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Opportunities for Undergraduate Research in Nuclear Physics

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Abstract

University of Dallas (UD) physics majors are offered a variety of undergraduate research opportunities in nuclear physics through an established program at the University of Kentucky Accelerator Laboratory (UKAL). The 7-MV Model CN Van de Graaff accelerator and the neutron production and detection facilities located there are used by UD students to investigate how neutrons scatter from materials that are important in nuclear energy production and for our basic understanding of how neutrons interact with matter. Recent student projects include modeling of the laboratory using the neutron transport code MCNP to investigate the effectiveness of laboratory shielding, testing the long-term gain stability of C_6D_6 liquid scintillation detectors, and deducing neutron elastic and inelastic scattering cross sections for ^{12}C. Results of these student projects are presented that indicate the pit below the scattering area reduces background by as much as 30%; the detectors show no significant gain instabilities; and new insights into existing ^{12}C neutron inelastic scattering cross-section discrepancies near a neutron energy of 6.0 MeV are obtained.

Keywords: Undergraduate research; MCNP calculations; neutron cross sections.

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1. Introduction

The University of Dallas (UD), through a collaborative program with the University of Kentucky and the United States Naval Academy (USNA), has offered undergraduate students the ability to conduct experimental nuclear physics research at the University of Kentucky Accelerator Laboratory (UKAL) for almost three decades. UKAL offers students the hands-on nuclear physics experience that many undergraduates seek as they discern their graduate school and career objectives. Several students who have participated in the research program in the last few years have gone on to graduate school in nuclear physics, nuclear engineering, and radiation medicine. Furthermore, the Bachelor of Science degree at UD requires that undergraduates complete an intensive research project, write a thesis, and give a presentation over their work at a professional conference. During most years two to five UD undergraduate student's complete nuclear physics projects at UKAL; the advantages of a university research laboratory and the variety of projects available at such a facility are immeasurable.

The projects completed most recently by UD students are part of an experimental program to measure high-precision absolute differential cross sections in both the neutron and γ-ray exit channels following neutron scattering reactions. The cross sections studied at UKAL are those considered most critical for the nuclear physics and engineering communities and are used by data evaluators trying to develop a global understanding of how neutrons interact with matter. The focus during the last few years has been neutron scattering cross section measurements on ^{23}Na (Vanhoy, 2015), ^{54,56}Fe, and ^{12}C, which are important in structural materials and coolants in reactor environments. During the last two years, student projects have been modeling the facilities at UKAL using the Monte Carlo N-Particle (MCNP) code (Los Alamos, 2016 and Goorley, 2014) to investigate the effectiveness of the pit under the neutron hall in reducing neutron-induced background; the measurement and analysis of neutron elastic and inelastic scattering differential cross sections from ^{12}C to investigate the nearly 40% discrepancies observed in existing values; and a study of the stability of the deuterated benzene (C_6D_6) scintillation detectors over extended experimental measurements.

2. Facilities

2.1. UKAL Accelerator and Neutron Production and Detection Facilities

The accelerator used for all experimental measurements at UKAL is a model CN 7 MV Van de Graaff that was installed in 1963 and has been used almost continuously for neutron scattering measurements, nuclear structure studies of stable nuclei, nuclear astrophysics, and applied physics research. The accelerator and facility are shown in Fig. 1. Beams of ^{1}H, ^{2}H, ^{3}He and ^{4}He ions are available at the facility in either DC or pulsed-beam mode. Beams are

Figure 1. Three views of the UKAL accelerator facility: (left) the silo in which the accelerator is housed on the University of Kentucky campus; (middle) the accelerator with tank on; and (right) the accelerator with the tank removed and the resistor column and terminal visible.

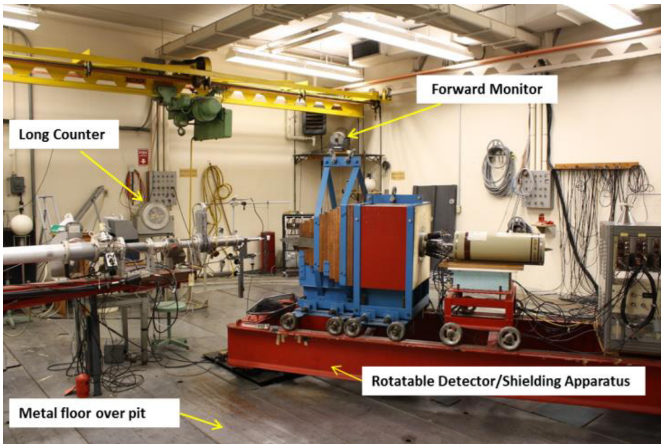

Figure 2: Neutron scattering hall with γ-ray detector and shielding apparatus shown to the right of the gas cell located at the end of the beamline. The long counter, the forward monitor, and the open pit under the metal floor were the subject of student projects modelling the UKAL laboratory through MCNP calculations.

pulsed with a repetition rate of 1.875 MHz, and the pulses can be bunched to have a time spread of $\Delta t \approx 1$ ns, which makes the facility valuable for time-of-flight (TOF) techniques utilized for both neutron and γ-ray detection.

Neutrons are produced for differential cross section measurements through either ^{1}H or ^{2}H ions impinging on a cylindrical gas cell 3 cm in length and 1 cm in diameter containing ≈ 1 atm of either tritium or deuterium gas and undergoing either the ^{3}H(p,n)^{3}He or ^{2}H(d,n)^{3}He reaction, respectively. The resulting nearly mono-energetic, forward-peaked neutrons scatter from isotopically enriched samples, and measurements are made of either the elastically and inelastically scattered neutrons, or of de-excitation γ-rays produced following the excitation of target nuclei. The experimental apparatus for the γ-ray detection experiments is shown in Fig. 2; also denoted in this figure are some of the items of focus in the MCNP modeling project, including the forward monitor, the long counter, and the metal floor over the pit below the neutron hall. The red carriage shown in Fig. 2 is rotatable about the center of the scattering sample resulting in angular distributions measurable typically between angles of 30° to 155°. Flight paths for neutron scattering measurements are limited to 1.5 – 4.0 m, and for γ-ray detection, the high purity Ge detectors are usually about 1 m from the gas cell. The forward monitor and main neutron detectors are deuterated benzene detectors, with the former used in addition to the long counter (Hanson and McKibben, 1947) to monitor neutrons produced by the source reactions. TOF techniques are used to detect the scattered neutrons, and a spectrum from our study of ^{12}C is shown in Fig. 3 for an incident neutron energy of E_n = 5.8 MeV. The first excited state of ^{12}C is at 4.44 MeV, which results in well-resolved elastic and inelastic scattering peaks.

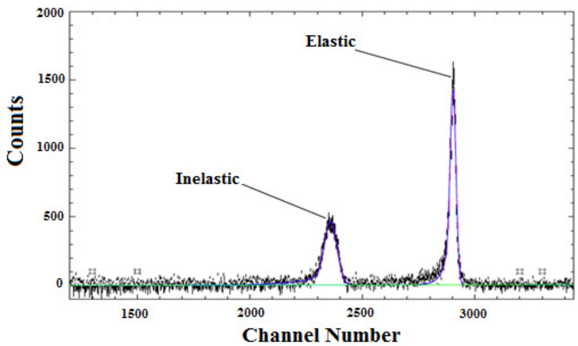

Figure 3: TOF spectrum for neutrons elastically and inelastically scattered from ^{12}C. Time increases from right to left in the figure.

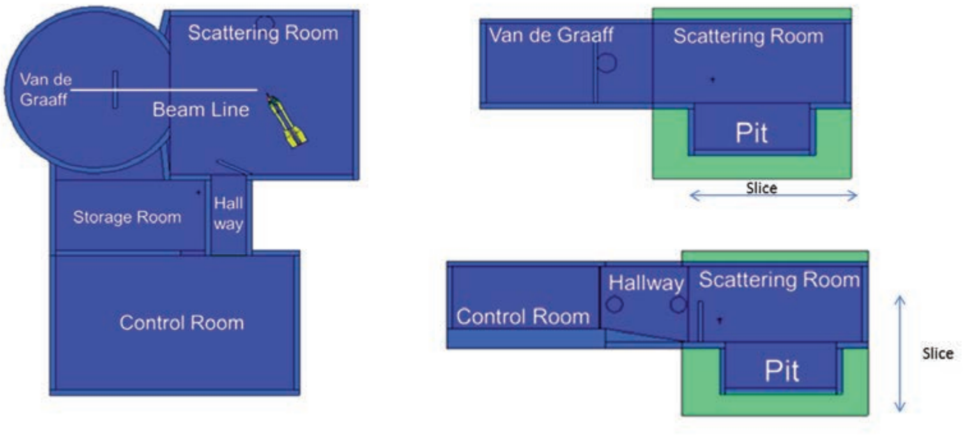

Figure 4: Model of the UKAL neutron scattering complex with pit under the detector/shielding assembly to scale for MCNP calculations.

3. Student Projects

UD students' projects reported here are associated with neutron scattering studies on ^{56}Fe and ^{12}C during the summers of 2015 and 2016. All students participated in the experimental measurements and analyzed at least one data set, but the foci of their projects included modeling of the laboratory, detector stability studies, and preliminary analyses of neutron scattering from ^{12}C.

3.1 Student Projects – MCNP Modeling of the UKAL Neutron Scattering Hall

Two UD students, D. Jackson and T. Nguyen, completed MCNP modeling projects, while also participating in neutron differential cross section measurements on ^{56}Fe in 2015. There were three questions the students investigated. Two were related to neutron scattering background in the neutron monitor detectors, and the third investigated the effectiveness of the pit under the detector/shielding apparatus. The former questions are laboratory dependent, but the latter question has broader importance as several laboratories are rebuilding neutron scattering and detection facilities. Specifically, the students investigated: (1) Does the angle of the detector and shielding apparatus affect the background seen in the long counter or forward monitor spectrum? (2) Is there some other source of background in the UKAL laboratory that could be affecting the spectra from either of the monitor detectors?; and (3) What effect does the pit below the scattering room have in reducing the overall background reaching various points in the laboratory and the control room? The scaled laboratory model used in the MCNP simulations is shown in Fig. 4. Additionally, the students tracked the neutron trajectories and energies to evaluate the neutron thermalization and containment capabilities of UKAL.

The simulations were completed by putting test spheres, as shown in Fig. 5, one meter in diameter and composed of air to avoid neutron attenuation or scattering in the constructs at various locations in the laboratory model and measuring the number and energy of neutrons entering the spheres. For each run, 1×10^7 neutrons leaving the gas cell were simulated and the first 1000 of those were tracked, as can be seen in Fig. 6 for one simulation. The complex itself was filled with air, which is composed of N, O, and about 1% Ar. The complex walls were modeled as concrete which is a mix of H, C, O, Na, Al, Si, K, Ca, Mg, and Fe. A layer of dirt (O, Na, Mg, Al, Si, K, Ca, Ti, Mn, and Fe) was modeled above and below the laboratory, and the detector carriage and shielding were composed of Cu, brass, W, and a polymer of Li, C, O, and H. The neutron detectors were C_6D_6.

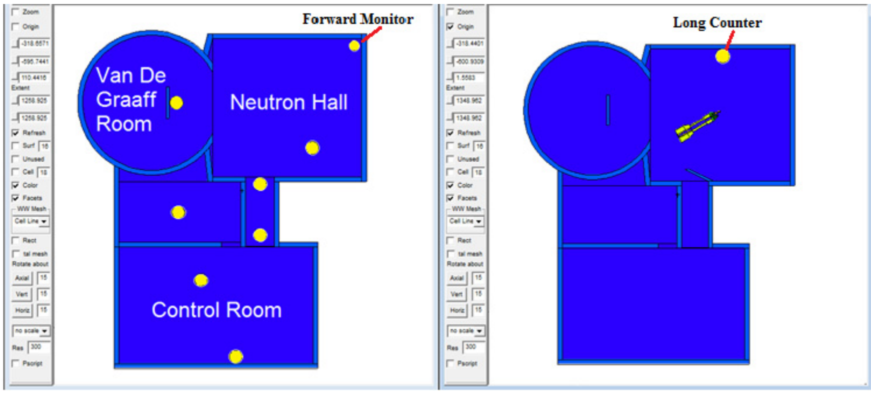

Figure 5: UKAL laboratory model for MCNP calculations with the location of some test spheres indicated by the yellow circles.

The simulation shown in Fig. 6 indicates that neutrons, whether from the source reaction or those that have scattered from anywhere in the room are contained predominantly within the neutron hall, many are trapped within the pit below the detector/shielding apparatus, a few made it into the hallway leading to the control room, and none are seen in the control room. Simulations trying to clarify the source of background in the monitor spectra found that neutrons reaching the monitor detectors came either directly from the source or from scattering off the detector/shielding carriage; however, the simulations showed the neutron energies were significantly reduced if they scattered off the shielding and, thus, do not contribute to the background under the TOF peaks in the forward monitor spectrum; differences as a function of angle could, however, affect the long counter yields.

The pit below the neutron hall is ≈ 3.7 m deep and was put in place to eliminate neutrons that are produced from the source or randomly scattered from objects in the room, so that they do not interfere with the desired signal of neutrons that have scattered off the samples of interest. To test the efficacy of the pit, it was modeled as it is currently constructed, and in a second test model, the pit was filled with the same dirt that was used in simulations of the ground above and below the laboratory; these two models are shown to scale in Fig. 7. For the simulations to investigate neutrons trapped in the pit versus those in the no-pit design, 1×10^7 neutrons produced at the gas cell were simulated and spherical test cells were placed around the laboratory to count the number of neutrons that entered the cells and their energies. The simulations were run for neutrons produced from the ^{3}H(p,n)^{3}He, ^{2}H(d,n)^{3}He, and ^{3}H(d,n)^{4}He reactions, although the last reaction is seldom used in the laboratory.

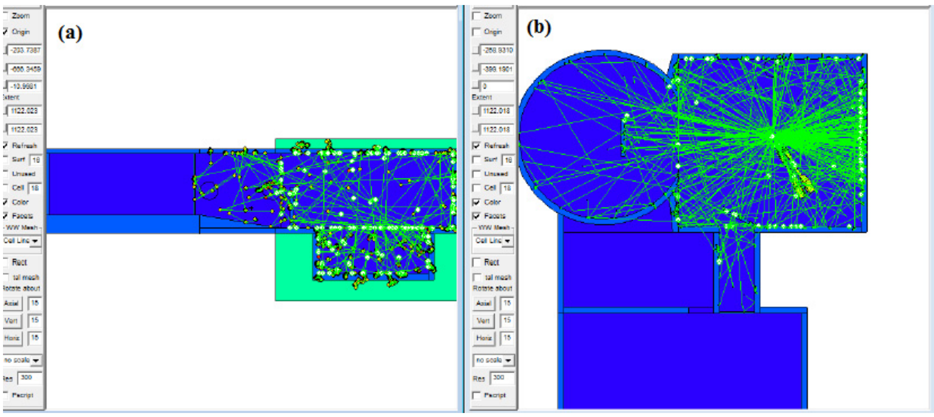

Figure 6: MCNP output showing 1000 neutron tracks in a simulation to see if scattered neutrons were contained in the laboratory.

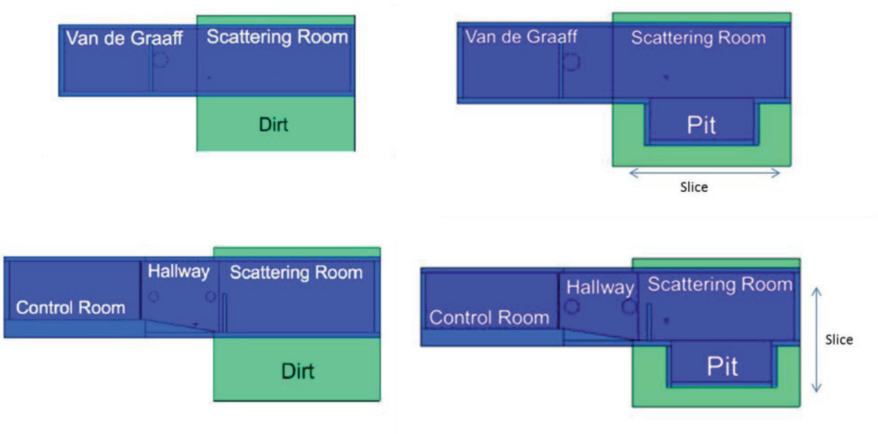

Figure 7: Model of the UKAL laboratory to investigate the effectiveness of the open pit below the neutron scattering hall. On the left the pit is filled with dirt modeled the same way as the dirt above and below the laboratory.

The pit appears to be effective in reducing neutron background at the spherical test cells by 10% in most locations and up to about 25-30% maximum reduction depending only slightly on the energy of the source neutrons. The reduction in neutron flux as a function of laboratory location is shown in Fig. 8.

3.2 Student Project – C_6D_6 Detector Stability

Measurements of elastic and inelastic scattering cross sections typically take about 4-7 days for each incident neutron energy. Detector stability is important and is typically monitored by the use of radioactive sources. UD student S. Block worked during the summer of 2016 to write a Python program to analyze the pulse-height spectrum from each experimental run. The goal of the project was to develop a technique to monitor detector stability continuously and without the need of stopping the data acquisition to use a radioactive source to test for shifts in the spectrum. Such shifts usually occur from changes in the detector bias voltage or in the output of the electronics modules used in processing the signal from the detector to the data acquisition system. A pulse-height spectrum is shown in Fig. 9. The Python program was designed to fit a third-order polynomial to the part of the spectrum highlighted in Fig. 9, differentiate the polynomial to find the absolute minimum, and find the channel corresponding to that minimum. Using this procedure for a large range of incident neutron energies, one can look for inconsistencies in the E_n versus channel number to monitor detector and electronics stability over time.

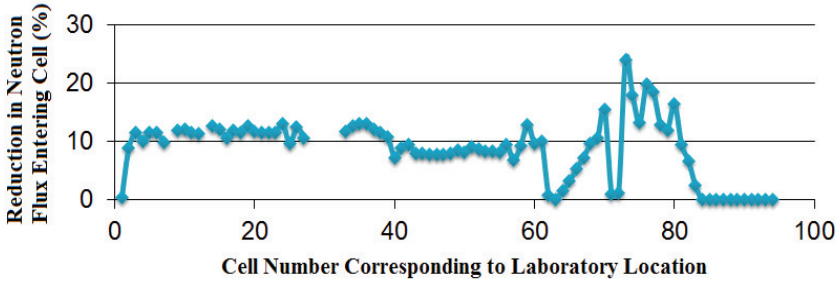

Figure 8: Reduction in neutron flux for E_n = 4 MeV observed at MCNP model laboratory test locations due to the presence of the pit below the neutron hall.

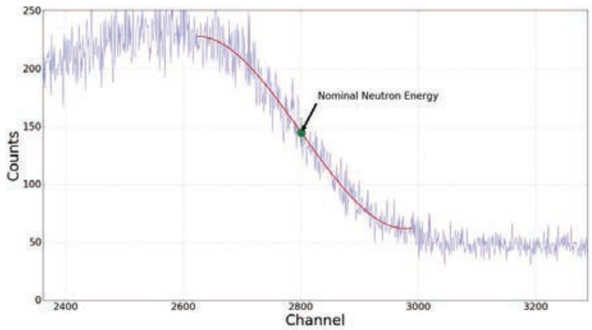

Figure 9: Evaluation of a pulse-height spectrum from the C_6D_6 scintillation detector used during the 3-week measurement of neutron scattering from ^{12}C. The channel number versus nominal neutron energy was analysed for each experimental run.

An example of the results of the analysis for a 10-h run, with backup files saved every hour, is shown in Fig. 10. There is some jitter about the mean channel, denoted by the dotted line in Fig. 10, but statistics are low in the spectrum for the first runs. The channel number associated with the nominal energy of 6.1 MeV stabilizes nicely after about six hours. While the program is not yet in its final form, this project has given us a valuable way to monitor detectors through the many-day experiments without having to stop and use radioactive sources.

3.3 Student Project –^{12}C Neutron Elastic and Inelastic Scattering Cross Sections

Measuring neutron scattering cross sections is the driving force behind the entire experimental program. While all students participate in the experiments, two students, M. Nickel and S. Byrd, had projects analyzing the neutron TOF spectrum for scattering from ^{12}C. The neutron elastic scattering differential and total elastic cross sections from ^{12}C are well known, but Hale (2016) reported discrepancies of nearly 40% in existing measurements of the inelastic scattering cross sections near 6 MeV incident neutron energy. The first excited state of ^{12}C is at 4.44 MeV and is the only inelastic channel open at this energy. As can be seen in Fig. 3, the resolution between the elastic and inelastic peaks in the TOF spectra is excellent, which at first glance makes one wonder why such large discrepancies exist between the results of previous measurements. The real challenge of determining the ^{12}C cross sections with high precision comes from knowing the neutron detection efficiency over such a large range of neutron energies. The kinematics of scattering from the ground state and an excited level at 4.44 MeV over angles ranging from 20° to

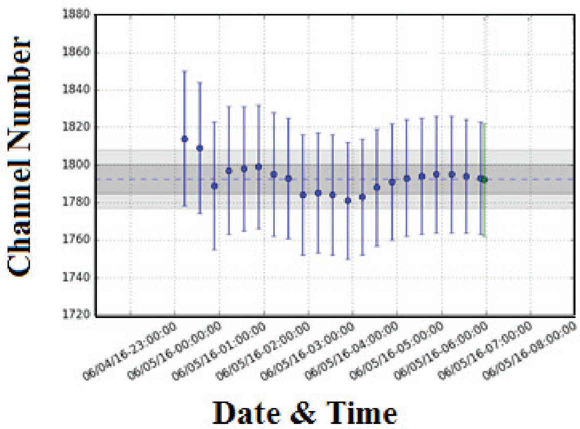

Figure 10: Results from the analysis of the channel number versus nominal neutron energy for a 10-h run in June 2016.

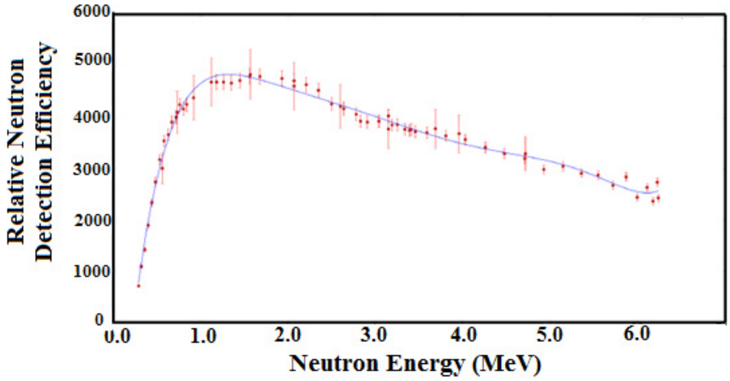

Figure 11: Relative neutron detector efficiency for the C_6D_6 scintillation detector used in the ^{12}C elastic and inelastic cross section measurements.

155° means the detector efficiency has to be well known for over 5 MeV. At UKAL, the detector efficiency is determined *in situ* for each measurement. A relative detector efficiency spectrum is shown in Fig. 11 from the summer 2016 measurements. One of the challenges in obtaining the relative efficiency spectrum is that none of the source reactions spanned the entire range of neutron energies needed, so not only did the incident deuteron energy have to change for the $^{2}H(d,n)^{3}He$ source reaction, but the source reaction and incident ion had to be changed to span the entire range of needed energies to determine the relative efficiencies to deduce the desired cross sections. The UD students did learn a lot about kinematics, detector efficiency, and problems that can be encountered in experimental physics. While the two students did completely analyze the angular distributions, the measurements are being repeated prior to publication.

Conclusions

Several University of Dallas undergraduate students participated in nuclear physics research at the University of Kentucky Accelerator Laboratory. Their projects are diverse and include learning how to model neutron scattering using MCNP, investigating the stability of detectors over extended periods through programming a Python code to monitor the pulse-height spectra from the detector, and analyzing neutron relative efficiency spectra and TOF spectra from neutron elastic and inelastic scattering measurements on ^{12}C. The UKAL laboratory offers students a valuable learning experience in nuclear physics research and has led to several students continuing on to graduate school in nuclear physics, engineering and medicine in the last several years.

The students completing MCNP calculations learned that the pit below the neutron scattering area reduced neutron background at various laboratory locations by 10% at most locations, but as much as 30% at others, and that while neutrons scattering off the detector/shielding apparatus did make it to the monitor detectors, they were substantially shifted in energy and would not contribute to the background in TOF spectra. The student who studied the stability of the neutron detector found that the detectors were for the most part very stable, although counting statistics play a significant role in the analysis. While all students participated in experimental measurements, two students analyzed detector efficiency measurements and neutron elastic and inelastic differential cross sections; challenges encountered during those measurements resulted in the need to repeat the experiments. The students, however, still gained a lot of experience in data acquisition and analysis. Of the five students who worked on these projects, two have graduated, and one of those is working on his Ph.D. in nuclear engineering at the University of Florida. This nuclear physics research is a valuable component of our undergraduate physics research program at the University of Dallas, which has resulted in over 70% of UD alumni receiving advanced degrees and over 23% receiving Ph.D.'s in physics, engineering, or a related field.

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