Development of a New Experimental Course in Nuclear Engineering

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INTRODUCTION

A new experimental course, the LINAC Laboratory, has been designed and implemented at Rensselaer Polytechnic Institute (RPI) to allow students to perform hands on measurements utilizing neutron induced reactions. A brand new state of the art classroom was constructed for the course, complete with high end computers and detector electronics and two dedicated neutron beam lines for experiments. The goal of the course is to provide students a greater understanding of the materials learned in their previous classes by designing specific experiments which highlight key nuclear engineering concepts. These experiments are performed with a combination of a ^{252}Cf spontaneous fission source and the RPI electron linear accelerator to provide the relevant neutron fluxes.

Fig. 1. The RPI LINAC Lab students shown discussing the experimental data taken during a laboratory on cross-section measurements.

The RPI accelerator, seen in Figure 2, generates electrons up to 60 MeV and accelerates them at a target made from a combination of tantalum and water. The electrons create photons through bremsstrahlung radiation, and those subsequent photons interact with the Ta plates in the target and generate neutrons through a (γ,n) reaction. This generates an isotropic, white source of neutrons which is then collimated down to a detector located approximately 15 meters away from the target. By using the neutron time-of-flight technique, and a time-of-flight clock, the neutrons incident on the detector as a function of time can be converted to an energy dependent neutron spectrum. This source of neutrons allows the students to perform several measurements which would not be able to be performed with other neutron sources.

In addition to the experimental measurements, the labs will often have a simulation component associated with them. The simulation tools used in this lab are the stopping range in matter code SRIM[1], the Monte Carlo transport code MCNP[2], and the code used to Doppler broaden cross-sections NJOY[3]. The combination of the theoretical knowledge from their previous courses, simulations using state of the art simulation tools, and the experimental measurements themselves provide students with a more complete understanding of different nuclear engineering concepts. In addition, students learn about the limitations on the theory, simulation, and experimentation, and the associated uncertainties with each. An overview of the current experimental modules taught in the laboratory course are as follows.

Fig. 2. The RPI Linear accelerator.

EXPERIMENTAL MODULES

The course was broken up into several experimental modules, each designed to provide greater insight and understanding on a topic relevant to neutron interactions in nuclear engineering. A brief description of some of the experiments and the simulation tools used in analysis is provided.

Neutron Detector Response

The first module was designed to familiarize students with how various neutron detectors work and the modes of detector operation based on applied voltage. For this lab students measured the detector response from a ^{252}Cf spontaneous fission source housed inside a polyethylene cube. This provided a thermal neutron flux to the various neutron detectors. The detectors for this lab consisted of a BF_3 gas detector, a He_3 gas detector and a boron lined detector. The students collected pulse height data using a multi channel analyzer (MCA) and were able to compare the spectra measured with those given in the literature. Here the students could see first hand the effects of the wall effect on the detector response and see how the different detectors respond to gamma and noise pulses. Additionally, the count rate was measured as a function of voltage for one of the detectors, and students could see the effects of count rate based on applied bias voltage. At RPI

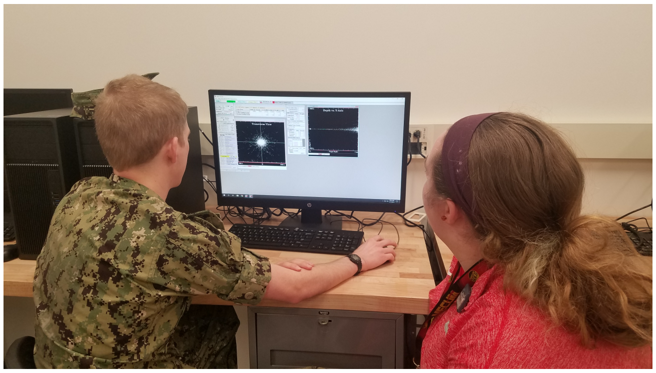

Fig. 3. The RPI LINAC Lab students performing simulations using the SRIM code to determine the optimal thickness of a Boron layer in a Boron lined neutron detector.

this reinforces the material taught in the Nuclear Instrumentation and Measurement course as well as providing a basis of neutron detection for subsequent labs. In addition to the experiment, the students perform simulations using the SRIM code which familiarizes them with how charged particles deposit their energy in matter. The students simulate the response of a Boron lined detector and determine the maximum thickness of a Boron layer to achieve optimal detection for a neutron detector shown in Figure 3. The combination of the theory mixed with the simulation and experimentation provides the students with a greater understanding of how thermal neutron detectors operate.

Neutron Flux in a Cube

Determining the neutron flux in a given medium is an important tool for a nuclear engineer. For this laboratory a ^{252}Cf spontaneous fission source was placed inside a polyethylene cube. A hole was drilled into the side of the cube which allowed for a small solid state neutron detector to be moved within the cube. The solid state detector was calibrated to discriminate out gamma events, and the neutron flux in the cube was measured as a function of position. This provided a spatial distribution of the neutron flux inside the cube. Figure 4 shows the polyethylene cube as well as the neutron detector hole which was used to perform the measurements. In addition to the measurements, the students performed multiple MCNP simulations to find the flux in the cube as a function of position. They performed both a simulation with the solid polyethylene cube as well as with a cube with the hole drilled out for the detector. This allowed the students to quantify the effects that the experimental modifications have on the flux within the cube. The accurate simulations were then compared to the experimental data and additionally, compared to the theoretical flux distribution in the cube. This reinforced neutron diffusion and transport theory which is presented to the students in the Physics of Nuclear Reactors (PNR) course at RPI. The combination of theory, simulation and experiment provides the students a better understanding of the neutron transport process, and also provides information on the perturbations that experimental measurements can have on theoretical calculations.

Fig. 4. (Left)The polyethylene cube with a ^{252}Cf spontaneous fission source in the center used for neutron flux measurements (Right) The experimental port used for the solid state neutron detector used to measure the flux in the cube as a function of the position.

Cross Section Measurements

Cross-sections are one of the nuclear data properties that are present in almost every aspect of nuclear engineering. The cross-section measurement lab utilizes the unique capabilities at RPI, particularly the electron linear accelerator, to perform these measurements. For the cross-section measurements, a lithium glass transmission detector is used to measure the neutron rate of the open beam and with several transmission samples in the beam. Knowing the dimensions of the sample and the ratio of the counts in the detector with and without sample, the cross-section of the material can be determined. Additionally, the time-of-flight method can be used in order to determine the cross-section as a function of incident neutron energy. The lab measures the transmission through thin plates of Ag, Ta and Cd and the students then calculate the energy dependent cross-sections in the low energy and thermal regions. Particularly, the students look at the low lying resonances in these materials and compare their experimental cross-sections in the resonances with those calculated through Briet Wigner single level resonance theory[4], which the students at RPI learn in their PNR class. They also compared their calculated and experimental peak cross-sections with the cross-section given by the evaluated nuclear data file (ENDF)[5] database. This allowed the students to gain information on the limitations of the theory, particularly that single level Breit Wigner assumes a temperature of 0K, and the experimental limitations as well. In regards to limitations on the measurement, the experiment does not take into account the broadening of the resonance due to the experimental resolution of the detection system. This lab highlights how cross-sections are experimentally measured, how well these measurements agree with theoretical calculations, and what corrections need to be made to the experimental data in order to obtain the evaluated cross-section.

Neutron and Photon Activation Analysis

Neutron and photon activation analysis can be used to determine the material composition of unknown materials through their activation and subsequent decay. For this lab several pennies as well as calibration samples of copper and zinc were irradiated using the RPI linear accelerator. RPI has a rabbit system which allows for the transport of samples into and out of the target room. This allows for irradiations to be performed without the need for target room entry. Following the irradiation of the samples, the students measure the decay of the samples with a high purity germanium detector, and an MCA spectra is obtained. The intensities of the decay lines were measured and, using the samples of known mass, the relative masses of copper and zinc in the pennies were determined. This was used to date the pennies based on their material composition. In addition to teaching the students about how activation analysis can be performed to determine the material composition of unknown samples, this lab also introduces the students to the calibration and use of a high purity germanium detector. The students also learn how to look up relevant decay information on the possible isotopes of interest using the interactive chart of the nuclides available at the nndc website. The operation of a high purity germanium detector and the applications of neutron and photon activation analysis emphasize material taught in the nuclear instrumentation and methods and radiation technology courses at RPI.

Doppler Broadening

The effects of temperature on cross-sections are particularly important to the design and operation of nuclear power plants. One of the most drastic effects on the cross-section is Doppler broadening of resonances, where the resonance broadens with an increase in the temperature of the material. While easy to explain in theory, this is a difficult concept to demonstrate experimentally. For this lab the RPI linear accelerator was once again utilized with a lithium glass transmission detector located at a distance of 15 meters. A sample of Tantalum was placed in a heating assembly which could be used to greatly heat up the Ta. A transmission measurement was performed with the Ta at room temperature and then again with the Ta heated to a temperature of 500 C. The students then compared the cross-section around the resonance at both temperatures and visually saw the broadening of the resonance. Additionally, one of the main concepts of Doppler broadening is that while the resonance changes shape the area under the resonance known as the resonance integral remains constant. This was also verified experimentally by the students. The students also compared the experiment to the high temperature Doppler broadening approximation of single level Briet Wigner theory[4], which the RPI students learn in their PNR course, and to the simulated cross-section using the NJOY code. This allows the students to determine how well the high temperature approximation works at these temperatures and introduces the students to a new simulation tool which can be used in order to Doppler broaden cross-sections.

Thermal Spectrum Measurements

Another effect that temperature can have on a reactor is an energy shift in the thermal spectrum. As the temperature of the reactor increases the thermal spectrum shifts to higher temperatures similar to the shifting of a Maxwellian distribution. In order to demonstrate this, the RPI linear accelerator was used and a volume of water was placed in between the target and a lithium glass transmission detector. A measurement was performed to determine the neutron flux on the detector from the target, with the additional water moderator at room temperature. The water was then heated to 90 C and a new measurement was performed with the higher temperature for the moderator. The students could then visually see the shift in the peak of the thermal spectrum through the heating of the water similar to moderator heating in a nuclear reactor. These experiments were then compared to theoretically determined thermal spectra using a Maxwellian distribution as well as detailed MCNP simulations of the experiment with the water moderator at different temperatures. This allows the students to familiarize themselves with some of the capabilities of the MCNP code to accurately model experimental setups as well as once again highlighting the connection between theory, simulation and experimentation. This provides the students with a greater understanding of how temperature in a reactor effects the thermal neutron spectrum which is presented to students at RPI in the PNR course.

Delayed Fission Gamma Measurements

The fission process is integral to the operation of nuclear reactors and is one of the core concepts in nuclear engineering. In order to experimentally measure the results of the fission process, the delayed gammas were selected to be measured. A sample of highly enriched Uranium is irradiated using the RPI accelerator and the rabbit system. First the sample is measured before irradiation using a calibrated high purity germanium detector and the natural radioactivity is measured. This allows the student both an initial activity which they can correct for in their measurements as well as a confirmation that the sample is almost pure ^{235}U by measuring the radioactive decay gamma lines present. The sample is then irradiated using the accelerator and the radioactive sample is carefully returned to the detection system. The students then perform a series of measurements over time looking at the rate of change of the prominent gamma rays which can be seen in Figure 5.

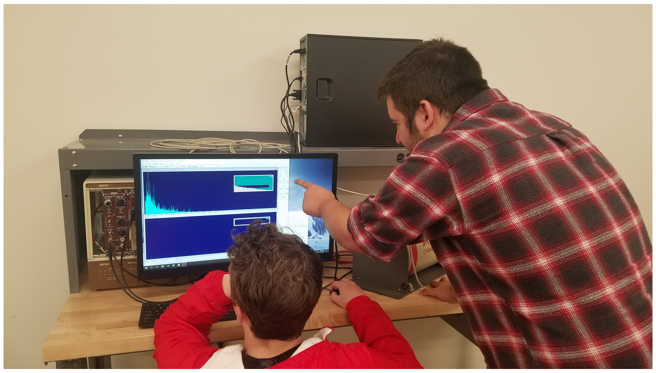

Fig. 5. The RPI LINAC Lab students collecting and MCA spectrum following the irradiation of a highly enriched Uranium sample.

Using the information on the gamma energies and calculated decay rates the students can then attempt to identify the fission decay products that generated those decay gammas.

This allows students to investigate the fission process using only the delayed gamma rays. This laboratory reinforces material learned in several of the nuclear engineering courses at RPI particularly PNR and Fundamentals of Nuclear Engineering. Future plans for this lab include simulations using the ORIGEN activation code in the SCALE package to compare the simulated decay inventory with that measured by the students.

RESULTS

The new experimental linear accelerator laboratory course was implemented and taught for the first time at RPI in the Spring of 2019. The course was met with an overwhelmingly positive response from the students. Several students highlighted the fact that performing the experiments and seeing the nuclear engineering concepts first hand allowed them a greater understanding of the underlying nuclear physics. Additionally, the students indicated that the combination of theory, experiment and simulation was extremely helpful in providing them a greater understanding of the topics covered in the course. Many of the students indicated that this was one of the courses in which they learned the most, which highlights the need for experimental courses to supplement and enhance the material taught in the traditional theoretical courses.

CONCLUSIONS

The new LINAC Lab experimental course at RPI, with a new state of the art research classroom, was very successful in providing students with an opportunity to perform experiments which verified the material they were exposed to in previous nuclear engineering courses. Through the combination of theory, simulation and experimentation the students were provided with a deeper understanding of the material and information regarding the relative uncertainties and limitations of each given method. Additionally, the course exposed the students to simulation tools currently used in the nuclear industry and academia as well as provided knowledge on where to find the resources for looking up nuclear data information. The course was met with excellent reviews by the students which reinforces the need for experimental courses to supplement the materials learned in the typical theoretical course structure.

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