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Informal Report

Measurement Committee of the U.S.

Cross Section Evaluation Working Group

Annual Report 1995

by

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and

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INTRODUCTION

The Cross Section Evaluation Working Group (CSEWG) is a long-standing committee charged with the responsibility for organizing and overseeing the U.S. cross-section evaluation effort. It's main product is the official U.S. evaluated nuclear data file, ENDF; the current version of this file is Version VI. All evaluations included in ENDF are reviewed and approved by CSEWG and issued by the U.S. Nuclear Data Center, Brookhaven National Laboratory. CSEWG is comprised of volunteers from the U.S. nuclear data community who possess expertise in evaluation methodologies and who collectively have been responsible for producing most of the evaluations included in ENDF.

In 1992 CSEWG added the Measurements Committee to its list of standing committees and subcommittees. This was based on recognition of the importance of experimental data in the evaluation process as well as the realization that measurement activities in the U.S. were declining at an alarming rate. The mission of the Committee is to establish a network of experimentalists in the U.S. which would provide encouragement to the national nuclear data measurement effort through improved communication and facilitation of collaborative activities. The Committee currently has 19 members, and interested scientists are welcome to join the network simply by contacting the Chairman. For reference, the names of the current members and contact information are contained in this report.

This annual report is the first such document issued by the Committee. It contains voluntary contributions from 10 laboratories in the U.S. which have been prepared by members of the Committee and submitted to the Chairman for compilation and editing. This report is being distributed in hard copy and is also available on-line via the National Nuclear Data Center, Brookhaven National Laboratory. It is hoped that the information provided here on the work that is going on at the reporting laboratories will prove interesting and stimulating to the readers.

Donald L. Smith, Chairman
CSEWG Measurement Committee
Argonne National Laboratory
August 1995

REPORTS FROM THE LABORATORIES

The following reports appear alphabetically in order of the submitting laboratory. The individuals who prepared the reports at each laboratory are indicated along with a contact address for reference. The individual contributions, and names of the contributors, appear as titled subheadings within each laboratory report. Note that there may be some overlap of the topical material submitted by the reporting laboratories. This is inevitable given the extensive ongoing collaborations between several of these organizations.

Argonne National Laboratory

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Measurements and Development of Analytic Techniques for Basic Nuclear Physics and Nuclear Applications

D. L. Smith, J.W. Meadows, B.J. Micklich and I.C. Gomes (*Argonne National Laboratory*), R.C. Haight (*Los Alamos National Laboratory*), T. Covell and S.M. Grimes (*Ohio University*), R.C. Ward (*Rensselaer Polytechnic Institute*), Y. Ikeda, Y. Uno and F. Maekawa (*Japan Atomic Energy Research Institute, Japan*), and A.A. Filatenkov (*Khlopin Radium Institute, Russia*)

Neutron activation cross sections have been measured from 13-15 MeV at JAERI using both elemental and isotopically enriched samples available at JAERI or provided by the Khlopin Radium Institute. Results have been published for ^{63,65}Cu(n,2n)^{62,64}Cu [1]. Data analysis is progressing for ^{11}B(n,p)^{11}Be, ^{16}O(n,p)^{16}N, ^{19}F(n,α)^{16}N, ^{19}F(n,p)^{19}O, ^{23}Na(n,p)^{23}Ne, ^{28}Si(n,p)^{28}Al, ^{37}Cl(n,p)^{37}S, ^{46}Ti(n,p)^{46m}Sc, ^{52}Cr(n,p)^{52}V, ^{53}Cr(n,p)^{53}V, ^{55}Mn(n,α)^{52}V, ^{89}Y(n,n')^{89m}Y, ^{119}Sn(n,p)^{119m}In, ^{138}Ba(n,2n)^{137m}Ba, ^{141}Pr(n,2n)^{140}Pr, ^{186}W(n,2n)^{185m}W, ^{204}Pb(n,2n)^{203m}Pb, ^{64}Ni(n,n'p)^{63}Co, ^{179}Hf(n,2n)^{178m2}Hf, and various reactions involving isotopes of Te and Tl. This information contributes to development of models and cross-section systematics for (n,2n), (n,p) and (n,α) reactions and satisfies data needs for various applications. A paper has been prepared and submitted for publication on the results from neutron activation cross-section measurements for Ag, Fe, Ni, Ti, Hf, Tb, Eu and Cu. This is part of a multinational collaboration coordinated by the IAEA.

Experiments have been carried out at JAERI that demonstrate a new radiation detector calibration scheme based on the ^{11}B(n,p)^{11}Be reaction and also verify the feasibility of merging absolute and shape efficiency data by means of the generalized least-squares method. An additional experiment was performed to explore a new concept for dosimetry of neutron radiation fields. The approach is based on neutron activation and it involves circulation of aqueous solutions of salts such as yttrium chloride. Analysis of data from all these investigations is currently in progress.

Data have been acquired at Ohio University for thick-target neutron production from ^{9}Be(d,n)^{10}B. These results will be of interest for R-matrix analyses of light nuclei and for practical applications such as nondestructive interrogation, boron neutron-capture therapy (cancer) and neutron radiography. The investigation to date has involved deuteron beams in the energy range 3-7 MeV and measurements at up to 20 angles between zero degrees and about 160 degrees. Analysis of these data is in progress as a student thesis project.

Various applications for 6+ MeV gamma rays from the decay of ^{16}N produced by ^{16}O(n,p)^{16}N reactions initiated by 14-MeV neutrons are being explored in collaboration with JAERI. A paper on photon radiography will soon be published. The possibility that the main magnets of ITER might be damaged by these γ-rays emerging from the cooling water is being explored. Photofission of ^{238}U by ^{16}N γ-rays has been observed and a possible application to the detection of fissionable material is being considered for the benefit of arms control technology. Measurements have been performed to demonstrate that formation of ^{16}N by the bombardment of metals and agricultural products provides a means for detecting oxygen contamination or measuring moisture content.

An algorithm which allows relative concentrations of H, C, N, O and other elements to be measured via transmission of pulsed neutron fields from the $^{9}Be(d,n)^{10}B$ reaction has been developed. It is being applied in nondestructive interrogation program supported by the Federal Aviation Administration and Counterdrug Technology Center.

A review of the status of neutron activation cross section data for a number of reactions leading to short-lived radioactive byproducts has been completed and published by the IAEA. This involved collaboration with Rensselaer Polytechnic Institute and the Argonne Fusion Power Program.

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[1] Y. Ikeda, D.L. Smith, Y. Uno, Y. Kasugai, C. Konno and H. Maekawa, **International Conference on Nuclear Data for Science and Technology**, Gatlinburg, Tennessee, 9-13 May 1994, Volume 2, p. 944 (American Nuclear Society, 1994).

Colorado School of Mines

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Low Energy Nuclear Reaction Studies at Colorado School of Mines

F.E. Cecil, J.S. Yan and J.A. McNeil (*Colorado School of Mines*), and R.J. Peterson and R.A. Ristinen (*University of Colorado-Boulder*)

During the last year we have completed a broad survey of the (d,p) and (d,α) reactions on the target nuclei ^{7}Li, ^{9}Be, ^{10}B and ^{11}B. In addition we have measured the reactions ^{9}Be(d,t)^{8}Be and the astrophysically interesting reaction ^{7}Li(^{3}He,p)^{9}Be. Our measurements include angular distributions at the higher energies E_{CM} = 30-80 keV. From these measurements we derive astrophysical S-factors for a total of 18 individual reactions. These S-factors are smooth functions of energy with no new resonances detected. The angular distributions are, in some cases, nearly isotropic and, in other cases, surprisingly non-isotropic. DWBA calculations of these reactions are able to roughly predict the total cross sections but yield predicted angular distributions in stark disagreement to the measurements.

The reaction ^{7}Li(^{3}He,p)^{9}Be may be used to predict the primordial and stellar nucleosynthesis of ^{9}Be and this, in turn, may be used to estimate a network whereby ^{12}C may be synthesized by a process alternative to the traditional "3-alpha" process. This network will involve the (d,p) measurements, in the case of the primordial nucleosynthesis, and our earlier measurements of the (p,γ) reactions on light nuclei, in the case of stellar nucleosynthesis. The reactions ^{9}Be(d,p_1)^{10*}Be and ^{10}B(d,p_1)^{11*}B may be used to study the contamination of the fusion plasmas in the large tokamaks JET and TFTR from the first wall evaporation by observation of the de-excitation gamma rays.

Los Alamos National Laboratory

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Fission Cross Sections

P. Staples, K. Morley, A. Gavron, and P. Lisowski (*Los Alamos National Laboratory*)

Neutron-induced fission cross sections over the range 1 to 200 MeV are being measured for ^{239}Pu, ^{240}Pu, ^{242}Pu, and ^{244}Pu, ^{nat}Pb and ^{209}Bi relative to the ^{235}U fission cross section. Preliminary data have been obtained. This experiment at the WNR spallation neutron source is planned to be completed in 1995.

Neutron-proton Scattering at 10 MeV

R.C. Haight (*Los Alamos National Laboratory*), O.A. Wasson and A.D. Carlson (*National Institute for Standards and Technology*), T.N. Massey, S.M. Grimes, F.B. Bateman, C.E. Brient and Ch. Elster (*Ohio University*), and H. Zhou (*Beijing Normal University, China*)

The relative angular distribution of neutron-proton elastic scattering at 10 MeV is being measured at Ohio University by Ohio University, Los Alamos, NIST and Beijing Normal University. The neutron energy is 10 MeV and the angular range is from 60 to 180 degrees in the center-of-mass in 24-degree steps using a total of 11 detector telescopes. Deviations from isotropy at the level of several percent have been confirmed. A target accuracy for this measurement is ± 2%.

Neutron-proton Scattering at 50 to 250 MeV

J.L. Ullmann, B.K. Park and W. Abfalterer (*Los Alamos National Laboratory*), J. Rapaport (*Ohio University*) and E. Sugarbaker (*Ohio State University*)

Backward-angle neutron-proton scattering is being investigated for proton-recoil angles from zero to 40 degrees (lab) using the WNR white-neutron source. For recoil angles near zero degrees, protons were deflected out of the neutron beam with a 0.55T magnet. An overall uncertainty of ≤ 10% is anticipated in the measurements, which are currently being analyzed.

^{10}B(n,$\alpha\gamma$) Cross Section

A.D. Carlson, O.A. Wasson and R. Schrack (*National Institute of Standards and Technology*) and P. Staples and R.C. Haight (*Los Alamos National Laboratory*)

The cross section of ^{10}B(n,α)^{7}Li (0.478 MeV) is being investigated at WNR by detection of the de-excitation gamma ray in ^{7}Li. The neutron energy range is approximately 0.1 to 20 MeV. This reaction is one of the neutron flux measurement standards. Preliminary data were obtained in 1994 and final runs are scheduled for 1995.

Proton-induced Spallation Yields

J.L. Ullmann, P. Staples, G. Butler, A. Gavron, W. Wilson, D. Jagnow, et al. (*Los Alamos National Laboratory*)

The spallation yield due to 800 MeV protons has been measured at several on- and off-axis locations in stopping length targets of W and Pb. The yields as a function of mass are compared with results of an intranuclear cascade model calculated using the LAHET code system in two ways: first, the measurements are compared with the calculated yields at the time of counting, with decay, buildup, and neutron activation taken into account by the code CINDER'90; secondly, the yields are extrapolated when possible to the end of bombardment and compared directly to the LAHET INC calculation [1].

Helium-production Cross Sections at 10 MeV

R.C. Haight (*Los Alamos National Laboratory*), D.W. Kneff, B.M. Oliver (*Rockwell International Corporation*), L.R. Greenwood (*Argonne National Laboratory and Pacific Northwest Laboratory*), and H. Vonach (*Institute fuer Radiumforschung und Kernphysik, Austria*)

Neutron-induced helium production has been measured at 10 MeV for elemental iron, nickel, and copper and ^{56}Fe and ^{58,60,61}Ni by helium-gas mass spectrometry. The irradiations were performed several years ago with the intense ^{1}H(t,n) quasi-monoenergetic neutron-source reaction at the LANL Ion Beam Facility. The data have undergone further analysis and a manuscript has been submitted for publication.

Carbon(n,xα) Reaction

R.C. Haight, T.M. Lee, S.M. Sterbenz, F.B. Bateman (*Los Alamos National Laboratory*), S.M. Grimes, R. Pedroni, V. Mishra (*Ohio University*), O.A. Wasson (*National Institute of Standards and Technology*), and H. Vonach (I*nstitute for Radiumforschung und Kernphysik, Austria*)

Alpha-particle emission induced by neutron bombardment of carbon has been studied from threshold to over 30 MeV at WNR. KERMA values are deduced from the data [2].

^{56}Fe(n,xα) Reaction

S.M. Sterbenz, F.B. Bateman, T.M. Lee, R.C. Haight, P.G. Young, M.B. Chadwick (*Los Alamos National Laboratory*), F.C. Goeckner, C.E. Brient, S.M. Grimes (*Ohio University*), P. Maier-Komor (*Technical University-Munich, Germany*), and H. Vonach (*Institut fuer Radiumforschung und Kernphysik, Austria*)

Alpha-particle emission in neutron reactions with ^{56}Fe has been studied from threshold to over 30 MeV at WNR. Cross sections, angular distributions and spectra were measured. The results agree with previous measurements near 14 MeV and resolve several discrepancies in the region from threshold to 14 MeV. Above 15 MeV, the data show a steadily rising cross section [3].

^{59}Co(n,xα) Reaction

F. Goeckner, S.M. Grimes, C.E. Brient (*Ohio University*), T.M. Lee, S.M. Sterbenz, F.B. Bateman, R.C. Haight, P.G. Young, M.B. Chadwick (*Los Alamos National Laboratory*), O.A. Wasson (*National Institute of Standards and Technology*), and H. Vonach (*Institut fuer Radiumforschung und Kernphysik, Austria*)

Alpha-particle production cross sections, spectra and angular distributions from neutron bombardment of ^{59}Co have been measured from threshold to 50 MeV at WNR [4].

^{207,208}Pb-207(n,Xn' γ) Reactions

H. Vonach and A. Pavlik (*Institute for Radiumforschung und Kernphysik, Austria*), M.B. Chadwick, R.C. Haight, R.O. Nelson, S.A. Wender, and P.G. Young (*Los Alamos National Laboratory*)

High-resolution gamma-ray spectra from the interaction of neutrons in the energy range from 3 to 200 MeV with ^{207,208}Pb were measured to obtain excitation functions of (n,Xn′) reactions with X=1 to 9. The results, when compared with calculations using the code GNASH show that above 30 MeV excitation energy, the level density prescription of Ignatyuk is strongly preferred over that of Gilbert and Cameron. The inclusion of multiple pre-equilibrium processes is important for incident energies greater than 40 MeV [5].

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[1] J.L. Ullmann, et al., **International Conference on Nuclear Data for Science and Technology**, Gatlinburg, Tennessee, 9-13 May 1994, Volume 1, p. 374 (American Nuclear Society, 1994).

[2] R.C. Haight, et al., **International Conference on Nuclear Data for Science and Technology**, Gatlinburg, Tennessee, 9-13 May 1994, Volume 1, p. 311 (American Nuclear Society, 1994).

[3] S.M. Sterbenz, et al., **International Conference on Nuclear Data for Science and Technology**, Gatlinburg, Tennessee, 9-13 May 1994, Volume 1, p. 314 (American Nuclear Society, 1994).

[4] F. Goeckner, et al., **International Conference on Nuclear Data for Science and Technology**, Gatlinburg, Tennessee, 9-13 May 1994, Volume 1, p. 318 (American Nuclear Society, 1994).

[5] H. Vonach et al., ***Phys. Rev.*** **C50**, 1952 (1994).

National Institute of Standards and Technology

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Measurement Program

A.D. Carlson, R.A. Shrack, and O.A. Wasson (*National Institute of Standards and Technology*)

Our neutron measurement program continues with studies of those neutron standard cross sections which are crucial to improved neutron fluence determination. We continue to collaborate in experiments at available neutron facilities.

The H(n,p) Angular Distribution at 10-MeV Neutron Energy

R. Haight (*Los Alamos National Laboratory*), F. Bateman, C. Brient, S. Grimes, and T. Massey (*Ohio University*), A. Carlson, and O. Wasson (*National Institute of Science and Technology*), H. Zhou (*Beijing Normal University, China*)

The approximately 3% differences between the ENDF/B-V and ENDF/B-VI evaluations of this important standard cross section in the 10-MeV energy region guided us to undertake this crucial measurement. The experiment was performed at the Ohio University Tandem Accelerator facility. Measurements were done of this angular distribution from 60 to 180 degrees in the center-of-mass system by detecting recoil protons. The data acquisition is complete. Detailed analysis and comparison with the predictions of various phase-shift parameter sets and one-boson exchange potentials is in progress.

Completion of the $^{10}B(n,\alpha_1)$ Standard Reaction Cross-section Measurement from 0.3 to 12 MeV Neutron Energy

R. Schrack, A. Carlson, and O. Wasson (*National Institute of Standards and Technology*), P. Staples and R. Haight (*Los Alamos National Laboratory*)

The purpose of this relative measurement is to extend the usefulness of this standard cross section to higher neutron energies and to extend the measurement to lower energies for normalization to the existing standard. The initial measurement was performed using the WNR facility at the LAMPF accelerator at LANL during the fall of 1994. The neutron fluence was measured from the $^{235}U(n,f)$ reaction while the 478-keV photons from the $^{10}B(n,\alpha_1)$ reaction were detected in an intrinsic Ge detector. The relative cross section was obtained from 0.3 to 12 MeV. The results are in good agreement with our earlier measurement [1] in the 0.2 to 4 MeV neutron energy region carried out at Oak Ridge, and thus verifies the deviation from the ENDF/B-VI values for energies greater than 2 MeV. We plan to complete this investigation in the fall of 1995 with measurements at lower neutron energies for normalization.

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[1] R. Schrack et al., ***Nucl. Sci. Eng.*** **114**, 352 (1993).

Oak Ridge National Laboratory

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On October 1, 1994, the ORELA facility was transferred to the ORNL Physics Division with a new mission in nuclear astrophysics, and other basic physics research as appropriate. Since then, we have operated the accelerator for a total of eight weeks.

Nuclear Astrophysics Studies

J. K. Dickens, K. H. Guber, J. A. Harvey, N. W. Hill, P. E. Koehler, D. C. Larson, S. Raman, M. S. Smith, and R. R. Spencer (*ORNL*), R. R. Winters (*Denison University*), J. C. Blackmon, A. E. Champagne, M. A. Hofstee, and D. C. Ralston (*UNC at Chapel Hill and TUNL*)

We have performed four measurements chosen for their importance to nuclear astrophysics problems; measurement of: 1) the ^{134}Ba(n,γ) and ^{136}Ba(n,γ) capture cross sections; 2) the ^{134}Ba and ^{136}Ba total neutron cross sections; 3) the ^{142}Nd(n,γ) and ^{144}Nd(n,γ) capture cross sections; and 4) the ^{7}Li(n,γ) capture cross section. The first three measurements impact our understanding of the stellar origins of these isotopes which are produced at critical branching points in the astrophysical s-process. Our work discovered a number of new resonances in the (previously unmeasured) 20 eV to 50 keV neutron energy range. This range is crucially important for a new class of stellar models attempting to explain new, high-precision heavy element isotopic abundance data from meteorite fragments. The results of these experiments will direct the ORELA nuclear astrophysics measurements we make next year. The fourth ORELA experiment was used to look for deviations of the ^{7}Li(n,γ) cross section from 1/v (*i.e.*, s-wave) behavior as a function of neutron energy, which may indirectly provide information on the solar neutrino problem. We exploited the capabilities of ORELA by taking data for approximately 6 weeks on four separate flight paths simultaneously. The ^{142}Nd and ^{144}Nd capture cross sections were measured with a rebuilt, high-efficiency BaF2 detector system, previously developed and used for measuring the ratio of capture to fission in ^{235}U. With additional work, this system has the potential for making neutron capture measurements on very small quantities (~ 10 mg) of expensive, separated isotopic materials which are of astrophysical importance.

Fundamental Properties of the Neutron

S. Kopecky, P. Riehs (*Technical University of Vienna*), J. A. Harvey, and N. W. Hill (*ORNL*)

Additional background studies were done to resolve some issues associated with high-precision neutron transmission measurements on lead done last year. The purpose of the measurements is to improve our value of the polarizability of the neutron. The goal is a reduction of the measurement uncertainty by a factor of two. Future work on this project, and a project to improve the value of the charge radius of the neutron, is planned.

Ohio University

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Measurement of the n-p Elastic Angular Distribution at 10 MeV

S.M. Grimes, C.E. Brient, T.N. Massey, F.B. Bateman, and J.F. Guillemette (*Ohio University*), R..C. Haight (*Los Alamos National Laboratory*), A.D. Carlson and O.A. Wasson (*National Institute of Standards and Technology*)

Measurements of the differential cross section for n-p at 10 MeV are currently underway. A multi-telescope system will allow measurements at 0, 12, 24, 36, 48 and 60 degrees. Each telescope consists of a ΔE and E detector; all detectors are silicon surface barrier detectors. All angles except 0° will be measured simultaneously with detectors to the left and right of 0°; this will both improve statistics and allow a check on whether the system is properly aligned. This system was tried out in a measurement in early 1995, and an additional run has been completed in May 1995. Analysis of the results of this last run is currently underway.

The goal of this work is to obtain a relative angular distribution for n-p scattering which is accurate to better than 2%. In this energy range, the capture cross section is negligible and the integral of the elastic cross section is, therefore, the total cross section. The very precisely known total cross section will allow a determination of the absolute differential cross sections to an accuracy which is limited only by the relative errors.

Measurements of the Be-10(α,n)C-13 Cross Section

S.M. Grimes, C.E. Brient, T.N. Massey, F.B. Bateman, and J.F. Guillemette (*Ohio University*)

The cross section and angular distributions for neutrons populating the first two levels in ^{13}C have been measured for a number of α energies between 4 and 10 MeV. An R-matrix analysis is being conducted which will lead to an improved prediction capability for neutron reactions of the type $^{13}C(n,\alpha)^{10}Be$ and $^{13}C(n,n')^{13}C$; but the cross section for $^{13}C(n,\alpha_0)^{10}Be$ can also be derived through detailed balance from that for $^{10}Be(\alpha,n_0)^{13}C$.

Measurement of ^{28}Si(n,p) and ^{28}Si(n,α)

S.M. Grimes, C.E. Brient, T.N. Massey, F.B. Bateman, and J.F. Guillemette (*Ohio University*), R.C. Haight (*Los Alamos National Laboratory*)

Cross sections for $^{28}Si(n,p)^{28}Al$ to the first four states in ^{28}Al and $^{28}Si(n,\alpha)^{25}Mg$ to the first four states in ^{25}Mg have been measured over the energy range $5 \le E_n \le 12$ MeV. These data can be used to determine the neutron detection efficiency of a silicon detector but also could be used through detailed balance to determine cross sections for $^{25}Mg(\alpha,n_o)$ or $^{28}Al(p,n_0)$ in astrophysics.

Pacific Northwest Laboratory

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Beta Decay Half-Lives and Delayed Particle Emission for Very Neutron-rich, Light-mass Nuclides

P.L. Reeder, Y. Kim, W.K. Hensley, H.S. Miley, R.A. Warner, and Z.Y. Zhou (*Pacific Northwest Laboratory*), D.J. Vieira, J.M. Wouters, and H.L. Siefert (*Los Alamos National Laboratory*)

We have used the Time-of-Flight Isochronous (TOFI) spectrometer at the LAMPF accelerator to systematically measure the half-life ($t_{1/2}$), delayed neutron emission probability (P_n), average energy of delayed-neutron spectra, and β-delayed α emission for a large number of neutron-rich isotopes for all Z values between Li and Cl. The TOFI spectrometer identifies the Z, A, and Q of each recoiling ion produced by fragmentation reactions from 800-MeV proton bombardment of a ^{232}Th target. These ions are stopped in a thin Si detector surrounded by a 2-mm-thick plastic scintillator plus a thick Si detector, which together are used to measure β particles. The vacuum pipe containing these detectors is surrounded by a polyethylene- moderated neutron counter. Ions are detected during the LAMPF beam pulse. β-decay products are detected during the 7-ms period between beam pulses (87.6% duty factor).

Half-lives are determined by a delayed coincidence technique based on time-interval histograms using the arrival time of a specific ion as the start time, and the arrival time of subsequent betas or neutrons as the stop time. The neutron yield relative to the number of ions of a specific type provides a measurement of the P_n; β-neutron coincidence counting gives an alternative measurement of P_n. An energy-dependent neutron counting efficiency is used based on a calibration curve of efficiency vs. the ratio of counts in the outer ring of neutron counter tubes to counts in the inner ring (ring ratio). Nuclides with well-known P_n values are used to construct the calibration curve. Similarly, average energies of delayed-neutron spectra are determined using a calibration curve of energy vs. ring ratio for nuclides with well-known energy spectra. β-delayed α spectra are obtained by gating the pulse height spectra in the thin Si detector by a specific nuclide and for a time interval of four half-lives following the arrival of the specific nuclide. Because the ions are implanted in the Si detector deeper than the range of the delayed-α particles, the measured pulse height spectrum includes the energy of both the α particle and the recoiling ion.

Preliminary results with this technique for about 30 nuclides were published previously [1]. Measurements are now available for about 60 nuclides based on data collected over several years. Half-lives have been measured for 55 nuclides, and include the first half-life measurements for ^{25}F, ^{26}F, ^{28}Ne, ^{35}Mg, ^{33}Al, ^{36}Al, ^{37}Si, and ^{41}S. We report P_n values for 40 nuclides including previously unmeasured P_n values for ^{14}B, ^{17}C, ^{18}N, ^{35}Mg, ^{32}Al, ^{33}Al, ^{36}Si, ^{37}Si, ^{38}P and ^{45}Cl.

Average neutron energies are reported for 14 nuclides ranging from ^{11}Li to ^{30}Na. The average neutron energies for ^{17}N and ^{29}Na measured here are in excellent agreement with average energies derived from spectra measured with He-3 spectrometers. However, the average energies measured here for ^{14}Be, ^{17}C, ^{18}C, and ^{18}N are much lower than average energies deduced from neutron spectra measured by a time-of-flight technique at Michigan State University [2]. This can readily be explained as being due to the high threshold at about 700 keV for the time-of-flight spectrometer. In particular, our average neutron energy of 0.60±0.06 MeV for ^{14}Be is below the threshold of the MSU detector and suggests that most of the delayed neutrons are emitted from a state at about 1.6 MeV in ^{14}B.

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[1] P. L. Reeder et al., *Phys. Rev.* **C44**, 1435 (1991).

[2] M. D. Belbot, et al., ***Phys. Rev.*** **C51**, 2372 (1995).

University of California-Davis

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65-MeV Fe, Sn, and Pb(n,n′X) Measurements Over the Continuum Region

E.L. Hjort (*Purdue University*), F.P. Brady, J.R. Drummond, B. McEachern, J.H. Osborne, and J.L. Romero (*University of California-Davis*), D.S. Sorenson (*Los Alamos National Laboratory*), H.H.K. Tang (*IBM East Fishkill Laboratory*)

Inelastic scattering continuum cross sections have been measured for Fe, Sn, and Pb targets using a detection system consisting of large area wire chambers and dExE scintillation detectors in conjunction with a CH_2 converter. The giant resonance continuum regions of the (n,n′X) spectra are compared with earlier (p,p′X) results and macroscopic model analyses are used to extract the ratio of neutron to proton matrix elements, M_n/M_p. The ratio is found to be consistent with the hydrodynamical model, (M_n/M_p about = N/Z) and inconsistent with pion inelastic scattering analyses. Comparisons of the data with continuum models are also made.

Elastic Scattering Cross Section for Neutrons with Energies up to 200 MeV

J.H. Osborne, F.P. Brady, and J.L. Romero (*University of California-Davis*), J.L. Ullmann, and D.S. Sorenson (*Los Alamos National Laboratory*), A. Ling (*TRIUMF, Canada*), R. Finlay, and J. Rapaport (*Ohio University*)

Elastic scattering cross sections have been measured for ^{12}C, ^{40}Ca, and ^{208}Pb targets from 5-21 degrees and 50-200 MeV using the White Neutron Source at the Los Alamos Meson Production Facility (LAMPF). A large acceptance drift chamber based (n,p) recoil detector telescope was used. This detector included two scintillating converters. The cross sections are being compared to a global Dirac phenomenology model and to microscopic optical models.

Fragmentation of Silicon Induced by 80-MeV Protons: A Study of the Nuclear Reaction $^1H(^{28}Si,\alpha)X$ at 80 MeV/Nucleon

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In March 1995, we performed an experiment to measure isotopic double differential cross sections (in angle, energy, Z and A) for the inclusive $^{28}Si(p,\alpha)X$ reaction, initially at a proton energy of 80 MeV and for A greater than about 12. Here A is the mass number of the outgoing nucleus from the fragmentation of ^{28}Si and X stands for anything else. The energy spectra for the products A are needed over nearly the complete kinematic range at a number of angles. In order to detect the heavy recoils, the experiment involved the use of reverse kinematics: a 80 MeV/nucleon ^{28}Si beam from the NSCL cyclotron impinged on a CH_2 target. We used the zero deg A1200 Mass Separator at NSCL to measure the fragments in the forward direction. By also measuring the spectra from a C target of similar thickness, the H cross section is obtained by subtraction.

On-line analysis shows average CH_2 to C counting rate ratios of about 1.5 to 2 for individual fragments. This will allow the extraction of the H cross section with good statistics. The results will be compared with and used in cascade-type statistical models, and will significantly extend the data base. We anticipate a continuing program at MSU involving a range of energies as well as O and C beams, which are also of great interest in radiotherapy and radiobiology. Such data would complement earlier measurements at UCD of the light particle (H and He ion) spectra.

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Collective Level Studies In and Near Rare Earths

C. McGrath, M. Yeh, D. DiPrete, M. Li, M. Villani, P. Garrett, and S.W. Yates (*University of Kentucky-Lexington*)

Multi-phonon excitations of the type E2(x)E2 and also E2(x)E3 have been sought and tentatively identified in ^{144}Sm and ^{142}Nd. Measurements have included (n,n′γ) excitation functions from 2.5 to 4 MeV incident neutrons, and γ-ray angular distributions at several incident energies. Separated-isotope samples have been used. Level schemes, spins of levels, decay branching ratios, and multipole mixing ratios have been determined for many levels. Lifetimes have been measured for E1 and E2 decays from those levels using Doppler Shift Attenuation Methods (DASM). These lifetimes aid in tentatively identifying levels as multi-phonon excitations. Lifetimes have also been measured for other levels.

Scissors mode (M1) excitations have been sought in ^{88}Sr and in the dysprosium isotopes with A = 162, 164. All of the known M1 excitations have been excited using (n,n′γ) methods, and their strengths measured using DASM to obtain lifetimes. The M1 excitations are shown to be collective, but anomalously strong M1 transitions previously reported from resonance fluorescence measurements at Stuttgart are not found in this study. The M1 excitations fit nicely into an M1 strength systematics developed for this mass region. Excitation functions and angular distributions have been measured for the (n,n′γ) reactions.

Coincidence Studies of the Shape-Transitional Xenon Nuclei

C.A. McGrath, M. Yeh, M.F. Villani, P. D. Garrett, and S.W. Yates (*University of Kentucky-Lexington*)

Xenon nuclei are difficult enough to have in any solid form; separated isotope samples are out of the question. However, it has been possible to obtain 50 gm of xenon diflouride, and isotope identification can be obtained using γ-γ coincidence measurements in the study of the Xe(n,n′γ-γ) reactions. A special system using highly collimated neutron fluences enables study in fairly conventional geometry without inundating the HpGe detectors with neutrons. Strong collimation of neutron fluences results in a collimated flux whose intensity drops by a factor of 50 at the edge of the transmitted flux. Forced reflection collimators enable such reduction factors up to an incident neutron energy of 7 MeV. Much sharper collimated flux edges are obtained for 3 to 4 MeV neutrons. These nuclei are especially interesting since, like nuclei of the Os-Pt region, they are expected to exhibit O(6) symmetry, with very strong importance of the gamma or axial asymmetry degree of freedom.

Multi-phonon Excitations in ^{144}Nd and ^{142}Ce

J. Vanhoy (*U.S. Naval Academy*), S.F. Hicks (*University of Dallas*), and S.W. Yates (*University of Kentucky-Lexington*)

Excitations of the type E2(x)E3 have been identified in both nuclei. The (n,n′γ) reactions are measured for neutron energies from 1.5 MeV to 3.5 MeV and used to place levels into a scheme, determine spins, decay branching ratios, and multipole mixing-ratios. Separated isotope samples were used in this work. Level lifetimes were measured with DASM methods to test the hypothesis of multi-phonon excitations. Good agreement was found between measured lifetimes and expected ones based on multi-phonon pictures.

Mixed Symmetry States and Very Fast E1 Transitions Are Studied In ^{146}Nd

D. DiPrete, C. McGrath, M. Villani, and S. W. Yates (*University of Kentucky-Lexington*), T. Belgya (*Hungary*)

DASM lifetime measurements have identified many E1 transitions considerably faster than 10^{-3} W.u., which seems to be a fairly clear signature that the corresponding states are collective. Although most collective, mixed symmetry states are 1+ states, several 2+ states have here been identified in ^{146}Nd which seem also to have mixed-symmetry character. Separated isotope samples were used in this work.

Decay Schemes and Level Identifications for Highly Excited Pb Isotopes

M. Yeh, M. Li, C. McGrath, G. Chen, P.D. Garrett, M.T. McEllistrem, and S.W. Yates (*University of Kentucky-Lexington*)

Gamma-ray decay schemes and level lifetimes of ^{206}Pb and ^{208}Pb are being measured in the (n,n′γ) reactions for levels up to about 6 MeV excitation energies using separated isotope samples. Lifetimes for high energy γ-ray decays may indicate the collective character of highly excited levels in these nuclei, and lead to identification of some multi-phonon excitations. Measurements to date are for excitation functions, or γ-ray yields as a function of neutron energy from 4 MeV incident to 6.5 MeV incident. Part of the purpose of these measurements is to complement the neutron detection experiments described below.

Level Schemes and Level Lifetimes in ^{116}Sn and ^{120}Sn

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Very complete level and γ-ray decay schemes have been measured for ^{116}Sn using a separated isotope sample. This work was aided by combining with it also the ^{115}Sn neutron capture work of S. Raman, ORNL. Levels were compared with shell model calculations. All expected levels of the calculations were identified; only a few others were also found. The unusually complete level scheme, together with neutron capture data, gave a level density picture from the ground state to 8 MeV excitation energy. Only the Generalized Superfluid Model (GSM) of Ignatyuk could represent the complete spectrum of levels over the entire energy range.

Work on ^{120}Sn is in progress also using a separated isotope sample. Detailed levels schemes, spin assignments, branching and mixing ratios are being identified. Level densities will be studied with backshifted Fermi Gas models and with the GSM model when the level studies are complete.

Neutron Scattering Studies

S.F. Hicks (*University of Dallas*), M. Li, G. Chen, M. Villani, M.T. McEllistrem, and J.L. Weil (*University of Kentucky-Lexington*)

Elastic and inelastic scattering to the 2+ and 3- levels of ^{204}Pb and ^{206}Pb have been measured at an incident energy of 8 MeV using separated isotope samples. The results from that work are combined with earlier, unpublished measurements of total cross sections made in our laboratory [1]. Analyses of all of these data, and comparisons with electromagnetic excitations of the same levels, revealed i-spin mixtures in transitions to the 2+ levels of both nuclei, but apparently single i-spin transitions to the 3- levels. These data suggest that comparable neutron and proton excitations across shell gaps are involved in the 3- levels, but the 2+ levels show more valence neutron excitation strengths than proton strengths.

Neutron elastic and inelastic scattering measurements have been completed for ^{140}Ce and ^{142}Ce at an incident neutron energy of 7.5 MeV using separated isotope samples. These data are being combined with previously measured total cross sections from the NNDC (Brookhaven National Laboratory) compilations and analyzed to reveal the i-spin character of collective excitations in these nuclei. We expect to be able to ascertain i-spin mixtures in transitions to first 2+ and 3- levels.

Neutron elastic and inelastic scattering measurements are being continued for incident neutrons at 7.5 MeV, and will be extended to 8.5 MeV later, for neutrons incident on ^{206}Pb and ^{208}Pb, using separated isotope samples. The focus of these experiments is the description of anomalously strong excitations particularly in ^{208}Pb near excitation energies from 4 MeV to about 5.5 MeV. These are clearly strongly collective levels of unknown origin, which are severely damped but still visible in ^{206}Pb. Although individual levels cannot be resolved in these neutron detection measurements, completed via time-of-flight (tof) techniques, individual level contributions can be separated by combining these data with the $(n,n'\gamma)$ measurements at the same incident neutron energies. The γ-ray measurements are discussed above.

Dispersion corrections to the mean scattering field for neutrons incident on several Sn isotopes are being developed for both spherical, or single channel mean field models, and for coupled channels models which explicitly include the 2+ excitations. Only the latter, coupled channels models describe all known scattering observables and bound single particle level energies in a single consistent framework.

^{81}Br(p,n)^{81}Kr and ^{55}Mn(p,n)^{55}Fe Q-Value Measurements

M. Villani, and M. T. McEllistrem (*University of Kentucky-Lexington)*

Calibration of an eventual Br solar neutrino detector would be done experimentally using a ^{51}Cr neutrino source. One of the levels of ^{81}Kr which would contribute to the neutrino absorption has an energy just below the energy of the neutrino energies from the ^{51}Cr source. Hence, to have an accurate efficiency calibration including that excited level, it is advisable to have the ^{81}Br(p,n) Q-value well known. Previous direct measurements have left an uncertainty close to 6 keV; but the ^{51}Cr neutrino energy is only 9 keV above the threshold for the ^{81}Kr capture to the 5/2- level. We have measured the Q-value for the Br(p,n) reaction with an uncertainty of 0.9 keV, greatly increasing accuracy and confidence in energies associated with these reactions.

Nucleosynthesis in the Cd-In-Sn Region

Z. Nemeth (*Budapest, Hungary*), T. Belgya (*Hungary*), and S.W. Yates (*University of Kentucky-Lexington*)

It has been difficult to account for natural abundances occurring for some In, even-A Sn, and Sb isotopes. Levels of ^{113}Cd were thought to be effective "gateway" levels, through thermal excitation in stellar conditions, relating to the synthesis of isotopes via the s-process in stars. Thus levels of ^{113}Cd were studied with the (n,n′γ) reactions on a separated isotope sample, and the 522-keV gateway level was confirmed [2]. This study has the result that the isomer, expected to play a strong role in s-process formation of these isotopes, is destroyed in stars. This means that the s-process branching at ^{113}Cd is strongly reduced compared to earlier expectations; the s-process is unlikely to account for the isotope abundances.

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Neutron Scattering Data and Fission Spectrum Measurements

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Neutron Scattering Data

^{235}U measurements: High resolution neutron time of flight spectra were measured to obtain differential and angle integrated cross sections for elastic (ground state + 77 eV + 13 keV levels) and inelastic scattering for low-lying excited states (46 + 52 keV levels) at 570 keV incident neutron energy. Data have been obtained at 9 angles. Further measurements will be made at several more incident energies.

^{239}Pu measurements: Angular distributions were measured at 570 keV and 700 keV for two level groups, ground + 7.9 keV state, and 57 + 76 keV levels. The angle-integrated cross sections at 570 keV for these two neutron groups are 5864 ± 264 mb, and 570 ± 42 mb, respectively. At 700 keV, the corresponding values are 5060 ± 308 mb and 518 ± 62 mb, respectively. The results have been submitted for publication.

^{197}Au measurements: Angular distributions have been measured for the ground, 77, 269 and 279 keV states in the angular range 45° to 145° in 10° steps at incident energies of 1.0, 1.5, and 2.0 MeV. In addition, total cross section measurements were made in a transmission experiment for energies 800 keV to 1.5 MeV.

Fission Spectrum Measurements

^{235}U and ^{239}Pu prompt fission neutron spectra induced by fast neutrons: Fission neutron energy spectra were measured for energies greater than the incident neutron energy to investigate the shape dependence of the spectra upon both the incident neutron energy and the mass of the fissioning nuclide, as predicted by the Los Alamos model of Madland and Nix [1]. Measurements were made for both nuclides at incident energies of 0.50, 1.50, 2.50, and 3.50 MeV. The data are in good agreement with the predictions of the model. A paper on this work has been accepted for publication in Nuclear Physics A.

Prompt fission spectrum measurements for energies less than the energy of the incident neutrons: We are currently tackling this formidable experimental problem using coincidence signals from three fast barium fluoride scintillation detectors, which observe fission γ-rays, as a trigger to tag an event as a fission event. Neutrons accompanying this fission tag are fission neutrons as distinguished from elastically or inelastically scattered neutrons. A preliminary report on this work was made at the 1994 Gatlinburg Conference [2].

Beta and Gamma Decay Heat Measurements Between 0.1s and 50,000s for Neutron Fission of ^{235}U, U-238 and Pu-239

W. Schier, G. Couchell, D. Pullen, P. Chowdhury, J. Campbell, S. Li, H. Nguyen, E. Seabury, and S. Tipnis (*University of Massachusetts-Lowell*)

A helium-jet/tape-transport system was used for the rapid transfer of fission products to a low-background environment where their aggregate β and γ-ray spectra were measured as a function of delay time after neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu. β and γ-ray energy distributions have been deduced for delay times as short as 0.2 s and extending out to 100,000 s. Instrumentation development during the initial phase of the project included: 1) assembly and characterization of a NaI(Tl) spectrometer for determining aggregate γ-ray energy distributions, 2) development and characterization of a β spectrometer (having excellent γ-ray rejection) for measuring aggregate β-particle energy distributions, 3) assembly and characterization of a Compton-suppressed HPGe spectrometer for determining γ-ray intensities of individual fission products to deduce fission-product yields. Spectral decomposition and analysis codes were developed for deducing energy distributions from measured aggregate β and γ spectra. Our aggregate measurements in the time interval 0.2 - 20 s after fission are of special importance since in this region data from many short-lived nuclei are missing and summation calculations in this region rely on model calculations for a large fraction of their predicted beta and gamma decay heat energy spectra.

Comparison with ENDF/B-VI fission product data was performed in parallel with the measurements through a close collaboration with Dr. T. England at LANL, assisted by one of our graduate students. Such aggregate measurements provide tests of the Gross Theory of β decay used to calculated missing contributions to this data base. Fission-product yields deduced from the HPGe studies will check the accuracy of the semi-empirical Gaussian dispersion model used presently by evaluators in the absence of measured yields. These studies, which involve several hundred identified γ-ray lines, also provide numerous microscopic tests of nuclear databases at the individual nuclide level. These measurements and their analysis for ^{235}U and ^{238}U fission products will be completed by the end of the current year. ^{239}Pu measurements were recently begun and should also be completed during this period.

During this past year a computer-based multiparameter, event-mode recording and analysis system was purchased, and its feasibility for future aggregate fission product studies demonstrated by using it to perform internal-conversion-electron/characteristic X-ray coincidence measurements. A number of internal conversion transitions in individual nuclides have been identified by sorting on characteristic x-rays.

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