cross sections gave a $(\gamma,p)/(\gamma,n)$ ratio much closer to unity. As a comparison study, we measured γ-ray spectra at $\theta_\gamma = 90°$ from the inverse reaction $^3H(p,\gamma_0)^4He$ over the energy range $E_p = 2.0$-15.0 MeV ($E_g = 21.3$ to 31.1 MeV). Absolute cross sections were obtained, and are in agreement with recent $^4He(\gamma,p_0)^3H$ results.[7]

Our capture results have been converted to (γ,p_0) cross sections by detailed balance and are compared to various photoproton and photoneutron data sets in Fig. 2 [see ref. 7]. The solid curves are the "best" values of these cross sections as presented in the Calarco review.[8] While the energy dependence of our (γ,p_0) cross section is similar to the upper curve, our new results are ~65% of the previous values. Clearly, the present results are much closer in magnitude to the neutron cross sections than to the previous proton results. Furthermore, above $E_\gamma = 28$ MeV the present measurements are in excellent agreement with the photoproton work of Bernabei *et al.*[7] The $(\gamma,p)/(\gamma,n)$ ratio derived from our proton capture results falls within the range 1.0-1.2 for energies $E_\gamma = 24$-31 MeV. This is consistent with current theoretical predictions and does not require any charge symmetry violation in ^4He.

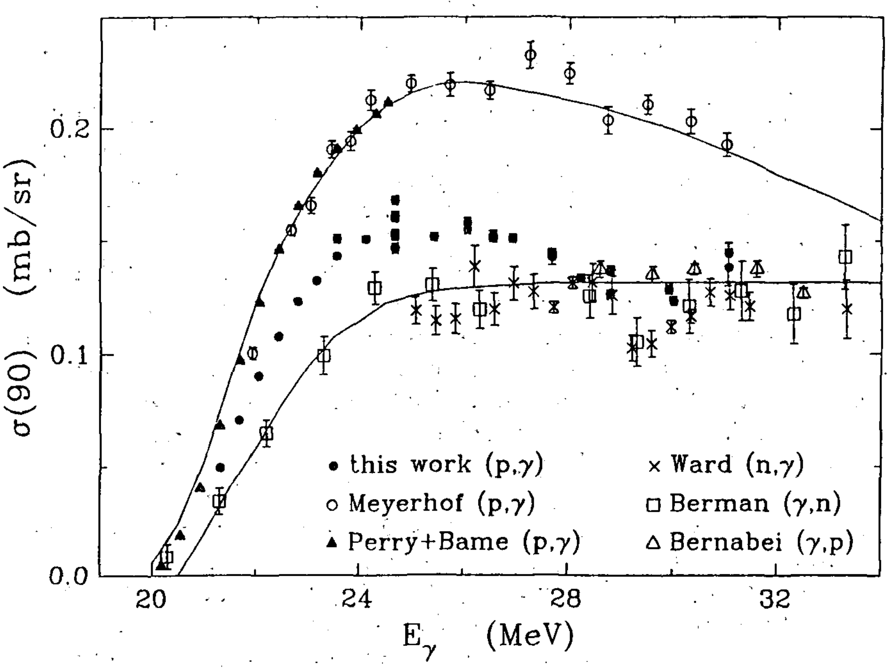

Fig. 2 Recent results from the $^3H(p,\gamma)^4He$ capture reaction, converted to (γ,p_0) cross sections by detailed balance, and compared to various photoproton and photoneutron data sets.[8] The upper and lower curves represent the (γ,p) and (γ,n) cross sections, respectively.

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[7] R. Bernabei *et al.*, Phys. Rev. **C38** (1988) 1990

[8] J. R. Calarco *et al.*, Phys. Rev. **C27** (1983) 1866; Phys. Rev. **C28** (1983) 483

8. Radiative Capture of Polarized Deuterons by ^{3}He (M. J . Balbes, G. Feldman, D. R. Tilley, H. R. Weller)

The $^3He(\vec{d},\gamma)^5Li$ reaction has been measured with vector and tensor polarized beam in the fusion resonance ($J^\pi=3/2^+$) region. An 800-keV deuteron beam was stopped in a 1-inch long ^{3}He gas target. Only S-wave capture is expected, resulting in an isotropic $\sigma(\theta)$ and no vector analyzing power $A_y(\theta)$. The tensor analyzing power $A_{yy}(\theta)$ will be isotropic for any admixture of channel spins S=3/2 and S=1/2 E1 radiation. Pure S=3/2 E1 capture, expected for a pure $3/2^+$ resonance, implies $A_{yy}(\theta)=0.2$. The cross section and both analyzing powers were fit simultaneously to extract the complex matrix elements, ^{2}S (E1), ^{4}S (E1), ^{2}P (M1) and ^{4}P (M1) independent of a model. (Here $^{2S+1}$L denotes the S and L of the scattering state.) The M1 radiation was introduced to account for deviations from the pure E1 predictions given above. A preliminary simultaneous fit to the data indicates that about 92% of the cross section is contributed by the ^{4}S E1 term.

9. Optical Model Description of the Neutron Interaction with ^{116}Sn and ^{120}Sn over a Wide Energy Range (P. P. Guss, R. C. Byrd, C. R. Howell, R. S. Pedroni, G. Tungate, R. L. Walter, J. P. Delaroche)

This work was published in Phys. Rev. C**39**, 405 (1989).

10. Phase-Shift Analysis of $^{12}C(n,n)^{12}C$ between 7 and 26 MeV (Z. P. Chen, W. Tornow)

Elastic, reaction and total n-^{12}C cross sections are of special interest in a number of applied areas. Detailed knowledge of such observables is required for fast neutron transport calculations in moderators, reflectors, and other components of both fission and fusion reactors. The n-^{12}C data are also being used as reference standards for neutron flux measurements and dosimetry. These are the main reasons for continued interest in the improvement of the n-^{12}C data base, and its interpretation in terms of models and other convenient parametrizations. As a by-product, interesting nuclear structure information can be obtained from such studies.

A phase-shift analysis seems to be the most accurate and straightforward tool for obtaining a convenient parametrization of data for n-^{12}C reaction and total cross section, $\sigma(\theta)$ and $A_y(\theta)$. This technique also allows quite reliable predictions for the observables of interest at energies for which experimental data are not available. Phase-shift analyses between 7 and 17 MeV were performed recently by Tornow *et al.*[9] In order to incorporate the new data that became available during the last two years, a new phase-shift analysis was performed. The analysis is now based on 69 $\sigma(\theta)$ and 37 $A_y(\theta)$ angular distributions. However, the $A_y(\theta)$ distributions are in general not as complete as the $\sigma(\theta)$. Hundreds of total cross section data are available in this energy range. A greatly improved version of our phase-shift search code was used. With the improved data base now available, we localized eight

[9] W. Tornow, E. Woye and R. L. Walter, J. Phys. G: Nucl. Phys. **13** (1987) 177 and references therein.

resonances in the 12.5 to 15.0 MeV region and determined their properties fairly accurately. Also, a much better parametrization was obtained above 15 MeV and for the first time it was possible to extend the analysis beyond 17 MeV. Here, six previously unknown resonances were found. In summary, the excitation energy, J^{π} and other parameters have been determined for 37 resonances in ^{13}C. The available experimental data are well described by the present phase-shift parameters in the entire energy range. From our experience gained in previous analyses we know that $A_y(\theta)$ data are very important for the unique determination of phase-shift parameters. To confirm our phase-shift results, $A_y(\theta)$ data are needed above 18 MeV.

11. <u>Unified Description of the Proton Mean Field in ^{40}Ca from -60 MeV to +200 MeV</u> (<u>W. Tornow</u>, Z. P. Chen, J. P. Delaroche*)

In continuation of our previous dispersive optical model analysis (DOMA)[10] of the p-^{40}Ca mean field we studied the properties of the bound states in ^{40}Ca. To illustrate the power of the dispersion relation model, we show our calculated bound state energies in Fig. 3. Here the column labelled EXP presents the experimentally known bound state energies derived from nucleon transfer and (e,e'p) reactions. The column labeled $\mathcal{V}_{HF} + \Delta\mathcal{V}$

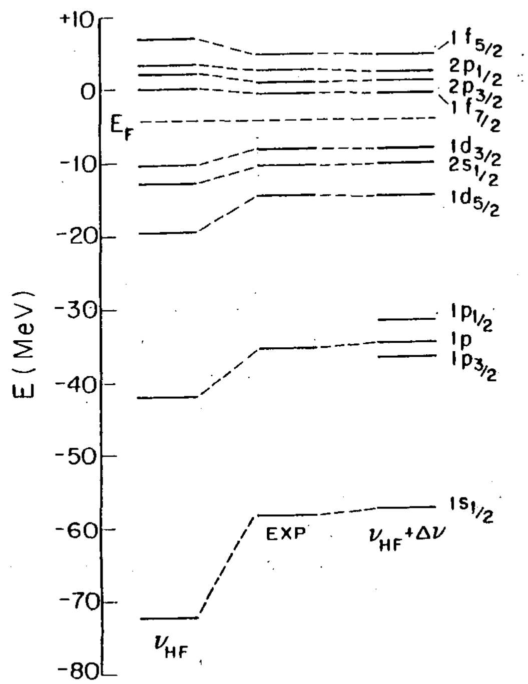

Fig. 3 Proton single-particle energies $E_{n\ell j}$ in ^{40}Ca. The column labeled EXP represents the experimental values. The columns labeled $\mathcal{V}_{HF}$ and $\mathcal{V}_{HF} + \Delta\mathcal{V}$ give the energies obtained from the Hartree-Fock potential and from the real part of the full mean field, respectively.

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[10] W. Tornow *et al.*, TUNL Annual Report XXVII (1987-88), p. 69

displays the calculated bound state energies. The Hartree-Fock component $\mathcal{V}_{HF}$ alone yields hole states ($E < E_F$) which are too tightly bound and particle states ($E > E_F$) which are too loosely bound. Our analysis predicts effective masses, root-mean-square radii $R_{n\ell j}$, occupation probabilities $N_{n\ell j}$, absolute spectroscopic factors $S_{n\ell j}$ and spectral functions. The predicted radius values $R_{n\ell j}$ for the proton single-particle orbits in ^{40}Ca can serve as a benchmark for testing the accuracy of the DOMA approach. Electron experiments offer an elegant technique to determine such radii.

12. The Neutron-^{54}Fe Mean Field from a Dispersive Optical-Model Analysis
(C. R. Howell, J. P. Delaroche,* R. L. Walter)

The observed energy dependence of the radius parameter of the real potential in our OM analysis of n-^{54}Fe scattering data indicated that dispersion relation effects should be considered. We are currently re-analyzing the data with an optical model which includes the DR. Our goal is to determine the Hartree-Fock potential for the n-^{54}Fe interaction by fitting the scattering data and the negative-energy bound-state data for the ^{55}Fe system. The OM parameters are being adjusted to fit neutron total cross-section data from 0.5 to 80 MeV, $\sigma(\theta)$ from 2 to 26 MeV, and $A_y(\theta)$ data at 10, 14, and 17 MeV. The energies of the single-particle states in ^{55}Fe are also included in the parameter search. A good overall description of the scattering data was achieved in our preliminary attempt. A status report was given at the Nuclear Physics meeting at Asilomar.

13. Extension of Dispersion-Relation Calculations for ^{208}Pb(n,n) to $A_y(\theta)$ Data
(M. L. Roberts,** Z. M. Chen, P. D. Felsher, D. J. Horen,+ C. R. Howell, K. Murphy,++ H. G. Pfützner, W. Tornow, R. L. Walter)

The TUNL high-accuracy $A_y(\theta)$ data reported last year for ^{208}Pb(n,n) at 6, 7, 8, 9 and 10 MeV have been combined with previous TUNL $A_y(\theta)$ data at 14 MeV and $\sigma(\theta)$ data from various labs (TUNL, MSU, OU) to provide a sizeable data base. We have extended previously reported OM analyses that incorporate the dispersion relation (DR). The DR employed in our model relates the imaginary potential to the real potential, yielding energy-dependent correction terms to the real potential having both volume and surface shapes. The new TUNL $A_y(\theta)$ data were measured primarily to test the optical model below 10 MeV, where the surface correction has a relatively large energy dependence. The $A_y(\theta)$ data also provide an anchor for the rest of the energy range from 0 to 40 MeV (scattering continuum) and from 0 to -20 MeV (bound states). One iteration was sufficient to give a good estimate of the DR terms and the underlying real potential term V_{HF}, the Hartree-Fock mean field. The single-particle bound state energies of ^{208}Pb were computed with the potential extended to negative energies. Quite good predictions resulted, but it was clear that a slight tune on the parameters could give better agreement. So, one final search on the scattering data, which included the known (measured) bound-state energies

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++ Now at Indiana University Cyclotron Facility, Bloomington, IN

as well this time, was performed. The final bound state energies were in appreciably better agreement. The OM derived in this work is very similar to that of Johnson, Horen and Mahaux,[11] except that the analyzing-power data are fit better with the present model.

14. <u>Phase-Shift Analysis of Low-Energy Neutron-^{208}Pb Scattering Data and Dispersive Optical-Model Analyses</u> (Z. P. Chen, <u>W. Tornow</u>)

The existing low-energy n-^{208}Pb elastic scattering data in the energy range from 4 to 15 MeV are generally considered to form an ideal data base for guiding the extrapolation of the OM potential from positive energies to the shell-model potential at negative energies. In fact, the first detailed dispersion-relation OM analysis for nucleon-nucleus scattering[11] is based on the n-^{208}Pb system. The $\sigma(\theta)$ data from the Ohio group and TUNL are available between 4 and 26 MeV. In addition, $A_y(\theta)$ measured at TUNL exist between 6 and 14 MeV.

Although the fits obtained in ref. 11 for the $\sigma(\theta)$ data are generally good, disturbing differences exist between the model prediction and the data. This fact prompted the authors of ref. 11 to introduce an orbital angular momentum dependence in the imaginary part of the mean field and an energy dependence of its surface diffuseness for neutron energies below 10 MeV. With this increased freedom, the quality of the predictions improved considerably, although the fits to the data were still not as good as expected.

Since we are not aware of any serious problems with the data, we decided to perform a phase-shift analysis of the available elastic $\sigma(\theta)$, $A_y(\theta)$ and total cross-section data. The analysis started from the phase-shift parameters obtained in a previous TUNL SOM analysis. Eleven resonances between $3.8 \leq E_n \leq 10.4$ MeV were suggested in the final phase-shift search. More data in smaller energy steps are needed to determine the resonance parameters more accurately. It is not surprising that OM analyses do not describe the experimental data as well as expected, since the n-^{208}Pb system is influenced by overlapping resonances.

15. <u>Microscopic Folding Model of the Nucleon-Nucleus Interaction</u> (L. F. Hansen,* F. S. Dietrich,* <u>R. L. Walter</u>)

Microscopic optical-model potentials based on nuclear matter calculations and various nucleon-nucleon interactions have been reasonably successful for predictions of $\sigma(\theta)$ for neutron elastic scattering and of neutron-interaction total cross sections. One such study[12] explored the Jeukenne-Lejeune-Mahaux (JLM)[13] model for describing a range of nuclei ($9 \leq A \leq 209$) at 14.6 MeV. Impressive agreement was achieved even though only two potential-strength parameters were allowed to vary from the theoretical prediction. No polarization data were included in this study, so the strength of the spin-

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[11] C. H. Johnson, D. J. Horen and C. Mahaux, Phys. Rev. C**36** (1987) 2252

* Lawrence Livermore National Laboratory, Livermore, CA

[12] Hansen, Dietrich, Pohl, Poppe and Wong, Phys. Rev. C**31** (1985) 111

[13] J. P. Jeukenne, A. Lejeune and C. Mahaux, Phys. Rev. C**16** (1977) 80

orbit potential, which originated in the effective interaction work of Bertsch *et al.*[14] (the so-called M3Y interaction), was used directly without any adjustment. Many other folding-model calculations have been made through comparisons to $\sigma(\theta)$ data for (n,n) over a range of energies for individual nuclei, but usually little or no polarization information was available for a complete test of the models.

The TUNL neutron group has accumulated a large amount of $A_y(\theta)$ data over the past years (along with considerable $\sigma(\theta)$ data) for a wide range of nuclei in the energy region 9 MeV < E < 17 MeV. Currently we are performing calculations at LLNL for 10 nuclei ranging from ^{6}Li to ^{208}Pb for $\sigma(\theta)$ and $A_y(\theta)$ for both (n,n) and (p,p) elastic scattering. We are primarily exploring the JLM and the Yamaguchi[15] effective interactions, and the strength of the spin-orbit, the real, and the imaginary potentials. The energy range of this study is about 8 to 40 MeV. The models produce reasonable quantitative agreement for a number of the nuclei, but several cases are inconsistent with the folding-model calculations. For example, in ^{40}Ca the diffraction structure is shifted in angle and in ^{9}Be the structure at backward angles is not reproduced, particularly for $A_y(\theta)$.

16. Influence of Dispersion Relations in the OM Potential on the Magnitude of Extracted Spin-Spin Potentials (M. M. Nagadi, J. P. Delaroche,* C. R. Howell, W. Tornow, R. L. Walter)

Spin-spin cross sections for ^{27}Al were measured by Gould *et al.*[16] using a polarized target and polarized neutrons between 5 and 17 MeV. They fitted the data using the optical model (OM) parameters of Varner *et al.* and using real and imaginary spin-spin potentials with a volume form factor. Additional data was obtained by Heeringa *et al.*[17] between 20 and 50 MeV, and they fitted all of the data by using OM parameters of Martin and using a surface spin-spin potential. One difficulty faced by both groups was the lack of an OM potential designed specifically for ^{27}Al below 14 MeV. We are developing such a model, but one which includes the dispersion relation (DR) constraint. Our preliminary calculations indicate that the spin-spin potential strengths that one obtains in fitting the spin-spin cross sections are sensitive to the inclusion of dispersion terms. When a satisfactory OM is obtained, first we will calculate the spin-spin cross section using the codes GENOA and ECIS in the manner of Gould *et al.* In the next stage we plan to study the spin-spin effects using the code SPINSOR.

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[14] Bertsch, Borysowicz, McManus and Love, Nucl. Phys. **A284** (1977) 399

[15] N. Yamaguchi, S. Nagata and T. Matsuda, Prog. Theor. Phys. (Japan) **70** (1983) 459

* Permanent address: Centre d'Études de Bruyères-le-Châtel, France.

[16] Gould, Haase, Seagondollar, Soderstrum, Nash, Schneider, and Roberson, Phys. Rev. Lett. **57** (1986) 2371

[17] W. Heeringa, H. O. Klages, and Chr. Wolfl (unpublished)

17. Spin-Spin Interactions in Nucleon-Nucleus Scattering (T. L. McAbee, W. J. Thompson, H. Ohnishi)

We have developed a formalism for the nucleon-nucleus spin-spin interaction in terms of generalized spin-spin operators. The formalism was then applied to DWBA calculations of spin-spin cross sections, in which target polarizations of higher order than vector polarization are included. A valence-nucleon model was used to derive potentials from effective nucleon-nucleon interactions, and exchange contributions to the spin-spin potential were estimated. Spin-spin cross sections were calculated for neutron scattering from ^{27}Al, ^{59}Co, and ^{93}Nb in the range 10 to 60 MeV. Good agreement with data from TUNL and Karlsruhe was obtained using a real spin-spin potential calculated directly from M3Y. We find no need to introduce other interactions to describe spin-spin cross sections. A paper has been accepted by Nuclear Physics A.

18. Nuclear Data for Compilations A = 3 to 20 (D. R. Tilley, H. R. Weller)

TUNL began work on a new compilation for the A = 4 system in Spring 1988. During the past year G. M. Hale of LANL agreed to collaborate in this work. It is expected that a preliminary version of the compilation will be available soon. The NRC Panel on Basic Nuclear Data Compilations recommended that the A = 3 to 20 data compilations be assigned to TUNL upon the retirement of Prof. Azjenberg-Selove. TUNL will begin evaluating A = 16 - 17 in 1990. We are working closely with Prof. Ajzenberg-Selove in transfer of materials to TUNL.