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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) Neutron elastic and inelastic scattering measurements on ^{14}N, ^{181}Ta, ^{232}Th, ^{238}U and ^{239}Pu.

(b) Prompt fission spectra for ^{232}Th, ^{235}U, ^{238}U and ^{239}Pu.

(c) Theoretical studies of neutron scattering.

(d) Neutron filters.

(e) New detector systems.

(f) Upgrading of neutron target assembly, data acquisition system, and accelerator/beam-line apparatus.

One Ph.D. and three M.S. theses were completed during the report period. Publications consisted of 4 invited papers, 11 refereed papers and 32 abstracts of presentations at scientific meetings. There are currently 8 Ph.D. candidates working on dissertations directly associated with the project. In addition 3 other Ph.D. candidates are working on dissertations involving other aspects of neutron physics in our laboratory.

NOTICE

I. RESEARCH

1. Neutron Inelastic Scattering for Higher Excited States in ^{232}Th and ^{238}U

The extension of our measurements on vibrational levels in the excitation energy range 600– to 1000–keV up to 3.0-MeV bombarding energy has been completed. Excitation functions were performed in 100-keV steps from 2.3 to 3.0 MeV. Angular distributions were measured at 2.4 and 2.8 MeV. The work includes data for the following vibrational levels or level groups: in ^{232}Th, 714.2 + 730.3 keV, 774.1 + 774.4 + 785.2 keV, 829.5 keV, 872.7 + 883.3 + 889.6 keV and 960.2 keV; and in ^{238}U, 680.1 keV, 731.9 keV, 827.1 keV and 927 – 998.3 keV. In addition we have obtained cross sections for the 6^+ ground state rotational levels at 333.2 keV in ^{232}Th and at 307.2 keV in ^{238}U.

Preliminary results for ^{232}Th for the excitation functions and the 2.4 MeV angular distributions were presented at the Mito Conference in 1988.[1] Preliminary results for ^{238}U were presented at the 1988 Fall Meeting of the Nuclear Physics Division of the American Physical Society at Santa Fe.[2] This work constituted the Ph.D. thesis research of Abobakr Aliyar who received his diploma in June, 1989. At this time the complete work is being prepared for submission to *Nuclear Science and Engineering*.

2. Inelastic Scattering from ^{232}Th and ^{238}U at 128 keV

A series of measurements of the neutron inelastic scattering cross section of the 2^+ states of ^{238}U at 44.9 keV and ^{232}Th at 49.4 keV were made at an incident energy of 128 keV for six scattering angles: 45°, 55°, 70°, 90°, 110° and 122.5°. A detector consisting of a scintillator viewed by 2 XP-2020 photomultipliers was used.

Very thin (13 keV) targets were made by depositing lithium on tantalum *in situ*, and repeated short runs with Th, U and Bi scatterers were summed to produce spectra for each of the three scatterers. The Bi spectrum was used to establish the elastic peak shape which was subtracted from the other two spectra in order to extract the inelastic spectrum.

Figure 1 shows a typical ^{238}U spectrum (solid line) with a normalized superimposed Bi spectrum (dotted line). The contribution from the 2^+ excited state is clearly evident.

Detector efficiency was measured using a ^{235}U fission chamber normalized to a BF_3 counter. Angular distribution results are consistent with the inelastic scattering differential cross section being symmetric about 90°.

This work was the subject of a paper presented at the Asilomar meeting[3] in 1989, and forms part of the Ph.D. dissertation of graduate student, Christopher Horton.

3. Elastic and Inelastic Scattering from ^{239}Pu

We have begun measurements on ^{239}Pu using a scatterer with a mass of only 28.7g. Extensive modifications were made to our accelerator-target-sample-detector configuration in order to accommodate the small scatterer. We measured angular distributions at 570 keV for two two-level combinations, ground plus 7.9-keV state and 57.3-keV plus 75.7-keV states. Figures 2 and 3 show the results plotted along with the ENDF/B-VI evaluation[4] shown as a solid line. Figure 4 shows a background subtracted time-of-flight spectrum taken at 125° with a flight path of 97 cm. These preliminary results were presented at the International Conference on Nuclear Data for Science and Technology[5] in Jülich, Germany this past May. This work is part of the Ph.D. dissertation of Gang Yue.

4. Elastic and Inelastic Scattering from ^{181}Ta

We have begun making measurements on ^{181}Ta in order to help to establish a data base with which to compare reaction model calculations for odd-A deformed nuclei. Figure 5 shows a 1-MeV spectra measured at 40° to the incident beam using a flight path of 120 cm. This work will be part of the Ph.D. dissertation of Michael O'Connor.

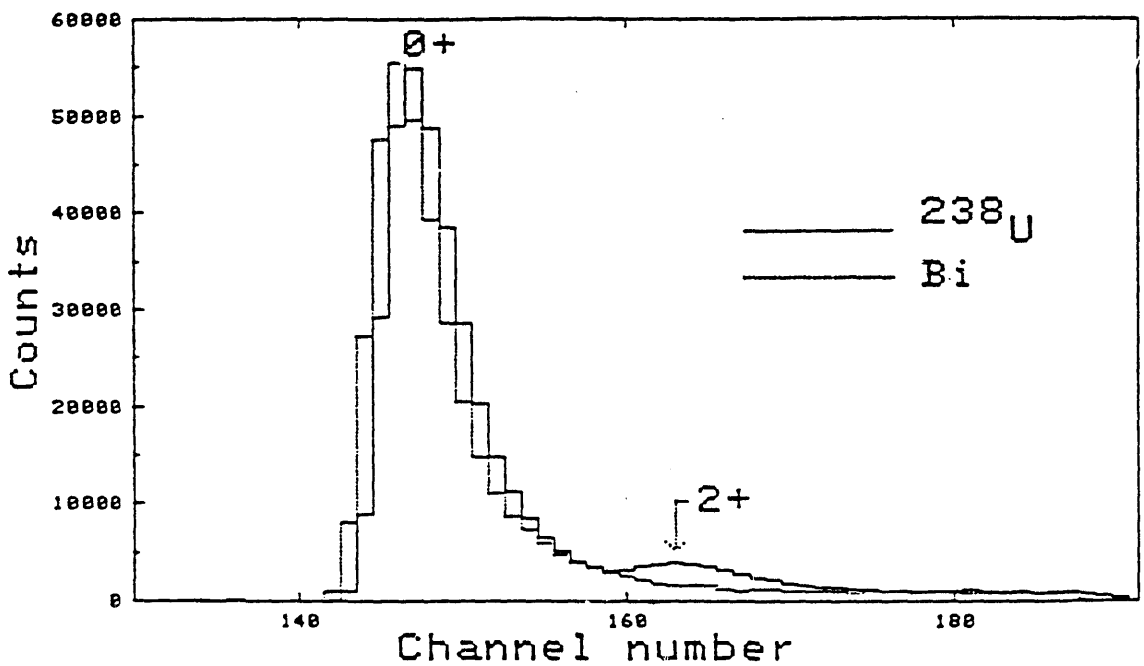


FIG. 1. Time-of-flight spectrum at 90° of ^{238}U (solid line) and Bi (dotted line) taken with 128-keV incident neutrons.

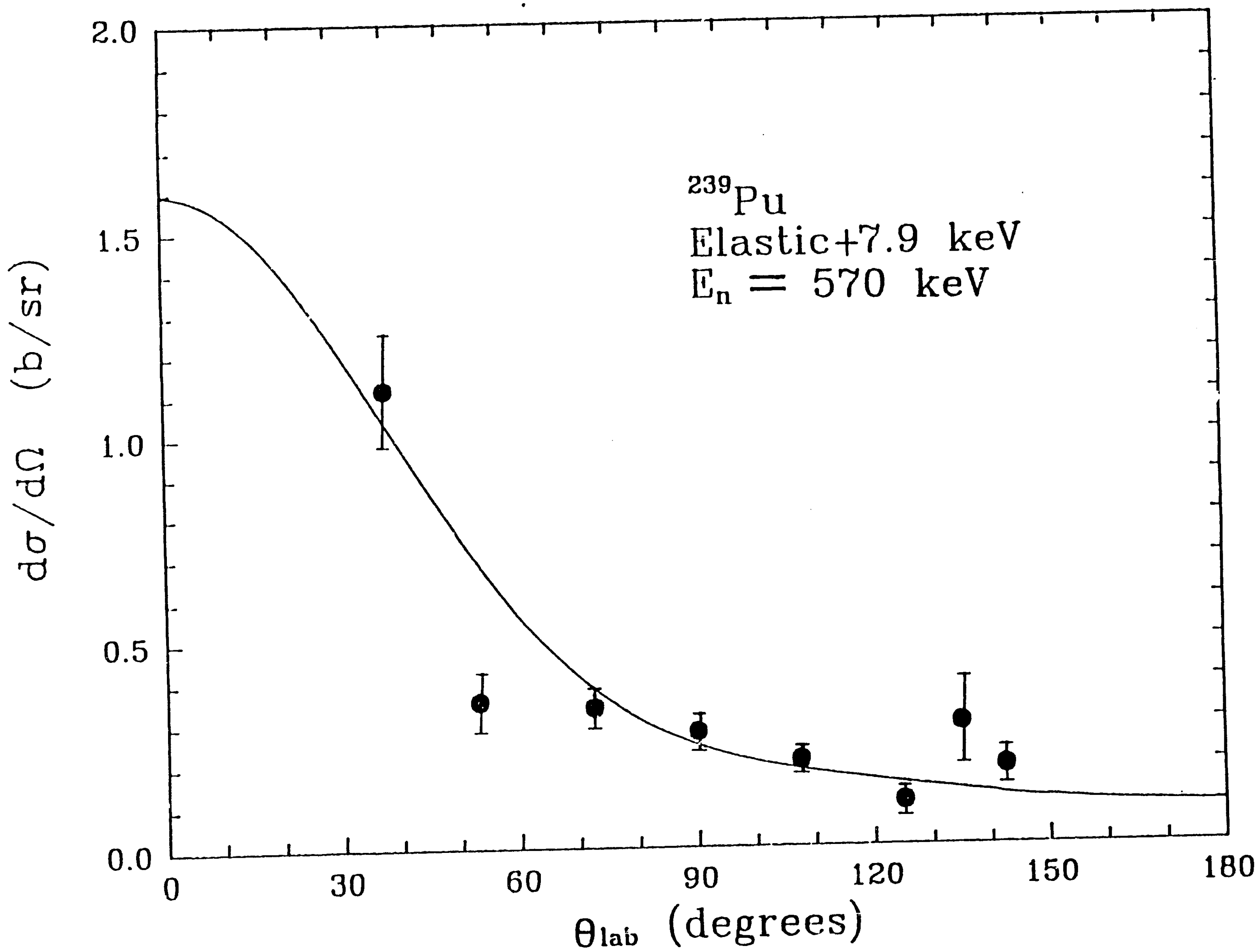


FIG. 2. Angular distribution for ground state and first excited state (7.9 keV) of ^{239}Pu for 570-keV incident neutrons. The solid line represents ENDF/B-VI.

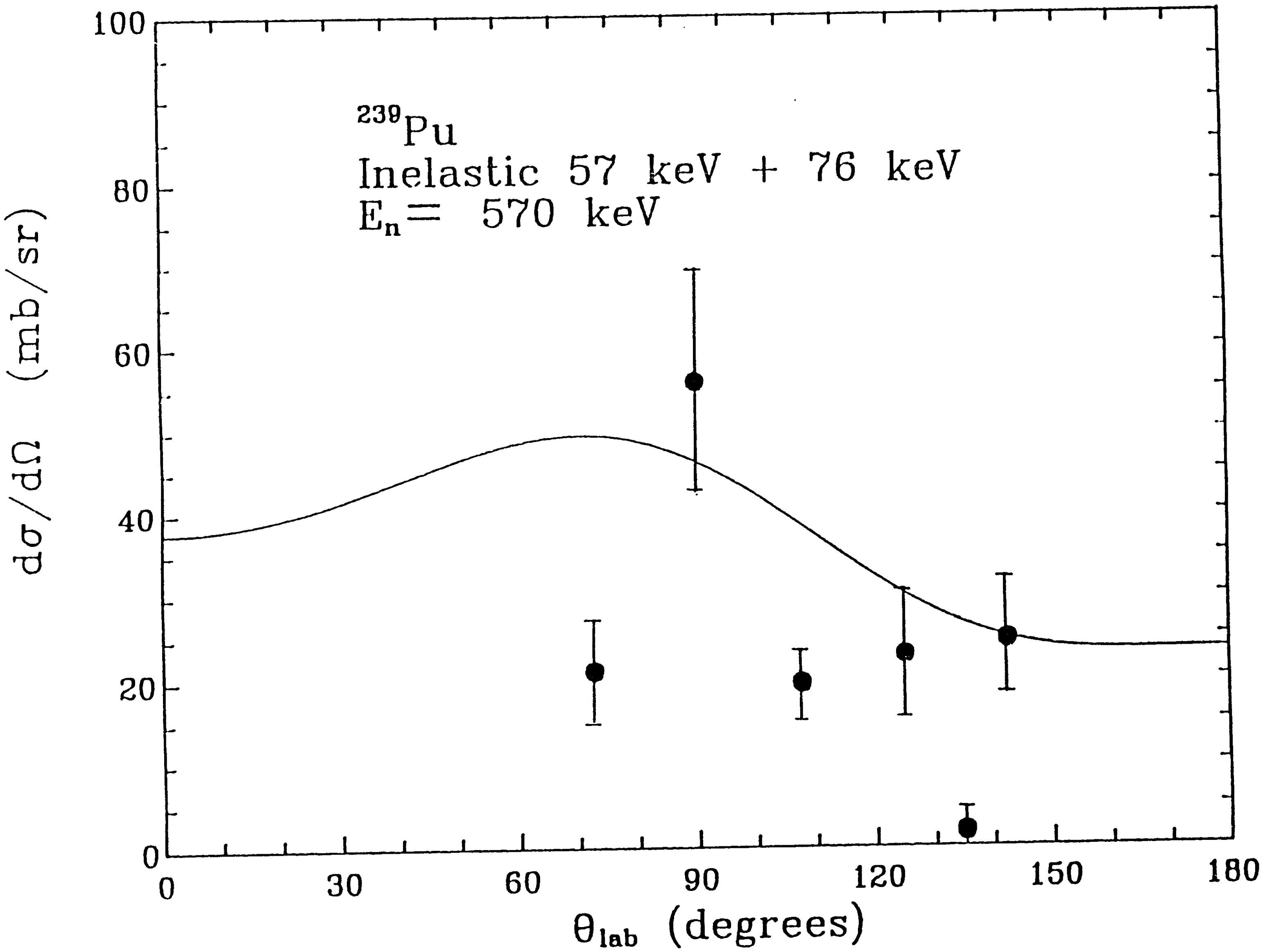


FIG. 3. Angular distribution for second (57 keV) and third (76 keV) excited states of ^{239}Pu for 570-keV incident neutrons. The solid line represents ENDF/B-VI.

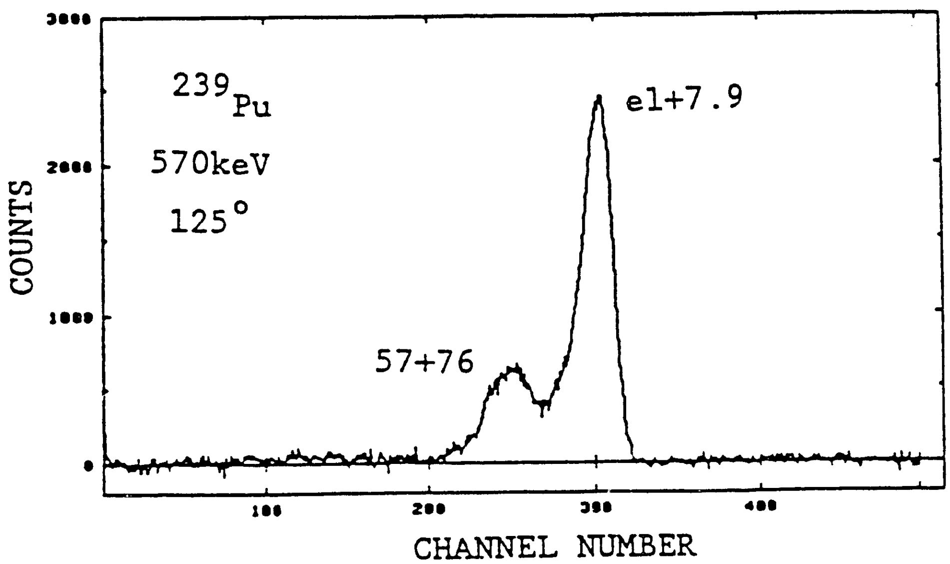


FIG. 4. Background-subtracted neutron time-of-flight spectrum of ^{239}Pu taken at 570 keV. The flight path was 97 cm.

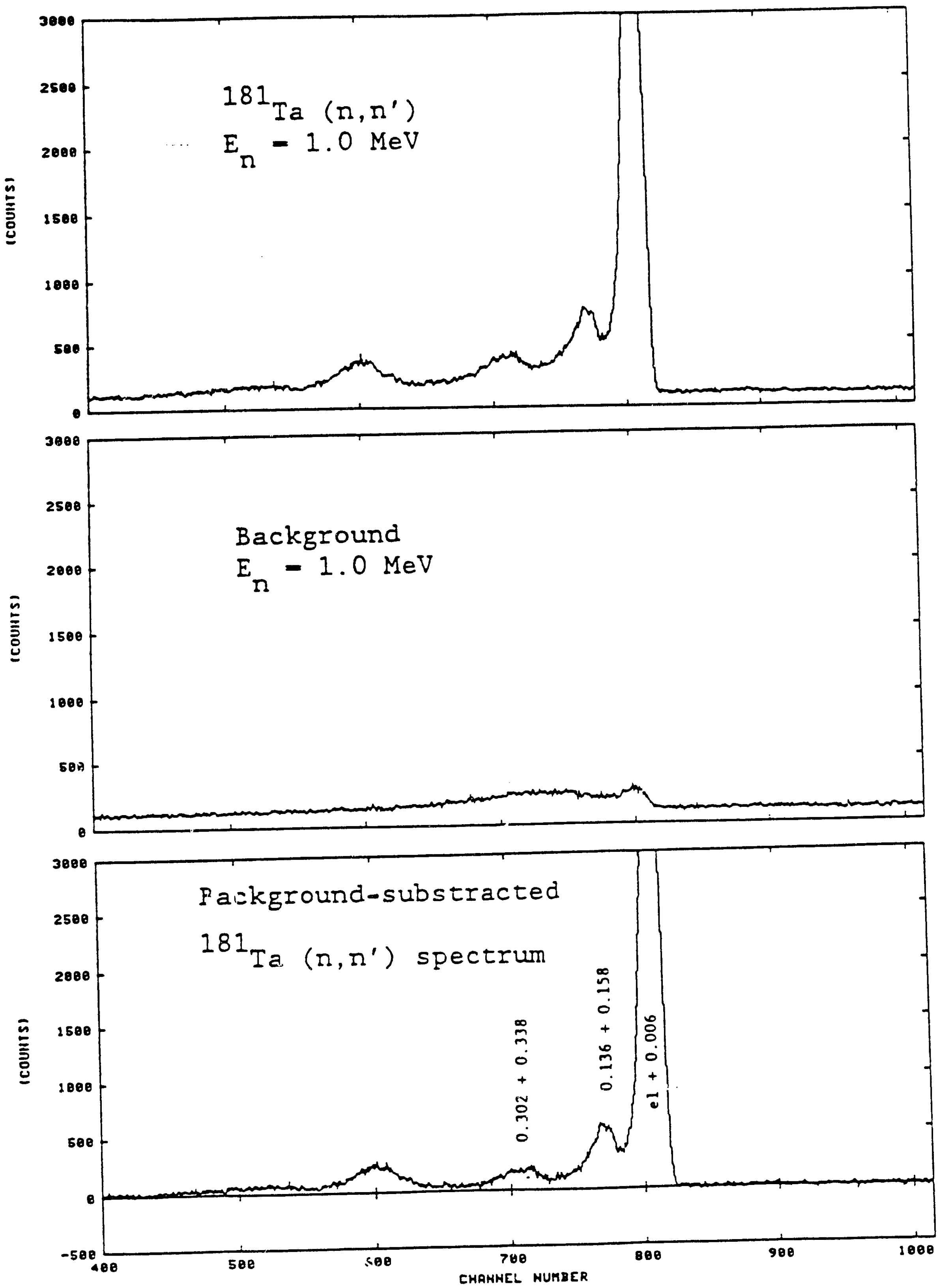


FIG. 5. Neutron time-of-flight spectrum at 40° of ^{181}Ta taken at 1.0 MeV. The flight path was 120 cm.

5. Inelastic Cross Section for the First Excited State of ^{14}N

The inelastic scattering cross section for the first excited state of ^{14}N at 2.313 MeV has been obtained from $^{14}N(n,n'\gamma)$ measurements for incident neutrons in the range 2.650 to 3.550 MeV. A gamma-ray production excitation function at 125° was measured in 100 keV steps. In addition an angular distribution was measured at 3.450 MeV. Figures 6 and 7 show these data.

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

Figure 8 shows the neutron scattering cross section inferred from the $(n,n'\gamma)$ measurements. These results were obtained by multiplying the 125° excitation function data by 4π, a reasonable approach in light of the good fit to the angular distribution using L=0 and L=2 Legendre polynominals.

The published earlier work of Bostrom *et al.*[6] and that of Day[7] are shown for comparison. These earlier measurements do not extend below 3.40 MeV. Shown also for comparison is the ENDF/B-VI evaluation[8].

The motivation for this work stems from recent efforts to develop an airport screening device for explosives secreted in baggage[9]. Such explosives are very difficult to detect with conventional airport x-ray security systems. Since most explosives contain large quantities of chemically bound nitrogen any exploitable feature in the neutron cross section might prove to be useful in the development of a detection device. The results of our investigation suggest that it will be difficult to realize a practical design based on the detection of the gamma rays following inelastic scattering from the first excited state of ^{14}N at low bombarding energies. The rather low cross section would necessitate the use of a copious source of fast neutrons with an additional difficulty from the proximity of the 2.312-MeV gamma line to the capture gamma line from $^1H(n,\gamma)^2H$ at 2.225 MeV which is produced in hydrogenous shielding materials. Separation of the two lines would require the use

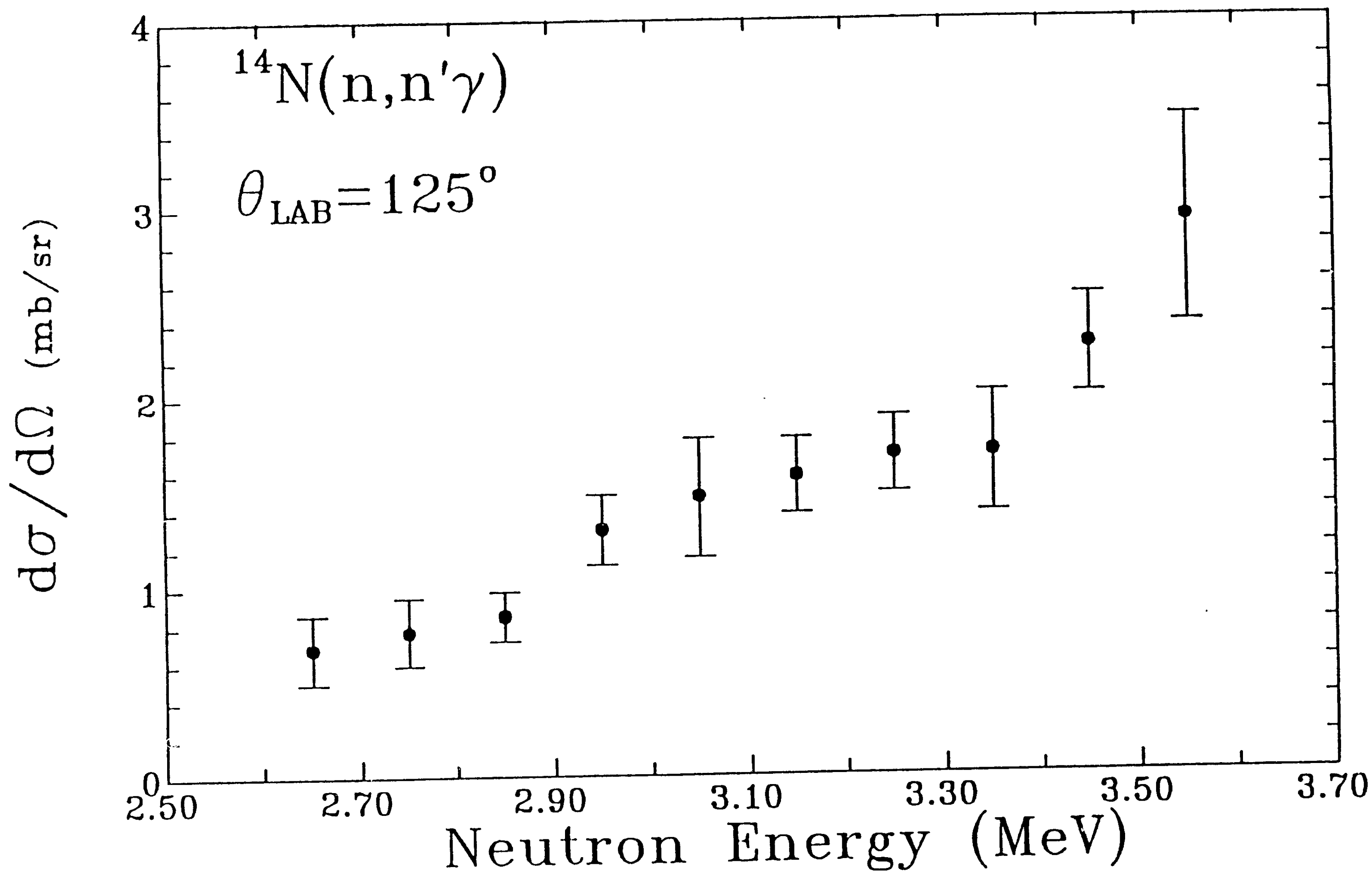


FIG. 6. Differential gamma-ray production cross section at 125° for the first excited state of ^{14}N at 2.313 MeV.

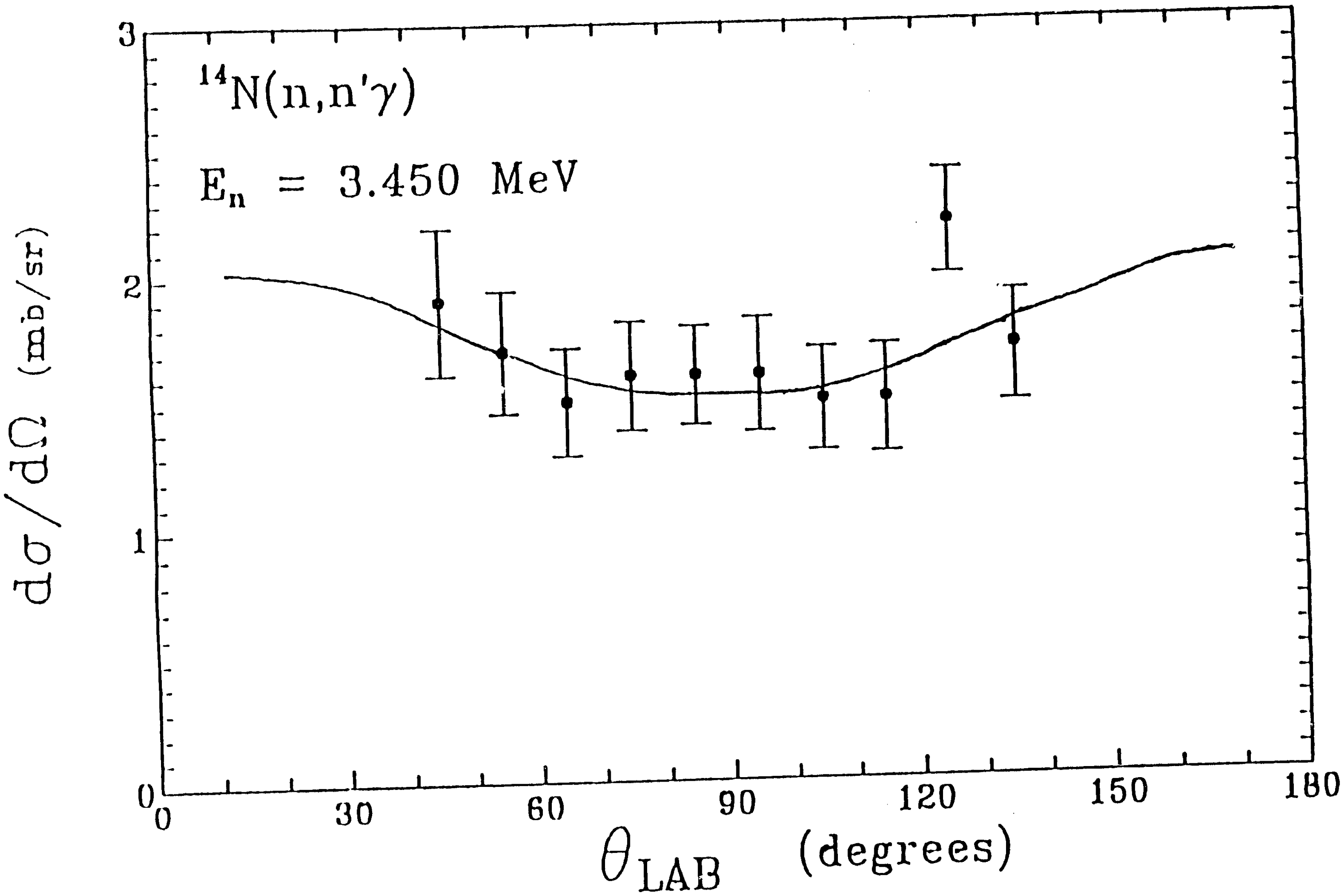


FIG. 7. Angular distribution for the 2.313 MeV first excited state of ^{14}N measured at a neutron energy of 3.450 MeV. The experimental data points are fit with a Legendre polynomial series consisting of only L=0 and 2 terms.

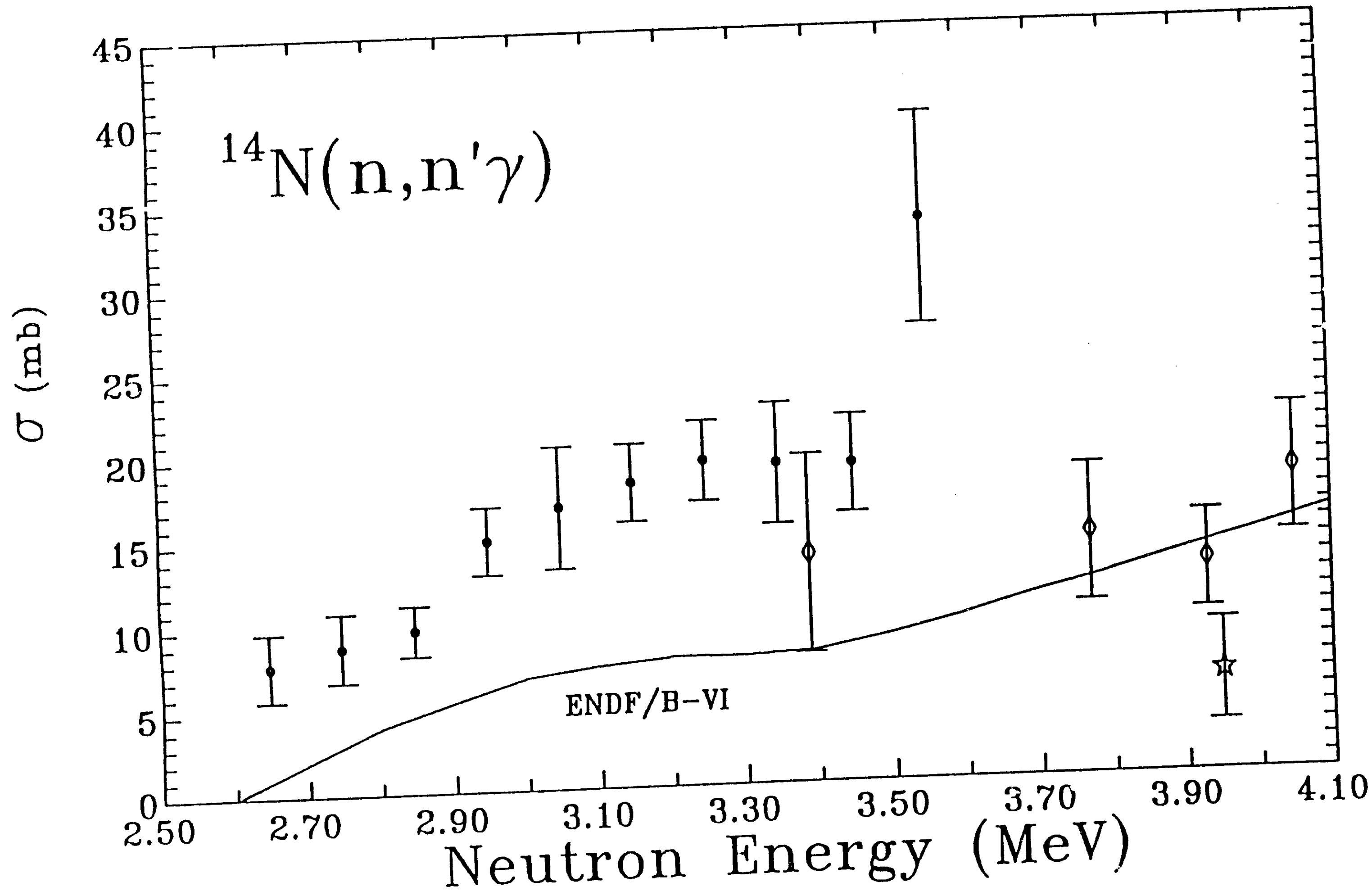


FIG. 8. Integrated neutron cross section for the 2.313 MeV first excited state of ^{14}N compared to measurements by Bostrom *et al.*[6] and by Day.[7]
solid dots - present work; — - ENDF/B-VI; diamonds - Bostrom *et al.*[6]; star - Day.[7]

of high resolution germanium detectors with their limitations due to small size compared to larger but poorer resolution, and therefore unsuitable, NaI(Tl) or BGO detectors.

A paper[10] on this work was presented at the Asilomar meeting of the Nuclear Physics Division of the American Physical Society in 1988. The work was the subject of the Master's thesis of graduate student Parrish Staples and is being prepared for publication.

6. Prompt Fast Fission Neutron Energy Spectrum Measurements

Madland and Nix[11] have proposed a theory of fission which predicts that the fission neutron energy spectrum should depend, to a degree, on the energy of the primary neutron inducing the fission. We have proposed to test this theory by measuring fission neutron energy spectra of ^{232}Th, ^{235,238}U and ^{239}Pu for primary neutrons between 0.5 and 3.0 MeV.

There are two Phases in these studies requiring different instrumentation. In Phase 1 we measure spectra of fission neutrons with energies exceeding that of the primary neutrons; in Phase 2 we cover the lower energy part of the fission spectrum.

We have completed construction of equipment for fast fission neutron energy measurements. We are commencing a program of prompt fast fission spectra measurements on ^{232}Th, ^{235}U, ^{238}U, and ^{239}Pu in the 0.5- to 3.0-MeV incident neutron energy range. We have prepared a BC-501 liquid scintillator mounted on an RCA 8854 photomultiplier tube. This detector is housed in a large paraffin, Li_2CO_3, and lead shield and oriented so as to view fission neutrons at 90° to the beam direction with a flight path which can be varied from 0.5 to 5 meters. The time-of-flight electronics and pulse shape discrimination system have been assembled and tested. Phase 1 measurements are underway at this time. Energy calibration of the time-of-flight spectrometer will be accomplished using the ^{9}Be(^{3}He,n)^{11}C reaction, and ^{3}He gas has been installed in our accelerator terminal for this purpose. Preliminary results will be reported at the Fall Meeting of the Nuclear Physics Division of the American Physical Society at East Lansing, MI. This work is part of the Ph.D. dissertation of Parrish Staples.

7. Theoretical Studies of Neutron Scattering

As a follow-up to previous analyses of theoretical (n,n') excitation-functions for fast neutron scattering on the principal actinide nuclei[12,13,14] we are examining our recently measured cross sections[15] for ^{232}Th and ^{238}U at higher incident energies (E_n = 2.3 - 3.0 MeV) by comparing the experimental data with calculated excitation functions for individual or grouped levels at excitation energies ranging from about 330 keV to approximately 1 MeV.

The calculations are performed without arbitrary adjustment of input parameters. Since a direct-interaction (DI) mechanism is likely to play a prominent role at these energies for such well-deformed, collective nuclei, a coupled-channels distorted-wave (DWDI) treatment is called for, as provided by the Karlsruhe[16] variant "KARJUP" of Tamura's[17] code "JUPITOR". The compound nucleus (CN) component added incoherently to the DI contribution is computed using the program[18] "CINDY" which employs the Hauser-Feshbach formalism with provision for Moldauer level-width fluctuations and incorporates additional competing exit channels. For consistency throughout the Bruyéres-le-Châtel set[19] of optical-potential parameters and deformations (or very slightly modified versions thereof) are adopted, varying only with energy in all computations. Some of our results[20] were presented at the Jülich conference in May. More recent angular distribution calculations for ^{232}Th and ^{238}U are shown along with our data in Figs. 9 and 10. Figure 11 shows our latest measurements of ^{239}Pu, our theoretical calculations and ENDF-VI evaluations.

8. Enhanced Mathematical Tools for Analysis of Neutron Scattering Data

A Monte Carlo study of neutron multiple scattering effects is in progress. A simulation of the neutron generation from a lithium target under proton bombardment was performed for the geometry that we use for neutron scattering measurements in our laboratory. An analysis of the number of multiply-scattered events was done for three of our disk-shaped scatterers (^{232}Th, ^{235}U and ^{238}U). The

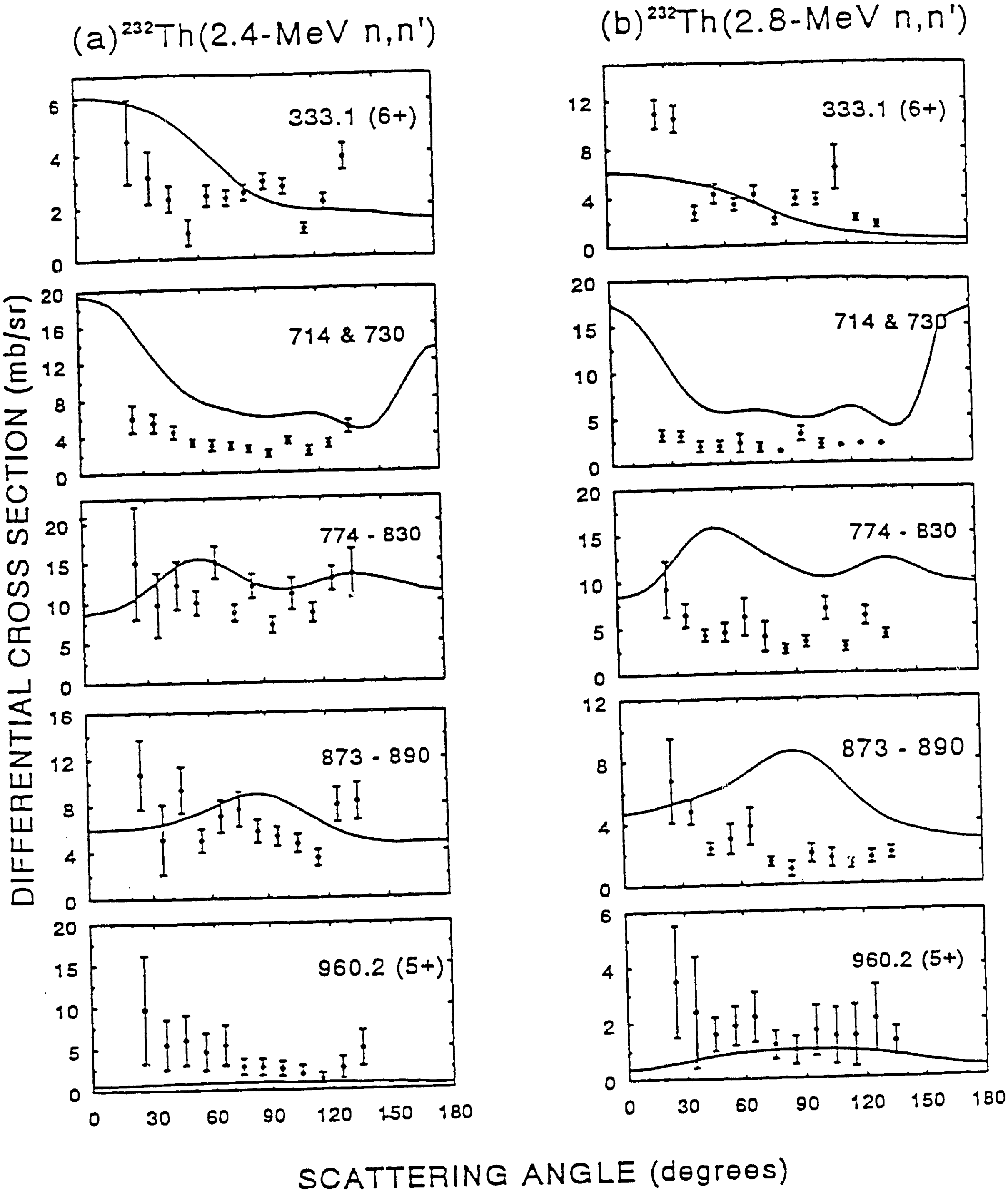


FIG. 9. Angular distributions for ^{232}Th (n,n') scattering to individual or grouped (unresolvable) levels up to $E^* = 960.2$ keV at (a) $E_n = 2.4$ MeV and (b) $E_n = 2.8$ MeV comparing the Lowell group's measured data (points, with error bars) with theoretical (CN+DI) differential cross sections computed with the programmes CINDY/KARJUP at Lowell (solid curves).

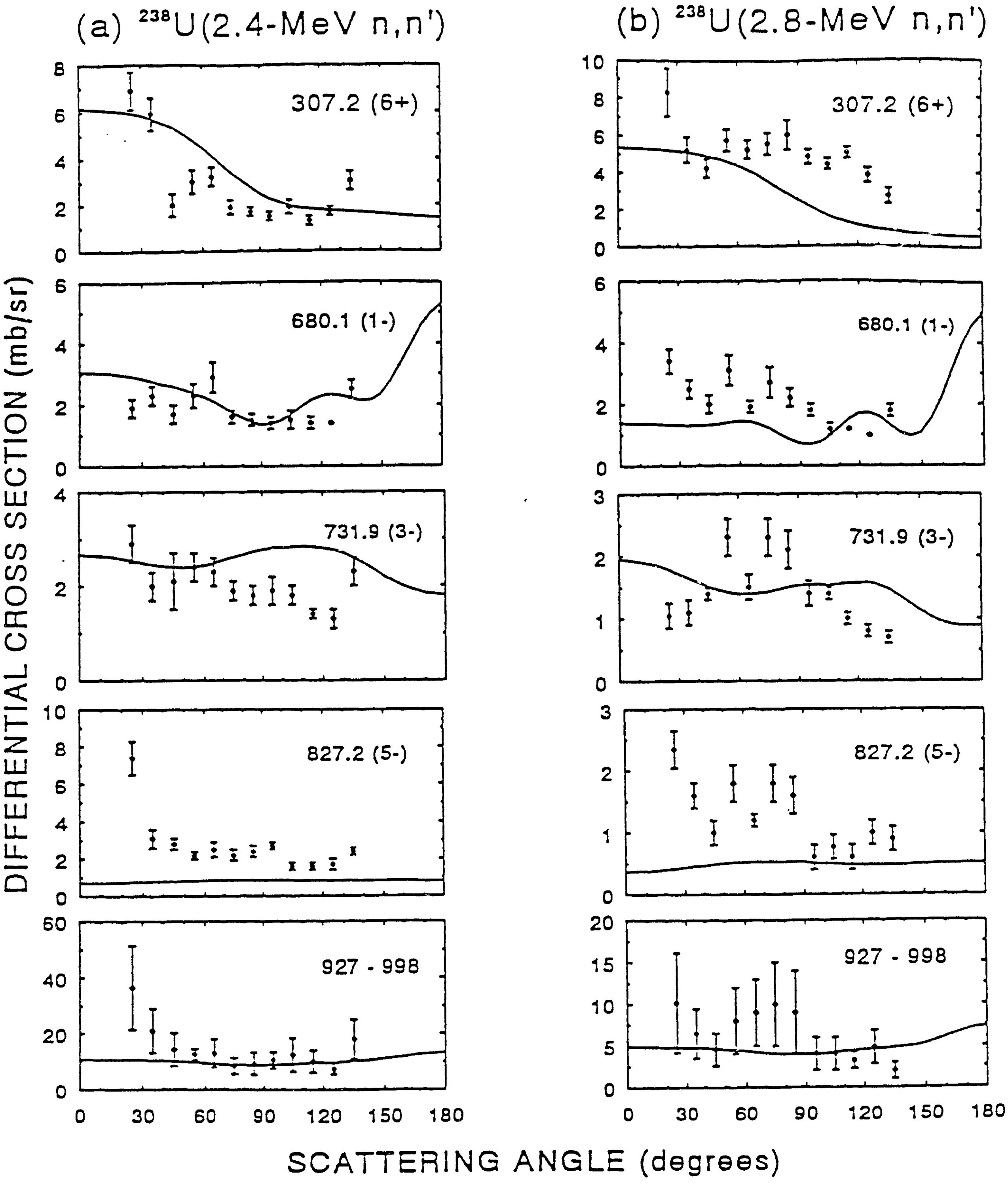


FIG. 10. Angular distributions for ^{238}U (n,n') to individual or composite (unresolvable) levels up to E* = 997.5 keV at (a) E_n = 2.4 MeV and (b) E_n = 2.8 MeV, comparing Lowell experimental data with theoretical (CN+DI) differential cross sections.

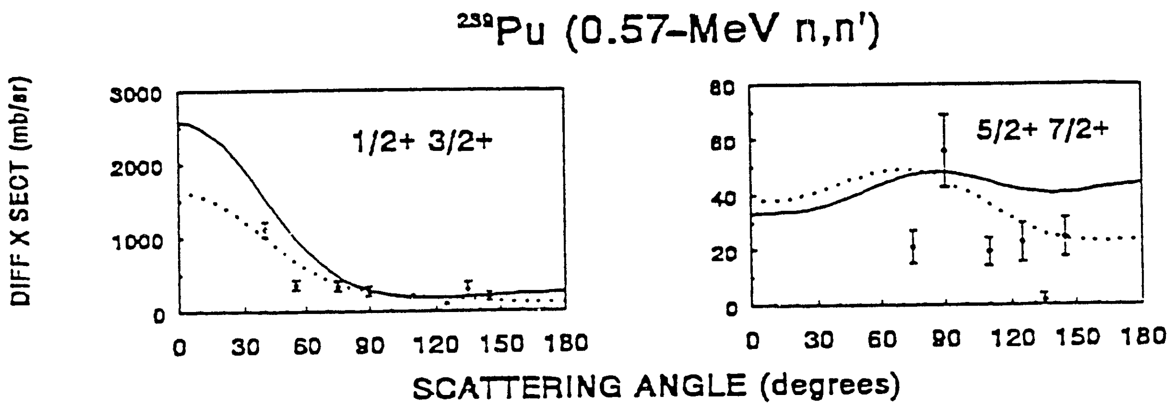


FIG. 11. Angular distribution for elastic and inelastic neutron scattering at $E_n = 0.57$ MeV on ^{239}Pu to paired members of the K= $1/2^+$ ground-state rotational band: (a) to the 0.00-keV ($1/2^+$) and 7.8-keV ($3/2^+$) levels, and (b) to the 57.3-keV ($5/2^+$) and 75.7-keV ($7/2^+$) levels, comparing Lowell experimental data (points, with error bars) with Lowell CN+DI computations (solid curves) and LANL computations, the latter being identical with ENDF/B-VI evaluations (dotted curves).

angular distributions of the scattered neutrons were taken from ENDF evaluations. A code was written in C programming language and a 386/387 PC DOS computer was used to perform the calculations.

As part of this research a detailed review of the best random number generators was done. We are currently using a random number generator which passes all known randomness testing algorithms and has a period of 2^{144}.

An alternative approach to the scattering problem is an analytical study which is also in progress. This involves diagonalization of large (72000 elements) sparse matrices. New computing tools are being developed to optimize the speed of computation. This work is being performed on a RISC machine.

This work forms part of the Ph.D. dissertation research of R. Venugopal.

9. Use of Neutron Filters in Low Energy Neutron Spectroscopy

We have studied the use of neutron filters (Fe for the resonance minimum window at 82 keV, Mg for its resonance maximum at 84 keV and S for its resonance near 120 keV) in conjunction with the pulsed beam from the Van de Graaff accelerator and a low-noise scintillation detector designed specifically for this work. Results of this investigation, were reported[21] at the Santa Fe meeting of the Division of Nuclear Physics in October, 1988. The technique was considered for use in measurement of inelastic scattering cross sections of low lying states of actinide nuclei, such as the 12-keV state of ^{235}U, which have not been successfully resolved by conventional techniques. Results of these studies are part of in the Ph.D. dissertation of Christopher Horton.

10. Morphology of Lithium Targets Used for the Production of Neutrons

We suspected that one mechanism for the degradation over time of Li-on-Ta targets used in our neutron time-of-flight (TOF) work is the progressive embedding of Li into the Ta substrate. To determine the extent and nature of this Li intrusion into Ta, Li was deposited on a Ta substrate and was bombarded with protons. This target was then removed and was thoroughly cleaned to remove the Li deposit. Thereafter it was remounted and subjected to proton bombardment, and the depth concentration of the residual Li was profiled using the TOF technique. The data strongly suggest that the dominant mechanism is the diffusion of Li into Ta, rather than Li recoil due to proton bombardment. This work was reported[22] at the Denton, TX, Conference on Accelerators in Research and Industry in November 1988.

Work in this area has continued with a careful study of vacuum deposition of metallic lithium onto various substrates using the Rutherford backscattering technique.

11. Determination of Lithium Isotopic Concentration in Metallic Lithium

We have developed a method for determining the atomic proportions of ^{6}Li and ^{7}Li isotopes in enriched ^{6}LiF, ^{7}LiF, and lithium metallic samples. The technique is based on measuring the energy spectra of alpha particles from $^{7}Li(p,\alpha)^{4}He$ and $^{19}F(p,\alpha)^{16}O$ reactions and those of backscattered protons. Enriched LiF targets were prepared by thermal evaporation of thermoluminescent dosimetry chips, TLD-700 (^{7}LiF) and TLD-600 (^{6}LiF), onto self-supporting carbon substrates. Targets of metallic lithium were prepared in the same way. The ^{6}Li enriched TLD-600 sample was found to contain 4.78 at.% of ^{7}Li; however, no significant amount of ^{6}Li was found in the TLD-700 sample. A 7.57 at.% concentration of ^{6}Li in lithium metallic target was determined by using the TLD-700 as a ^{7}Li isotope content standard. This value is consistent with the reported 7.5 at.% natural abundance of ^{6}Li. A complete description of the technique will appear in a paper which has been accepted for publication to Nuclear Instruments and Methods. This work forms part of the Ph.D. dissertation research of Causon Jen.

Figures 12, 13 and 14 show ^{6}LiF, ^{7}LiF and metallic Li proton-backscattered spectra. Note the presence of the alpha groups from $^{19}F(p,\alpha)^{16}O$ in Figs. 12 and 13. These groups serve to normalize the two spectra.

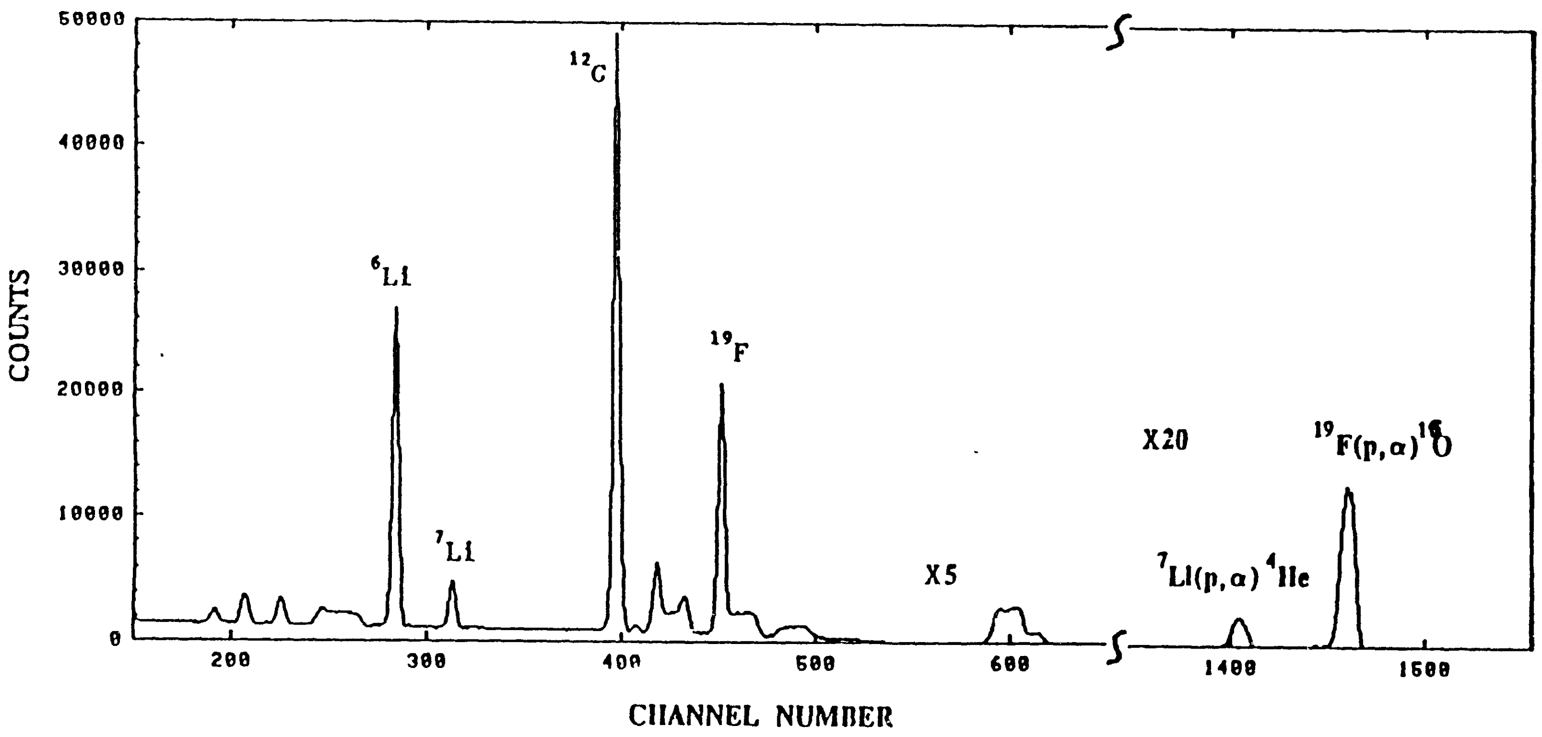


FIG. 12. Proton-alpha spectrum at 165° for a thin ^{6}LiF target. The incident proton energy was 3 MeV.

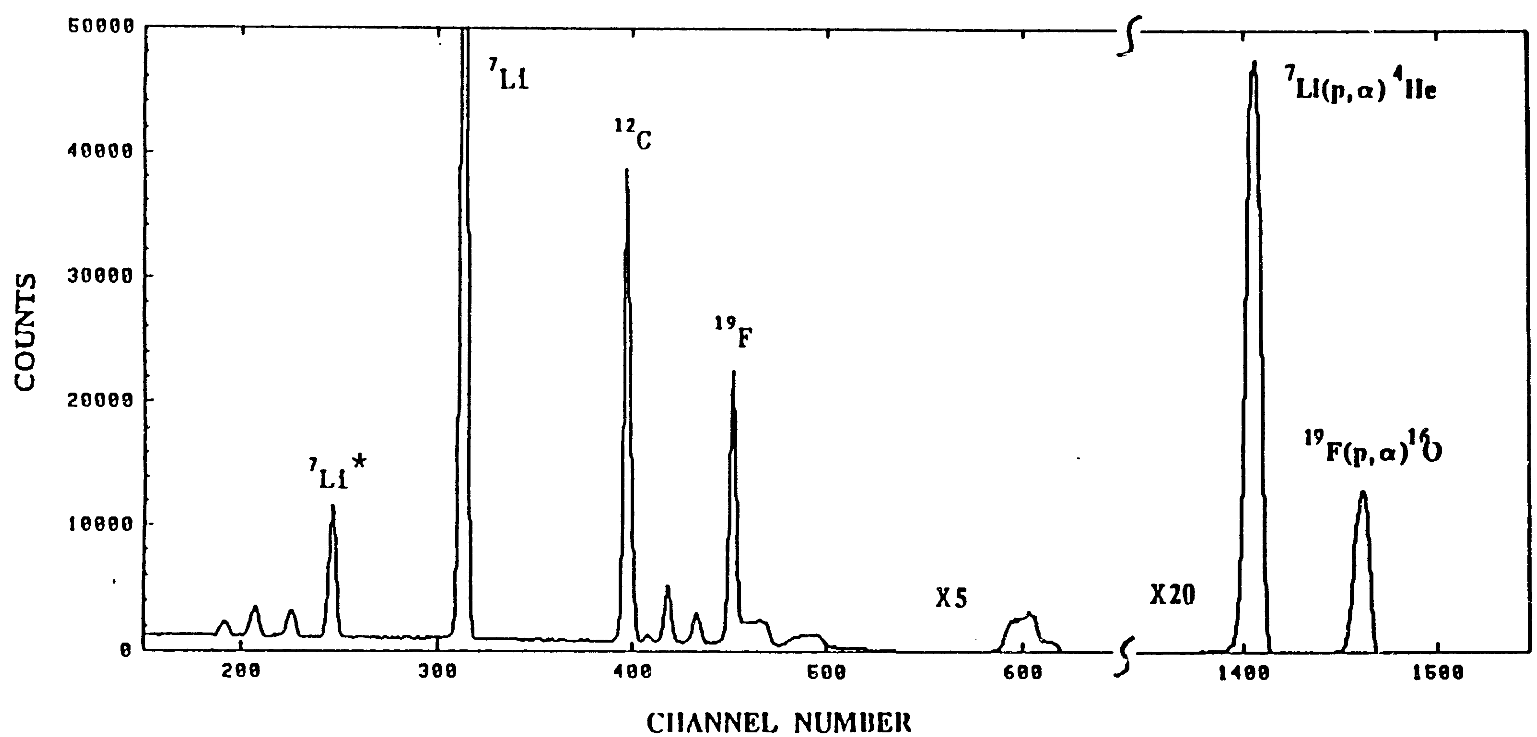


FIG. 13. Proton-alpha spectrum at 165° for a thin ^{7}LiF target. The incident proton energy was 3 MeV.

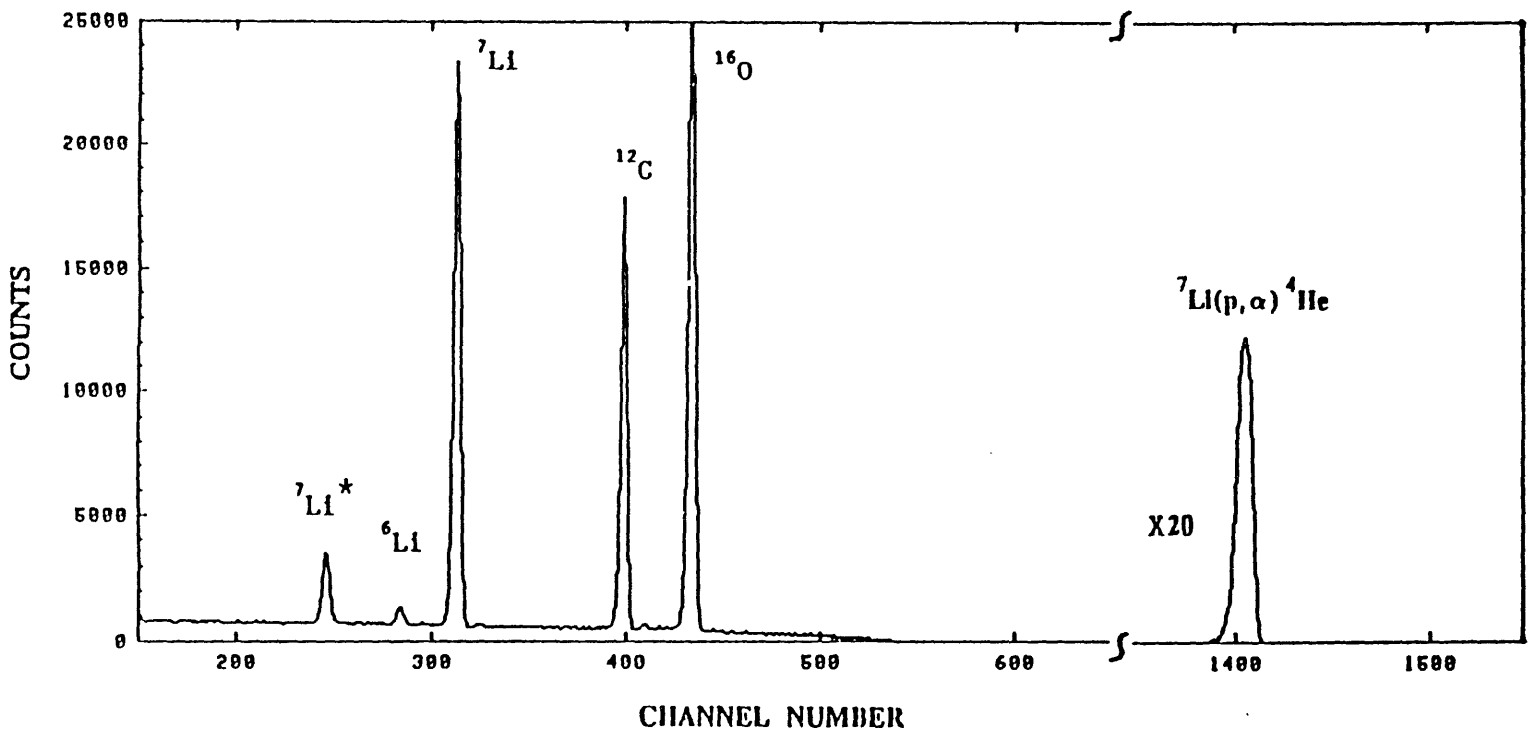


FIG. 14 Proton-alpha spectrum at 165° for a thin metallic lithium target. The incident proton energy was 3 MeV.

12. Pseudo-White Neutron Source and Its Use in Detector Efficiency Measurements

Recent neutron scattering experiments at Lowell have revealed the advantages of frequent checks of the time-of-flight spectrometer efficiency especially if the neutron cross sections studied are small. In the past we normally compared the response of our spectrometer to that of a ^{235}U fission ionization chamber so that the efficiency of our detector is based on the well known ^{235}U fission cross section. These comparisons are time consuming because the fission chamber efficiency is low; therefore it is not suitable for daily use. The energy spectrum of neutrons following spontaneous fission of ^{252}Cf has also been used to determine spectrometer efficiencies. This method also requires a considerable amount of time. In recent years we have used thick metallic lithium targets irradiated with MeV protons to generate pseudo-white neutron spectra[24]. We now use this procedure to generate standard neutron spectra suitable for rapid efficiency determinations. The method has two major advantages. (1) The neutron fluence is high i.e., 40 to 80 neutrons/(s . cm^2 . keV), in the 500- to 3500-keV range at a distance of 250 cm from the target with a 10-μA, 5.5-MeV incident proton beam. (2) Each neutron generated leaves one ^7Be atom behind, hence the neutron dosimetry is simplified by a ^7Be activity determination. The ^7Be decay scheme is simple and ^7Be has a convenient half life of 52 days. We can calculate neutron energy spectra from thick lithium targets spectra using differential cross section data for the Li(p,n) reaction[25] and stopping cross sections[26] for protons in Li. These calculations include corrections for proton multiple scattering, for the isotopic composition of lithium, for the surface area and the time resolution of the detector, and for ^7Li depletion by proton induced nuclear transformations. This work was presented at the Jülich conference in May.[27]

13. Neutron Target Assembly and Beam Line Improvements

We have installed a new target assembly on the neutron time-of-flight beam line. This assembly supported by an overhead steel beam incorporates an oil diffusion pump, two proton beam pulse pickups, a water cooled collimator, a lithium metal resistive heating evaporator along with the target backing which consists of a 1.5 inch diameter tantalum planchette mounted on the end of the beam line held in place by an indium vacuum seal. The whole assembly was designed to minimize virtual leaks in the feed-throughs and other incorporated hardware. Figure 15 shows the target and scatterer arrangement. We routinely achieved pressures of the order 10^{-7} torr with this assembly during the ^{239}Pu measurements described in Section 3, despite the fact that it was opened to atmosphere every other day to replace tantalum target blanks in preparation for the evaporation of a new target. No significant target deterioration was apparent after 48 hours of running with proton beams of 8–10 μA. Figure 16 shows a schematic representation of the new beam line and target assembly. The new overhead support beam replaces one which interfered with scattering measurements at back angles beyond 130°.

In order to improve proton beam transmission through our Mobley magnet and ultimately through the collimator system to the target we have constructed and installed a beam steering magnet based on a design of Heikkinen.[28] Construction of the magnet including winding the coils was a summer research project of undergraduate physics major Peter Bertone.

14. Computer Interface for Multi-Dimensional Data Acquisition

An interface for two parameter data acquisition has been designed and constructed specifically to facilitate event-mode recording of time-of-flight and pulse height information in our Hewlett-Packard computer. This device built by graduate student Mitchell Woodring is currently being tested by using it in the measurement of lifetimes of certain low-lying excited states in ^{181}Ta and ^{201}Hg. A block diagram of the electronics to be used is shown in Fig. 17. Ultimately the interface will be used extensively in the prompt fission spectrum measurements of Section 6. The design and construction of the interface along with the measurement of nuclear lifetimes using BaF_2 scintillators (see Section 15) will form part of the M.S. thesis research of Mitchell Woodring.

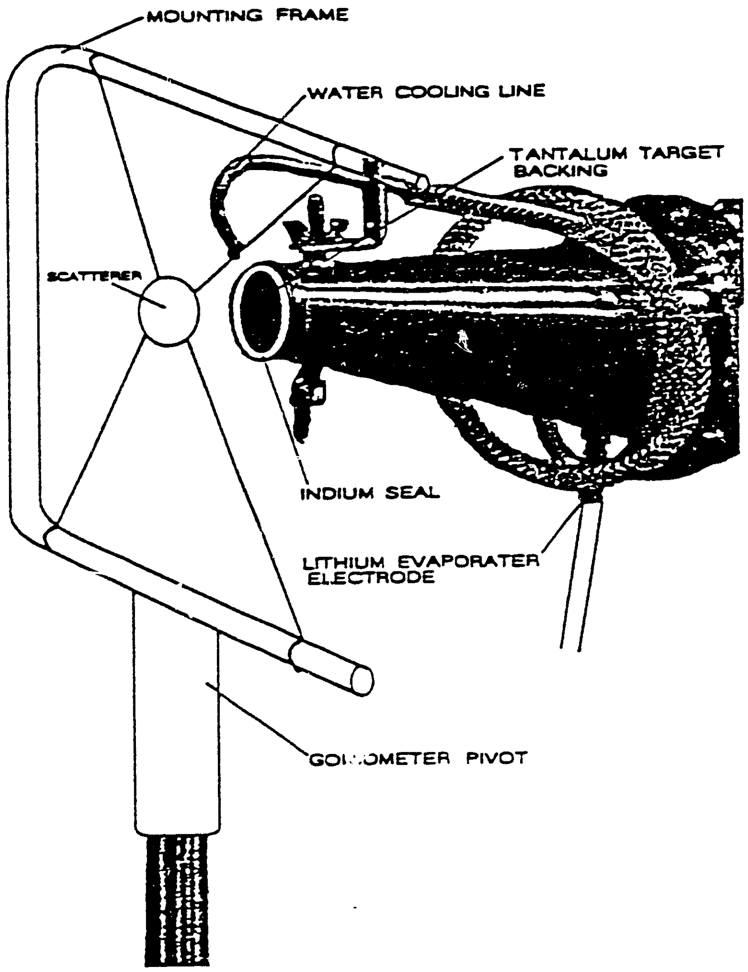
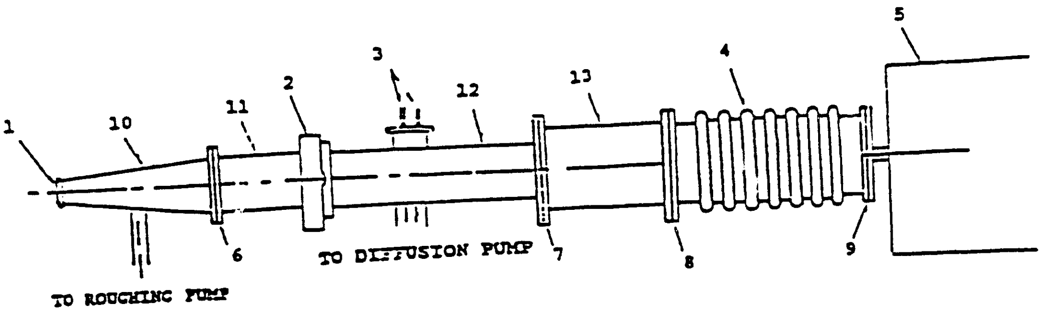
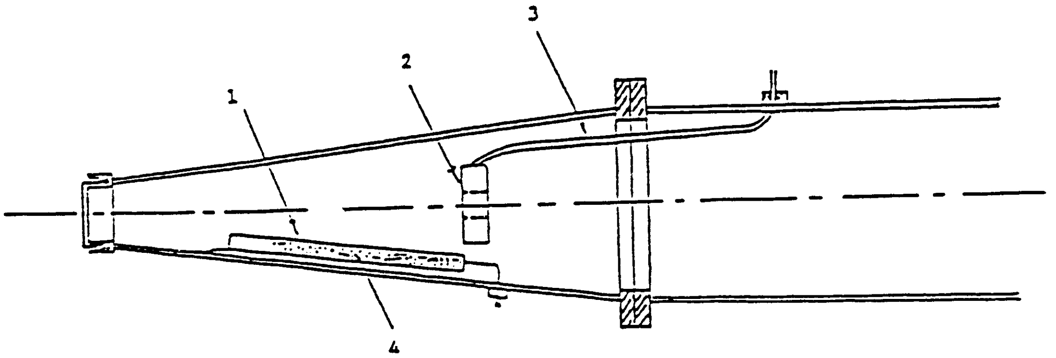


FIG. 15. New target assembly for producing neutrons via $^{7}Li(p,n)$ reaction and the support system for mounting the scatterer.



1. Li-7 TARGET WITH TANTALUM BACKING
2. GATE VALVE
3. BEAM PICK UP
4. BELLOWS
5. COMPRESSION MAGNET
6,7,8,9. FLANGES
10,11,12,13. STEEL PIPES



1. TUBULAR EVAPORATION BOAT
2. COLLIMATOR
3. WATER LINE
4. Li METAL

FIG. 16. Top: Details of modified beam line used for neutron scattering measurements. Bottom: Details of lithium target-making apparatus along with water-cooled collimator.

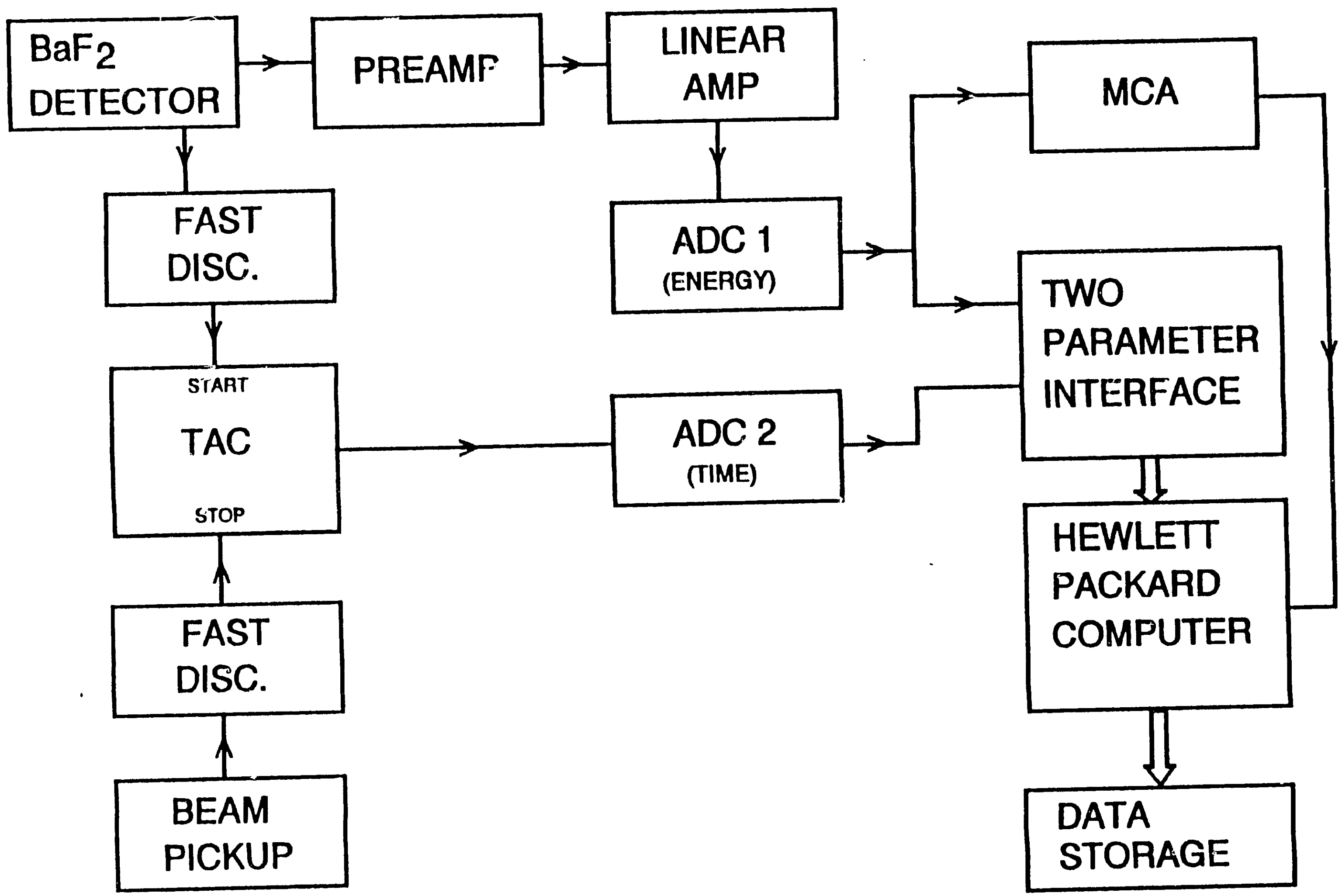


FIG. 17. **Electronics block diagram for nuclear lifetime measurements using the two-parameter interface.**

15. Time - Resolution Studies With BaF_2 Scintillators

In our prompt fission neutron spectral measurements the occurrence of a fission event will be indicated by the detection of prompt gamma rays in fast barium fluoride (BaF_2) scintillation detectors. Three BaF_2 detectors have been assembled and tested. Testing involved a coincidence requirement between pairs of BaF_2 detectors with their associated electronics to determine the time resolution of the system. The resolution of the system, obtained from the full width at half maximum of a coincidence time-spectrum peak using a ^{22}Na source is 233 ps. This coincidence system was developed by graduate student David DeSimone in his M.S. thesis work. One of the BaF_2 detectors is currently being used for the lifetime measurements of Section 14.

16. Response of Plastic Scintillators to Low Energy Neutrons

Computer programs have been written by graduate student Christopher Horton to predict photon production in a hydrogenous scintillator due to a neutron interaction as a function of scintillator dimensions and neutron energy and, given the mean scintillator light output, to predict the probability of detection of a neutron by a single photomultiplier or by two in coincidence where the discriminator is set to detect one-photoelectron or two-photoelectron events.

Figure 18 shows the mean number of photons per interacting neutron for a 1-cm thick, 6-cm diameter BC-418 scintillator, and the probability of an interaction for a 1-cm thick BC-418 scintillator vs. incident neutron energy.

Figure 19 shows the mean number of photons per interacting neutron and the probability of an interaction for a 6-cm diameter scintillator and 80-keV incident neutrons vs. scintillator thickness.

Figure 20 shows the mean depth of first neutron interaction for 80-keV neutrons vs. scintillator thickness.

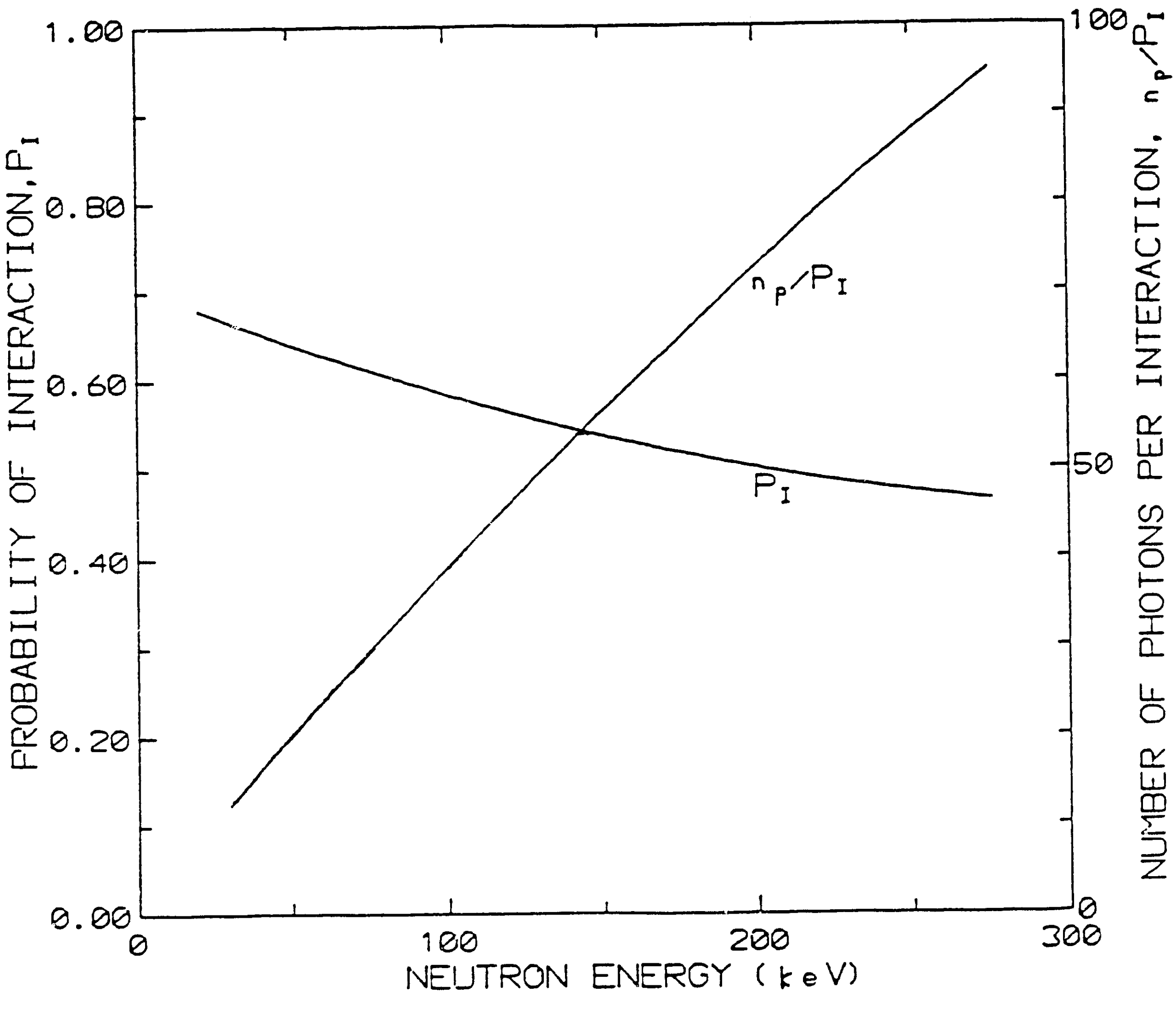


FIG. 18. The mean number of photons per interacting neutron for a 1-cm thick, 6-cm diameter BC-418 scintillator, and the probability of an interaction for a 1-cm, 2-cm, and 3-cm thick BC-418 scintillator vs. neutron energy.

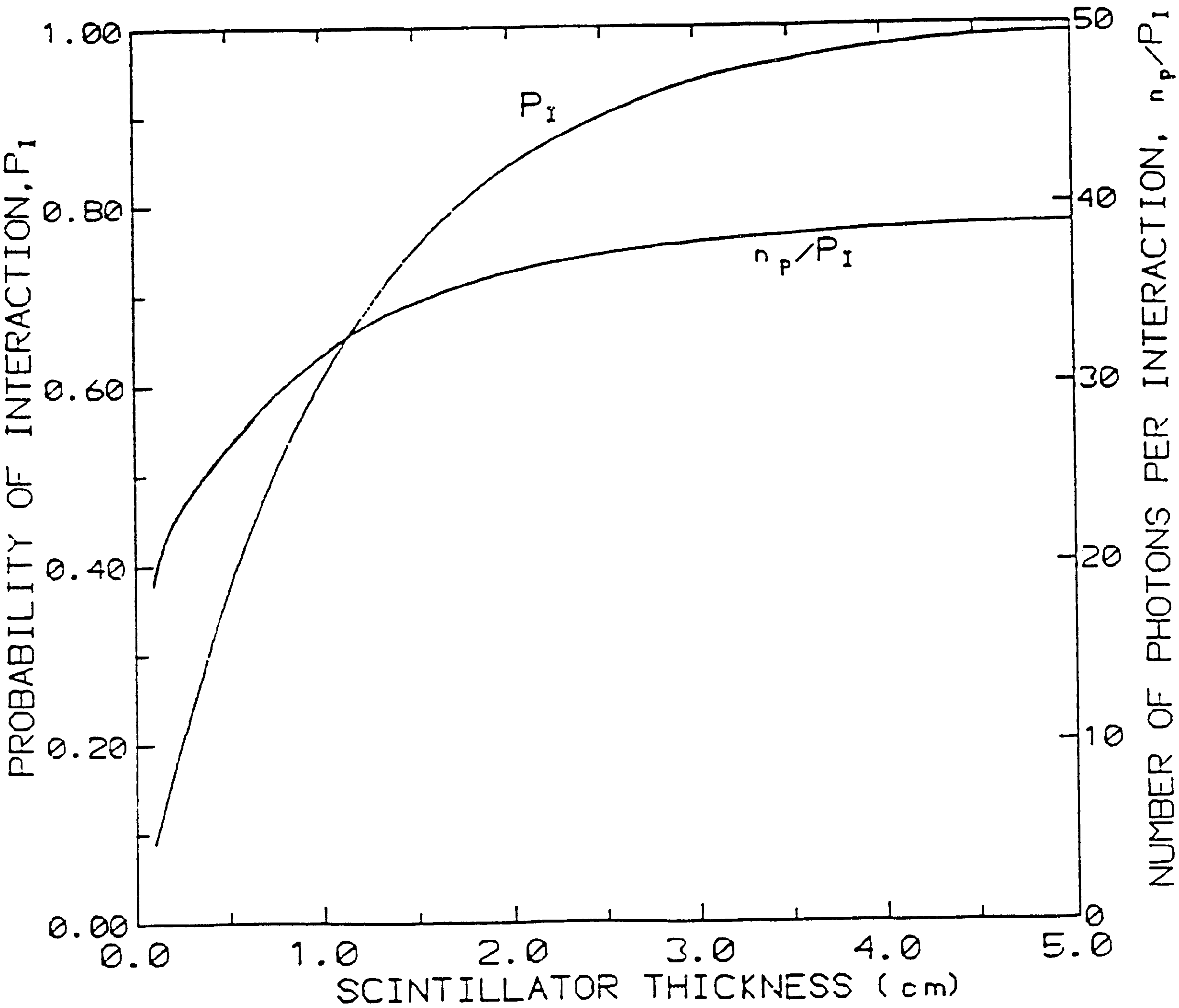


FIG. 19. The mean number of photons per interacting neutron and the probability of an interaction for a 6-cm radius scintillator and 80-keV incident neutrons vs. scintillator thickness.

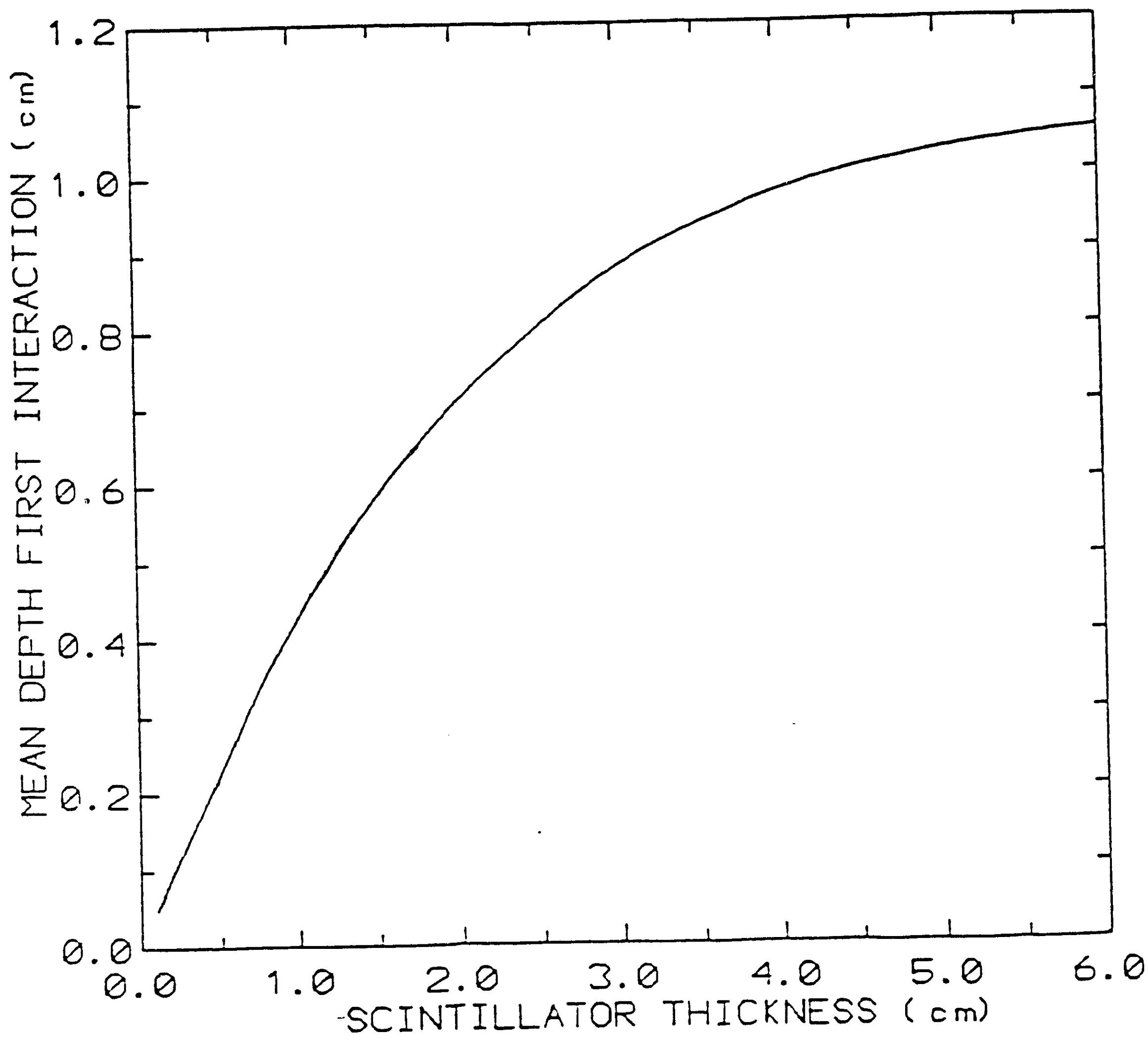


FIG. 20. The mean depth of first neutron interaction for 80-keV neutrons vs. scintillator thickness.

17. Construction of a "Black Neutron Detector"

We have constructed a "black neutron detector" according to the design of Poenitz[28]. The unit is a cylinder with a diameter of 12.18 inches and length 15.75 inches filled with BC 501 liquid scintillator which will be viewed by five 3-inch photomultiplier tubes (RCA 4879C). A massive shield of lead, polyethylene and Li_2CO_3 is currently under construction. We can use pulse-shape discrimination to suppress the gamma response of the scintillator. We expect that time-of-flight techniques will allow us to separate neutron and gamma peaks at low energies where pulse shape discrimination is impractical. Figure 21 is a schematic diagram of the "black neutron detector". Figure 22 shows the detector arrangement along with its shielding. The detector was assembled and tested by graduate students Parrish Staples and Patrick Dugan. The shielding is being constructed by graduate student David DeSimone and undergraduate Peter Bertone. The detector will find several applications, among them the determination of accurate neutron yields from thin or thick metallic lithium targets.

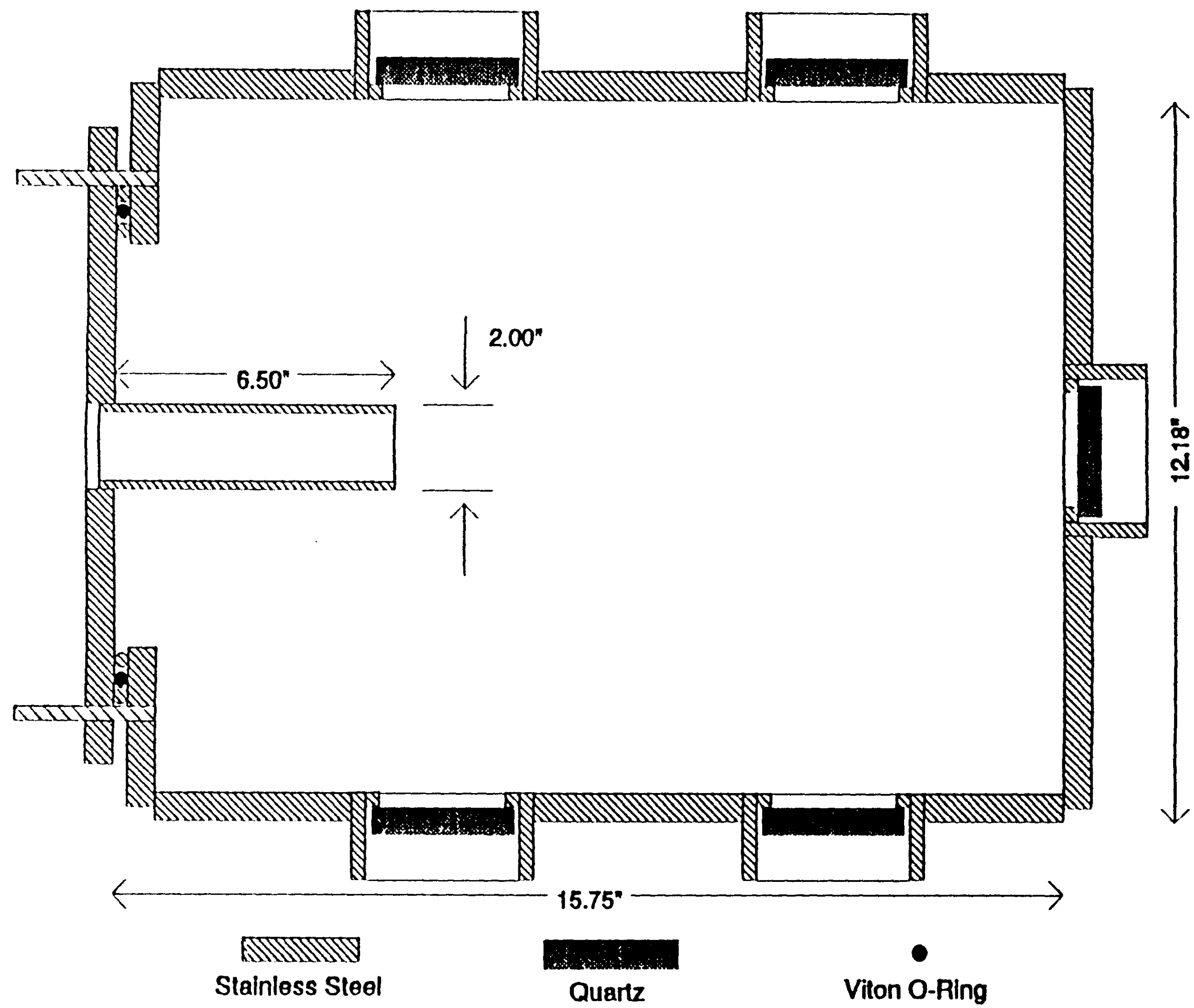


FIG. 21. Schematic midplane-cut view of the "black neutron detector", showing its entrance channel at the left and the quartz window viewing ports for the photomultiplier tubes.

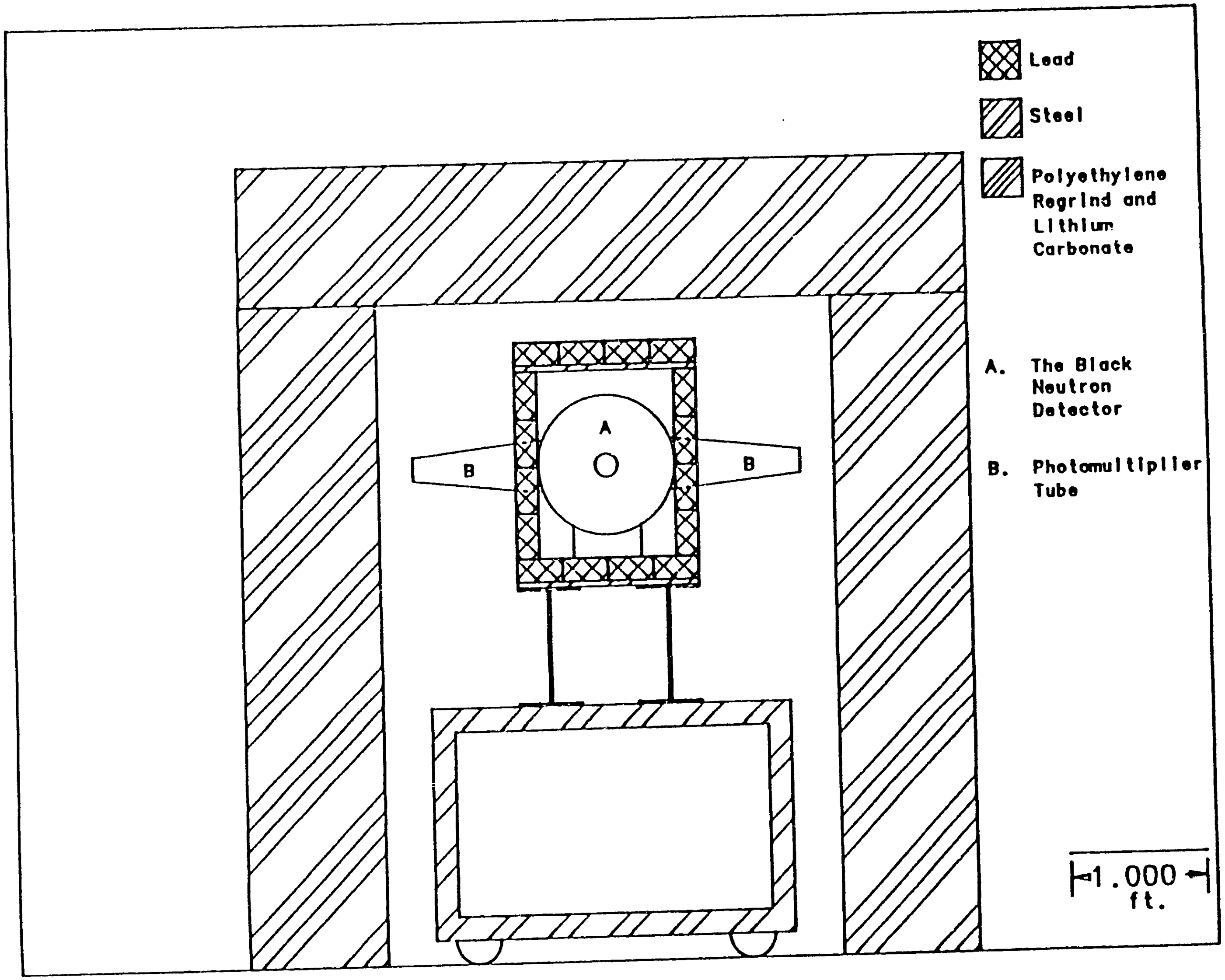


FIG. 22. Schematic front view of the "black neutron detector" with its shielding (front shield is not shown).

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III PROJECT PERSONNEL

Faculty Involved in the Project

Leon E. Beghian, Ph.D., Professor of Physics
James J. Egan, Ph.D., Professor of Physics
Gunter H.R. Kegel, Ph.D., Professor of Physics
Arthur Mittler, Ph.D., Professor of Physics
Eric Sheldon, Ph.D., Professor of Physics

Staff Members

David Shaw, Accelerator Engineer
Kathleen Marks, Secretary

Students Associated with the Project[†]

Abobakr Aliyar
Peter Bertone (undergrad)
Diane L. Case
Wen-Liang W. Chang*
David J. DeSimone
Patrick F. Dugan
Joseph Dumont (undergrad)
Gerald A. Falo
Ganesh C. Goswami*
Eric Hale (undergrad)
Mark Griffon
Christopher A. Horton
Causon K.C. Jen*
Richard Leone (undergrad)
Chandrika Narayan*
Michael A. O'Connor
Mark Sobkowicz (undergrad)
Parrish A. Staples
Deying Sun*
Ramakrishnan Venugopal
Mitchell L. Woodring
Gang Yue*

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† Not all were involved during the entire project.
* International Student

IV. PUBLICATIONS

1. Invited Papers

(1) "Fast Neutron Generation with a Type CN Van-de-Graaff Accelerator," G.H.R. Kegel, Bull. Am. Phys, Soc. *33*, 1741 (1988).

(2) "Fast Neutron Scattering Experiments at the University of Lowell", G.H.R. Kegel, Institute of Atomic Energy, Beijing, P.R. China (1990).

(3) "Application of PIXE and RBS in Material and Life Sciences", G.H.R. Kegel, Institute of Atomic Energy, Beijing, P.R. China (1990).

(4) "Cosmochronology and Nucleochronometry," Eric Sheldon, to be presented at the 22nd International Summer School on Nuclear Physics, Piaski, Mazuria (Poland), August 26–September 5, 1991.

2. Refereed Publications

(1)–(3) The following three papers were published in the Proc. of the Intl. Conf. on Nuclear Data for Science and Technology, May 30–June 3, 1988, Mito, Japan, S. Igarasi, Ed., Japan Atomic Energy Research Institute, Saikon Publ. Co. Ltd., Tokyo (1988).

- "Inelastic Scattering Cross Sections of Vibrational States in ^{232}Th for Neutrons from 2.3 to 3.0 MeV," J.J. Egan, A. Aliyar, C.A. Horton, G.H.R. Kegel and A. Mittler, p. 63.
- "Actinide Neutron Elastic Scattering Data Analyses," Eric Sheldon, p. 105.
- "Improvements in Neutron Time-of-Flight Spectra Processing," G.H.R. Kegel, A. Aliyar, J.H. Chang, J.J. Egan, C.A.Horton and A. Mittler, p. 399.

(4) "Neutron Scattering Cross Sections up to 2.4 MeV for the Ground and First Two Excited States of ^{232}Th," I.G.C. Goswami, J.J. Egan, G.H.R. Kegel, A. Mittler and E. Sheldon, Nucl. Sci. Eng. *100*, 48 (1988).

(5) "Fast Neutron Generation with a Type CN Van de Graaff Accelerator," G.H.R. Kegel, Nucl. Instrum. Methods B40/41, 1165 (1989).

(6) "Radiation Studies with Accelerator Generated Fast Neutrons," Gunter H.R. Kegel and Causon K.C. Jen, J. Electronic Mat. *19*, 629 (1990).

(7)–(9) The following three papers were presented at the International Conference on Nuclear Data for Science and Technology, Jülich, Federal Republic of Germany, May 13–17, 1991.

- "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.
- "Neutron Energy Spectra from Proton Irradiated Thick Li Targets," Gunter H.R. Kegel, Patrick F. Dugan, James J. Egan, Causon K.C. Jen, Arthur Mittler and Parish A. Staples.
- "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, A. Mittler and E.D. Arthur.

(10) "Measurement of the Lithium Isotopic Concentration," Causon K.C. Jen and Gunter H.R. Kegel, accepted for publication in Nucl. Instrum. Methods, B (1991).

(11) "Neutron Irradiation of Insulated Gate Field Effect Transistors," A. Reisman, M. Walters and G.H.R. Kegel, accepted for publication in the Journal of Electronic Materials (1991).

3. Presentations at Scientific Meetings

(1) "Scattering Cross Sections for States Above 300 keV in U-238 for 2- to 3-MeV Neutrons," G.H.R. Kegel, A. Aliyar, J.J. Egan, C.A. Horton and A. Mittler, Bull. Am. Phys. Soc. *33*, 1568 (1988).

(2) "Two-Stage Neutron Filters for Measuring Inelastic Scattering Cross Sections of Low-Lying Nuclear States," C.A. Horton, L.E. Beghian, J.J. Egan, E. Hale, G.H.R. Kegel, R. Leone and A. Mittler, Bull. Am. Phys. Soc. *33*, 1568 (1988).

(3) "Concentration Profiling of Lithium Implanted into Tantalum by Proton Impact," C.A. Horton, D.J. DeSimone, J.J. Egan and A. Mittler, Bull. Am. Phys. Soc. *33*, 1729 (1988).

(4) "Fast Neutron Irradiation of the Highly Radioresistant Bacterium *Deinococcus radiodurans*," D.L. Case, G.H.R. Kegel and D.T. Eberiel, Bull. Am. Phys. Soc. *34*, 1270 (1989).

(5) "The $^{14}N(n,n'\gamma)$ Cross Section of the 2.313–MeV First Excited State," P.A. Staples, J.J. Egan, G.H.R. Kegel, A. Mittler and D.J. DeSimone, Bull. Am. Phys. Soc. *34*, 1831 (1989).

(6) "Neutron Inelastic Scattering Angular Distributions for Th-232 and U-238 at 129-keV Incident Energy," C.A. Horton, J.J. Egan, C. Jen, G.H.R. Kegel and A. Mittler, Bull. Am. Phys. Soc. *34*, 1831 (1989).

(7) "Radiation Studies by Accelerator Generated Fast Neutrons," Gunter H.R. Kegel and Causon K.C. Jen, Proceedings of the Second Workshop on Radiation-Induced and/or Process-Related Electrically Active Defects in Semiconductor-Insulator Systems, Publ. by the Microelectronics Center of North Carolina, MCNC No. PREADSIS9-89, p. 45 (1989).

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(11) "Use of an Indium Seal for Target Mounting," G. Yue, J.J. Egan, G.H.R. Kegel and A. Mittler, Bull. Am. Phys. Soc. *35*, 1545 (1990).

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(13) "Design and Test of Ultra-Fast Gamma-Ray Detectors," D.J. DeSimone, G.H.R. Kegel, J.J. Egan and A. Mittler, Bull. Am Phys. Soc. *35*, 1545 (1990).

(14) "Applications of X-PIXE Technique to Determine the Surface Composition of Metal Coins," M. O'Connor and G.H.R. Kegel, Bull. Am. Phys. Soc. *35*, 1545 (1990).

(15) "Neutron Inelastic Scattering in Nitrogen," P. Staples, J.J. Egan, G.H.R. Kegel, A. Mittler, C. Jen and D.J. DeSimone, Bull. Am. Phys. Soc. *35*, 1546 (1990).

(16) "Oxidation Rates of Lithium Metal Surfaces," C.K.C. Jen and G.H.R. Kegel, Bull. Am. Phys. Soc. *35*, 1546 (1990).

(17) "Special and General Relativistic Insights Propagated at the Speed of Light," Eric Sheldon, Bull. Am. Phys. Soc. *35*, 1547 (1990).

(18) "A Novel Method to Determine the Thickness of Thin Li-Containing Layers via the ^{7}Li (p,α) ^{4}He Nuclear Reaction," C.K.C. Jen and G.H.R. Kegel, presented at the Eleventh International Conference on the Application of Accelerators in Research and Industry, University of North Texas, November 5–8, 1990.

(19) "Diffusion Study of Cr–Al Bi–Metallic Structures using Rutherford Backscattering Spectroscopy," Chandika Narayan, M. O'Connor, G.H.R. Kegel and J.J. Egan, presented at the Eleventh International Conference on the Application of Accelerators in Research and Industry, University of North Texas, November 5–8, 1990.

(20) "Fast Neutron Irradiation of the Radioresistant Bacterium *Deinoccus radiodurans*," D. Case, G. Kegel and D. Eberiel, presented at the International Colloquium on Neutron Radiation Biology, Bethesda, MD, November 5–7, 1990.

(21) "Relativistic Optics Demonstrated with Computer Graphics," Eric Sheldon and Marcel F. Villani, Bull. Am. Phys. Soc. *36*, 1677 (1991).

(22) "Coincidence and Pulse-Height Discrimination in Low-Energy Neutron Time-of-Flight Spectroscopy," C.A. Horton, J.J. Egan, G.H.R. Kegel, Bull. Am. Phys. Soc. *36*, 1680 (1991).

(23) "Measurements and Analyses of ^{232}Th and ^{238}U (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).

(24)–(30) The following seven abstracts were submitted for the Division of Nuclear Physics meeting of the American Physical Society to be held in East Lansing, MI, October 24–26, 1991.

- "Neutron Energy Spectra from Proton Irradiated Thick Li Targets," D.J. DeSimone, G.H.R. Kegel, C.K.C. Jen, J.J. Egan, D.L. Case, P. Bertone and A. Mittler.

- "Differential Scattering Cross Sections of the 45-keV State in ^{238}U and the 49-keV State in ^{232}Th at 128-keV Incident Neutron Energy," C.A. Horton, G.H.R. Kegel, J.J. Egan and A. Mittler.

- "Measurement of the $^{6}Li/^{7}Li$ Ratio in Lithium Shielding and Target Materials," C.K.C. Jen, G.H.R. Kegel and C. Narayan.

- "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.

- "The Prompt Fission Neutron Energy Spectra Induced by Fast Neutrons," P. Staples, J. J. Egan, G.H.R. Kegel, A. Mittler, M.A. O'Connor and M.L. Woodring.

- "The Use of BaF_2 Detectors and Fast Timing Techniques in Measurements of Nuclear Lifetimes," M.L. Woodring, G.H.R. Kegel, J.J. Egan, A. Mittler, D. DeSimone, P. Staples and G. Yue.

- "Neutron Elastic and Inelastic Scattering Angular Distributions in Pu–239 at 570 and 700 keV," Gang Yue, J.J. Egan, G.H.R. Kegel, A. Mittler, M. O'Connor, P.A. Staples and M.L. Woodring.

(31) "Measured and Calculated Neutron Scattering Cross Sections for the Actinide Nuclei ^{232}Th, ^{238}U and ^{239}Pu," E. Sheldon, E.D. Arthur, J.J. Egan, G.H.R. Kegel, A. Mittler and P.G. Young, to be presented at the 22nd International Summer School on Nuclear Physics, Piaski, Majuria (Poland), August 26–September 5, 1991.

(32) "A Framework for Understanding Fast-Neutron Induced Defects in SiO_2 MOS Structures," Wen-Liang Chang, accepted for presentation at the Third Workshop on Radiation-Induced and/or Process-Related Electrically Active Defects in Semiconductor-Insulator Systems, Research Triangle Park, North Carolina, Sept. 10–13, 1991.

VI. DOCTORATES IN NUCLEAR PHYSICS (Cumulative)

The following is a list of students who obtained their Ph.D. in nuclear physics from the University of Lowell (or Lowell Technological Institute). The first and the present position or place of employment (where known) are given and are separated by a "/".

1969	Vail, Patrick	US Air Force/Kirtland AFB, N.M.
1973	Prevo, Frederick J.	US Bureau of Radiological Health Rockville, MD
1973	Correia, John A.	Medical Physicist Mass. General Hospital and Harvard University
1973	Donati, Donald R.	Assoc. Director of Computer Center, University of Lowell/ Director of Enrollment Services, University of Lowell
1973	Sanin, Luis G.	Returned to Colombia, University Faculty Position
1973	LeClaire, Russell V.	Staff Physicist, Florida State University Nuclear Laboratory/ Texas Instruments Corp.
1980	Dave, Jessy H.	Post-doctoral Appointment at Triangle Universities Nuclear Laboratory/ Applied Research Corp., Landover, MD
1981	Chan, Desmond W.S.	General Physics Corporation Columbia, MD
1983	Ciarcia, Christopher A.	Assistant Professor Rochester Institute of Technology/ E.G.&G. Corporation Los Alamos, N.M.

1984	Shao, Ji-Qun	General Ionex Corporation Newburyport, MA/ Eaton Corp Beverly, MA
1985	Ring, Joseph P.	Senior Health Physicist Harvard University
1985	Tanczyn, Robert S.	Post-doctoral Appointment at Rutgers/ Faculty position at East Stroudsburg State University (PA)
1986	Goswami, Ganesh C.	Post-doctoral Appointment Department of Oncology, University Massachusetts Medical Center Worchester, MA/ Assistant Professor Albert Einstein College of Medicine New York, NY
1986	Brady, Gerald D. Jr.	Tennessee Valley Authority/Knolls Atomic Power Laboratory Schenectady, NY
1986	Sharfuddin, Quazi	Staff Engineer General Physics Corp. Mohawk Nuclear Training Center Pottstown, PA
1987	Ila, Daryush	Assistant Professor Alabama A&M University Normal, Alabama
1987	Haghighi, Mahmoud H.	GPU Nuclear Industries, Bechtel National Inc. Middletown, Pennsylvania
1988	Aliyar, Abobakr	Post-doctoral Position at Medical College of Ohio, Department of Radiation Therapy, Toledo, Ohio

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