Neutrino Flux from Beta-Decaying Isotopes at the SNS

Samuel Vasquez[1], Rebecca Rapp[1], Diana Parno[1]
[1]Neutrino Physics Group, Carnegie Mellon University, Pittsburgh PA 15213

Introduction

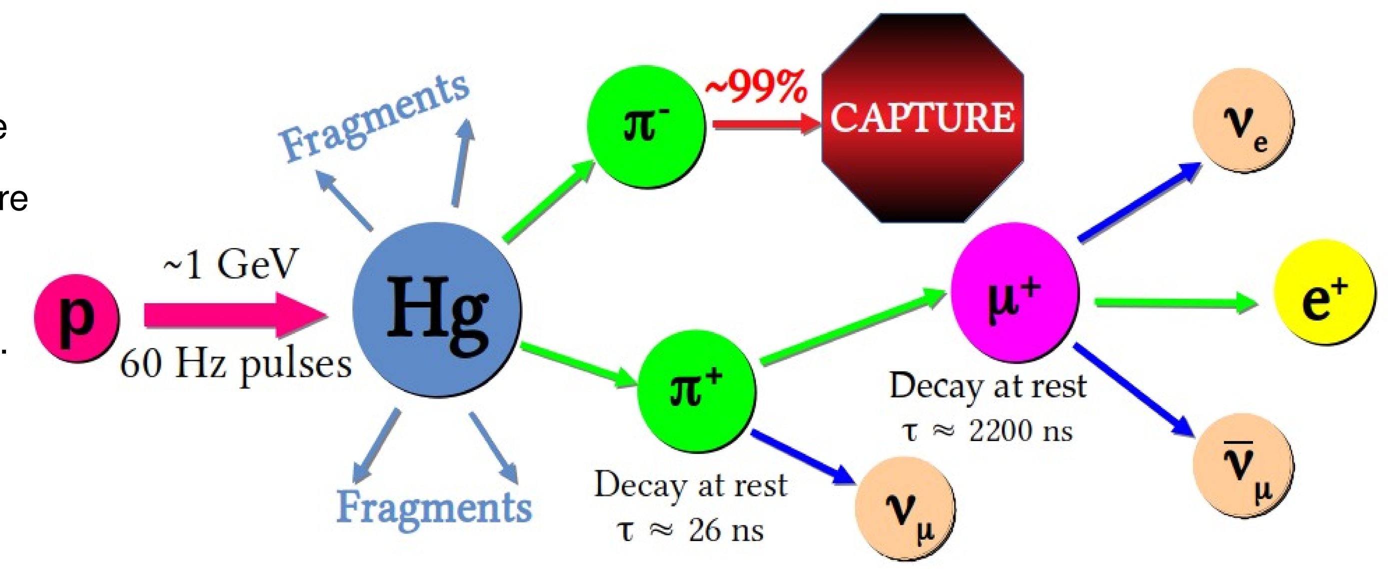
The COHERENT Collaboration studies coherent elastic neutrino-nucleus scatterings (CEvNS) on various nuclei, using neutrinos from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. At the SNS, a 60 Hz pulsed proton beam strikes an Hg target, producing copious amounts of neutrons and pions. In turn, the pions' decays at rest give us a high intensity neutrino source.

We simulate neutrino production at the SNS to better quantify the neutrino flux. Our simulation produces neutrinos by modelling 1 GeV protons incident on a simplified geometry, tracking the pion production and subsequent decays. Evaluating the accuracy of pion production implementation, we have calculated the simulated flux to 10% uncertainty. [1]

However, pion decays are not the only source of neutrinos at the SNS. Among the miscellaneous spallation products are radioactive nuclei, some of which beta decay. Some might decay within the length of a single beam pulse, which can be understood as a direct contribution to neutrino count per proton on target (POT); some might have relatively long halflives, which can be understood as a steady background source of neutrinos.

This ongoing research has been dedicated to implementing radioactive decay physics into our simulation, in order to investigate its contribution to the SNS neutrino flux, and ultimately to introduce the possibility of calculating the flux to greater precision.

Figure 1: A diagram summarizing the results of SNS operation. We are interested in radioactive isotopes among the "Fragments".



Technical Background

- The neutrino flux simulation code is written in Geant4 10.7.2. [2]
- Our code defines a simplified construction of the SNS. (See figure below.)
- Physics models are selectively activated; This project modifies the standard QGSP_BERT physics list to include the radioactive decay physics used by QGSP_BERT_HP.
- With this physics list activated, isotopes decay according to a comprehensive internal dataset.
- We supplement the base Geant4 tracking to collect creation information of neutrinos and nuclei, outputting a ROOT file for data analysis.

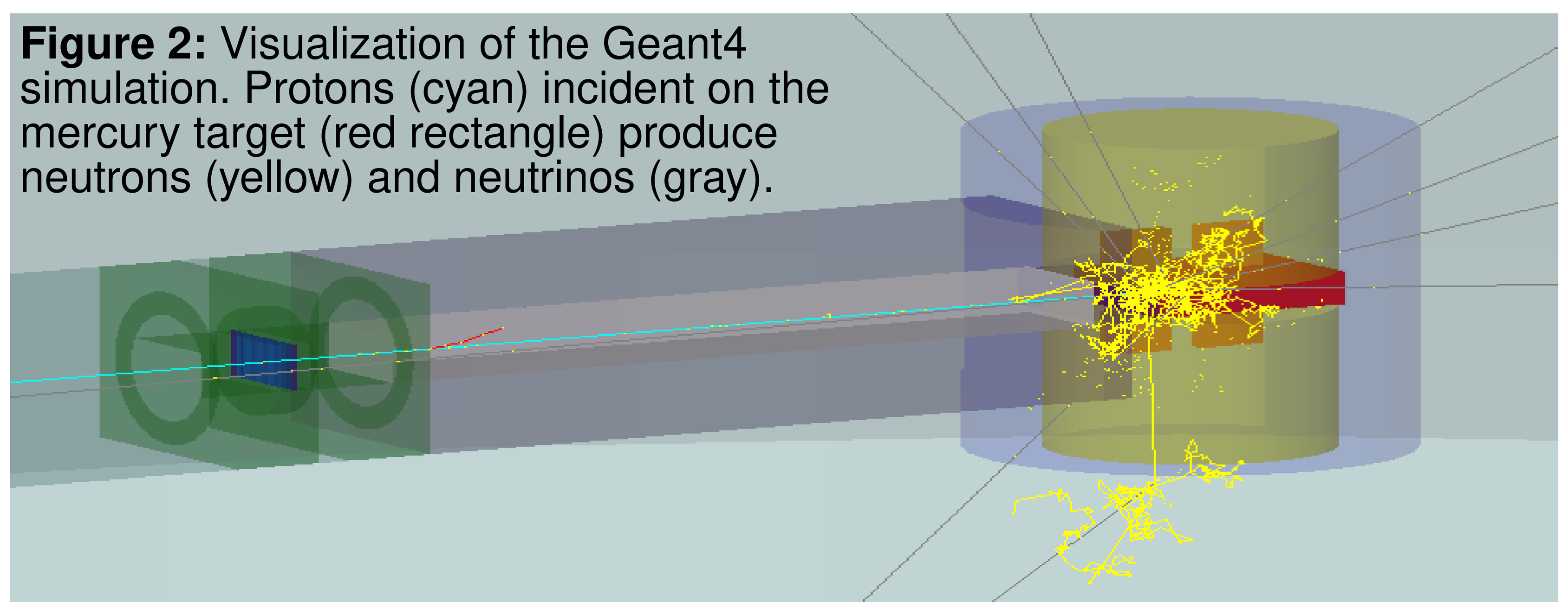


Figure 2: Visualization of the Geant4 simulation. Protons (cyan) incident on the mercury target (red rectangle) produce neutrons (yellow) and neutrinos (gray).

Isotopes at the SNS

Our study of SNS radioactivity is informed from two approaches.

- We have a table of predicted isotope presences at SNS, inherited from calculations during early construction to predict how much shielding and regular material replacement would be necessary to safely maintain long-term operations.
- Simulating single protons incident on SNS geometry results in spallation that appears realistic, including generating radioisotopes which Geant4 also decays.

These results come from studying the table. First we sorted through this table by activity, selecting for isotopes whose decays produce neutrinos with an energy detectable by CEvNS measurements, to obtain a list of isotopes suitable for simulation studies. The first five of these results are shown below.

Nuclide	Halflife (Hrs)	Activity (Curies)
Au198	64.7	31530
Hg195	9.9	17630
Au193	17.6	16570
Pt191	69.7	13090
Au192	4.9	12730

Figure 3
Total activities per nuclide, expected after 39 years of 2MW operation. Each nuclide decays via beta decay or electron capture decay, with Q-value exceeding 1 MeV.
These isotopes, and all others above 6000 Curies, have extremely long halflives on the order of hours.

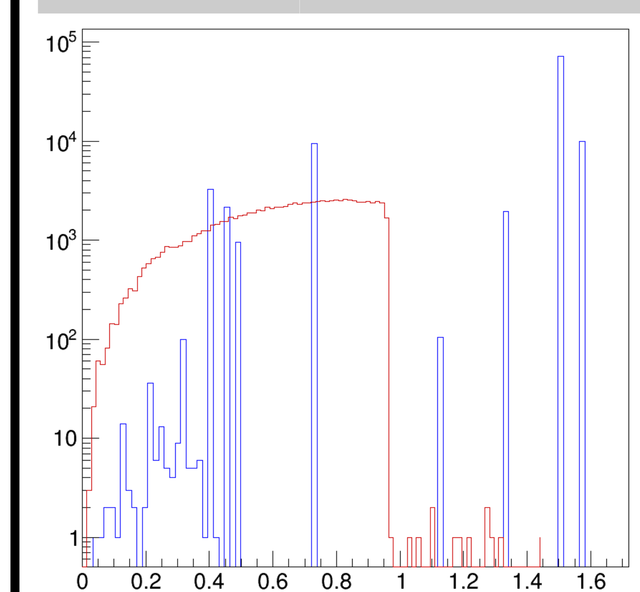


Figure 4a
Kinetic energy of neutrinos at their creation from simulating the decays of 100,000 Au198 (red) and Hg195 (blue) nuclei.

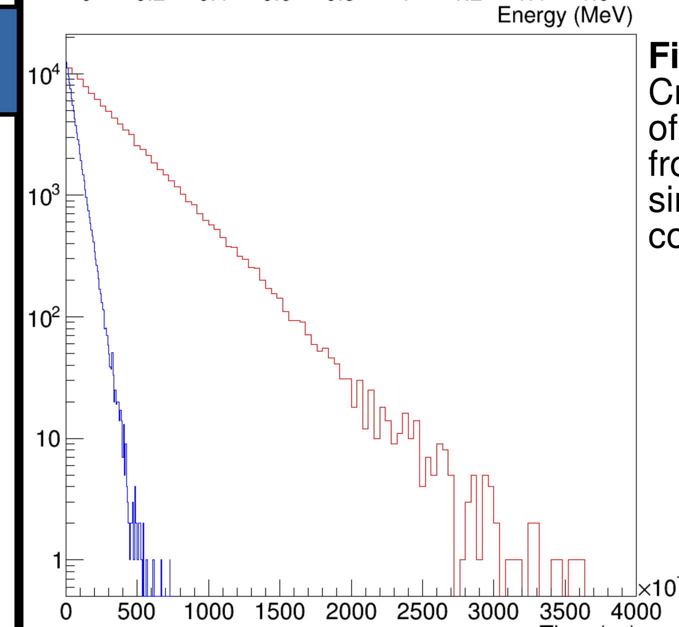


Figure 4b
Creation times of neutrinos from the same simulation conditions.

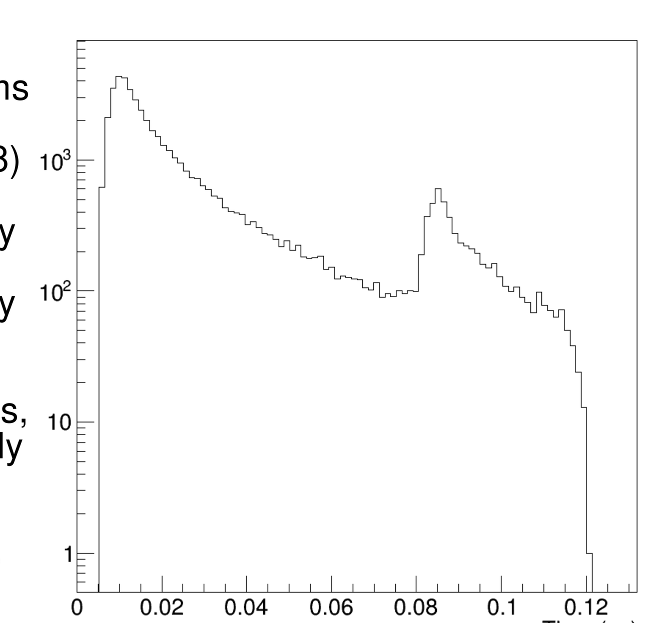
We modified the simulation to place specific nuclei directly into the center of the target at rest and allow them to decay naturally. The figures to the left show neutrino results from simulating Au198 and Hg195 this way.

The neutrino creation times follow the expected decay with appropriate halflives.

The energy spectra are explained by seeing that Geant4 decays nuclei according to an internal dataset, which fully differentiates between beta decays and particular kinds of electron capture decays.

Aside from minor exceptions (see figure 5), we conclude that Geant4 gives mostly reliable results.

Figure 5
Creation time histograms from all neutrinos from simulated POT (figure 8) reveals that certain nuclei decay unnaturally early. This histogram shows the time of decay events for 100,000 Re172 nuclei. Re172 has halflife ~15 seconds, but Geant4 is apparently applying a far shorter halflife instead. Investigation into this is ongoing.



Nuclide	Activity (Curies)	Q-Value (MeV)
Hg191	3081	3.180
Au191	10340	1.830
Pt191	13090	1.019

Figure 6
In its beta decay, Au191 decays to Pt191. Au191 is also the result of beta decay from Hg191. Both of these events produce neutrinos, and all three isotopes have significant activities in the table. We are unable to tell from the table alone how much of every isotope is created directly from the beam vs created from other decaying isotopes in the table, giving importance to the other approach.

Simulating SNS Operation

We simulated 100,000 protons individually incident on the SNS target, resulting in neutrinos sourced from a combination of the usual pion decays at rest and radioactive isotopes across an extensive time scale.

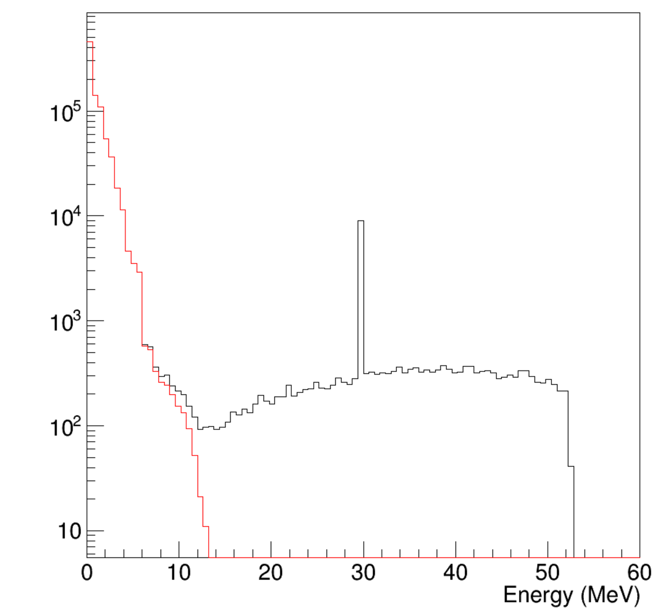
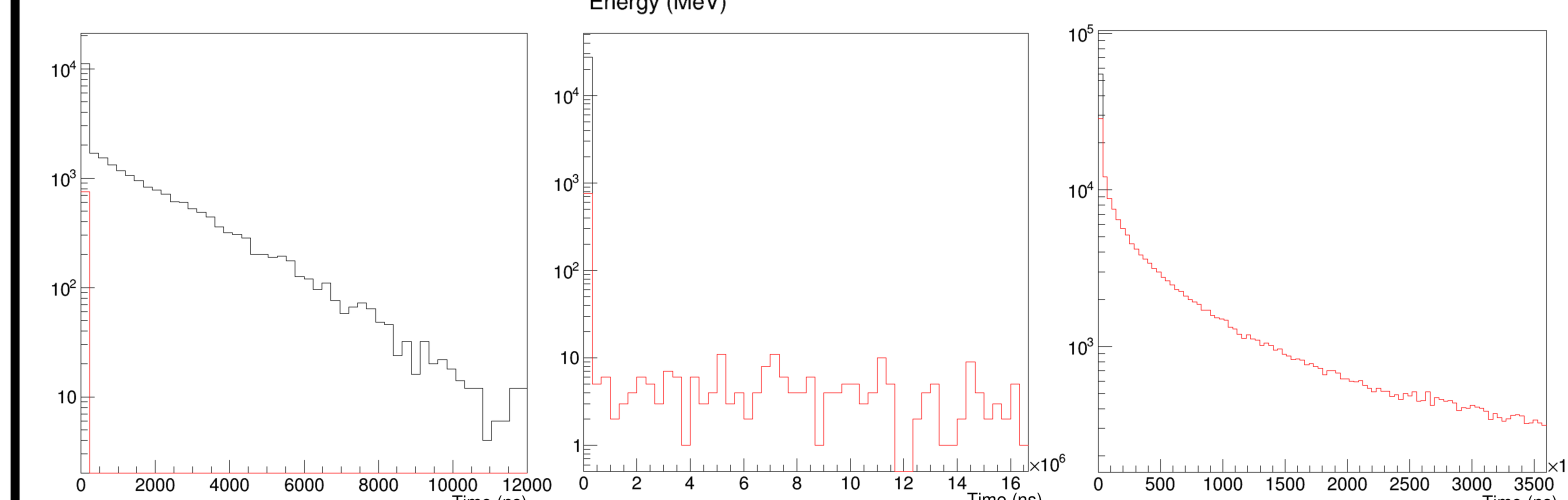


Figure 7
In red, neutrinos created solely from radioactive decay events. In black, neutrinos created from all sources.

- 8.688 neutrinos per POT were created in total.
- 96.9% came from radioactive decays.
- 37.5% had kinetic energy greater than 1 MeV, an approximate threshold to be detectable by CeVNS experiments.

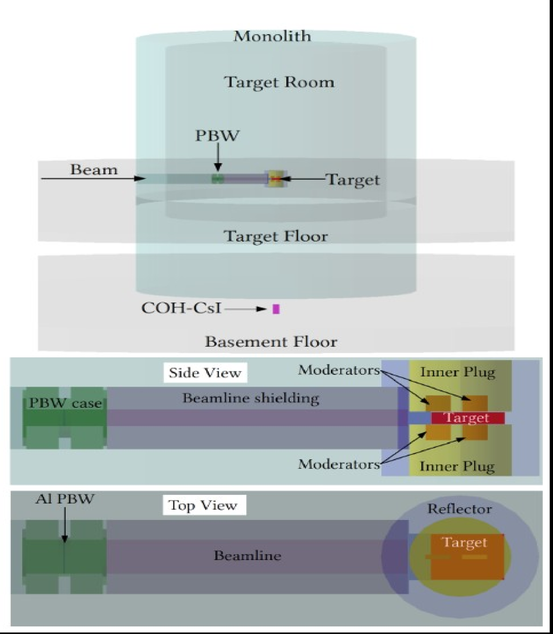
This gives 3.158 such neutrinos per POT in total, 2.892 per POT from radioactive decays.



These three figures collectively show neutrino creation times. Red is nuclear decay, black is all decays. Neutrinos with kinetic energy less than 1 MeV are omitted.
Figure 8.a (Left): In the first 12 microseconds, neutrino creation is dominated by pion decays. There is a large spike of nuclear decay in the first bin, but this appears to be a technical anomaly. (See figure 5). The 12 us window following a beam spill contains the majority of pion-produced neutrinos, and can be used as the signal region for CevNS studies.
Figure 8.b (Center): In the duration of one beam pulse, there is a spike of pion decay activity in the first bin, and low levels of steady nuclear decay events. This demonstrates that the beta decay production of neutrinos can be treated as a steady-state background.
Figure 8.c (Right): In the first hour, we see much larger levels of nuclear decay as isotopes with longer halflives begin to decay. This agrees with the table telling us that all the most active nuclei have large halflives.

Location	Count	Location	Count
Target	695852	H2 Moderators	78
Target Casing	7845	Steel Reflector	74098
Top Plug	4908	PBW	187
Bottom Plug	4913	Steel Room	54297
H2O Moderator	17	Monolith	0

Figure 9
This table identifies the locations of neutrinos produced from decaying isotopes, same simulation conditions as above. We find that most isotopes are created in the target, while a considerable number are in the steel reflector and steel room.



Acknowledgements

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References

[1] COHERENT Collaboration. D. Akimov *et al.*, "Simulating the Neutrino Flux from the Spallation Neutron Source for the COHERENT Experiment." arXiv:2109.11049.
[2] Agostinelli, S., et al. "Geant4—a Simulation Toolkit." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, July 2003, pp. 250-303.