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NEUTRON SCATTERING STUDIES IN THE
ACTINIDE REGION

Progress Report

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ABSTRACT

During the report period we have investigated the following areas:

- (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) Inelastic neutron scattering studies in ^{197}Au .
- (f) Elastic and inelastic scattering studies in ^{239}Pu .
- (g) Neutron induced defects in silicon dioxide MOS structures.

Three Ph. D. and one M.S. theses were completed during the report period. Publications consisted of one invited talk, three journal articles, one conference proceeding, and five abstracts of presentations at scientific meetings.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe on privately-owned rights.

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

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

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

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

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

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

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. The 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) enables two signals from the BaF_2 detector, corresponding to time of arrival and energy of an incident gamma ray to be stored as a correlated pair in computer memory. This two-parameter storage scheme (γ energy, γ time) is in contrast to the present use of a multi-channel analyzer to examine a single parameter. After data acquisition, the 2PIN allows a "virtual" type of experimentation where time of arrival spectra of gamma rays, in a specified energy range, are extracted from the data through computer manipulation. Lifetimes obtained via this method were compared to previously measured values. A sample spectrum of a three-dimensional plot of time-of-flight (TOF) versus pulse-shape-discrimination (PSD) information for a fission neutron study using the two-parameter interface is shown in Fig. 6. This work is part of the M.S. research of Mitchell L. Woodring.

3. "Black" Neutron Detector

We have acquired five new Philips photomultiplier tubes, XP4312B/D2, and have built and tested photomultiplier tube bases. The tubes and the bases are mounted on the "Black" Neutron Detector (BND)⁴. Using neutrons from the $^7\text{Li}(p,n)$ reaction we have experimented with combining the five anode signals in various ways. Requiring three-fold coincidence among the five anode signals the

Figure 6. Three-dimensional plot of TOF versus PSD information for the fission neutron study using the two-parameter interface.

output was used in the time-of-flight (TOF) mode and gave us the best signal-to-noise ratio. At present results are unsatisfactory for neutron energies below 1 MeV. We are in the process of assembling ten new preamplifiers to improve that situation. We are also investigating the possibility of using high density concrete for the neutron/gamma ray shield surrounding the BND. This work is part of the Ph.D. 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 was developed to simulate the disk geometry arrangement used in the Lowell neutron scattering experiments. A modern random number generator developed by Marsaglia⁵ 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, sparse matrix method and the Rayleigh-Ritz^{6,7} variational method were found to be inadequate to solve the problem. This work is part of the Ph.D. research of Ramakrishnan Venugopal.

5. Inelastic Neutron Scattering Studies in ^{197}Au

For our extension of inelastic neutron scattering studies in ^{197}Au to higher incident energies, we have built a detector comprised of a Hamamatsu R4143 photomultiplier tube, with a NE102 plastic scintillator. Initial tests of this detector look encouraging. Final testing, however, has been delayed due to several component failures of the accelerator. Most of these have been addressed and we expect to resolve our outstanding concerns in the upcoming weeks. This work is part of the Ph.D. research of Michael O'Connor.

6. Elastic and Inelastic 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 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 + 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. Young⁸ as listed in ENDF/B-VI. The agreement is very good. The results were also compared with calculations by Sheldon⁹. 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.¹⁰ The results were in good agreement. This work is part of the Ph.D. research of Gang Yue.

7. Neutron Induced Defects in Silicon Dioxide MOS Structures

A theoretical investigation was 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 RECOIL¹¹ was used to extract the detailed reaction-dependent recoil spectra that went into energy partitioning. The computer code SIM¹² 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 the experimental results and the 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 theory¹³ were compared. Finally, the ionization and displacement effects in MOS devices resulting from fast neutron bombardment were investigated. This work is part of the Ph.D. research of Wen-Liang Chang.

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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) "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.
- (3) "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).

3. Conference Proceedings

- (1) "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.

4. Published Abstracts

- (1) "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).
- (2) "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).
- (3) "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).
- (4) "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).
- (5) "Construction of a "Black Neutron Detector" at the U.Mass 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).
- (6) "ESR Bone Dosimetry of Fast Neutrons", J. Copeland, K. Kase, G. Chabot, G. Kegel, and F. Greenway, Bull. Am. Phys. Soc. 37, 1869 (1992).

IV. STUDENTS ASSOCIATED WITH THE PROJECT

Graduate Students

Diane L. Case
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John Copeland
David J. DeSimone
Joseph E. Dumont
Christopher A. Horton
Chandrika Narayan
Michael O'Connor
Parrish A. Staples
Ramakrishnan Venugopal
Mitchell L. Woodring
Gang Yue

Undergraduate Students

Barbara Beaudette
Peter Bertone
Guy DeMartinis
Christopher Geggis

V. THESIS DEFENSES

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", January, 1993

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

"Theoretical Investigation of Neutron Induced Defects in Silicon Dioxide MOS Structures", April, 1993

Parrish A. Staples (Ph. D.)

"Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons", April, 1993

Gang Yue (Ph. D.)

"Neutron Elastic and Inelastic Scattering Cross Sections of ^{239}Pu ", June, 1993

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.

"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", January, 1993

Mitchell L. Woodring (M.S.)

"Theoretical Investigation of Neutron Induced Defects in Silicon Dioxide MOS Structures", April, 1993

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

"Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons", April, 1993

Parrish A. Staples (Ph. D.)

"Neutron Elastic and Inelastic Scattering Cross Sections of ^{239}Pu ", June, 1993

Gang Yue (Ph. D.)

Fluences and Spectra of Accelerator Generated Fast Neutrons

Gunter H.R. Kegel, Peter F. Bertone, Diane L. Case, David J. DeSimone,
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Abstract

A fast neutron irradiation station has been designed at the University of Massachusetts - Lowell. The fluence delivered by this station is less than that of a nuclear reactor but it is essentially free of slow neutrons and the admixture of gamma rays is small. We describe the station, dosimetry methods, a computer code, verification techniques and applications. The information we provide should enable others to construct a similar station on their type CN or tandem accelerators.

I. INTRODUCTION

Neutron scattering studies in the MeV-region have been performed at Lowell in the past 25 years. In much of this work neutrons were generated by irradiating a thin metallic lithium target with protons produced by the Lowell 5 MS MV, type CN Van de Graaff accelerator. For the purpose of obtaining a neutron spectrum, which covers in a continuous form fast neutron energies from zero to 3 MeV, we have started using thick metallic lithium targets in 1983. These thick targets have not yet been used in our neutron scattering work, but they have found application in a variety of studies. We estimate that, to this date, about 100 thick lithium targets have been used with a total run time in excess of 1000 hours. It seems, at this writing, that the technique and associated procedures have matured and that our experience should be reported to a wider audience.

Applications of our neutron source cover a broad spectrum. Most work involved radiation damage studies in electronic devices, but it also included investigations of optical devices, irradiation of living biota, such as bacteria and sand seeds, and of dead specimens, e.g. bone. Our fast neutron source does not have the same fluence as a nuclear reactor, it generates about 6.2×10^{10} neutrons/s or about as

much as 1 W (thermal) reactor or as much as a 25 Ci californium source. This source would cost close to $\$2 \times 10^6$, not including shielding and handling equipment.

Some users prefer our fast neutron station to a reactor because they see one or the other of the following advantages: (i) The small number of gamma rays accompanying the neutron flux, typically one 422-keV gamma per 20 fast neutrons or about 3×10^{10} neutrons/cm² rad(Si), (ii) the open geometry, which allows the placement of large pieces of auxiliary equipment such as ovens, dewars, pressure or vacuum chambers etc. right up to the fast neutron station, (iii) the simple neutron dosimetry based on ^7Be assays, (iv) the point-like nature of the source which generates a fluence with a $1/r^2$ dependence, and (v) the possibility of using the source with a pulsed beam with a 0.25 ns burst duration. Our station shares with fast burst reactors the advantage of the virtual absence of slow neutrons ($E < 10 \text{ keV}$), with a slow-to-fast ratio under 0.1%.

II. SOURCE DESCRIPTION

A. The nuclear reactions

The cycle of isotopes involved is shown in Fig. 1 [1]. Protons incident upon ^7Li transform it into ^8Be , which decays to ^7Be , via neutron emission. The decay may proceed to the ground state of ^7Be , involving n_0 , the first neutron group, or it may lead to the first excited state of ^7Be , via n_1 , the second neutron group. The relative intensity of n_0 and n_1 is a function of the incident proton energy. The percentages given in Fig. 1 refer to 4-MeV protons incident upon a thick Li target.

The gamma transitions following n_1 are the source of the gamma radiation which accompanies the neutron fluence. The gamma radiation is isotropic in space whereas the neutron fluence is peaked in the forward direction.

Ion beam analysis of Li diffused Ge-Li interfaces

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Lithium was evaporated onto 0.012 in.-thick high purity germanium substrates and was diffused into these samples at temperatures ranging from 175 to 260 °C for periods of several weeks in a vacuum of 5×10^{-8} Torr. The Ge-Li interface thus obtained was examined by 3-MeV proton backscattering coupled with the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction and also by scanning electron microscopy (SEM). The lithium-to-germanium ratio at the interface was measured by comparing the α yield of the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction to the proton backscattered yield from germanium. A Li_2GeO_3 sample was used as a standard in verifying the analysis approach. SEM micrographs indicate that lithium deposit on the germanium surface at 200 °C forms a 13- μm thick layer possibly in the form of an intermetallic compound.

I. INTRODUCTION

Diffusion of lithium into Ge followed by lithium drift is a standard technique to produce gamma-ray radiation detectors known as Ge(Li) detectors. In this application lithium, a donor, is drifted into germanium to compensate acceptor sites and to obtain a large volume of intrinsic Ge. As high purity germanium (HPGE) became available, with impurity concentrations as low as 10^{-10} cm^{-3} , the lithium compensation process was no longer necessary to produce detectors with large active volumes. However, lithium is still used to form a $n+$ contact, on HPGE, an important process in preparing such a radiation detector. Lithium diffuses rapidly into germanium even at low temperatures, a process which has been studied extensively by Reiss *et al.*¹⁻³ These investigators calculated the solubility of lithium in pure germanium by measuring the solubility of lithium in doped germanium, using a Ge-Li alloy as the external phase. The composition of this phase was not determined. These conditions lead us to study the lithium diffused Ge-Li interfaces using ion-beam analysis. These results will be interesting for further studies on the lithium solubility in HPGE.

In ion-beam analysis, the Rutherford backscattering (RBS) method⁴ is commonly used to study material composition. A drawback of RBS is the poor sensitivity to light elements, like lithium, when they occur together with heavy elements. The small signal from lithium rides on the background from heavier elements and is difficult to recognize. Hence, nuclear reaction analysis (NRA) techniques including like ${}^7\text{Li}(p,\alpha){}^4\text{He}$,^{5,6} ${}^7\text{Li}(p,n){}^7\text{Be}$,⁷ and ${}^7\text{Li}(p,\gamma){}^8\text{Be}$ (Ref. 8) reactions were used to detect lithium in different types of materials. The ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction has a large Q value of 17.346 MeV,⁹ the emitted α particle has a high energy signal which is free from background signals from low energy protons. Another advantage of this reaction is the easy detection of charged particles using a silicon surface barrier detector. In this work both, proton backscattering and ${}^7\text{Li}(p,\alpha){}^4\text{He}$ nuclear reaction tech-

niques were employed for the Li-Ge interface studies. A simple but unique method was developed and is presented in this article, which allows us to obtain the composition and lithium content of a material.

II. SAMPLES PREPARATION

High purity germanium, in rod form, 0.5-cm diam, 5-cm long, was obtained from Canberra Industries, Inc.¹⁰ This material had been removed from the center of a large ingot of HPGE, to be made into a well-type HPGE radiation detector. The material had a resistivity value of 47 $\Omega \text{ cm}$. The rod of Ge was cut into slices along its axis. Each Ge slice was polished and etched to obtain smooth surfaces for lithium deposition. After cutting, polishing and etching the slice thickness was about 0.012 in. Two samples at a time were put into a vacuum evaporation chamber. The pressure inside the chamber reached 2×10^{-7} Torr after 10 h of pumping. Lithium was then deposited and diffused into the sample at temperatures ranging from 175 to 260 °C. During the diffusion period, the pressure approached 5×10^{-8} Torr. After the samples were saturated with lithium, they were released from vacuum and were cooled to room temperatures within minutes. Samples were kept under these conditions until a Ge-Li interface layer at the surface became detached. These surface layers were then used as the samples for the Ge-Li interface studies.

III. EXPERIMENTS AND METHODS

A. ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction kinematics

The backscattering and reaction experiments were carried out using the type CN Van-de-Graaff accelerator at the University of Massachusetts at Lowell. A 3-MeV proton beam collimated to an area of 1.5 mm^2 with a current density of about 5 $\mu\text{A}/\text{cm}^2$ impinged normally on the surface of the sample. The emitted α particles from the ${}^7\text{Li}(p,\alpha){}^4\text{He}$ reaction and the scattered protons were detected at an angle of 165° to the incident beam by a silicon

Radiation Damage Studies with Accelerator Generated Neutrons

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Summary

The fission of ^{235}U results in the generation of neutrons and gamma quanta. Both radiations cause damage in semiconductor devices although they interact with matter in totally different ways. The strong gamma component (about eight gamma quanta per neutron) tends to obscure the effects of neutron radiation damage, making it difficult to identify a damage mechanism. These and other considerations have led us to study other methods of neutron generation using charged particle accelerators.

Of all reactions considered we found the $^7\text{Li} (p,n)^7\text{Be}$ reaction most suitable because (i) the cross section is well known, (ii) the number of gamma rays is small, viz. one 478-keV gamma quantum per 20 neutrons, and (iii) the residual Be nuclei are radioactive so that a measurement of the Be activity determines the total number of neutrons generated. This greatly simplifies neutron dosimetry.

We have constructed a fast neutron irradiation station on our type CN Van de Graaff accelerator and we have used it in radiation damage studies and in other work. We describe the station, dosimetry methods, a computer code, verification techniques, and applications.

Fast Neutron Irradiation of the Highly Radioresistant Bacterium *Deinococcus radiodurans*.
D.L. Case, G.H.R. Kegel, Department of Physics, University of Massachusetts - Lowell, USA

Fast neutron survival curves for the bacterium Wild Type *Deinococcus radiodurans*, renowned for its unusually high resistance to gamma, x-ray, and ultraviolet radiation, but for which fast neutron response is unknown, have been generated at the University of Massachusetts - Lowell USA, 5.5-MV type CN Van de Graaff accelerator facility. The fast neutrons are generated from the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction by bombarding a thick metallic lithium target with a 4-MeV proton beam. The University of Massachusetts - Lowell Van de Graaff accelerator facility provides several experimental and analytical advantages compared to reactor generated neutron sources such as: fast neutrons with virtual absence of gamma rays and slow neutrons, minimal extraneous scattering objects, a predictable neutron fluence and energy spectrum, and a simple, well defined dosimetry technique. The bacteria cells are harvested to stationary or logarithmic phase and are uniformly distributed over the surface of 150-mm diameter agar plates. The surface of the agar plate is positioned parallel to the lithium target and perpendicular to the beam line for irradiation. The area of the agar plate is divided into concentric rings of increasing diameter from the center to the periphery, and the average neutron dose within each ring is calculated as the product of kerma factors and precisely known fluences under conditions of charged particle equilibrium. The neutron absorbed dose for a 3.5 hour exposure ranges approximately from 5 kilorads at the periphery, to 250 kilorads at the center of the plate. Percent survival for *Deinococcus radiodurans* as a function of dose is derived from the ability of the irradiated cells to produce visible colonies within each ring compared to that of a nonirradiated control population. The bacterium *Escherichia coli* B/r, known to be a relatively more sensitive organism, has been irradiated under identical conditions for comparative purposes. The survival response of *Deinococcus radiodurans* as a result of cumulative exposures was also investigated. Preliminary results of several irradiated samples strongly suggest that *Deinococcus radiodurans* is considerably more resistant than *Escherichia coli* B/r at both logarithmic and stationary phases. The survival curve generated for *Deinococcus radiodurans* also exhibits a shoulder region, wherein survival remains 100 percent for doses up to several kilorads. This response is generally uncharacteristic of neutron survival curves, which suggests that *Deinococcus radiodurans* cells may be able to sustain or repair multiple damage sites adequately to maintain cell division. The investigation of *Deinococcus radiodurans* cell survival after highly ionizing fast neutron irradiation will provide valuable information about damage and repair mechanisms under extreme cellular stress, and may provide new insight into the origin of this bacterium's unprecedented radiation resistance.

SUGGESTED TITLE OF SESSION IN
WHICH PAPER SHOULD BE PLACED
INSTRUMENTATION

ABSTRACT SUBMITTED
FOR THE DNP MEETING
OF THE AMERICAN PHYSICAL SOCIETY
14-17 OCT., 1992
SANTE FE, NM

PHYSICS AND ASTRONOMY
CLASSIFICATION SCHEME
NUMBER

Studies with a Poenitz-Type Black Neutron Detector.

D.J. DeSIMONE, G.H.R. KEGEL, P. STAPLES, P.F. BERTONE,
J.J. EGAN and A. MITTLER. Univ. of Mass Lowell.--- At our
laboratory we have constructed a Black Neutron Detector(BND) of
the Poenitz type¹ to be used in frequent checks of scintillation detector
efficiencies. Time resolution data for the BND were obtained by
observing gamma rays from an aluminum target bombarded by a
subnanosecond pulsed proton beam from our Van de Graaff
accelerator. We have calculated the efficiency of our BND using a
Monte Carlo code written by Poenitz¹. The BND was used to
measure the neutron spectrum of a thick metallic lithium target
bombarded with a pulsed proton beam. Results of these measurements
were compared to computed spectra based on Liskien and Paulsen's²
recommended ${}^7\text{Li}(p,n){}^7\text{Be}$ cross section.

* Work supported in part by the Department of Energy.

1. W.P. Poenitz, ANL-7915, 1972.

2. H. Liskien and A. Paulsen, At. Data Nucl. Data Tables 15, 57
(1975).

Prefer standard session

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SUGGESTED TITLE OF SESSION IN
WHICH PAPER SHOULD BE PLACED
NEUTRONS

ABSTRACT SUBMITTED
FOR THE DNP MEETING
OF THE AMERICAN PHYSICAL SOCIETY
14-17, OCT. 1992
SANTA FE, NM

PHYSICS AND ASTRONOMY
CLASSIFICATION SCHEME
NUMBER 20.54

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, Univ. of Mass. Lowell--- Neutron scattering angular distributions for Pu-239 were measured via the time-of-flight technique with the neutron energy 570 keV. The sample consisted of a disk of metallic Pu-239, with a mass of 28.67 g, covered with aluminum. Neutrons were generated, using the Univ. of Mass. Lowell Type CN Van de Graaff accelerator, with a pulsed proton beam, Mobley compressed to < 0.5 ns, and irradiating a 10-keV thick metallic Li target. A spectrum unfolding code developed in our laboratory¹ was used in an attempt to separate the spectral contributions of neutrons scattered via the 57-keV and 76-keV states. The results are compared to ENDF/B-VI.

* Work supported in part by the U.S. Department of Energy.

1. G.H.R. Kegel, A. Aliyar, J.H. Chang, J.J. Egan, C.A. Horton and A. Mittler, Nuclear Data for Science and Technology (Mito Conference), p.399(1988).

Prefer Standard Session

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PHYSICS AND ASTRONOMY
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NUMBER 25.40

Neutron Scattering Angular Distributions for 1-MeV
Neutrons on ^{197}Au M. O'CONNOR, G. YUE, CHANDRIKA
NARAYAN, R. VENUGOPAL, C.A. HORTON, W. CHANG,
G.H.R. KEGEL, J.J. EGAN and A. MITTLER, University of
Massachusetts Lowell.--Elastic and inelastic angular distributions
for 1-MeV neutrons impinging on ^{197}Au have been measured using
the (n,n') time-of-flight technique. The University of Massachusetts
Lowell's subnanosecond-pulsed Van de Graaff accelerator with a
Mobley bunching system was used to generate neutrons via the
 $^7\text{Li}(p,n)^7\text{Be}$ reaction. The metallic targets had thicknesses on the
order of 10 keV. The scattering sample was composed of 1-ounce
Canadian Maple Leaf coins. Scattering spectra from iron and
bismuth provided the line shapes for yield extraction from the time-
of-flight spectra. Our results are compared to ENDF/B-VI.

*Work supported in part by the U.S. Department of Energy.

F Prefer Standard Session

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PHYSICS AND ASTRONOMY
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NUMBER 25.40

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. WOODRING. Univ. of Mass. Lowell.--- Prompt fission neutron spectra for ^{235}U and ^{239}Pu up to 13 MeV have been measured for incident neutron energies in the range from 0.5 MeV to 3.5 MeV via the time-of flight (TOF) technique. The measured ^{235}U spectra are compared to calculations by Madland and Nix.^{1,2} In addition, the spectra are fit to a Watt type analytical expression to facilitate comparison to previous experimental results. Pulse-shape discrimination techniques for background reduction were used. The calibration and efficiency determination of the neutron TOF spectrometer will be discussed.

¹D.G. Madland & J.R. Nix, Nucl. Sci. Eng. **81**, 213 (1982).

²D.G. Madland, 50 Years with Nuclear Fission, edited by J.W. Behrens & A.D. Carlson (Am. Nucl. Soc. 1989), pp. 429-435.

^{*}Work supported in part by the U.S. Department of Energy.

Prefer Standard Session

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Abstract Submitted
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Oct. 4-5, 1991

Bates College, Lewiston, Maine

Construction of a "Black Neutron Detector" at the U.Mass - Lowell Accelerator Laboratory. P.F. BERTONE, D.J. DeSIMONE, P.F. DUGAN, J.J. EGAN, G.H.R. KEGEL, P.A. STAPLES. U.Mass Lowell.--In many experiments involving fast neutrons generated in nuclear reactions initiated by accelerator produced charged particle beams, it is important to be able to determine accurately the neutron yield from the target. A detector suitable for such applications should have: a constant efficiency over a large energy range; a fast time response; and the ability to discriminate between gamma rays and neutrons. We have constructed a "black neutron detector" based on the design of Poenitz¹ that has these characteristics. At the Lowell Van de Graaff accelerator laboratory neutrons are produced via the ${}^7\text{Li} (p,n) {}^7\text{Be}$ reaction using a pulsed proton beam which impinges on metallic lithium targets². The pulsed beam enables the detector to be used in a time-of-flight spectrometer. Use of BC501 liquid scintillator permits neutron-gamma discrimination. The scintillator is viewed by five RCA 48796 photo tubes. The detector is housed in a massive shield of lead, polyethylene and lithium carbonate. The characteristics and use of this detector will be discussed.

*Work supported in part by the U.S. Dept. of Energy.

1. W.P. Poenitz, Argonne National Lab Report, ANL 7915, (1972)
2. G.H.R. Kegel, Nucl. Instrum. Meth. B40/41, 1165 (1989).

Prefer Standard Session
(Oral Presentation)

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ESR BONE DOSIMETRY OF FAST NEUTRONS*

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³Radiation Physics, SLAC, Stanford, CA, 94309

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The radiation-induced electron spin resonance (ESR) signal in human and ovine cortical bone was studied as a function of neutron dose and energy. Bone samples were irradiated in the field produced from a Van de Graaff accelerator using the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction. Comparisons were made with ${}^{60}\text{Co}$ photon irradiations. To investigate the ESR response as a function of dose, a thick lithium target was irradiated with protons of approximately 4 MeV. The resultant neutron spectra, modelled using the MURI code [1], were weighted by the corresponding energy-dependent kerma factors for human cortical bone [2] to obtain an estimate of the neutron bone dose for the human and ovine samples. The ESR response was a linear function of neutron dose to approximately 700 Gy. The ESR neutron dose response, at 50 Gy, was approximately 3 to 7 times lower than the ESR ${}^{60}\text{Co}$ dose response for the various sample conditions studied. For the energy study a thick lithium target and lower incident proton energy were used, as well as the ${}^{235}\text{U}$ fission spectrum, to obtain neutrons in the range from approximately 0.3 to 2 MeV. The ESR g-values were the same for photon and neutron irradiations of either human or ovine cortical bone ($g_1 = 2.0015$, $g_2 = 1.9970$), as were the power saturation effects. This work is continuing and will investigate the ESR response of bone to additional sources of neutrons as well as the ESR response of other materials to various radiation types and energies.

[1] Kegel, G. (1985). Fluences and Energy Spectra of Fast Neutrons from a Proton-Irradiated Thick Lithium Target. *Computer Physics Communications*, 36, 321-336.

[2] Caswell, R., J. Coyne, and M. Randolph (1980). Kerma Factors for Neutron Energies below 30 MeV. *Radiation Research*, 83, 217-254.

*Presented at the Spring meeting of the New England Section of the American Physical Society, Wellesley College, Wellesley, Massachusetts, April 3 and 4, 1992. Abstract submitted for publication in the *Transactions of the American Physical Society*. Also presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, Utah, March 14-18, 1992. Paper to be submitted for publication in *Radiation Research*.

"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", January, 1993

Mitchell L. Woodring (M.S.)

Abstract

Lifetimes of excited nuclear states produced by Coulomb excitation in ^{152}Sm , ^{182}W , and ^{184}W nuclei have been measured using fast timing techniques. The University of Massachusetts Lowell 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. The 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 was designed and constructed. The two-parameter interface (2PIN) enables two signals from the BaF_2 detector, corresponding to time of arrival and energy of an incident gamma ray to be stored as a correlated pair in computer memory. This two-parameter storage scheme (γ energy, γ time) is in contrast to the present use of a multi-channel analyzer to examine a single parameter. After data acquisition, the 2PINS allows a "virtual" type of experimentation where time of arrival spectra of gamma rays, in a specified energy range, are extracted from the data through computer manipulation. Lifetimes obtained via this method were compared to previously measured values.

"Theoretical Investigation of Neutron Induced Defects in
Silicon Dioxide MOS Structures", April, 1993

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

ABSTRACT

A theoretical investigation was 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 RECOIL computer code was used to extract the detailed reaction-dependent recoil spectra that went into energy partitioning. The computer code SIM 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 are shown to agree with the experimental results and the analytical estimates of neutron damage in silicon. The profiles of damaged regions in bulk oxide generated from the simulation are shown to demonstrate the morphology of neutron damage. The 1-MeV neutron damage equivalences calculated from the simulation and the LSS theory are compared. Finally, the ionization and displacement effects in MOS devices resulting from fast neutron bombardment are discussed.

"Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons", April, 1993

Parrish A. Staples (Ph. D.)

ABSTRACT

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 MeV, 1.50 MeV, 2.50 MeV and 3.50 MeV. The data are presented either as relative yields or as ratios of a measured spectrum to the ^{235}U spectrum at 0.50 MeV. Incident neutrons were produced by the $^7\text{Li}(p,n)^7\text{Be}$ reaction using a pulsed, bunched proton beam from the 5.5 MV Van de Graaff accelerator at the University of Massachusetts Lowell Pinanski Energy Center. 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 measurements are compared to calculations based on the Los Alamos Model of Madland and Nix to test its predictive capabilities. The data are fit by the Watt equation to determine the mean energy of the spectra, and to facilitate comparison of the results to previous measurements. The data are also compared directly to previous measurements

"Neutron Elastic and Inelastic Scattering Cross Sections of ^{239}Pu ", June, 1993

Gang Yue (Ph. D.)

ABSTRACT

Neutron elastic and inelastic scattering angular distributions for ^{239}Pu with incident energies 570 keV and 700 keV have been measured via the (n,n') time-of-flight (TOF) technique. The energy resolution was maintained at 20-25 keV. Particular care was taken in removing the tail of the elastic peak which underlines the inelastic peak in the TOF spectrum. The angle integrated cross sections obtained for two scattered neutron groups, one corresponding to the elastic + 7.9 keV and the other corresponding to the inelastic 57 keV + 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 Young as listed in ENDF/B-VI. The agreement is very good. The results were also compared with calculations by Sheldon. At large scattering angles the data are in reasonable accord with Sheldon's calculation. For 700-keV incident neutrons, the data were compared with the previous measurements of Haouat et al. The results were in good agreement.

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