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NEUTRINO CROSS-SECTION MEASUREMENTS AT THE SPALLATION NEUTRON SOURCE*

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In this paper we discuss the proposal to build a neutrino facility at the recently-completed Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL). This facility can host an extensive, long-term program to study neutrino–nucleus cross-sections in the range of interest for nuclear astrophysics and nuclear theory.

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1. Introduction

The high beam intensity and short duty-factor of the ORNL SNS would allow an exciting program of high statistics neutrino–nucleus cross-section measurements. These cross-sections are of great interest to the fields of nuclear structure physics and astrophysics. In particular, they would be of immediate use in the study of core-collapse supernovae, especially because of the fortuitous similarity between the SNS neutrino spectrum and the neutrino spectrum produced in a supernova explosion — as illustrated in Fig. 1 below.

We propose to build at the SNS a shielded, instrumented enclosure which will host an initial set of two detectors to carry out a long term program of cross-section measurements on a range of appropriate nuclear targets. The tentative name for the proposed facility is Neutrinos at the SNS, or briefly ν–SNS.

At present, only neutrino cross-sections on ^{12}C have been measured well (about 4–10% errors) [1, 2]. The only other reported results are for ^{2}H, ^{56}Fe [3], and ^{127}I [4], albeit with significantly higher errors (about 40%).

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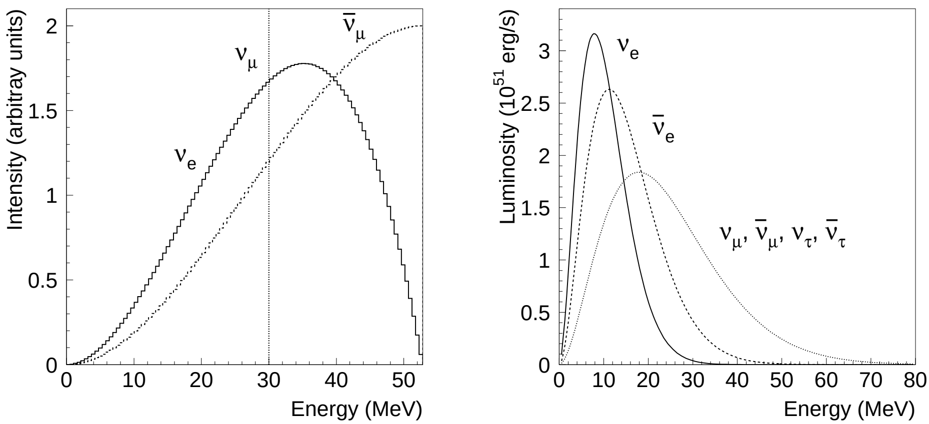

Fig. 1. Energy spectra of the different neutrino species produced at the SNS (left), and core-collapse supernovae neutrino energy spectra (right).

We show below that at ν–SNS it is feasible to measure the charged-current neutrino–nucleus cross-section for any selected nuclear target species to a statistical accuracy better than 10% in one year. With clever detector designs that allow reuse of the detector with different target materials it becomes feasible to develop a true program to measure the cross-sections for many nuclear species. Theoretical interest in these cross-sections spans the entire range of nuclear species and must be tempered by the realization that neutrino cross-sections are exceedingly small (of the order of $10^{-41}\,\mathrm{cm}^2$), so that even with the prodigious neutrino flux at the SNS the maximum target size is of the order of 10 tons. Therefore, viable target materials must be affordable in large quantity. Based on these considerations an initial three-year program might consist of measurements of the neutrino cross-section on lead, iron, carbon, and oxygen. Future directions would be guided by the results of this initial program and by theoretical interest. Neutral-current and double differential cross-section measurements are perhaps possible at ν–SNS given an appropriate detector development and shielding design.

2. Scientific motivation

Core-collapse supernovae are among the most energetic explosions in the universe, releasing 10^{53} ergs of energy in the form of neutrinos of all flavors at a staggering rate of 10^{57} neutrinos per second and 10^{45} watts. As the name suggests, these supernovae result from the collapse of the core of a massive star at the end of its life. The collapse proceeds to supernuclear densities, at which point the core becomes incompressible, rebounds, and launches a shock wave into the star that is ultimately responsible for the explosion. The shock wave stalls, however, due to several enervating processes, and the shock is believed to be revived in part by the intense flux of neutrinos mentioned above, which emanates from the proto-neutron star at the center of the explosion.

The Spallation Neutron Source will produce 10^{15} neutrinos per second from pions and muons decays, and will be the most intense pulsed source of neutrinos on earth. The short pulse structure of the SNS beam allows to separate between neutrinos of different species, as clearly illustrated in Fig. 2. The availability of such an intense neutrino source with neutrino energy spectra matching those emanating from distant supernovae is ideal for neutrino-nuclear astrophysics research. The combination of such "made to order" intense neutrino fluxes and the strong current interest in neutrinos for supernova science makes a compelling case for a neutrino-nuclear astrophysics research program to be developed at the SNS.

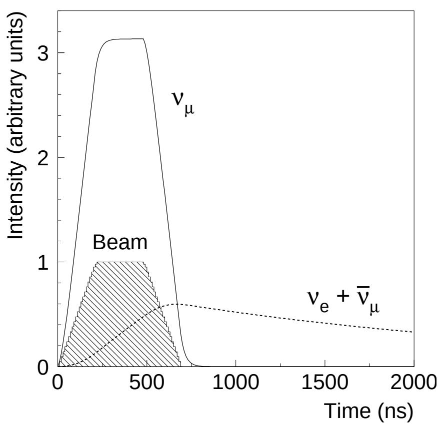

Fig. 2. Time structure of the different neutrino species produced at the SNS.

Neutrino–nucleus cross-section measurements of relevance to supernova astrophysics fall into three categories: (a) supernova dynamics [5,6], (b) supernova nucleosynthesis [7], and (c) terrestrial supernova neutrino detection [8,9].

3. Neutrino flux, detector enclosure and location

The neutrino detector and shielding enclosure would be located in the SNS target hall. An acceptable location has already been identified on the north side of the beam-line, at a mean distance of 21 m from the spallation target, and at an angle of 160° relative to the incoming proton beam direction. The available floor space is $20\,\text{m}^2$ with a clear height of 6.5 m.

At full power (1.4 MW, expected to be sometime in 2010) the SNS will bombard its mercury target with a 1.1 mA, 1.3 GeV proton beam, producing 0.13 neutrinos of each species per incident proton on target. The resulting neutrino flux at the detector location will be $1.7\times10^7\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$ of each flavor, giving several tens of neutrino interactions per day for a 10-tons detector. This must be compared with the cosmic ray muon (neutron) flux through this volume of 2.5×10^8 (1.4×10^6) events per day. Such cosmic-ray events will be suppressed through a combination of the SNS time structure of the beam (695 ns at 60 Hz), an active veto counter and shielding. Special attention will be paid to the background from neutrons generated at the SNS target.

First beam on target has been delivered in 2006, and the power has been gradually increasing up to about 700 kW in November 2008. The accelerator complex was down during this workshop (for a 2 months shutdown in January and February 2009), but resumed operations in March 2009 and reached about 900 kW at the end of April 2009. A set of preliminary measurements indicate that the neutron backgrounds are in good agreement with the existing Monte Carlo calculations, and that they scale linearly with the beam power.

Initial studies indicate that a shielded enclosure with a 1 m thick roof and 0.5 m thick walls and an active veto system with an efficiency of more than 99% can reduce the cosmic-ray background to an acceptable level. Preliminary calculations, incorporating the SNS target and shielding assemblies and materials from nearby neutron scattering instruments show that this shielding, together with benefits from the SNS time structure, is also sufficient to shield against the SNS-generated neutrons for measurements of neutrino interactions via charged-current week interactions. For measurements of neutrino interactions via the weak neutral current, future shielding studies are required after detailed layout of the closest neutron beam-lines will be available.

4. Possible detectors

Several different types of detectors are being investigated. The two that appear most promising are segmented and homogeneous detectors, as described below.

4.1. Segmented detector

Individual elements of the segmented detector would be composed of a position-sensitive gas proportional counter surrounded by a thin-walled cylindrical tube made of the target element. Signals would be read out from both sides of each individual channel to provide three-dimensional position information. Direction information can be extracted from the reconstructed track, while the particle energy is obtained from the range of the particle track. In principle, this detector can be constructed in such a way that the detector elements are reusable; when a measurement with one target material is complete the target/detector combinations would be unstacked, the detector elements would be removed and loaded into a new set of target tubes, and the new target/tube combinations re-stacked. This has great benefits for systematic error reduction as well as for long-term ease of operation and cost. From the list of nuclei of interest given above, cylindrical tubes of ^{9}Be, ^{27}Al, and ^{56}Fe are easily obtainable. Suitable tubes of many other target other elements can be manufactured as powder contained in a plastic matrix.

4.2. Homogeneous detector

Some nuclei are difficult or impossible to obtain as solid compounds. It is more efficient to measure such targets (*e.g.*, ^{2}H, ^{12}C, ^{16}O, ^{127}I) in the form of a liquid or an aqueous solution. Therefore, we propose to have a second, homogeneous detector that can be filled with various liquids. The detector would be built as a steel, light-tight vessel with a size of $27\,\mathrm{m}^3$. Scintillator and/or Cherenkov light would be detected by photo detectors covering about 40% of the inner wall (*e.g.*, 600 8 inch photomultiplier tubes). The recorded charge and time information at the photo detectors will allow for a full event reconstruction (position, direction and energy), with a resolution driven by the Cherenkov to scintillation light ratio.

The first target for this detector would likely be ^{12}C (liquid scintillator), as the ^{12}C cross-section has already been measured [1, 2], but higher statistics data are desired. For ν-SNS the expected rate is 10 events per day (2000 events per year) assuming a detection efficiency of 50%. An additional benefit of an early ^{12}C measurement is that it will provide a calibration of the SNS neutrino flux. This is critical to allow a systematic accuracy of these measurements which is comparable to the expected statistical precision.

5. Time scale

Our schedule is guided by the expectation of full-power beam at the SNS by the end of 2010, as well as funding availability. From the beginning of the detector construction and the engineering of the shielded enclosure to the commissioning of the detectors we expect a time interval of no more than two years. Meanwhile, we are continuing to perform detailed design and optimization studies of the two detectors and carrying out measurements of the beam-induced neutron backgrounds at the planned detector location.

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