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NEUTRON SCATTERING STUDIES IN THE
ACTINIDE REGION

Progress Report

For Period August 1, 1991 - July 31, 1994

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ABSTRACT

During the period August 1, 1991 to July 31, 1994 we report progress on the following:

- (a) Prompt fission neutron energy spectra for ^{235}U and ^{239}Pu .
- (b) Two-parameter measurement of nuclear lifetimes.
- (c) "Black" neutron detector.
- (d) Data reduction techniques for neutron scattering experiments.
- (e) Elastic and inelastic neutron scattering studies in ^{197}Au .
- (f) Elastic and inelastic neutron scattering studies in ^{239}Pu .
- (g) Neutron induced defects in silicon dioxide MOS structures.
- (h) Response of a ^{235}U fission chamber near reaction thresholds.
- (i) Efficiency calibration of a liquid scintillation detector using the WNR facility at LAMPF.
- (j) Prompt fission neutron energy spectrum measurements below the incident neutron energy.
- (k) Multi-parameter data acquisition system.
- (l) Accelerator improvements.
- (m) Non-DOE supported research.

Eight Ph.D. dissertations and two M.S. theses were completed during the report period. Publications consisted of 6 journal articles, 10 conference proceedings, and 19 abstracts of presentations at scientific meetings. One invited talk was given.

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Table of Contents

I. Research	1
1. Prompt fission neutron energy spectra for ^{235}U and ^{239}Pu	1
2. Two-parameter measurement of nuclear lifetimes	1
3. "Black" neutron detector.....	2
4. Data reduction techniques for neutron scattering experiments.....	4
5. Elastic and inelastic neutron scattering studies in ^{197}Au	5
6. Elastic and inelastic neutron scattering studies in ^{239}Pu	6
7. Neutron induced defects in silicon dioxide MOS structures.....	7
8. Response of a ^{235}U fission chamber near reaction thresholds	7
9. Efficiency calibration of a liquid scintillation detector using the WNR facility at LAMPF	8
10. Prompt fission neutron energy spectrum measurements below the incident neutron energy	9
11. Multi-parameter data acquisition system	9
12. Accelerator improvements.....	10
13. Non-DOE supported research.....	11
II. References	38
III. Publications	40
1. Invited Papers	40
2. Journal Articles	40
3. Conference Preceedings	41
4. Published Abstracts	42
IV. Students Associated with the Project.....	45
V. Thesis Defenses.....	46
VI. Abstracts of Publications and Theses.....	48

I. RESEARCH

1. Prompt Fission Neutron Energy Spectra for ^{235}U and ^{239}Pu

Prompt fission neutron energy spectra for ^{235}U and ^{239}Pu have been measured for fission neutron energies greater than the energy of the incident neutrons inducing fission. The measurements were undertaken to investigate the shape dependence of the fission neutron spectra upon both the incident neutron energy and the mass of the nucleus undergoing fission. Measurements were made for both nuclides at the following incident neutron energies: 0.50, 1.50, 2.50, and 3.50 MeV. The data are presented either as relative yields or as ratios of the measured spectrum to the ^{235}U spectrum at 0.50 MeV. Figure 1 shows the relative fission yield for ^{235}U for 0.50 MeV incident neutrons. Figure 2 shows the relative fission yield for ^{235}U at 2.50 MeV and Fig. 3 shows the ratio of the 2.50 MeV results to that of the 0.50 MeV values. The relative fission yield and ratio for ^{239}Pu are shown in Figs. 4 and 5, respectively. The measurements are also compared to calculations (solid line in each of the figures) based on the Los Alamos model of Madland and Nix^{1,2} to test its predictive capabilities. Incident neutrons were produced by the $^7\text{Li}(p,n)^7\text{Be}$ reaction using a pulsed, bunched proton beam from our 5.5 MV Van de Graaff accelerator. The neutrons were detected by a thin liquid scintillator with good time resolution capabilities. Time-of-flight techniques were used for neutron energy determination; in addition pulse-shape-discrimination was used to reduce gamma-ray background levels. The data were fit by the Watt³ equation to determine the mean energy of the spectra and to facilitate comparison of the results to previous measurements. The data have also been compared directly to previous measurements. A paper on the results has been submitted to Nuclear Physics.⁴

This work was part of the Ph.D. dissertation research of Parrish A. Staples.

2. Two-Parameter Measurement of Nuclear Lifetimes

Lifetimes of excited nuclear states produced by Coulomb excitation in ^{152}Sm , ^{182}W , and ^{184}W nuclei were measured using fast timing techniques. The Van de Graaff accelerator was used to produce mono-energetic proton pulses and a Mobley bunching system was used to compress the beam pulses to sub-

nanosecond duration. Proton pulses were incident on elemental samples to excite the target nuclei through the Coulomb interaction. The subsequent nuclear decay gamma-rays were detected with a fast barium fluoride (BaF_2) scintillation detector. To store and analyze digitally converted analog signals from the BaF_2 detector a two-parameter computer interface (2PIN) was designed and constructed to enable two signals from the BaF_2 detector, corresponding to time of arrival and pulse height for an incident gamma ray to be stored as a correlated pair in computer memory. A diagram of the two-parameter interface in a data acquisition system is shown in Fig. 6. A diagram of the interface circuitry is shown in Fig. 7. Extensive software development to control 2PIN by the HP2100A computer and operate with the HP5416B analog-to-digital converter (ADC), and HP5410A multi-channel analyzer (MCA) was also completed. A simplified block diagram of the program execution is seen in Fig. 8. The experiment used a BaF_2 crystal coupled to a Hamamatsu R2083Q photomultiplier tube. Barium fluoride scintillators will also be used in the second phase of the fission neutron spectra measurements for energies less than the incident energy to signal the occurrence of a fission event by detecting the prompt fission gamma-rays. Lifetimes obtained by this technique were compared to previously measured values.

The development and testing of the two parameter interface and the lifetime measurements formed the basis of the M.S. thesis research of Mitchell L. Woodring.

3. "Black" Neutron Detector

We have constructed a black neutron detector (BND) of the Poenitz design.⁵ It is a cylindrically shaped detector of length 15.75 inches and a diameter of 11 inches filled with 28 liters of BC501 liquid scintillator. Absorbed oxygen was removed from the BC501 by bubbling oxygen-free nitrogen through it. This scintillator was chosen because of its pulse shape discrimination characteristics. Initially five photomultiplier tubes viewed the liquid scintillator. This was later reduced to four as in Poenitz original design. Figure 9 shows a picture of our BND. A detailed drawing is given in Fig. 10.

In 1993 we acquired five higher gain Philips photomultiplier tubes, XP4312B/D2, to replace the original lower gain tubes and built and tested the photomultiplier tube bases. Using neutrons from the $^7\text{Li}(p,n)^7\text{Be}$ reaction we experimented with combining the five anode signals in various ways. Requiring three-fold coincidence among the five anode signals gave us the best signal-to-noise ratio in a time-of-flight (TOF) spectrum. The results, however were unsatisfactory for neutron energies below 1 MeV. We added fast amplifiers to obtain larger signals to improve the low energy response.

We have made significant advances with the BND this past year. Instead of placing neutron shielding around the detector we have decided to put it around the target. Figure 11 shows the target shield. It consists of paraffin loaded with lithium carbonate (Li_2CO_3). The shield is 26-inches wide and 36-inches long. A 6-inch diameter aluminum pipe traverses the shield permitting the insertion of collimators.

A second collimating shield is placed between the BND and the target shield to further reduce the background at the BND. This shield consists of a mixture of water and boric acid with a 2-inch diameter hole. A third collimator consisting of paraffin loaded with Li_2CO_3 and having a 0.75-inch diameter hole is placed between the BND and the second collimating shield. This collimator limits the neutron beam size so as to only let neutrons enter the BND through the entrance channel.

Another shield/collimator with a 1.5-inch diameter hole is placed directly in front of the BND to attenuate the scattered neutrons from the second and third collimators. It consists of a slab of borated polyethylene 24-inches wide, 24-inches high and 4-inches thick.

The BND is surrounded with three inches of lead except at the entrance channel and where the photomultiplier tubes (PMT) are located. The entire shielding arrangement is shown in Fig. 12. Four PMT's are now used to observe the light in the BND. Each PMT has its own preamplifier and fast amplifier. Figure 13 shows a diagram of the TOF electronics associated with the BND.

The purpose of this work is to develop the BND for use as a fluence monitor to determine the zero-degree neutron fluence. The BND will be permanently placed at zero degrees. It will also be used for a quick determination of the efficiency of our main detector in scattering experiments by observations of the zero-degree fluence with both detectors normalized by a third auxiliary monitor detector.

In order to check the accuracy of the BND we are making measurements for the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction using an infinitely thick (for protons) metallic lithium target. We are making measurements at 100-keV incident proton energy intervals over the 1 to 2.2 MeV range. By subtracting spectra from adjacent energy intervals we can obtain the 100-keV averaged zero-degree differential cross section. Comparison of these values to the accepted ${}^7\text{Li}(p,n){}^7\text{Be}$ cross section will allow us to assess the accuracy of the BND, an instrument which measures absolute neutron fluences.

Figure 14 shows neutron TOF spectra A and B obtained for protons incident on a thick lithium target at two different proton energies. Spectrum C is a typical background run. The background was measured for each proton energy and was used to correct the thick target TOF spectra. Spectrum D is the difference between the background subtracted TOF spectra.

Use of the BND as a fluence monitor is much simpler and faster than using a ${}^{235}\text{U}$ fission chamber for this purpose, and will be satisfactory for routine fluence measurements.

This work is part of the Ph.D. dissertation research of David J. DeSimone.

4. Data Reduction Techniques for Neutron Scattering Experiments

Advanced mathematical tools have been developed for calculating corrections that are applied to neutron scattering data in order to account for the finite size of the scattering samples. The multiple scattering events (due to finite size) that occur in a neutron scattering experiment typically comprise 8 to 10 % of the total measured scattering events. A Monte Carlo program NUSCAT was developed to simulate the disk geometry arrangement used in the Lowell

neutron scattering experiments. A modern random number generator developed by Marsaglia⁶ which passes all known randomness tests was implemented in the Monte Carlo program. A direction-biasing method was applied in order to improve the statistical results of the Monte Carlo simulation. The ratio of the probability of $n+1$ scatterings to n scatterings was investigated for the disk geometry. The Monte Carlo calculation was also used to simulate the time-of-flight spectra and energy spectra. Corrections for multiple scattering were calculated for two sets of data; one at 128 keV and the other at 200 keV. The Monte Carlo results provided significant improvement over previous results. A parallel study was carried out to determine the feasibility of calculating the corrections analytically. Analytical techniques involving eigenfunction expansion, the sparse matrix method and the Rayleigh-Ritz^{7,8} variational method were found to be inadequate to solve the problem.

This work was part of the Ph.D. dissertation research of Ramakrishnan Venugopal.

5. Elastic and Inelastic Neutron Scattering Studies in ¹⁹⁷Au

During the 1991-94 period, several improvements have been made to the neutron time-of-flight spectrometer and several milestones have been reached. They include: an improved shielding arrangement, a new main detector, extensive computer code development, and presentation of preliminary results at an international conference.

We are constantly striving to improve our resolution and reduce our background. In pursuit of these goals we have currently adopted a multi-component shielding arrangement for our neutron time-of-flight spectrometer. It is comprised of a paraffin/copper/lead shadow bar used in conjunction with two shields which are separated by an air gap. This arrangement has produced essentially featureless background (i.e. scatterer out) spectra. A typical spectrum is shown in Fig. 15 along with a schematic of the shielding arrangement in Fig. 16. For these measurements we employed a Hamamatsu R4143 photomultiplier with a NE-102 scintillator. We utilized this detector arrangement for the preliminary results that were presented at the International Conference on

Nuclear Data for Science and Technology held in Gatlinburg, Tennessee⁹ in May 1994.

Currently we are updating the Monte Carlo code NUSCAT, an in-house computer code, which was developed to calculate multiple-scattering and finite scatterer size corrections (see Section 4 of this report). In its initial formation, it was specifically written to accommodate only the isotopes ^{235}U , ^{238}U , and ^{232}Th . We have written and tested additional code so that numerous, though not all, isotopes are accessible.

This work is part of the Ph.D. dissertation research of Michael O'Connor.

6. Elastic and Inelastic Neutron Scattering Studies in ^{239}Pu

Neutron elastic and inelastic scattering angular distributions for ^{239}Pu with incident energies of 570 and 700 keV were measured via the (n,n') time-of-flight technique. The results are shown in Figs. 17-20. The energy resolution was maintained at 20-25 keV. Particular care was taken in removing the tail of the elastic peak which underlies the inelastic peak in the time-of-flight spectra. The angle-integrated cross sections obtained for two scattered neutron groups, one corresponding to the elastic plus the 7.9-keV level and the other corresponding to the inelastic 57 and 76 keV levels, were 5864.6 mb, 570.5 mb for 570 keV incident neutrons and 5060 mb, 518.9 mb for 700-keV incident neutrons, respectively. These results were compared with theoretical calculations by P. Young¹⁰ as listed in ENDF/B-VI. The agreement is very good. The results have also been compared with calculations by Sheldon.¹¹ At large scattering angles the data are in reasonable accord with Sheldon's calculations. For 700-keV incident neutrons, the data were compared with the previous measurements by Haouat *et al.*¹² The results are in good agreement. The results have been submitted for publication in Nuclear Science and Engineering.¹³

This work was part of the Ph.D. dissertation research of Gang Yue.

7. Neutron Induced Defects in Silicon Dioxide MOS Structures

A theoretical investigation has been made of neutron radiation damage in silicon dioxide layers in metal-oxide-semiconductor structures. The neutron energy spectra used in these calculations mimic those that one could generate using an infinitely thick lithium target and a beam of protons of several MeV in energy. The computer code RECOIL¹⁴ was used to extract the detailed reaction-dependent recoil spectra that went into energy partitioning. The computer code SIM¹⁵ was used to calculate the division of atomic recoil energy into ionization and displacements components. Analytical estimates of neutron damage were also made. The simulation predictions were shown to agree with experimental results and analytical estimates of neutron damage in silicon. The profiles of damaged regions in bulk oxide generated from the simulation were shown to demonstrate the morphology of neutron damage. The 1-MeV neutron damage equivalences calculated from the simulation and the LSS theory¹⁶ were compared. Finally, the ionization and displacement effects in MOS devices resulting from fast neutron bombardment were investigated. Figures 21a and b depict the displacement in SiO₂ resulting from one 100-keV knock-on silicon atom and one 100-keV knock-on oxygen atom respectively.

This work was part of the Ph.D. dissertation research of Wen-Liang Chang.

8. Response of a ²³⁵U Fission Chamber Near Reaction Thresholds

A code has been written in FORTRAN (MS-FORTRAN v.4.0) to analyze efficiency measurements made with a ²³⁵U fission chamber in the vicinity of the ⁷Li(p,n)⁷Be reaction threshold, where the neutron production at 0° becomes double-valued. The code compares the fission chamber yield to that of a scintillation detector and computes the absolute efficiency of the latter assuming the efficiency of the former. The code takes into account the detailed kinematics (non-relativistic) of the reaction in three dimensions, the cross section of the reaction over the energy range of the incident protons, the fission cross section over the full range of neutron energies and angles of incidence on surfaces of the fission foils. A model of the expected fission chamber time-of-flight spectrum helps the experimenter determine what weight to give to the contribution to the

fission chamber response from the "second group" neutrons. The fission chamber and scintillator detector need not subtend the same solid angle, but must be normalized to the yield of a third detector. The code was used to analyze neutron scattering data from ^{232}Th , ^{238}U , and ^{209}Bi at 127 keV.

This work was part of the Ph.D. dissertation research of Christopher A. Horton.

9. Efficiency Calibration of a Liquid Scintillator Detector using the WNR facility at LAMPF

Heretofore the efficiency of our main neutron detector for fission neutron spectrum measurement was only known relative to a ^{235}U fission chamber up to 3 MeV. Above this energy we relied on a calculation using the code SCINFUL.¹⁷ In a proposal by Staples, Egan, and Kegel a collaborative effort between our research group and P. Lisowski at the Weapons Neutron Research Facility (WNR) of the Los Alamos Meson Physics Facility (LAMPF) was established to determine the absolute efficiency of the UML Main Neutron Detector (MND). The MND is a right circular aluminum cylinder with a quartz window, 1.27 cm thick by 10.82 cm in diameter, filled with BC-501 liquid scintillator¹⁹ viewed by an RCA type 8854 photomultiplier tube.²⁰ The MND was placed in the "white" neutron beam at WNR at beamline 40 L. It was then possible to record the MND response to the incident neutron fluence using a time-of-flight arrangement where the stop signal was the time-delayed anode signal from the MND and the start signal was a beam pick-up signal near the neutron source. Since the WNR incident neutron fluence was too intense for the MND neutrons, were scattered out of the main beam to the MND which was 23 degrees off the main beam axis and 1.627 m from the scatterer as seen in Fig. 22. Two different scatterers, polyethylene (CH_2n) and carbon (graphite), were used to obtain TOF spectra with the UML MND. After normalizing to a fission chamber (placed upstream during both runs) the carbon TOF spectrum was subtracted from the polyethylene TOF spectrum. Further dividing by the hydrogen cross section (for the appropriate energy range) and the WNR neutron beam energy profile, the UML MND absolute efficiency was determined as shown in Fig. 23. The details of this work were reported¹⁸ at the Gatlinburg Conference in May 1994.

10. Prompt Fission Neutron Energy Spectrum Measurements Below the Incident Neutron Energy

Measurements of the fission neutron spectra for energies above that of the incident neutron energy (Phase 1) have been completed.⁴ Progress in measurements of fission neutron spectra for neutron energies below that of the incident neutron is reported here.

Neutrons from fissioning nuclei are accompanied by fission gamma rays. It is possible to use these fission gamma rays as a trigger for a discrimination circuit to distinguish the fission neutrons from incident neutrons, scattered neutrons, and second group neutrons from the ${}^7\text{Li}(p,n){}^7\text{Be}^*$ reaction in time-of-flight spectra. To detect the fission gamma rays three fast barium fluoride (BaF_2) detectors have been constructed based on work of Refs. 21 and 22. The time resolution of these detectors has been measured²¹ to be 250 ps. An overview of the UML target room in Fig. 24 shows the placement for the BaF_2 detectors, main neutron detector, and fissionable sample.

This work is part of the Ph.D. dissertation research of Mitchell L. Woodring.

11. Multi-parameter Data Acquisition System

Data acquisition for the FNS measurements below the incident neutron energy will be made in a multi-parameter event mode fashion where a typical data burst consists of the correlated data (neutron TOF, pulse-shape, fission-gamma trigger). The current UML data acquisition system was upgraded as described in Section 2 of this report to handle two-parameter data acquisition. However, limitations in the current computer microprocessor speed and severe constraints in the current data storage capability led us to obtain a new Data Acquisition Environment (DAE). The system consists of a 50 MHz AT computer with an Intel 486DX50 microprocessor and a 32-bit input/output bus with a SCSI I/O controller, a Hewlett-Packard 4 Gigabyte, 4 mm, Digital Audio Tape (DAT) storage drive, a National Instruments fast digital input/output card (AT-DIO 32F), a Canberra 8223 8-input analog multiplexer (MUX), and a Canberra 8713 fast, 13-bit analog-to-digital converter (ADC). Due to the unique nature of the

Van de Graaff laboratory computing and data needs, a custom DAE was required to integrate the new equipment with the existing accelerator electronics and hardware. The DAE Graphical User Interface (GUI) for the computer was developed using MicroSoft Visual BASIC in a MicroSoft Windows environment while controlling the input/output card, ADC, and MUX, allowing 8-parameter data acquisition with or without event mode recording, simultaneous display of selected parameters, replay of event mode data with various gating options, and spectrum manipulation including mathematical operations on spectra. Data obtained with this system will allow the extraction of the fission neutrons from all neutron signals based on pulse-shape, TOF, and gamma-ray flash from the main neutron detector in an event mode "replay" manner. An example of data collected in this fashion using the two-parameter acquisition system is shown in Fig. 25.

This work is part of the Ph.D. dissertation research of Mitchell L. Woodring.

12. Accelerator Improvements

During the period of this report several improvements have been made or initiated on the UML accelerator:

(i) The entire beam line, from the analyzing magnet through the Mobley compression box, Mobley magnet and up to the neutron target has been carefully realigned as per HVEC installation instructions.

(ii) We have acquired from Vivirad HighVoltage (the successor to HVEC) the right to copy their advanced sweeping terminal. The company has supplied us with pertinent shop drawings and has assisted us in several ways. Materials have been purchased and awaits machine shop time.

(iii) Bids for a new inclined field accelerator tube have been solicited, received, and are under review.

13. Non-DOE Supported Research

It is recognized that operation of the UML Van de Graaff laboratory would hardly be possible were it not for the support provided by DOE. It follows that other projects, while not formally supported by DOE, nevertheless exist only because DOE provides for a substantial fraction of laboratory support. In this section we describe briefly several of these projects.

Neutron Radiation Damage in Field-Effect Transistors (FET). A pseudo-white neutron source²³ has been developed in our laboratory. This source has minimal gamma admixture (5 gamma / 100 neutrons) and virtually no thermal neutron component. This source has been used to study the degree of radiation hardness of semiconductor devices. In a study²⁴ by Resisnian, Walters, and Kegel it was found that in FETs the damage mechanism of gamma rays differs profoundly from that of fast neutrons. In these devices gamma rays create a finite polarization of the gate oxide, which shifts the device's operating point and thus renders the device inoperative unless the shift is compensated for externally. Neutrons, on the other hand, produce interstitials and vacancies in the semiconductor, specifically the source-drain channel, and they reduce neutron carrier lifetimes and affect carrier mobilities. These two interaction mechanisms could not be distinguished earlier because the radiation sources used nuclear reactions which produce a mixture of gamma rays and neutrons (typically 400 gammas / 100 neutrons).

In order to obtain a better understanding of the interactions of neutrons with gate oxides Wen-Liang Chang extended the Lindhard-Scharff theory²⁵ in his Ph.D. dissertation research. Some details of his work are given in Section 7 above.

Radiation Damage in High Energy Physics Detectors and Amplifiers. In high energy physics "calorimeters", semiconductor detectors and preamplifiers are often buried deep inside large (10-meter diameter) complex structures and must operate in a severe radiation environment for many years. Scientists of the Brookhaven National Laboratory Instrumentation Division routinely use our neutron source to assess the neutron radiation hardness of their detectors and amplifiers.

Biological Effects of Fast Neutron Irradiation. The bacterium *Deinococcus radiodurans* is known to possess extraordinary resistance to gamma, x-ray, and ultraviolet irradiation. Diane Case who received her Ph.D. degree in June 1994 examined the neutron hardness of this species as part of dissertation research and found a similar radiation resistance. This was very unexpected since an interacting neutron damages an individual bacterium far more severely than an interacting gamma ray. It was found that a LD₅₀ dose (a radiation dose leading to 50% survival) for *Deinococcus radiodurans* is more than thirty times larger than that of the common *Escherichia coli* species.

Fig. 1 The relative fission neutron yield for ^{235}U at an incident neutron energy of 0.50 MeV.

Fig. 2 The relative fission neutron yield for ^{235}U at an incident neutron energy of 2.50 MeV.

Fig. 3 The ratio of the fission neutron yield for ${}^{235}\text{U}$ at 2.50 MeV to that at 0.50 MeV.

Fig. 4 The relative fission neutron yield for ^{239}Pu at an incident neutron energy of 3.50 MeV.

Fig. 5 The ratio of the fission neutron yield for ^{239}Pu at 3.50 MeV to that of ^{235}U at 0.50 MeV.

Fig. 6 Block diagram for typical data acquisition electronics used in conjunction with the two-parameter interface.

Fig. 7 Schematic of the two-parameter interface.

Fig. 8 Simplified block diagram and flow chart for the program controlling the two-parameter interface.

Fig. 9 A photograph of the black neutron detector with lead and borated polyethylene shield at the front face (right side).

Fig. 10 Dimensions of the black neutron detector.

Fig. 11 Cross-sectional view of target shield used with thick lithium target measurements.

Fig. 12 Shielding arrangement for thick target measurements using the BND.

Fig. 14 Spectra A and B are thick target TOF spectra at two different incident neutron energies. Spectrum C is a typical background spectrum and spectrum D is the difference of the background subtracted TOF spectra.

Fig. 15 Neutron time-of-flight spectra. A scattered neutron spectrum and a background spectrum are shown.

Fig. 16 Schematic of shielding arrangement used for neutron time-of-flight measurements.

Fig. 17 Neutron scattering angular distributions for ^{239}Pu at 570 keV and 700 keV. The solid line is the ENDF/B-VI evaluation.

Fig. 18 Neutron scattering angular distributions for ^{239}Pu at 570 keV and 700 keV. The solid line is the ENDF/B-VI evaluation.

Fig. 19 Neutron scattering angular distributions for ^{239}Pu at 570 keV and 700 keV. The solid line is the ENDF/B-VI evaluation. The squares are the data of Haouat *et al.*¹². The dots with error bars are the Lowell results.

Fig. 20 Neutron scattering angular distributions for ^{239}Pu at 570 keV and 700 keV. The solid line is the ENDF/B-VI evaluation. The squares are the data of Haouat *et al.* The dots with error bars are the Lowell results.

Fig. 21a Cascade of displacements in SiO_2 resulting from one 100-keV silicon atom traveling from bottom to top. The size of the cubes represents the energy deposited.

Fig. 21b Cascade of displacements in SiO_2 resulting from one 100-keV oxygen atom traveling from bottom to top. The size of the cubes represents the energy deposited.

Proton Storage Ring

Note: Not to Scale.

Fig. 22 Plan view of the WNR spallation neutron source and the experimental area used for MND efficiency determination.

Fig. 23 The efficiency curve for the MND as given by measurements at WNR (points) and as calculated from SCINFUL (solid line). This figure is taken from Ref. 18.

Fig. 24 Experimental arrangement and beamline overview for fission neutron spectrum measurements.

Fig. 25 Two-dimensional plot of time-of-flight versus pulse-shape discrimination using the MND.

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23. G.H.R. Kegel, Nucl. Inst. Meth. Phys. Res., B40/41, 1165 (1989).
24. A. Reisnian, M. Walters, and G.H.R. Kegel, Journ. Elect. Mat., 20, 935 (1991).
25. J. Lindhard, M. Scharff, and H.E. Schiott, Kon. Dan. Vid. Selsk, Matfys. 33, 10 (1963).

III. PUBLICATIONS

1. Invited Papers

Gunter H.R. Kegel gave an invited talk given at University of Kentucky on accelerator work carried out in the Radiation Laboratory. (November 19, 1992)

2. Journal Articles

- (1) "Fluences and Spectra of Accelerator Generated Fast Neutrons", G.H.R. Kegel, P. Bertone, D.L. Case, D. J. DeSimone, C.K.C. Jen, C. Narayan, M. O'Connor, and P. Staples, IEEE Trans. Nucl. Sci. NS - 39, December 1992.
- (2) "A Framework for Understanding Fast-Neutron Induced Defects in SiO₂ MOS Structures", W. Chang, J. Elect. Materials 21, 693 (1992).
- (3) "Ion Beam Analysis of Li Diffused Ge-Li Interfaces," Causon K.C. Jen, Gunter H.R. Kegel, and Kei-Peng Jen, J. Vac. Sci. Technol. A 10(4), Jul/Aug 1992, p. 2832.
- (4) "Radiation Damage Studies with Accelerator Generated Neutrons," Gunter H.R. Kegel, Peter F. Bertone, Diane L. Case, David J. DeSimone, Causon K.C. Jen, and Chandrika Narayan, "First International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors", Firenze, Italy, July 7-9, 1993 (submitted to "Nuovo Cimento" for publication).
- (5) "Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons," P. Staples, J.J. Egan, G.H.R. Kegel, A. Mittler, and M.L. Woodring (submitted to Nucl. Phys. A).
- (6) "Neutron Scattering Angular Distributions in ²³⁹Pu at 570 keV and 700 keV," Gang Yue, Michael O'Connor, James J. Egan, and G.H.R. Kegel (submitted to Nucl. Sci. Eng.).

3. Conference Proceedings

- (1) "Neutron Scattering in ^{239}Pu from 0.2 to 1.0 MeV," J.J. Egan, G.H.R. Kegel, G. Yue, A. Mittler, P.A. Staples, D.J. DeSimone, and M.L. Woodring, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, 13-17 May, 1991, Jülich, Germany S.M. Qaim (Ed), Springer Verlag, Berlin, 1992, p.59.
- (2) "Neutron Energy Spectra from Proton Irradiated Thick Li Targets," G.H.R. Kegel, D.J. DeSimone, P.F. Dugan, J.J. Egan, G.K.C. Jen, A. Mittler, and P.A. Staples, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, 13-17 May, 1991, Jülich, Germany S.M. Qaim (Ed), Springer Verlag, Berlin, 1992, p.433.
- (3) "Fast Neutron Inelastic Scattering Cross Sections from 2.3 to 3.0 MeV for the Actinide Nuclei ^{232}Th and ^{238}U ," E. Sheldon, A. Aliyar, J.J. Egan, G.H.R. Kegel, and A. Mittler, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, 13-17 May, 1991, Jülich, Germany S.M. Qaim (Ed), Springer Verlag, Berlin, 1992, p.989.
- (4) "Measured and Calculated Neutron Scattering Cross Sections for the Actinide Nuclei ^{232}Th , ^{238}U , ^{239}Pu ," E. Sheldon, E.D. Arthur, J.J. Egan, G.H.R. Kegel, A. Mittler and P.G. Young, in Selected Topics in Nuclear and Astrophysics: Proceedings of the 22nd Masurian Lakes Summer School on Nuclear Physics, Plaski Poland 26 Aug. - 5 Sept. 1991, ed. by Z. Sujkowski and G. Szefflinska, Soltan Institute for Nuclear Studies, SINS 2124/A Otwock-Swierk, Poland (1991) p. 88.
- (5) "Fast Neutron Irradiation of the Highly Radioresistant Bacterium *Deinococcus radiodurans*," D.L. Case and G.H.R. Kegel, in Proceedings of DNA REPAIR: Mechanisms of DNA Repair of Oxidative Damage, 23-27 June, 1993, Holmenkollen, Norway.
- (6) "Extension of Prompt Fission Neutron Spectrum Measurements to Energies Below the Incident Neutron Energy," M.L. Woodring, J.J. Egan, G.H.R. Kegel, and P. Staples, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, 9-13 May, 1994 (to be published).
- (7) "Elastic and Inelastic Neutron Scattering in ^{197}Au at 1.5 MeV," M. O'Connor, G. Yue, J. Chen, Chandrika Narayan, G.H.R. Kegel, and J.J. Egan, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, 9-13 May, 1994 (to be published).

- (8) "Application of a Poenitz-type Black Neutron Detector in the Development of a Neutron Standard," D.J. DeSimone, G.H.R. Kegel, J.J. Egan, A. Mittler, P.F. Bertone, and P. Staples, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, 9-13 May, 1994 (to be published).
- (9) "Neutron Scattering Cross Sections for ^{239}Pu at 700 keV," G. Yue, M. O'Connor, J.J. Egan, and G.H.R. Kegel, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, 9-13 May, 1994 (to be published).
- (10) "Use of the WNR Spallation Neutron Source at LAMPF to Determine the Absolute Efficiency of a Neutron Scintillation Detector," P.A. Staples, J.J. Egan, G.H.R. Kegel, M.L. Woodring, D.J. DeSimone, and P.W. Lisowski, in Proc. of the Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, 9-13 May, 1994 (to be published).

4. Published Abstracts

- (1) "Measurements and Analyses of ^{232}Th and ^{238}Pu (n,n') Cross Sections at 2.4 and 2.8 MeV," E. Sheldon, J.J. Egan, G.H.R. Kegel, A. Mittler, and A. Aliyar, *Bull. Am. Phys. Soc.* 36, 2041 (1991).
- (2) "Neutron Energy Spectra from Proton Irradiated Thick Li Targets," D.J. DeSimone, G.H.R. Kegel, C. Jen, J.J. Egan, D.L. Case, P. Bertone, and A. Mittler, ", *Bull. Am. Phys. Soc.* 36, 2119 (1991).
- (3) "Neutron Scattering Cross Sections for Low-Lying Levels in ^{181}Ta and ^{197}Au ," M. O'Connor, G.H.R. Kegel, J.J. Egan, A. Mittler, C.A. Horton, G.Yue, and C. Narayan, , *Bull. Am. Phys. Soc.* 36, 2116 (1991).
- (4) "Neutron Elastic and Inelastic Scattering Angular Distributions at 570 and 700 keV," G. Yue, J.J. Egan, G.H.R. Kegel, A. Mittler, M. O'Connor, P.A. Staples, and M.L. Woodring, ", *Bull. Am. Phys. Soc.* 36, 2119 (1991).
- (5) "Differential Scattering Cross Sections of the 45-keV State in ^{238}U and the 49-keV State in the ^{232}Th at 128-keV Incident Neutron Energy," C.A.

Horton, G.H.R. Kegel, J.J. Egan, and A. Mittler, , Bull. Am. Phys. Soc. 36, 2119 (1991).

- (6) "The Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons," P.A. Staples, J.J. Egan, G.H.R. Kegel, A. Mittler, M. O'Connor, and M.L. Woodring, , Bull. Am. Phys. Soc. 36, 2119 (1991).
- (7) "Measurement of the $^6\text{Li}/^7\text{Li}$ Ratio in Lithium Shielding and Target Materials," C.K.C. Jen, G.H.R. Kegel, and C. Narayan, Bull. Am. Phys. Soc. 36, 2119 (1991).
- (8) "The Use of BaF_2 Detectors and Fast Timing Techniques in Measurement of Nuclear Lifetimes," M.L. Woodring, G.H.R. Kegel, J.J. Egan, A. Mittler, D.J. DeSimone, P.A. Staples, and G. Yue, ", Bull. Am. Phys. Soc. 36, 2145 (1991).
- (9) "Studies with Poenitz-Type Black Neutron Detector," D.J. DeSimone, G.H.R. Kegel, P. Staples, P.F. Bertone, J.J. Egan, and A. Mittler, Bull. Am. Phys. Soc. 37, 1276 (1992).
- (10) "Neutron Scattering Angular Distributions for Pu-239 at 570 keV," Gang Yue; M. O'Connor, J.J. Egan, G.H.R. Kegel, A. Mittler, C. Narayan, M.L. Woodring, and J. Dumont, Bull. Am. Phys. Soc. 37, 1289 (1992).
- (11) "Neutron Scattering Angular Distributions for 1-MeV Neutrons on ^{197}Au ," M. O'Connor, G. Yue, C. Narayan, R. Venugopal, C.A. Horton, W. Chang, G.H.R. Kegel, J.J. Egan, and A. Mittler, Bull. Am. Phys. Soc. 37, 1289 (1992).
- (12) "The Prompt Fission Neutron Energy Spectra of ^{235}U and ^{239}Pu Induced by Fast Neutrons," P. Staples, J.J. Egan, G.H.R. Kegel, A. Mittler, P.F. Bertone, D.J. DeSimone, J.E. Dumont, C.K.C. Jen, and M.L. Woodring, Bull. Am. Phys. Soc. 37, 1300 (1992).
- (13) "Construction of a 'Black Neutron Detector' at the UMass Lowell Accelerator Laboratory," P.F. Bertone, D.J. DeSimone, P.F. Dugan, J.J. Egan, G.H.R. Kegel, and P.A. Staples, Bull. Am. Phys. Soc. 37, 1866 (1992).
- (14) "Analyses and Evaluations of $^{239}\text{Pu}(n,n)$ and (n,n') Angular Distributions at 0.57 and 0.70 MeV," E. Sheldon, A. Mittler, and P.G. Young, Bull. Am. Phys. Soc. 37, 1866 (1992).
- (15) "ESR Bone Dosimetry of Fast Neutrons," J. Copeland, K. Kase, G. Chabot, G. Kegel, and F. Greenway, Bull. Am. Phys. Soc. 37, 1869 (1992).
- (16) "Production of ^{99}Mo by Neutron Capture," G.H.R. Kegel, S. Coelho, M. Montesalvo, and J. Correia, Bull. Am. Phys. Soc. 39 (1994).

- (17) "The Development of a Neutron Standard based on the ${}^7\text{Li}(p,n){}^7\text{Be}$ Reaction," D.J. DeSimone, G.H.R. Kegel, J.J. Egan, P. Bertone, and P. Staples, Bull. Am. Phys. Soc. 39 (1994).
- (18) " BaF_2 Scintillator Response to Neutrons with Energies up to 18 MeV," M. Woodring, J.J. Egan, G.H.R. Kegel, A. Mittler, and P. Staples, Bull. Am. Phys. Soc. 39 (1994).
- (19) "Excitation Functions for Low Lying Levels in ${}^{197}\text{Au}(n,n')$ from 1.0 MeV to 2.5 MeV," M. O'Connor, J. Chen, J.J. Egan, G.H.R. Kegel, C. Narayan, and G. Yue, Bull. Am. Phys. Soc. 39 (1994).

IV. STUDENTS ASSOCIATED WITH THE PROJECT

Graduate Students

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V. THESIS DEFENSES

Causon Ko-Chuan Jen (Ph.D.)

"The Study of Li-Ge Binary System" (1992)

Ramakrishnan Venugopal (Ph.D.)

"An Investigation of Mathematical Tools for Data Reduction Techniques in Neutron Scattering Experiments" (1992)

Christopher A. Horton (Ph.D.)

"Low Energy Neutron Scattering from Heavy Nuclei" (1992)

Chandrika Narayan (Ph.D.)

"Tuning of the Schottky Barrier Height using Bi-metallic Layered Structures" (1992)

Diane L. Case (M.S.)

"Fast Neutron Fluence Mapping near a Thick Lithium Target" (1992)

Mitchell L. Woodring (M.S.)

"Two-Parameter Measurement of Lifetimes of Coulomb-Excited, Low-Lying Nuclear States in ^{152}Sm , ^{182}W , and ^{184}W using a BaF_2 Detector" (1993)

Wen-Liang (William) Chang (Ph.D.)

"Theoretical Investigation of Neutron Induced Defects in Silicon Dioxide MOS Structures" (1993)

Parrish A. Staples (Ph. D.)

"Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons"
(1993)

Gang Yue (Ph. D.)

"Neutron Elastic and Inelastic Scattering Cross Sections of ^{239}Pu " (1993)

Diane L. Case (Ph.D.)

"Fast Neutron Irradiation of the Highly Radioresistant Bacterium
Deinococcus radiodurans" (1994)

VI. ABSTRACTS OF PUBLICATIONS AND THESES

The following pages contain abstracts of the publications listed in Section III and abstracts of student theses listed in Section V completed during the project period.

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