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Informal Report

# Measurement and Basic Physics Committee of the U.S. Cross-Section Evaluation Working Group

# Annual Report 1997

by

**Donald L. Smith, Chairman**
Argonne National Laboratory

and

**Victoria McLane**
Brookhaven National Laboratory

**Compiled and Edited at Argonne National Laboratory**

**October 1997**

**National Nuclear Data Center**
**Brookhaven National Laboratory**
**Upton, NY 11973-5000**

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# Introduction

The Cross-Section Evaluation Working Group (CSEWG) is a long-standing committee charged with 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, as well as periodic modifications and updates to the file, 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 action was based on a 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 and needed considerable encouragement to avoid the loss of this resource. The mission of the Committee is to maintain contact with experimentalists in the U.S. and to encourage them to contribute to the national nuclear data effort. Improved communication and the facilitation of collaborative activities are among the tools employed in achieving this objective. In 1994 the Committee was given an additional mission, namely, to serve as an interface between the applied interests represented in CSEWG and the basic nuclear science community. Accordingly, its name was changed to the Measurement and Basic Physics Committee.

The present annual report is the third such document issued by the Committee. It contains voluntary contributions from several laboratories in the U.S. Their contributions were submitted to the Chairman for compilation and editing. This report is available in hard copy and on the Internet, along with earlier reports from 1995 and 1996, at the National Nuclear Data Center, Brookhaven National Laboratory. The Web site URL is http://www.nndc.bnl.gov/ (look under "Reports").

I hope the information provided here on nuclear data work in progress at the reporting U.S. laboratories will prove both interesting and stimulating to the reader.

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# Reports from the Laboratories

The following reports appear in alphabetical order, sorted by submitting laboratory. The individual(s) who prepared the reports at the various contributing laboratories are indicated along with a contact address(es) for reference. Titles of individual contributions and the authors appear as titled subheadings within each laboratory report wherever such information was available to the compiler. Note that there may be some duplications of topical material submitted by the reporting laboratories. This is inevitable given the extensive and very desirable ongoing collaborations between several of these organizations.

## Argonne National Laboratory

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### Use of Gamma Rays from the Decay of 13.8-sec $^{11}$Be to Calibrate a Germanium Gamma Ray Detector for Measurements up to 8 MeV

Y. Ikeda, F. Maekawa and Y. Uno (*Japan Atomic Energy Research Institute, Tokai, Japan*); D.L. Smith (*Argonne National Laboratory*); A. Filatenkov (*Khlopin Radium Institute, St. Petersburg, Russia*)

It is difficult to calibrate germanium (Ge) gamma-ray detectors for accurate measurements above 3-MeV because of the limited availability of convenient radiation sources with well-known gamma-ray emission probabilities. One approach which has been used with some success is to employ prompt high-energy gamma rays from (n,$\gamma$) reactions initiated by low-energy neutrons. However, to accomplish this requires thermal- or epithermal-neutron beams from a reactor or sources of moderated neutrons from an accelerator. Also, there are difficulties with this approach associated with the fact that the relative intensities of the gamma rays used for calibration will depend upon which resonance(s) are excited in neutron capture, and hence on the neutron spectrum. The present approach utilizes the decay of 13.8-sec $^{11}$Be which is produced by the $^{11}$B1(n,p)$^{11}$Be reaction. The reaction Q-value is -10.724 MeV and the threshold is about 11.7 MeV. In the present investigation, $^{11}$Be was produced by this reaction using the intense 14-MeV neutron source provided by the FNS accelerator at JAERI. The cross section for this reaction is around 5.5 millibarn at 14 MeV [1]. A sample of elemental boron in the form of tetra-boron carbide was placed in a nylon capsule, transported by a pneumatic system to the vicinity of the FNS target, irradiated with neutrons and then returned promptly to a remote location for counting with a germanium detector. The relative efficiency of this detector could then be determined above 3 MeV using the following $^{11}$Be decay gamma rays (with relative intensities indicated in percent): 2.124 MeV (35.5%), 4.666 MeV (1.82%), 5.019-MeV (0.467%), 5.852 MeV (2.13%), 6.790 MeV (4.48%) and 7.975 MeV (1.90%) [2]. The present investigation has explored this approach by performing measurements, developing data analysis procedures, and establishing which corrections to raw data are required to develop a reliable efficiency curve for a Ge detector.

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[1] Evaluated Nuclear Data File, ENDF/B-VI, NNDC, Brookhaven National Laboratory, USA.
[2] E. Browne and R.B. Firestone, *Table of Radioactive Isotopes*, Wiley, New York, 1986.

### Neutron Spectrum Adjustment Using Reaction Rate Data Acquired with a Liquid Dosimetry System

D.L. Smith (*Argonne National Laboratory*); Y. Ikeda, Y. Uno, and F. Maekawa (*Japan Atomic Energy Research Institute, Tokai, Japan*)

A new concept of fast-neutron dosimetry has been reported recently [1]. It is based on continuously circulating a liquid containing dissolved chemicals between a localized neutron field and a remote location where the induced radioactivities are detected. This approach has been pursued further by examining procedures for analyzing dosimetry data acquired with such a system. Reaction rates were determined for the relatively short-lived radioactivities generated in a solution of yttrium-chloride hexahydrate by the $^{16}O(n,p)^{16}N$, $^{37}Cl(n,p)^{37}S$ and $^{89}Y(n,n')^{89m}Y$ reactions. These reactions exhibit widely different thresholds so they provide complementary information which is useful for neutron-spectrum adjustment purposes. The technique was applied to an analysis of the neutron spectrum generated in the vicinity of the the target of the JAERI FNS accelerator. This spectrum is dominated by neutrons near 14-MeV, but it also includes lower-energy neutrons resulting from scattering interactions near the target. A prior representation of this spectrum was generated from Monte-Carlo neutron transport calculations. The present spectrum-adjustment procedure is based on Bayesian principles as embodied in a generalized-least-squares algorithm [2,3]. This approach combines prior subjective information (a calculated spectrum) and new objective information (the measured reaction rates) in an optimal fashion, tests the consistency of these results and provides uncertainty estimates for the adjusted group cross sections. The present application of this approach yielded reasonably consistent results, but it also indicated a need for better-quality differential cross-section data for those particular neutron-induced reactions which were employed in this investigation.

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[1] D.L. Smith, Y. Ikeda, Y. Uno, and F. Maekawa, *Proc. 9th International Symposium on Reactor Dosimetry*, Prague, Czech Republic, 2-6 September 1996.
[2] D.L. Smith, *Probability, Statistics and Data Uncertainties in Nuclear Science and Technology*, American Nuclear Society, LaGrange Park, Illinois, USA, 1991.
[3] D.L. Smith, Report ANL/NDM-128, Argonne National Laboratory, Illinois, 1993.

### Data Compilation and the Derivation of Reaction Rates at Stellar Energies for (p,γ) and (p,α) Reactions in the Mass Range A = 30-50

D. Smith (*Argonne National Laboratory*); J. Daly (*Indiana University, South Bend, Indiana*); L. Van Wormer and R. Miller (*Hiram College, Hiram, Ohio*); M. Wiescher (*University of Notre Dame, South Bend, Indiana*)

Reactions of the type (p,γ) and (p,α) play important roles in stellar nucleosynthesis [1]. This work has been carried out in the framework of an ongoing collaboration between Argonne National Laboratory, Indiana University, Hiram College and University of Notre Dame. The objective of this work is to compile data on these specific reactions, and on the corresponding compound nuclei which are formed, for the mass range A = 30-50. This project is part of a larger international endeavor to improve the data base of nuclear reaction information employed in astrophysical analyses. Using this collected information, reaction rates and their associated uncertainties are being determined at center-of-mass interaction energies corresponding to Maxwell-Boltzmann distributions for stellar temperatures which range from $T_9 = 0.01$ to 10 in units of $10^9$ degree Kelvin, *i.e.*, for kT = 0.86 to 860 keV. Depending upon the individual reactions and compound nuclear systems formed, reaction rates under these conditions may be dominated by a few isolated resonances, by so many resonances that they can be treated statistically, by direct (non-resonant) interactions, or by various combinations of these mechanisms. Regardless of the situation, the calculated reaction rates are found to be extremely sensitive to the stellar temperature $T_9$. During the past year work has been in progress for the following specific reactions: $^{31}P(p,\gamma)^{32}S$, $^{31}P(p,\alpha)^{28}Si$ and $^{32}S(p,\gamma)^{33}Cl$. Summaries of pertinent references found in the literature are being prepared and files of data published therein are being assembled in the EXFOR format [2] for transmittal to data centers. In the case of $^{32}S(p,\gamma)^{33}Cl$, an Argonne National Laboratory report has been issued summarizing the work on this reaction [3]. Reaction-rate calculations have been performed based on consideration of both known individual resonances and a Hauser-Feshbach approach which can treat the compound nucleus as a continuum of levels. Uncertainty estimates for these reaction rates have also been generated. They are based on the propagation of errors in parameters which figure in the reaction-rate calculations.

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[1] C. Rolfs and W. Rodney, *Cauldrons in the Cosmos*, University of Chicago Press, Chicago, Illinois, USA, 1988.

[2] IAEA Nuclear Data Center, International Atomic Energy Agency, Vienna, Austria.

[3] R.E. Miller and D.L. Smith, Report ANL/NDM-143, Argonne National Laboratory, 1997.

### $^{53}$V Half-life Determination

D.L. Smith (*Argonne National Laboratory*); A. Fessler (*Institute for Reference Materials and Measurements, Geel, Belgium*)

The half life of $^{53}V$ has been determined by measurements of $^{53}V$ radioactivity produced via $^{53}Cr(n,p)^{53}V$ and $^{54}Cr(n,np+d)^{53}V$ reactions that were induced by the irradiation of an elemental chromium metal sample with fast neutrons. Neutrons with an average energy of 19.1 MeV were generated by $^{3}H(d,n)^{4}He$ reactions in a titanium-tritide target irradiated with 3-MeV deuterons from a Van de Graaff accelerator. The full-energy-peak yield of 1006-keV gamma rays from $^{53}V$ decay was measured with an intrinsic germanium detector. Twenty five independent decay curves were acquired through repeated irradiations followed by gamma-ray counting. The acquired data (171 data points in all) were analyzed using the method of weighted least-squares. Each individual decay curve yielded an independent value for the $^{53}V$ half life. The 25 independent half-life values determined in this way were averaged to yield a final value for the $^{53}V$ half life: 93.4 ± 1.3 seconds (one standard deviation error). Although smaller than all but one of the other values reported in the literature, it is consistent with most of them within the given errors. The present result and the earlier experimental values were then used to produce a new evaluation (recommended value) for the $^{53}V$ half life: 92.4 ± 1.1 seconds (one standard deviation error).

## Measurement of the $^{52}$Cr(n,p)$^{52}$V, $^{52}$Cr(n,2n)$^{51}$Cr, $^{51}$V(n,p)$^{51}$Ti, and $^{51}$V(n,$\alpha$)$^{48}$Sc Cross Sections Between 7.9 and 14.4 MeV

W. Mannhart and D. Schmidt (*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*); D.L. Smith (*Argonne National Laboratory*)

The cross sections for $^{52}$Cr(n,p)$^{52}$V, $^{52}$Cr(n,2n)$^{51}$Cr, $^{51}$V(n,p)$^{51}$Ti, and $^{51}$V(n,$\alpha$)$^{48}$Sc were measured at 15 neutron energies between 7.9 and 14.4 MeV. With a deuterium gas target, neutrons were produced via the D(d,n)$^{3}$He reaction. The neutron energies were determined by time-of-flight techniques. The neutron fluence was monitored using a low-mass $^{238}$U fission chamber. Metallic samples, 10 mm in diameter and 1 mm thick, were attached to the front of the fission chamber and were irradiated at zero degrees at a distance of 6 cm between gas target and samples. The induced radioactivity was measured with a calibrated HPGe detector of 300 cm$^3$. Extensive corrections were applied for background and deuterium breakup neutrons to derive high-precision data on monoenergetic neutron cross sections. The results are compared with previous measurements and with ENDF/B-VI, EFF-2.4 and a few other recent evaluations.

## Neutron Activation Cross Sections for Short-lived Isotopes in the Energy Range 16-20 MeV

A. Fessler and E. Wattecamps (*Institute for Reference Materials and Measurements, Geel, Belgium*); Y. Ikeda (*Japan Atomic Energy Research Institute, Tokai, Japan*); S.M. Qaim (*Forschungszentrum-Juelich, Juelich, Germany*); D.L. Smith (*Argonne National Laboratory*)

Neutron activation cross section measurements for the production of short-lived isotopes have been carried out at the IRMM 7-MV Van de Graaff accelerator facility, Geel, Belgium, for five neutron energies in the range 16-20 MeV using the T(d,n)$^4$He neutron source reaction. The activities observed in this work had half lives ranging from 7 seconds to several hours, but most were from 10 seconds to a few minutes. The induced radioactivities were measured by observing $\gamma$-rays emitted from irradiated samples with a germanium detector. A pneumatic sample transport system (rabbit) was built and a collection of natural and isotopically-enriched sample materials was made available by JAERI. The enriched isotopes and compounds were: $^{25}$Mg (MgO), $^{46}$Ti and $^{50}$Ti (TiO$_2$), $^{52}$Cr, $^{53}$Cr, and $^{54}$Cr (Cr$_2$O$_3$), $^{54}$Fe (Fe$_2$O$_3$), $^{57}$Fe (Fe metal), $^{62}$Ni (Ni metal), $^{119}$Sn (SnO$_2$) and $^{138}$Ba (BaCO$_3$). The reference cross sections for this investigation were $^{27}$Al(n,p)$^{27}$Mg, $^{27}$Al(n,$\alpha$)$^{24}$Na and $^{93}$Nb(n,2n)$^{92m}$Nb reactions. Data were acquired for some 30 reactions. In several cases isomer ratios could also be measured. The cross sections derived from these data are compared with experimental results from the literature and with values calculated using the nuclear model code STAPRE-H95 [1].

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[1] M. Avrigeanu, M. Ivascu, and V. Avrigeanu, *STAPRE-H - "A Computer Code for Particle Induced Activation Cross Sections and Related Topics"*, NEA Data Bank, IAEA 0971/03 (1995).

# Colorado School of Mines

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**Low-energy Nuclear Physics Program**

F.E. Cecil, J.A. McNeil, and M.A. Hofstee (*Colorado School of Mines*)

Our low-energy nuclear physics program is currently devoted to four projects:

*Thin-thick Target Experiments*

Use of "thin-thick" targets in which a low-energy beam stops in a target while exothermic reaction products are able to pass through the target and be detected in transmission geometry at forward angles, including zero degrees. Using this technique, we have successfully measured the (d,p), (d,t) and (d,α) reactions for deuteron bombarding energies of 100 and 150 keV. When combined with our previous measurements of these reactions at backward angles using standard reflection geometry, we now have angular distributions for these reactions from zero to 165 degrees laboratory scattering angles. We are currently applying this technique to the deuteron-induced reactions on $^{6}$Li, $^{7}$Li, $^{10}$B and $^{11}$B.

*Measurements of (d,n) Reactions on Light Nuclei*

We are undertaking a series of measurements of (d,n) reactions on light nuclei as analogue reactions to the (d,p) reactions discussed above. We have acquired and are in the process of calibrating a large volume BC-505 fast-liquid-scintillation detector. The system will be calibrated using the well-measured D(d,n)$^{3}$He and $^{6}$Li(d,n)$^{7}$Be reactions before undertaking our measurements on heavier nuclei.

*Theoretical Studies of the Origins of Highly Non-Isotropic (d,p) Angular Distributions*

We are continuing our theoretical efforts to understand the highly non-isotropic angular distributions of the (d,p) reactions discussed above (*Thin-thick Target Experiments*). This effort will incorporate explicit exchange effects in the single-nuclei transfer reaction calculations. Preliminary results are able to reproduce the experimentally observed strong backward peaking in the $^{9}$Be(d,p)$^{10}$Be reaction. We expect to extend these calculations to the (d,n) reactions whose measurements are discussed above (*Measurements of (d,n) Reactions on Light Nuclei*).

*$^{7}Be(p,\gamma)^{8}B$ Experiment*

As part of an extramural collaboration, one of us (MAH) is involved with the $^{7}Be(p,\gamma)^{8}B$ project at Oak Ridge National Laboratory. This project is still in the developmental stages and our collaboration will continue.

## Los Alamos National Laboratory

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### $^{171}$Tm(n,$\gamma$) Cross Section

J.B. Wilhelmy, R.S. Rundberg, M.M. Fowler, G.G. Miller, K. Ullmann, J.L. Ullmann, and R.C. Haight (*Los Alamos National Laboratory*)

As part of a new program to study neutron capture cross sections on radioactive nuclides, neutron capture gamma rays were measured for neutrons incident on radioactive $^{171}$Tm. A target consisting of about 2.7 Ci (2.5 mg) of the 1.9-year $^{171}$Tm was prepared by irradiation of $^{171}$Er in the INEL reactor. The Tm was chemically separated from the Er source and electro-deposited on a 0.5-mil Be foil that had been coated with about 700 Angstroms of Ti. A cover foil of 0.5 mil Be was placed on top of the target. The target sandwich was irradiated at the Lujan Center pulsed neutron facility at the Los Alamos Neutron Science Center (LANSCE). Prompt gamma rays were measured using two deuterated-benzene liquid scintillators. Neutron energies were determined by time-of-flight techniques. The useful range was from 1 eV to more than 100 keV incident neutron energy. To verify the procedure, several stable species were measured using the same chemical techniques and experimental set up. These consisted of $^{169}$Tm, $^{165}$Ho, $^{171}$Yb, blank Be backings, and Au foils. The on-line analysis showed very distinctive structure that could be identified with capture reactions on $^{171}$Tm. Data reduction is currently in progress to convert the results into neutron energy-dependent capture cross sections. These data are of interest in s-process astrophysical applications.

### Neutron Total Cross Sections on a Wide Range of Materials from 5 to 600 MeV

F.S. Dietrich (*Lawrence Livermore National Laboratory, Livermore, California*); W.P. Abfalterer, R.C. Haight, G.L. Morgan, and F.B. Bateman (*Los Alamos National Laboratory*); R.W. Finlay (*Ohio University, Athens, Ohio*).

Total neutron cross sections of 37 samples, from H through Th, were measured in a good geometry transmission experiment from 5 to 600 MeV at the Los Alamos Weapons Neutron Research (WNR) spallation source. Neutron energies were determined by standard time-of-flight techniques. Refinements were made to allow measurements on separated isotopes, such as $^{182,183,184,186}$W and $^{54,56}$Fe, and other materials only available in small quantities. Typical accuracy of the results is 1%.

### $^{58,60}$Ni(n,x$\alpha$) Reactions

R.C. Haight, F.B. Bateman, and S.M. Sterbenz (*Los Alamos National Laboratory*); S.M. Grimes (*Ohio University, Athens, Ohio*); O.A. Wasson (*National Institute for Standards and Technology, Gaithersburg, Maryland*); H. Vonach (*Institut fuer Radiumforschung und Kernphysik, Vienna, Austria*); P. Maier-Komor (*Technische Universitat, Munich, Germany*)

Alpha-particles emitted in the interaction of neutrons with $^{58}$Ni and $^{60}$Ni have been studied and cross sections, emission spectra and angular distributions have been obtained for incident neutron energies from threshold to 50 MeV. In the region of nuclear data evaluations (up to 20 MeV), significant differences were found between these results and ENDF-B/VI except near 14 MeV. Our results however are consistent with other measurements reported in the literature. Thus we conclude that normalization of calculations at one energy (*e.g.*, 14 MeV) can give erroneous results at other energies.

### Si(n,p), (n,d), and (n,$\alpha$)

F.B. Bateman, R.C. Haight, S.M. Sterbenz (*Los Alamos National Laboratory*); H. Vonach (*Institut fuer Radiumforschung und Kernphysik, Vienna, Austria*)

Neutron-induced reactions that produce charged particles are particularly important for silicon because these reactions can cause single-event upsets (SEU) and other effects in computers and burnout in solid-state electric-power components. Radiation damage of silicon detectors in nuclear physics experiments is also a serious concern. We are studying the cross sections, angular distributions and charged particle spectra from threshold to 50 MeV with the WNR spallation source of fast neutrons at LANSCE. Data have been taken with silicon targets from 2.7 to 42 microns thick. Preliminary results are in agreement with the few measurements reported in the literature. Our data will fill in the entire neutron energy range up to 50 MeV. We are comparing these data with nuclear-model calculations based on compound and pre-compound particle-emission theories.

### S(n,p) and (n,$\alpha$)

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

Proton and $\alpha$-particle production by neutrons on sulfur is being studied with neutrons from threshold to 50 MeV to investigate isospin effects in these reactions. Preliminary data show distinct fluctuations for several MeV above threshold and may give information on nuclear level densities in this region when analyzed by fluctuation theory.

### Fission Cross Sections

P. Staples and K. Morley (*Los Alamos National Laboratory*)

Neutron-induced fission cross sections over the range 0.5 to 300 MeV have been measured for $^{239,240,242,244}$Pu, $^{197}$Au, $^{nat}$Pb and $^{209}$Bi relative to the $^{235}$U fission cross section. A manuscript has been submitted for publication.

### $^{235,238}$U and $^{239}$Pu (n,xn$\gamma$)

GEANIE collaboration: R.O. Nelson, Contact (*Los Alamos National Laboratory*)

Cross sections of neutron-induced gamma rays are being used to deduce (n,2n) and (n,3n) cross sections on $^{235,238}$U and $^{239}$Pu from threshold to over 20 MeV. The GEANIE (GErmanium Array for Neutron-Induced Excitations) array of Compton-suppressed germanium detectors is used to detect gamma rays in the cascade forming the residual nuclides. Preliminary data have been obtained on 4+ to 2+ and higher transitions in even-even residual nuclides.

# National Institute of Standards and Technology

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### Measurement Program (Overview)

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

This measurement program continues with studies of important neutron cross-section standards which are needed for improved determinations of neutron cross sections and neutron fluence. Work continues on collaborative experiments at available neutron facilities and efforts are made to encourage additional measurements to improve the standards.

### The Hydrogen Scattering Cross Section at 10-MeV Neutron Energy

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

The hydrogen scattering cross section is one of the most important neutron cross-section standards. Concerns about significant differences between the well-established ENDF/B-V and the new ENDF/B-VI evaluations of this cross section in the 10-MeV energy region led this collaboration to undertake new high-accuracy measurements of this standard. An initial experiment was performed at the Ohio University Tandem Accelerator facility. Preliminary measurements were made of the angular distribution from 60 to 180 degrees in the center-of-mass system by detecting recoil protons. Though the uncertainties place limits on the results, the data suggest that the problem may be with the ENDF/B-VI hydrogen evaluation. Further data taking is planned this November with an improved experiment which reduces systematic error by using a common electronic system for all detectors so that the dead time losses are the same for all detectors. Higher statistical accuracy is also expected.

## Measurements Supporting Improvements in the $^{10}B(n,\alpha)$ Cross-section Standards

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

As part of an NEANSC-endorsed inter-laboratory collaboration to extend the usefulness of the $^{10}B(n,\alpha)$ standard cross section to higher neutron energies, further measurements are planned of the shape of the $^{10}B(n,\alpha_1\gamma)$ cross section using a new experimental setup at the WNR facility at Los Alamos National Laboratory. For this work, the neutron fluence will be measured using the $^{235}U(n,f)$ reaction and the $^{10}B(n,\alpha_1\gamma)$ reaction rate will be determined by detecting the 478-keV photons from this reaction with an intrinsic Ge detector. The data will be obtained from about 0.2 to 10 MeV neutron energy. Preliminary measurements of this cross section were made previously at WNR.

The need for very accurate cross section measurements for special applications in such fields as astrophysics requires the standards to be determined to even higher accuracies than they are now known. There is a strong need for better standards in the keV-energy region. Often such measurements use a low-energy (thermal) normalization. A measurement of the $^{10}B$ total cross section at very low energies (about 4 meV) at NIST is now being planned. The scattering cross section is small and well known so the $^{10}B(n,\alpha)$ cross section in the 1/v-energy region can be determined from this measurement. The experiment will be done on a guide tube at the NIST Cold Neutron Research Facility which employs a liquid-hydrogen moderator. A pyrolytic-graphite monochromator with a beryllium filter has been designed for this work. The monochromator will have an energy uncertainty of 0.1% and an energy spread of 1%. This facility should be operational by the end of this year. Backgrounds should be small since the guide tube allows the experiment to be done far from the reactor. A well-characterized liquid sample is being prepared for this work.

# Ohio University

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## Overview

S.M. Grimes and T.N. Massey (*Ohio University*)

Research activities at Ohio University were concentrated in the areas of exotic light nuclei, systematics of total neutron cross sections, nuclear level densities, and neutron source spectra.

## Excited Levels of $^{8}$He

No author list provided

A study of the excited levels of $^{8}$He was completed in collaboration with a group of scientists at the Hahn-Meitner Institute in Berlin. A beam of 357-MeV $^{12}$C particles was obtained from the cyclotron at the Hahn-Meitner Institute and was used to bombard a $^{10}$Be target. The reaction $^{10}$Be($^{12}$C,$^{14}$O)$^{8}$He was studied with a magnetic spectrograph. The fact that $^{14}$O has only one particle-stable state means that $^{14}$O particles observed at less than the maximum energy correspond to excited states in $^{8}$He. Reaction products were seen corresponding to the ground state and four excited states in $^{8}$He. In addition to the energies and widths of these states (three of which are reported for the first time), we have deduced limits on the spins of these levels. These results have been reported in a paper by Stolla *et al.* (Zeitshrift Fuer Physik **A356**, 231, 1996).

## Total Cross Section Measurements

No author list provided

Total neutron cross sections have been measured over the range of 5 to 600 MeV for a number of targets by Finlay *et al.* (reported in Physical Review). These cross sections have small error bars (< 2%). In collaboration with John Anderson and Rudy Bauer (LLNL) and Vic Madsen (Oregon State), we have been looking at the systematics of these cross sections. A Ramsauer model provides a parameterized mathematical form of the total cross section which can be fitted to available data. There are two parameters, radius R and reduced wavelength $\alpha$ (a parameter between 0 and 1). The latter is a phase angle corresponding to the phase difference between the wave which passes through the nucleus and the wave which goes around the nucleus. We have used this mathematical form and deduced values of R and $\alpha$ and which fit the data from 6 to 60 MeV to about 2%. The values of R and $\alpha$ thus obtained are found to be physically reasonable in magnitude. A poorer quality of fit was obtained with the global parameterization when the fitting region is extended to 150 or to 600 MeV. The use of relativistic kinematics produced some improvement and the fits resulting from this change are good enough that further efforts to improve the parameterization seems warranted. A paper reporting the results for the 6-60 MeV region has been submitted to Nuclear Science and Engineering by R.W. Bauer *et al.* Further work is continuing on the 6-600 MeV range.

### Stopping-target Neutron Spectrum from $^{27}$Al(d,xn)

No author list provided

Measurements of the stopping-target spectrum of neutrons from the $^{27}$Al(d,xn) reaction have been completed and a paper has been submitted to Nuclear Science and Engineering by T.N. Massey *et al.* The measurements were at an energy of $E_d = 7.44$ MeV and at angles of 90°, 110°, and 120° using NE-213 detectors. Further measurements were made at 120° with a $^{235}$U fission chamber provided by Argonne National Laboratory in a time-of-flight spectrometer. The absolute neutron fluence was determined at each energy bin to better than 5%. The resulting data provide a means of calibrating a neutron detector over the range $0.2 \leq E_n \leq 15$ MeV.

### Level-density Studies

No author list provided

A paper has been published by F. Bateman *et al.* (Phys. Rev. **C55**, 133, 1997) giving measured values for the level density of $^{29}$Si from 3 MeV to 22 MeV. The Ericson fluctuations in the reactions $^{27}$Al(d,n)$^{28}$Si, $^{28}$Si(n,p)$^{28}$Al and $^{28}$Si(n,$\alpha$)$^{25}$Mg were studied in measurements carried out at WNR (Los Alamos) and at Ohio University. Also included in the analysis were level-density values from summing up resolved levels. A set of level-density parameters is derived that fits the level density over the range 3 MeV $\leq$ E $\leq$ 22 MeV.

### Neutrons from Protons and Deuterons Incident on Stopping Targets of Beryllium

No author list provided

The production of neutrons from stopping targets of beryllium by both protons and deuterons is of interest for applied and medical physics. This work has been a collaboration with Argonne National Laboratory and MIT. To investigate the production of neutrons from a stopping beryllium target, we have made measurements with both NE-213 and lithium-glass detectors. The Al(d,n) reaction at 120° and 7.44 MeV incident energy was used to obtain the detector efficiency from 0.2 to 15.0 MeV.

The neutron production from proton bombardment of beryllium is being considered as a source reaction for the boron neutron therapy treatment of cancer. Thus, the low-energy portion of the spectrum is extremely important. We have completed measurements at incident energies of 2.0-4.0 MeV. Of special interest in our preliminary results is the relative importance of the neutrons produced from inelastic scattering to the first and second excited states of $^{9}$Be.

We have completed precision measurements of the angular and energy dependence of neutrons from the $^{9}$Be(d,n) reaction at incident deuteron energies of 2.6, 3.0, 3.4, 3.8, 4.2, 4.6, 5.0, 5.4, 5.8, 6.2, 6.6, and 7.0 MeV using NE-213 detectors. A measurement of the low-energy neutrons has been completed from 3.0 and 7.0 incident deuteron energy using a Li glass detector array.

### Deuteron Optical-model Studies in Fe and Al

No author list provided

An investigation into the deuteron optical model near the Coulomb barrier in $^{56}$Fe and $^{27}$Al is in progress. We have completed initial measurements of the neutron, proton, deuteron and alpha channels at energies from 2.5 to 7.0 MeV. This set of data includes all of the open channels available in the bottom part of this energy range. The result of these studies will help improve our knowledge of transmission coefficients near the Coulomb barrier for Hauser-Feshbach calculations.

### Reaction-channel Widths from Shell-model Wave Functions

No author list provided

We have developed a technique of calculation of the widths of various reaction channels using wave functions obtained from shell-model diagonalization. These widths are then used to predict the cross section of reactions which cannot be directly measured. We have extensively studied the $^{10}$Be and $^{14}$C compound nuclei and are beginning studies of $^{11}$B and $^{12}$B. These will be studied with (p,n) and (d,n) reactions on a $^{10}$Be target.

## University of California - Davis

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### Measurement of Neutron Elastic-scattering Cross Section for $^{12}C$, $^{40}Ca$, and $^{208}Pb$ at Energies from 52.5 MeV to 225 MeV with Angles from 7 Degree to 23 Degree

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

Differential neutron elastic-scattering cross sections for three isotopic targets ($^{12}C$, $^{40}Ca$, and $^{208}Pb$) have been measured using the continuum-neutron source at the Los Alamos Meson Production Facility (LAMPF). Incident-neutron kinetic energies ranged from 45 MeV to 250 MeV. The data are placed in angle and energy bins during analysis. Cross sections are computed for mean energies of 52.5, 65, 75, 85, 95, 107.5, 127.5, 155, 185, and 225 MeV. The scattering-angle bins are 2 degree wide with the cross sections computed for mean laboratory angles varying from 7 degree to 21 degree. The detector system is based on the conversion of scattered neutrons to protons in plastic scintillators. The recoil protons are detected in a large area E-dE detector telescope that uses drift chambers to measure angles and determine hit locations on the various detectors. The measured cross sections are compared with the predictions of three different Optical Models.

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* Ph. D. dissertation, Department of Physics, University of California - Davis, 1995.

### Hydrogen Depth Profiling Using Coincidence-proton Elastic Scattering

R.S. King*, T.A. Cahill, C.M. Castaneda, and J.L. Romero (*University of California - Davis*)

A dual ion coincidence technique utilizing proton-proton elastic scattering is studied for use in depth profiling hydrogen concentration in thin targets. Particular attention is paid to understanding the effects of multiple scattering, energy straggling, and macroscopically non-homogeneous target media on the spectra of summed coincident-proton energy. Experimental results for 2.5-MeV protons incident on thin sandwich targets of carbon/mylar and porous Teflon/mylar clearly show the layered hydrogen depth profile. In order to better understand experimental results a numerical simulation program, CPESS, was developed. One immediate and important application of this new technique is discriminating between organic vapor and particulate residues in quartz and Teflon air filters used to sample fine organic atmospheric aerosols. The measurements were performed at the Crocker Nuclear Laboratory 76-inch cyclotron.

* Ph. D. dissertation, Department of Physics, University of California - Davis, 1996.

**Fragmentation of Si Induced by 80 MeV Protons using Reverse Kinematics**.

J.L. Romero, F.P. Brady, D.A. Cebra, J. Chance, J. Kintner, and J.H. Osborne (*University of California - Davis*); D.J. Morrissey, M. Fauerbach, R. Pfaff, C. Powell, and B.M. Sherrill (*Michigan State University, East Lansing, Michigan*); H.K. Tang (*I.B.M. Microelectronics, Semiconductor Research and Development Center, East Fishkill Laboratory, Hopewell Junction, New York*)

Differential cross sections of charged fragments near zero degree were measured for the $^{1}H(^{28}Si,A)x$ reaction at 80 MeV/nucleon, using the A1200 zero-degree spectrometer at the National Superconducting Cyclotron Laboratory, Michigan State University. $CH_2$ and C targets were used. The fragments detected ranged from A=5 through A=28. Preliminary results for selected fragments ($^{10}Ne$, $^{24}Mg$, and $^{27}Al$) and comparison with the intra-nuclear cascade-statistical model developed by Henry Tang *et al.* at I.B.M. (code NUSPA) were presented at the 1996 International Conference on Application of Accelerators in Research and Industry, Denton, Texas, and published in Ref. [1]. Further analysis is in progress.

[1] J.L. Romero, H.K. Tang, D.J. Morrissey, M. Fauerbach, R. Pfaff, C. Powell, B.M. Sherrill, F.P. Brady, D.A. Cebra, J. Chance, J. Kintner, and J.H. Osborne, *American Institute of Physics Conference Proceedings No. 392*, 655-658, 1997.

# University of Kentucky - Lexington

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Methods Developments in Nuclear Structure Studies with Neutrons

### Coincidence Arrays for use in Neutron Inelastic Scattering

Michael Strano, P.E. Garrett, Minfang Yeh, and S.W. Yates (*University of Kentucky*)

An interim design, three detector array has been used successfully for coincidence detection of gamma rays from neutron inelastic scattering. A modified Spencer design, forced reflection collimator is used to collimate the neutrons to a nearly paraxial 2-cm-diameter flux. This has enabled the placement of the faces of 50+% HpGe detectors to within approximately 6 cm of the center of the flux, enabling good coincidence geometry without excessive damage to the detectors. Now a more carefully designed four 50+% HpGe array carriage is in construction. The mounting frame for the four detectors has shielding which reduces crosstalk between the detectors. This improved array will enable twice the coincidence detection rate that had been enjoyed with the earlier three detector array, and considerably improved background conditions. The new array will be in service by November, 1997.

Multi-phonon Quadrupole Excitations - Spherical Nuclei

### Three-phonon multiplets in Cd nuclei

H. Lehmann, J. Jolie (*Fribourg University, Fribourg, Germany*); M. Kadi, P.E. Garrett, and S.W. Yates (*University of Kentucky*)

Many examples exist for two-phonon quadrupole triplets near twice the energy of the one-phonon 2+ excitation, but the persistence of quadrupole collectivity to higher excitation energies is still an open question. Clear evidence of the persistence of quadrupole collectivity would be evidence for three-phonon multiplets, at about three times the energy of the single phonon excitation. The Cd isotopes seem to be the best place to search for multi-phonon excitations. Extensive measurements of gamma-ray spectra as a function of incident neutron energy (excitation functions) for confident placement of levels and angular distributions of gamma rays have given both spin assignments and limitations and lifetimes of levels. Measurements have been concluded for $^{112}$Cd and are in progress for $^{116}$Cd using isotopically highly enriched samples.

### Three-phonon Quadrupole Excitations

Vladimir Sorokin and Jesse L. Weil (*University of Kentucky*); Zoltan Gacsi (*Institute of Nuclear Studies, Debrecen, Hungary*)

New measurements of excitation functions and angular distributions have been made for $^{124}$Sn, where early work identified a quintuplet of states which only decayed into the two-phonon triplet of states. Angular distributions have been measured for the purpose of extracting lifetimes using DSAM techniques. Additional measurements of angular distributions and lifetimes are planned for the next couple of years. If the lifetimes indicate adequate collectivity, that would be convincing evidence of a three-phonon multiplet in that nucleus.

## Collective Levels in the Rare Earth Region via (n,n'γ) Studies

### Band Structures in $^{166}$Er

P. E. Garrett, Minfang Yeh, M. Kadi, S.W. Yates (*University of Kentucky*); H. Lehmann, J. Kern, J. Jolie, and N. Warr (*Fribourg University, Fribourg, Germany*)

Angular distribution and excitation function measurements for $^{166}$Er provided new lifetime measurements which showed that the state previously identified as the K = 4 two-gamma phonon bandhead was too slow to be that collective state. Instead, another bandhead which has collective E2 decays was identified 50 keV higher than the previously suspected bandhead. Also a 0+ state was found which is the 0+, K = 0 bandhead of a double gamma phonon excitation. Finally, another 0+ level has been identified as the beta bandhead. Thus several band structures have been clarified in that deformed nucleus.

Lifetime measurements were completed with our HpGe detector inside an anti-Compton BGO shield. This detection system enables measurement of angle-dependent energy shifts to a precision of about 0.01 keV; this sensitivity means we can fix well lifetimes for neutron scattering from heavy nuclei.

In order to investigate the properties of higher spin states than can be achieved with (n,n'γ) studies, the $^{164}$Dy(α,2nγ) reaction has been employed at the Paul Scherrer Institute (Villingen PSI, Switzerland). Analysis of this data is in progress.

### Level Structures in $^{178}$Hf

P.E. Garrett, Minfang Yeh, M. Kadi and S.W. Yates (*University of Kentucky*)

The BGO-shielded anti-Compton spectrometer is being used to measure level thresholds, angular distributions of gamma rays, and lifetimes of levels in $^{178}$Hf. The goal of this work is to search for multi-phonon structures.

## Level Structures in Quasi-vibrational Nuclei

### Transition Rates in $^{207}$Pb

M. Kadi, P.E. Garrett, Minfang Yeh, and S.W. Yates (*University of Kentucky*)

DSAM measurements of lifetimes in $^{207}$Pb have been completed. This nucleus has several single particle levels at low energies, some of which can decay via single particle E1 transitions. At the same time, a well known octet of levels exists from coupling of the g7/2 single particle excitation to the 3- collective excitation in $^{208}$Pb. The E1 transitions from those levels to the lower-lying single particle levels destroy the octupole excitation. Thus it is possible, in principle, to compare E1 rates of these two types of transition. If the comparison is promising, there may be a means of distinguishing those E1 transitions de-exciting E3 excitations from those of other, non-collective excitations. That would be very useful in seeking multi-phonon structures involving E3 collective excitations.

### Levels and Transition Rates in $^{116}$Sn and $^{120}$Sn

V. Sorokin and J.L. Weil (*University of Kentucky*); Zoltan Gacsi (*Institute of Nuclear Studies, Debrecen, Hungary*)

Lifetime data has been taken using the DSAM technique, and the voluminous data sets are now being examined to see whether the transition speeds are consistent with the extended shell model calculations of Bonsignori and Allart. The level scheme of $^{116}$Sn is beautifully represented by these broken pair calculations. The question arises whether the lifetimes, or transition rates will also be found to be consistent, and whether evidence can be adduced for multi-phonon excitations.

**Decay Properties and Lifetimes of States in $^{124}$Te**

S. J. Etzkorn, P.G. Burkett, and Sally F. Hicks (*University of Dallas, Dallas, Texas*); J.R. Vanhoy and B.R. Champagne (*U.S. Naval Academy, Annapolis, Maryland*); P.E. Garrett and Minfang Yeh (*University of Kentucky*).

Excited levels of $^{124}$Te have been studied using the (n,n'γ) reaction. Gamma-ray excitation functions were measured to 3.3 MeV excitation in $^{124}$Te. Multipole-mixing ratios, branching ratios and lifetimes were deduced. These experimental results were compared to predictions based on the interacting-boson model II (IBM-II) and those based on the particle-core coupling model.

**Development and testing of the GEANIE coincidence array at LANSCE**

R.O. Nelson, G.D. Johns, W.S. Wilburn, D.M. Drake, and R.S. Rundberg (*LANSCE, Los Alamos National Laboratory, Los Alamos, New Mexico*); D.E. Archer, J.A. Becker, L.A. Bernstein, K. Younes, and W. Hauschild (*Lawrence Livermore National Laboratory, Livermore, California*); G.E. Mitchell (*TUNL, North Carolina State University, Raleigh, North Carolina*); P.E. Garrett and S. W. Yates (*University of Kentucky*)

The development and construction of the 20 anti-Compton shielded-detector array named GEANIE was done primarily by LANSCE and LLNL personnel, but background tests were done with the collaboration of the two people from the University of Kentucky. This array is now in use, and LANSCE is accepting proposals for experiments where neutron induced reactions leading to rather high multiplicity decays would benefit from the use of such an array. The GEANIE array is based largely on the HERA array which had been in use at the Lawrence Berkeley National Laboratory prior to the arrival of GAMMASPHERE at that laboratory.

This facility, with the capacity to measure simultaneously over a neutron energy range from 1 MeV to several-hundred MeV incident-neutron energy will enable studies of nuclei reachable only by (n,xn) reactions -- and not reachable by any charged particle reactions. As the facility develops, this will be its capacity of highest importance.

**Tests of Nucleosynthesis of $^{180}$Ta**

P.E. Garrett and S.W. Yates (*University of Kentucky*); R. Nelson (*LANSCE, Los Alamos National Laboratory, Los Alamos, New Mexico*); D. Archer, L. Bernstein, J. Becker, G. Johns, and W. Younes (*Lawrence Livermore National Laboratory, Livermore, California*)

Most mechanisms invoked to explain the abundance of $^{180}$Ta must rely on the assumption that once formed, the naturally occurring long-lived isomeric level cannot be depopulated by excitation to other levels which can then decay to the unstable ground state. Unfortunately, the nuclear structure of $^{180}$Ta is not well known. Attempts were made to develop a good picture of the low-lying levels of this nucleus using the white source techniques of LANSCE and the GEANIE gamma-ray detection array, but tests show that runs will have to be much longer than the allotted time for the experiment. Further runs will be attempted to gain adequate statistics to establish a level scheme for this nucleus.

Neutron Inelastic Scattering and Separating Isoscalar and Isovector Transitions

**Neutron Scattering in $^{140}$Ce and $^{142}$Ce**

Gang Chen, Min Li, J.L. Weil, and M.T. McEllistrem (*University of Kentucky*)

Differential cross sections for excitation of 2+, 3-, and 4+ levels of $^{140}$Ce had been completed last year. Additional measurements had been made also for the 2+ and 3- levels of $^{142}$Ce. Unfortunately, writing errors in last year's CSEWG Annual Report provided errors. The strength of both the 2+ and 3- level excitations found in neutron scattering were compared with strengths found in electromagnetic excitation. Contrary to last year's report the 2+ and 3- levels of $^{140}$Ce were strongly dominated by valence proton excitations. But the corresponding levels of $^{142}$Ce were differently excited. The 2+ level of $^{142}$Ce was still dominated by proton excitations, but was much closer to being an isoscalar transition than in $^{140}$Ce. However, the 3- level of $^{142}$Ce changed from being dominated strongly by protons in $^{140}$Ce to being strongly dominated by neutrons in $^{142}$Ce.

Another surprise was that the 4+ level of $^{140}$Ce was most strongly excited by a single phonon E4 amplitude; the two phonon E2 amplitude was almost insignificant. Problems with the $CeO_2$ target which had to be used for the $^{142}$Ce experiment prevented measurement of cross sections for the 4+ level of that nucleus; but it was clear that it was much weaker than the 4+ excitation of $^{140}$Ce.

Applied Physics Projects

**Tests of Neutron Transmission Detection of Contraband in Luggage**

T.G. Miller, Peter VanStaagen, and Cameron Gibson (*Tensor Technology, Madisonville, Alabama*); M.T. McEllistrem (*University of Kentucky*)

A heavily shielded, flux-collimated $^{9}$Be(d,n)$^{10}$B neutron source has been developed with thick Be targets to provide an approximately white neutron source. The 5-degree neutron flux is transmitted through suitcases and cargo boxes. The transmitted-neutron spectrum is recorded with a 99-detector array, to localize the volume elements in the suitcase which give rise to particular transmission spectra.

The total cross section signatures, which depend largely on resonance structure in the elemental cross sections, are used to de-convolve the composite attenuation of neutrons into the individual elemental components. The nearly unique element ratios of either narcotics or explosives enable identification of these materials. A powerful neural net is trained with element total cross sections and many signatures of materials likely to be found in normal suitcases. Materials which fall outside the normal limits are then tagged as needing further examination. The detection and analysis systems are still under development.

# University of Massachusetts - Lowell

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### Neutron Scattering Data and Fission Spectrum Measurements

G.H.R. Kegel, J.J. Egan, A. Mittler, D.J. DeSimone, C. Narayan, M.L. Woodring, Y. J. Ko, P.-N. Seo, D.J. Souza, J.R. Tedesco. D.-S. Kim, and T.J. Morancy (*University of Massachusetts - Lowell*)

There are three separate projects to report in this category:

*High-resolution Neutron Total Cross Sections of $^{235}U$ from 200 to 400 keV*

High-energy-resolution total neutron cross section measurements on $^{235}$U in the 200- to 400-keV range reveal fluctuations from 7 to 17 barns [1], while broad-resolution measurements average over these resonances and lead to smooth curves [2]. The level structure of $^{235}$U is such that high resolution (10 keV) measurements are required in neutron scattering experiments to separate elastic and several inelastic neutron groups from each other. Interpretation of these data is difficult if the elastic (like the total) cross section has significant fluctuations with energy. With this problem in mind we set out to determine whether the 10-keV-resolution total cross section of $^{235}$U shows appreciable fluctuations by making higher resolution (2-5 keV) measurements over a limited energy range.

We used the UML Van de Graaff accelerator with Mobley buncher to produce proton pulses with sub-nanosecond durations. A thick metallic lithium target was used to produce neutrons via the $^{7}$Li(p,n)$^{7}$Be reaction generating a pseudo-white neutron spectrum. Neutron time-of-flight spectra were acquired using a thin (1.3 cm) fast plastic scintillator coupled to a Burle 8850 photomultiplier tube. The neutron flight path was 309 cm. The neutron time-of-flight resolution was better than 2 ns for neutrons above 200 keV. This datum together with the 1.3-cm flight path dispersion due to scintillator thickness lead to an energy resolution of about 5 keV at 400-keV neutron energy and 2 keV at 200-keV neutron energy.

After making corrections for "wrap around" contributions to the time-of-flight spectra, data analysis was accomplished by forming the quotient of sample-in to sample-out spectra, suitably normalized, channel-by-channel. The resulting "quotient spectrum" with appropriate algebraic operations can be converted into a cross section vs. energy curve. Preliminary results indicate that large cross section fluctuations are not observed in this high resolution data and therefore should also be absent in 10-keV resolution data. However we do observe small fluctuations in the data which exceed statistical uncertainties and they are presumably real. The results agree with ENDF/B-VI near 200 and 400 keV but are somewhat less than ENDF between 250 and 350 keV.

As a check on our technique we measured the carbon total cross section in this energy region. The carbon data exhibit no fluctuations and agree well with ENDF/B-VI.

*Neutron-induced Fission-neutron Spectra of $^{235}U$ and $^{239}Pu$ for Energies Below the Incident Energy*

We have completed measurements of fission-neutron energy spectra of $^{235}$U and $^{239}$Pu for energies below the incident energy and are preparing the results for publication. The region of the fission-neutron spectrum below the incident energy has been particularly difficult to measure using high resolution time-of-flight techniques because of the difficulty in distinguishing elastically and inelastically scattered neutrons from fission neutrons. Our experiment accomplishes this by employing three fast barium-fluoride scintillation detectors located very close to (6 cm away from) the fission sample to observe fission gamma rays in two-fold coincidence to act as a "fission gate" for the main neutron detector time-of-flight electronics. The ultra-fast barium-fluoride detectors used in coincidence mode provide very clean time-of-arrival spectra in which fission gamma-ray signals are well separated in time from signals due to gamma-rays generated in the neutron producing target, as well as from signals produced by neutrons interacting in the barium fluoride detectors.

Using this technique we were able to extend our earlier measurements [3] of fission spectra at 1.5 and 2.5 MeV down to 800 keV providing more data with which to compare to predictions of theoretical models of the fission mechanism such as that of Madland and Nix [4]. Extending the measurements to lower energy also provide a better experimental basis for determination of the mean energy of the fission spectrum and for determination of fitting parameters used in empirical expressions used to represent the spectrum such as the Watt equation [5].

*Decay Rate Measurement for $^{7}Be$ in Tantalum and $^{7}Be$ in Lithium*

Measurements are in progress of the decay rate of $^{7}$Be in two different chemical environments. Beryllium-7 decays by electron capture so its decay rate is proportional to the electron density at the nucleus. Hence $^{7}$Be may decay at different rates when in different chemical environments. Samples of $^{7}$Be in lithium and $^{7}$Be in tantalum were prepared by proton bombardment via the $^{7}$Li(p,n)$^{7}$Be reaction. A quasi-differential setup similar to that first described by Huber *et al.* [6] is being used to determine any difference in decay rates.

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## Fission-Product Studies

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

This report summarizes aggregate decay-heat measurements and individual fission-product nuclide cumulative and independent yield measurements that have been both completed and analyzed. The research covered three separate areas of fission product studies:

- aggregate gamma-energy distributions and decay heat of $^{235,238}$U and $^{239}$Pu;
- aggregate beta energy distributions and decay heat of $^{235,238}$U and $^{239}$Pu;
- cumulative and independent yields of short-lived fission-product nuclides of $^{235,238}$U.

The primary reason for these studies was to provide tests for evaluated nuclear data files associated with fission, particularly extending down to very short delay times where no reliable measurements existed.

Aggregate gamma-ray energy spectra have been measured for fission products resulting from the thermal-neutron fission of $^{235}$U and $^{239}$Pu, and from the fast-neutron fission of $^{238}$U. The measurements were performed using a beta-gated 5"x5" NaI (TI) spectrometer and covered an energy range of 0.1-8.0 MeV. Spectra were taken over a decay time range of 0.1 - 40,000s, with measurements made at approximately three decay times per decade. An average gamma-ray energy was determined for each spectrum and the gamma-ray decay heat as a function of decay time was deduced from the average gamma-ray energy, measured gamma-to-beta activity ratio and the measured beta activity as a function of time. Since the noble gases transferred by the helium jet are not retained by the tape transport system, these results represent the gamma decay heat excluding noble gases. CINDER[1] calculations were used to estimate the noble-gas contribution at each decay time. Correction factors were thus generated to account for the loss of noble gases. Corrected gamma-ray decay heats for $^{235,238}$U and $^{239}$Pu were compared with CINDER calculations and with earlier ORNL [2,3] and YAYOI [4-6] measurements. The agreement is generally good except at the shortest and longest decay times. At the shortest decay times there are no earlier measurements for comparison, but our decay heat values are somewhat higher than the CINDER calculations. At the shorter decay times the ENDF/B-VI fission-product data base used in the CINDER calculations is supplemented by theoretical estimates based on the Gross Theory [7,8] of beta decay and a gamma-ray cascade model [9] for estimating the gamma-ray spectra for many unmeasured fission products. Our measurements suggest that the discrepancy lies mainly with the aggregate gamma-to-beta activity ratio, rather than with the average gamma-ray energy or the relative beta activity.

Beta energy spectra have been measured for the aggregate fission products resulting from thermal neutron fission of $^{235}$U and $^{239}$Pu, and from fast neutron fission of $^{238}$U. The beta spectrometer consisted of a 3"x3" plastic scintillator, gated by an optically isolated thin-disk scintillator mounted on its surface for gamma-ray suppression. Measured spectra covered a beta energy range of 0.15-8.00 MeV and spanned a decay time range of 0.4 - 40,000s in steps of approximately three decay times per decade. The average beta energy was calculated for each energy distribution, after correcting for the 150-keV cutoff of our spectrometer. The beta decay heat was obtained by forming the product of the average beta energy times the relative beta activity. Again the result was corrected for loss of noble gases. Results of the present study were compared with the earlier ORNL measurements [2,3] in the case of $^{235}$U and $^{239}$Pu and with the YAYOI beta decay heat results [4-6] for $^{238}$U. The present results have been normalized to give the best overall agreement with the CINDER10 calculations. For $^{235}$U and $^{239}$Pu our results are in excellent agreement with those of ORNL throughout their region of overlap. Excellent agreement was also observed between our $^{238}$U beta decay and that reported in the YAYOI study. For $^{235}$U and $^{239}$Pu both our measurements and the ORNL results are in excellent agreement with the CINDER10 calculation everywhere, except in the vicinity of 1000s decay time where both measurements suggest a slightly higher value for the beta decay heat. The UML and YAYOI beta decay heat measurements for $^{238}$U are also in excellent agreement with CINDER10 calculations, with only a similar slight discrepancy in the vicinity of 1000s.

These studies have also determined independent and cumulative fission-product yields following fission of $^{235,238}$U. Measurements of high-resolution gamma-ray spectra, following the thermal-neutron fission of $^{235}$U have been made with a Compton-suppressed, beta-gated, high-purity germanium detector at the UML Van de Graaff facility. The gamma spectra were measured at delay times ranging from 0.2s to nearly 10,000s following rapid transfer of the fission fragments with a helium-jet system. On the basis of known gamma transitions, forty isotopes have been identified and studied. By measuring the relative intensities and lifetimes of these transitions and using their published beta-branching ratios, the relative probabilities for direct production of the various precursor nuclides have been calculated. Metastable and ground state yields have been measured in several cases. The division between metastable and ground-state yields tends to be quite uncertain in the ENDF/B-VI compilation and therefore the current measurements are an important contribution to this file. Elemental yields for rubidium, cesium, strontium and barium fission products have been compared to those in ENDF. Even-odd effects in the distributions of partial elemental yields were also clearly observed.

Measurements of gamma-ray spectra following fast-neutron fission of $^{238}$U with the HPGe system described above were performed in a fast-neutron port on the UML Research Reactor. The cadmium-shielded fission chamber resided near the core and the counting system was located at a nearby shielded area. The gamma spectra were measured over delay times ranging from 0.3s to 4,000s. A total of 63 independent yields and 63 cumulative yields have been determined from our measurements and compared to ENDF/B-VI. Our experimental values typically have uncertainties of 10% or less while the ENDF values have typical uncertainties of 25% or more. Only 28% of the nuclides in this study have previously measured independent and cumulative yield values listed in ENDF with the remainder based solely on model calculations. The overall agreement with ENDF/B-VI is reasonable, with 57% of the values falling within one standard deviation (68% expected) and 81% falling within two standard deviations (95% expected).

As expected, a near-Gaussian distribution of elemental yields in our measurements was observed for rubidium, strontium, yttrium, cesium, barium, and lanthanum. In most cases the distributions are quite similar to those of ENDF, although our measured distribution for yttrium indicates a shift to lower mass numbers.

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