SPS Chapter Research Award Final Report

Project Title	Neutron Production and Detection Techniques Around A 15 MeV Medical LINAC
Name of School	Suffolk University
SPS Chapter Number	6917
Total Amount Awarded	$2,000
Total Amount Expended	$2,000
Project Leader	John Thomas

Abstract

High purity metal foils may be used for activation analysis in the determination of the energy spectrum of a neutron energy flux. The objective of this research is to determine the neutron environment around a linear accelerator (LINAC) beam head used in oncology treatments at Massachusetts General Hospital (MGH). This investigation will use an NaI scintillation analyzer to observe beta and gamma decays emitted from the irradiated metal foils. It is expected from previous simulation and comparison of equipment that the neutron flux will be on the order of and a mean energy between 100 keV and 500 keV [1]. For successful completion of this experiment, a range of energy resonances for neutron absorption must be observed. A kit of high purity foils must be purchased to accomplish this. This research will benefit students as it increases understanding of nuclide reaction chains, and develops experience in the entire investigatory process including design, rehearsal, setup, all the way through statistical analysis of results.

Statement of Activity

The entire Statement of Activity should be no more than three pages, and organized as follows. Note that some of the information requested may be taken directly from your proposal, but it is anticipated that the research questions, goals, and methods/designs/procedures have evolved over the course of most projects. The information provided in this report should reflect those changes.

Overview of Award Activity

The Overview should be a detailed description of the work that was completed on the proposed project. Provide sufficient background information for a non-specialist to understand how your knowledge has advanced through the work that you did.

This section should include:

- Research question – What question did the research aim to address?
- Brief description of project and results – What did the research project entail, and what, if any, new elements influenced the overall aim of the research along the way?
- Any changes in the scope of project – Indicate whether the project turned out to be more complicated or more straightforward than expected and why; influencing factors might include personnel, research scope, materials and equipment availability.
- Progress on research goals – What did you accomplish? If you did not meet all of the goals outlined in your proposal, please explain why.
- Personnel – Who was involved in the research activities and in what ways? How many participants were SPS national members? Members of your local chapter?

The original intent of this research project was to determine the thermal neutron flux surrounding a 15MV LINAC, by irradiation high purity metal foils with photoneutrons produced in the beam head. In order to determine the thermal flux, analysis of the epithermal flux must be conducted due to the fact that the isotopes in the foils have at least two neutron cross sections, on in the thermal range, and at least one in the epithermal range. By covering foils with Cd covers, which have an enormous thermal cross section, absorption of thermal neutrons by that foil can be eliminated. This allows analysis of the epithermal absorption of the foil, then these results are compared to those of foils of the same isotope that were irradiated without Cd covers, meaning the foil can absorb neutrons in both the thermal and epithermal energy range. To obtain data, the foils are suspended in an array at a known distance from the beam head, and irradiated for a know time period. Afterwhich, the foils are transferred to a beta liquid scintillator detector to measure the decay of the nuclei that underwent neutron capture. Analysis of the beta decays allows us to calculate the original number of nuclei in the foil that absorbed neutrons. By comparing the thermal flux to the combined thermal and epithermal flux, allows for analysis of the thermal flux. Naturally, the research question has expanded to include analysis of the epithermal neutron spectrum, as it is necessary to understand the epithermal flux in order to determine the thermal flux.

The epithermal and thermal neutron spectrum only represents a small portion of the total energy spectrum of neutrons emitted by the LINAC (0.025eV - 250keV), but the LINAC could potentially produce neutrons with energies up to about 8MeV. Once analysis was conducted on the foils to determine the thermal flux, we wanted insight into the full energy spectrum. To do this we acquired an organic liquid scintillator detector, with the ability to detect fast neutrons (200keV - 15MeV), and allows for analysis of the energy of the individual events it detects, so with this new detector we can map the neutron flux of the entire energy spectrum produced by the LINAC. Through strengthening relationships between the Suffolk University Physics Department, MGH, and our SPS chapter, we have recently been granted access to an AmBe neutron source of known activity that MGH uses for equipment calibration. This will allow us to confirm our experimental procedures that we used with the LINAC. Each AmBe source has a unique energy distribution of neutron energies, so we are now seeking to employ our methods used on the LINAC to characterize the energy spectrum of the AmBe source, using both high purity metal foils as well as the organic liquid scintillator detector.

In order to analyze the signal output of the detector, a digitizer is required to turn the signal into a form that can be processed by software. We did not have access to a digitizer, so as part of their senior project, students Jackson Nolan and John Thomas, augmented code acquired from the Keysight software development team to use the oscilloscope in place of a digitizer. Due to a faulty power supply, tests with the new detector could not be detected, so the students devised an experiment to determine that the oscilloscope would function as a way to transfer data from the detector to a computer. Test were successful, but show some limitations. Now that we can gather data from the full spectrum of neutrons emitted, we can map the energy spectrum of the AmBe source and compare it to the known activity.

Personnel: Our team will be made up of four seniors, one junior, four sophomores, and unknown incoming freshmen as well as Dr. Johnson, Dr. Gierga, Jacky Nyamwanda, and Tara Medich. The senior students will continue to take on leadership roles in designing experimental setups and procedures while working with the underclassmen to train them in understanding the experiment and analysis of the data. The current upperclassmen have been a part of this project since the beginning and have gathered a wealth of knowledge in all of the aspects of the project and will take individual components to specialize in and train sets of students to that one topic, such as; experimental design, analysis, or simulations. This will allow each upperclassmen the chance to focus on a specific aspect of the project and lighten the workload for each other as they will no longer need to focus on all aspects of the research.

Description of Research - Methods, Design, and Procedures

This section should provide a synopsis of your research experiment, simulation, or study. It should include a description of the set-up, procedures, and methods of data collection and analysis used. This section may be bulleted, but must include enough detail that it is clear to others who are not familiar with the topic.

In our most recent experiment we used a wooden array with the metal foils placed in paper holders that were then fixed to the wooden arms, this allowed us to ensure that the foils would not move as well as have the most surface are possible facing the head of the LINAC. In the array we had four indium, four gold, and three copper foils. Two indium and two gold foils were covered in cadmium and two indium and two gold foils were left uncovered. The three copper foils were all left uncovered and one copper foil was perpendicular to the head of the machine. The array can be seen below in *Figure 1.* The foils were then irradiated for 30 minutes after which they were then brought down to a liquid beta scintillator were we placed six foils in the cassette, two indium, two gold, two copper, and one blank vial for background detection. We ran this cassette once then placed the two more indium and two more gold foils into the cassette to run cycling through night measuring each foil for fifteen minutes. We proceeded to leave for the night and returned in the morning after the fourth cycle was complete.

Based on the results in our experiment with the LINAC, confirmation of results were required. Two possible solutions were present, subsequent experiments using the same foils and the LINAC or find a source of neutrons with a known activity. Since this LINAC has yet to have a published value for its neutron activity, confirmation of methods became the higher priority. In MGH's Proton Therapy Center an AmBe source is used for calibration of equipment. This AmBe source has well documented activity dated back to its first measurement on April 5th, 1985. The activity measured in 1985 was determined to be . The activity of the source has since dropped due to the half-life of americium, though not much since the half-life is 432.6 years, which equates to an activity of . Americium-241 undergoes alpha decay following this reaction:

$$^{241}_{95}Am \rightarrow \, ^{237}_{93}Np + \, ^{4}_{2}He + \gamma \; 59.5keV$$

The emitted alpha particle then interacts with the beryllium-9 under the following reaction:

$$^{9}_{4}Be + \, ^{4}_{2}He \rightarrow \, ^{12}_{6}C + \, ^{1}_{0}n + \gamma$$

This neutron emitted ranges in energy from 0.025eV to about 8MeV with an unknown distribution as it is different for each source.

Discussion of Results

This section should include your results, and a discussion of the significance of your results. Also include discussion of any limitations, constraints or errors related to your results. Examples of results to discuss may include, but are not limited to, constraining a parameter, characterizing a material, or testing an apparatus.

LINAC Experiment:

Our first foil array was designed to hold a total of eleven foils; three Cu, four In, and four Au. Out of this, two In, and two Au were covered with Cd, while the remaining to two In and two Au were left bare each parallel to the beam head of the LINAC. As for the Cu, one foil was placed perpendicular to the beam head of the LINAC as the other two were placed parallel to the head. Of the two Cu foils facing the beam head, one of them was twice the thickness of the other. This significant difference was to confirm the dependency of foil thickness in beta emission of each metal. Covering a foil with Cd allows for the isolation of epithermal neutron due to the extremely high thermal cross section of Cd. As seen in figure 1:

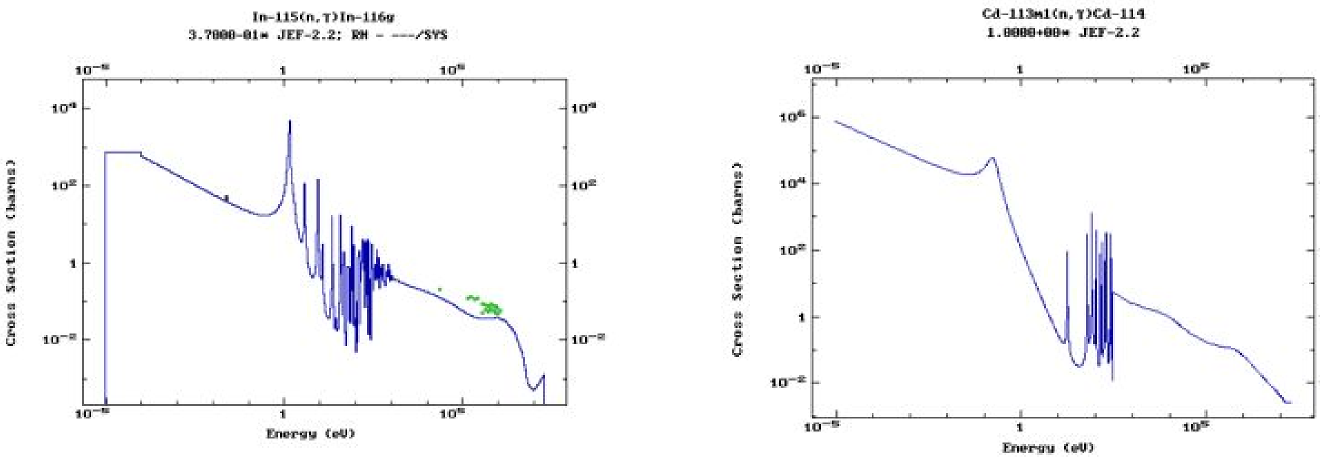

Figure 1 IAEA NGATLAS Atlas of Neutron Capture Cross Section (In-115 Left, Cd-113 Right)

When a foil is covered with Cd, the respective resonance peak of the inside foil is the only measurable neutron absorption. In figure 1 we see that the thermal cross section of Cd is about 20615 barns where the thermal cross section of In is only 81 barns. This allows for near complete absorption of thermal neutrons. The epithermal region spans from above 0.025 eV to 250 keV, and for each metal there lies an epithermal or resonance cross section with a peak at a defined energy window. For In, the energy window is 1-3eV where Cd has a resonance peak around 10eV. This lack over overlap allows for analysis of distinct energy windows by measuring the corresponding beta decay. As for Cu however, the experiment was to determine if there is a thickness dependence on beta emission. To our suspicion there is self shielding of betas inside of a foil. This lead to the determination of three distinct foil conditions. These conditions are of the form:

1: $s < t1/2$

2: $t1/2 < s < t$

3: $t < s$

Were s is the average beta range and t is the thickness of the foil. If a foil falls into condition 1, then at a certain point, the thickness of foil will begin to shield the betas being emitted. For our foils, we found that Cu fell into this condition. Both our thick and our thin foil were emitting the same number of betas. This in turn lead to the discovery of the beta range correction factor to adjust for both the thickness and the beta range in the detection of the number of betas emitted and recorded by the beta scintillator. As for In and Au, the beta range falls into condition 2. This is extremely significant in determining the neutron properties of the LINAC. This condition is then used in determining a correction factor for the number of betas detected by the scintillator, with which, would report a value lower than the true number of beta decays a foil underwent. With this correction factor and multiple foils we were able to determine an average thermal neutron flux of 2.6 ± 0.8 $neutron/cm^2s$ which is within one standard deviation or reported thermal neutron flux of older models of this LINAC.

AmBe Experiment:

Based on the calculated activity of the AmBe source, the foils were placed radially at 9.5cm from the source. A total of seven foils were placed in a 3D printed array; three In, two Au, one Dy, and one W. A total of six foils were placed tangent to the neutron flux sphere; In-A with a Cd cover, Au-E with a Cd cover, In-B bare, Au-F bare, Dy-J bare, and W-M bare. The seventh foil, In-C, was placed orthogonal to the neutron flux sphere and was also bare. Figure 2 below shows the source holder and foil holder 3D printed:

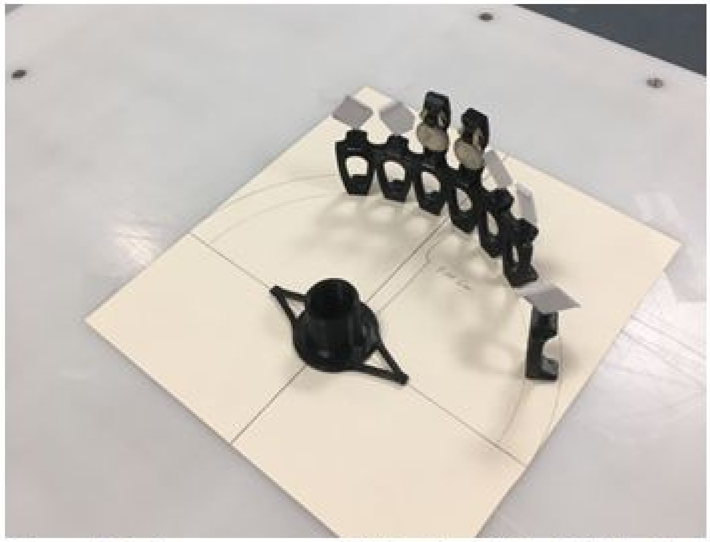

Figure 2 AmBe source array, foil order left to right; In-B, Au-F, In-A with Cd cover, Au-E with Cd cover, Dy-J, W-M, and In-C

The paper flights were used to hold the thin foils without damaging them as they are extremely fragile. The cross section of paper was neglected in the calculation of neutron absorption as it is near zero. These foils were irradiated for 71.56 minutes before transfer to the beta detector. Each foil was placed in a vial with a proprietary scintillation fluid provided by MGH. This fluid captures the emitted beta particle from the beta decay of the foil, once captured a photon is emitted at a range of energies. The results are then reported by the beta scintillator and analysed using MATLAB. The only foil that gave measurable results above background were the three In foils, however do to complexity of cross sectional detection area of the In foil that was orthogonal to the neutron flux sphere and its radial position, analysis of this foil has yet to be done. As for the In-A and In-B values for both the thermal and epithermal (1eV to 3 eV) flux values has been determined, as seen in table 1:

flux	fluxValues	error
'Resonance Flux 1'	[1.6490]	[0.1216]
'Resonance Flux 2'	[2.2621]	[0.1686]
'Thermal Flux 1'	[15.3752]	[3.3107]
'Thermal Flux 2'	[20.5818]	[4.7270]

Table 1 Neutron Flux values reported in (n/cm^2s) where Resonance Flux 1 was determined by In-A detection 1, Resonance Flux 2 was determined by In-A detection 1, Thermal Flux 1was determined by In-B detection 1, Thermal Flux 2 was determined by In-B detection 2

However these values are within error of each other, it is hard to determine with certainty whether they accurately resemble the neutron distribution of the AmBe source as each measured AmBe source has a different neutron energy distribution.

Testing the process of operating the Organic Liquid Scintillator, EJ-301, using a waveform generator, an oscilloscope, and a data acquisition code (skeleton received from Keysight) we were able to resolve multiple test conditions. The first was a series of waveforms; sin, square, and noise. The raw data was then transferred into MATLAB and recreated to see if there would be a loss of data. The results are shown in figure 3:

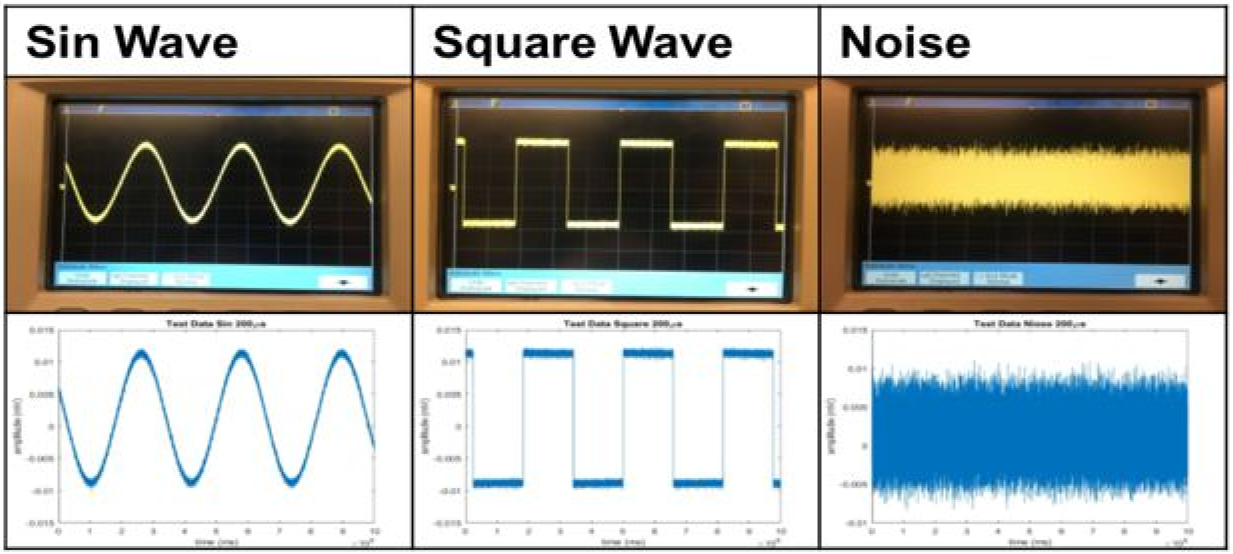

Figure 3 Frequency of 1.575 kHz

From here we began calculating the expected arrival rate of neutrons based on the calculated activity, the position of the detector, the efficiency, and the cross section area of detection. An efficiency of 33% is estimated based on the reported efficiency of the EJ-309 detector which is near identical to our detector, EJ-301. All together we expect to see a neutron activity of 1575 neutrons/s which would equate to a frequency of 1.575 kHz. The results are shown in figure 4:

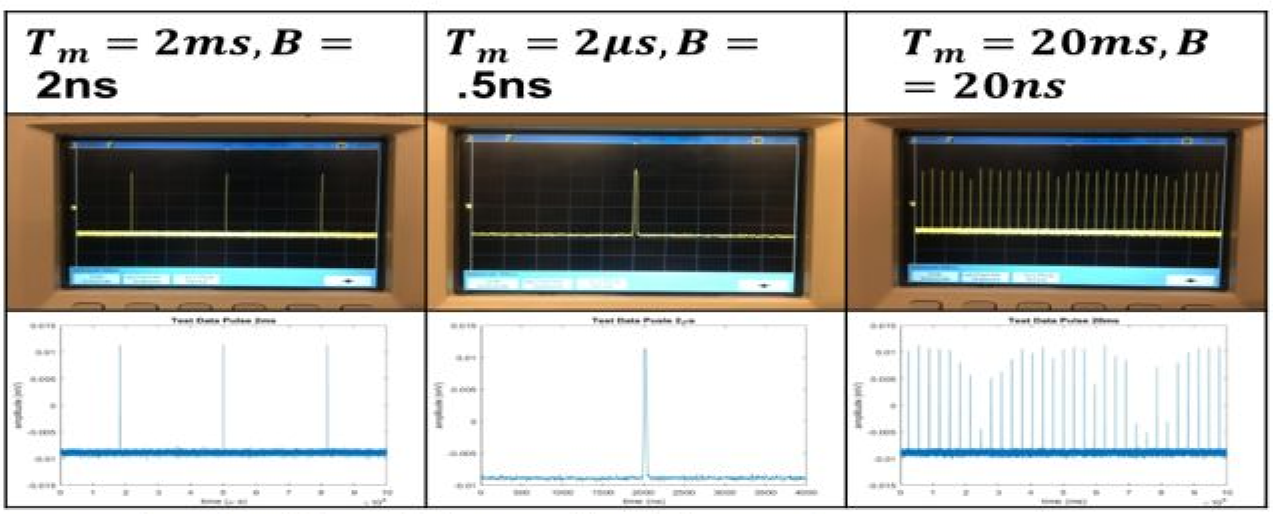

Figure 4 P for each trial left to right,(1,000,000),(4,000),(1,000,000)

Based on the results above we are able to resolve both neutrons and gammas a limited efficiency. In order the resolve gammas the resolution of the data would need to be around 2ns, however at this resolution due to the ratio of data transfer time and the time measured on the oscilloscope, we would only record 0.07 seconds on the hour. If however we choose only to resolve neutron then we have a time measurement window max of 20ms as shown in the third graph of figure 4. As the number of data point P is held to a max at 10^6. A neutron at this resolution can be split in half across the bin causing a loss in information about the amplitude of the event neutron. The amplitude of the neutron event is proportional to the energy of the incident event, therefore in order to accurately resolve neutrons we must use a time measure less than 20ms. At 10ms, the next time step down, the neutrons are resolved at full amplitude and our data acquisition is six minutes on the hour. This is still a small percentage but after enough experiments a model can be made off the integral of the counts. Once we can build an accurate neutron energy spectrum for an AmBe source with a known activity we can then repeat this process back at the LINAC with greater confidence as our experimental process will have been confirmed.

Dissemination of Results

This section should describe how you have disseminated your results. This might include poster presentations, research talks, papers submitted for publishing, etc. You may attach copies of products to this report.

We presented our results at APS April 2018 in Columbus, OH in a poster presentation called *Neutron Distributions Surrounding a Medical Linear Accelerator*.

We also wrote an article that was published in the SPS Observer Fall 2018 which is available here:
https://www.spsnational.org/the-sps-observer/fall/2018/mapping-neutron-flux-distribution-near-medical-linac

Additionally, we are working on submitting a paper to the American Journal for Physics (AJP) by the end of the year.

Bibliography

Cite all resources referenced in the final report here.

Nolan, J., McDonough, M. and Thomas, J. (2018). *Mapping the Neutron Flux Distribution Near a Medical LINAC*. [online] Society of Physics Students. Available at: https://www.spsnational.org/the-sps-observer/fall/2018/mapping-neutron-flux-distribution-near-medical-linac [Accessed 21 Dec. 2018].

Impact Assessment:

How the Project Influenced your Chapter

This section should include your reflections on:

- The overall experience – Was this experience worthwhile? What are the biggest lessons you/your chapter learned? What surprises did you encounter along the way? How will this experience influence future research projects?
- The SPS connection – How did the activity strengthen your SPS chapter and your physics department?
- What advice would you give to chapters applying for future SPS Chapter Research Awards?

This grant allowed our SPS Chapter to expand the project we had already been working on. This experience was immensely worthwhile as it allowed our SPS chapter members to gain valuable research experience in preparation for graduate school and industry alike. This project has been huge for our chapter, allowing us to receive more publicity from the university and make SPS and the Physics department more recognized on campus. The biggest lesson our chapter learned was that research ebbs and flows causing our goals and focuses to change over time. Along with this, we ran into some surprises, specifically we discovered that every AmBe source varies and some of the papers we had been using as valuable resources may be questionable. We also discovered that we forgot to take into account the cross section of Cd which would have an effect on the number of neutrons absorbed by the foil.

In the future, we would advise chapters applying for the future SPS Chapter Research Awards to cover all the bases in the proposal, allowing for some flexibility in funding in order to accommodate for changes that often come along with research projects.

Key Metrics and Reflection

How many students from your SPS chapter were involved in the research, and in what capacity?	10 people from our SPS chapter were involved; each student worked on a variety of tasks: write ups, planning and execution of experiments, data analysis
Was the amount of money you received from SPS sufficient to carry out the activities outlined in your proposal? Could you have used additional funding? If yes, how much would you have liked? How would the additional funding have augmented your activity?	Yes- it covered everything we outlined in our proposal. Although, as with all research projects, the more funding we could get the more we could do. We could have purchased more foils which would have allowed for more consistency checks.
Do you anticipate continuing or expanding on this research project in the future? If yes, please explain.	Yes, we applied (and received!) the SPS Chapter Research Award for this upcoming year.
If you were to do your project again, what would you do differently?	Project is ongoing and developing.

Press Coverage (if applicable)

If your project received press coverage, please include references or URLs to the coverage. When possible, attach copies of articles to this report.
https://www.suffolk.edu/news/74996.php
https://thesuffolkjournal.com/24734/news/from-suffolk-to-mars/

Expenditures

Expenditure Table

Item	Please explain how this expense relates to your project as outlined in your proposal.	Cost
Foils (Cd, Au, In,W,Dy)	These were the foils we anticipated on buying to use for neutron activation analysis.	$1232 from SPS

Liquid Scintillator	The scintillator was used to help determine the full neutron spectrum of the 15 MV LINAC	\$768 from SPS \$2253 from department
Total of Expenses Covered by SPS Funding		\$1768

Activity Photos

Please include captions and credits for each photo. By including photos below, you are giving SPS and the American Institute of Physics permission to use these photos in their online and printed publications.

Note that you will be encouraged to upload high resolution copies of your best photos directly to SPS via the FluidReview site when you submit your report.