Neutrino-Nucleus Cross Section Measurements using Stopped Pions and Low Energy Beta Beams

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Two new facilities have recently been proposed to measure low energy neutrino-nucleus cross sections, the \( \nu \)-SNS (Spallation Neutron Source) and low energy beta beams. The former produces neutrinos by pion decay at rest, while the latter produces neutrinos from the beta decays of accelerated ions. One of the uses of neutrino-nucleus cross section measurements is for supernova studies, where typical neutrino energies are 10s of MeV. In this energy range there are many different components to the nuclear response and this makes the theoretical interpretation of the results of such an experiment complex. Although even one measurement on a heavy nucleus such as lead is much anticipated, more than one data set would be still better. We suggest that this can be done by breaking the electron spectrum down into the parts produced in coincidence with one or two neutrons, running a beta beam at more than one energy, comparing the spectra produced with pions and a beta beam or any combination of these.

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I. INTRODUCTION

Neutrino-nucleus cross section measurements are desirable from the point of view of understanding nuclear structure, but they are perhaps even more desirable for astrophysical reasons. The supernova is the best studied astrophysical environment where neutrino scattering reactions have significant impact. Proper inclusion of the reverse process, electron capture on nuclei, has recently been shown to factor significantly in the prospects for obtaining a supernova explosion \cite{1}. Furthermore, neutrino-nucleus interactions figure heavily in determining the nucleosynthesis that is produced during the course of a supernova explosion. Neutrino nucleosynthesis, which occurs when neutrinos spill neutrons and protons off of pre-existing nuclei, is driven entirely by neutrino-nucleus interactions \cite{2, 3}. Several papers have suggested that the r-process of nucleosynthesis may be impacted heavily by neutrino-nucleus interactions, e.g. \cite{4, 5}. In fact these reactions may have such a detrimental effect that they are an effective tool in constraining the environment \cite{6}. Thirdly, neutrino-nucleus measurements are needed to calibrate supernova neutrino detectors. For a description of supernova neutrino detection using lead, see \cite{7}. A recent review of different techniques used to calculate neutrino-nucleus cross section measurements is given in \cite{8}.

Traditional neutrino beams are created using pions which produce both muon neutrinos and muon antineutrinos, and either electron neutrinos or electron antineutrinos. This is the case for the proposed \( \nu \)-SNS which will produce neutrinos from pions decaying at rest by way of the Spallation Neutron Source at Oakridge National Laboratory \cite{9}. This facility will make improvements on existing measurements of nuclei such as carbon and iron \cite{10, 11, 12} and measure cross sections on new nuclei such as lead.

Newly proposed beta beam facilities \cite{13} produce either electron neutrinos or antineutrinos from beta-plus or beta-minus decays of radioactive ions. Feasibility studies for beta beams are underway and a design is discussed in \cite{14, 15}. Beta beams were originally proposed as a way to make high energy neutrinos for use in long-baseline studies to determine the third, and as yet unknown mixing angle in the neutrino mixing matrix, \( \theta_{13} \) and to investigate CP-violation in the lepton sector \cite{16, 17}. However, lower energy beta beams have been proposed by Volpe \cite{17} and an application for neutrino magnetic moment measurements has been discussed in \cite{18}.

In this paper we consider neutrino-lead measurements using spectra that would be produced by the \( \nu \)-SNS and from a beta beam facility. We consider a target mass of 10 tons, 20 meters away from the pion source and 10 meters away from the end of a straight section of a beta beam ring. We examine the spectra of the electrons that would be produced from charged current interactions.

We explore the signals which can be produced if the electrons can be identified as being created in coincidence with zero, one or two spalled neutrons. We also suggest the possibility that low energy beta beams be operated at more than one energy, therefore producing different neutrino energy spectra.

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FIG. 1: **Beta Beam, \( \gamma = 5 \) and \( \gamma = 10 \)**: Figure shows the boosted spectrum of \( \nu_e \)s produced at a rate of \( 10^{13} \) s\(^{-1} \) from \( ^{18}\text{Ne} \). Calculated for a target that has a cross sectional area of 4m and is located 10m from one end of the ring, which has a straight side length of more than 90m. These numbers are further reduced by the fraction of time the ions spend on the straight section of the ring.

FIG. 2: **Electron neutrinos from stopped pions**: Figure shows the spectrum of \( \nu_e \)s from a \( 10^{15} \) s\(^{-1} \) neutrino source coming from stopped pions. The target is assumed to be 20 m away with a cross sectional area of 4 m\(^2\).

### II. NEUTRINO SPECTRA

In order to explore the effect of using different neutrino spectra to probe the nuclear response of \( ^{208}\text{Pb} \), we must first compare the various neutrino spectra themselves. We are particularly interested in the charged current interactions of electron neutrinos, since lead is largely Pauli blocked in the electron antineutrino capture direction, and muon neutrinos and antineutrinos are not energetic enough to produce muons for the energy range we consider here.

Electron neutrinos coming from stopped pions are produced by the decay of pions into muons which then decay into electrons, \( \pi^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu \). Electron neutrinos produced with a low energy beta beam would come from beta-plus decay of a radioactive nucleus such as \( ^{18}\text{Ne} \rightarrow ^{18}\text{F} + e^+ + \nu_e \). Neon-18 decays in its rest frame with a half life \( \tau_{1/2} = 1.67 \) seconds and has a difference of nuclear masses of \( Q_n = 3.93 \) MeV, and therefore the maximum energy for the neutrinos is about 3.4 MeV. This energy is lower than that of most neutrinos that are produced in a supernova. These have approximately thermal spectra and average energies between 10 and 25 MeV although the exact values depend on the model, and the subsequent neutrino mixing. However if Neon-18 were boosted to \( \gamma \sim 10 \) or even \( \gamma \sim 5 \) then the spectrum falls in the same range as that of supernova neutrinos.

In Figs. 1 and 2 we show three different electron neutrino spectra. One comes from stopped pions, another from a Neon-18 beta beam boosted to \( \gamma = 10 \) and a third with a lower boost of \( \gamma = 5 \). Although for a particular target geometry and set up spectra will need to be calculated more precisely, we can obtain a general idea of the relative effects of these different sources using the following rough estimates. In the case of the pions we assume that the ten ton target has a cross sectional area of 4 m\(^2\) and is located 20 meters from the source of the neutrinos. For the beta beams we assume that the same target is located 10 meters from the end of a straight section in the ring of 90m in length. The spectrum for the beta beams takes on a different shape and magnitude depending on how large an opening angle the detector subtends. The opening angle for the beam is the about 7 degrees right as the ions reach 10 meters from the detector, although the opening angle, and therefore the flux falls off quickly as the distance from the source increases.

For the pions we take a decay rate such that \( 10^{15} \) s\(^{-1} \) electron neutrinos are produced, which is the order of magnitude discussed in the \( \nu\)-SNS proposal \( ^{[9]} \). For isotropically emitted neutrinos, the number hitting the target is reduced by \( \sim 4m^2/[4\pi(20m)^2] = 0.08% \) for this geometry. For the beta beams we take a production rate of \( 10^{13} \) ions per second as discussed in \( ^{[14]} \). However, the beam is collimated, since the relativistic boost will shift the neutrinos toward the forward direction. Some estimates can be made by starting with isotropically emitted neutrinos in the rest frame of the ion, boosting the component of neutrino momentum along the beam line, calculating the lab frame angle for the neutrino and determining if it is less than \( \theta = \tan^{-1}(R/L) \), where R is the radius of the circular cross section of the detector and L is the distance of the neutrino from the target. For \( \gamma = 10 \), the flux entering the detector...
falls to 1.5% when the ions are 100 meters from the target and the integrated fraction of the flux which enters the target that has been emitted between 10 meters and 100 meters is 8%. Furthermore, for $\gamma = 5$, the flux entering the detector falls to 0.3% when the ions are 100 meters away from the detector and the integrated fraction emitted from between 10m and 100m is 2%. Even for a larger boost of $\gamma = 15$, the fraction entering the detector is only 3.5% at 100m away, and the integrated fraction is 14%. Longer straight sections therefore do not help much to increase the flux. Since all the numbers must be further reduced by the fraction of the entire ring of which these 90 meters consist, smaller rings are advantageous. A more complete discussion of how ring and detector geometry influences fluxes and total event rates is given in [19].

It can be seen from the figures that although the spectra are of the same order of magnitude in energy, they do not have the same shape or even the same average energy and will therefore produce a different signal from the same target nucleus.

### III. ELECTRON SPECTRA

The next step is to investigate the electron signal produced from the neutrinos interacting with the lead target. In particular we investigate $\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi} + e^-$. The Bismuth may produce one or more spalled neutrons as a result of this charged current reaction. Some neutrons will also be produced from neutral current interactions as well, but they are not investigated here. Natural lead is a primarily $^{208}\text{Pb}$ but it contains also a significant amount (almost half) of other isotopes. In this paper we use pre-existing calculations of $^{208}\text{Pb}$, as no calculations of other isotopes exist to date. Although they are expected to be similar, a complete analysis of a neutrino-lead experiment would involve all nuclei present in the target. There are many papers which calculate the cross section of $^{208}\text{Pb}$ [20, 21, 22, 23, 24]. We use cross sections from [23] in order to illustrate what can be expected from such experiments. All calculations agree at low energy, although at high energy they begin to diverge. This is because the nuclear response at low energy transfer primarily consists of allowed transitions which are best understood. However, even for the allowed transitions, there are open questions, such as the relative weight of the vector and axial vector couplings in the nucleus. The results of any neutrino-nucleus cross section experiment will be used to calibrate theory and differentiate between different calculations.

We first plot numbers of electron events as a function of energy for the stopped pion source. This is shown in Fig. 3. In Fig. 4 we show the number of electron events for the $^{18}\text{Ne}$, $\gamma = 10$ beta beam. As can be see from Table I the total number of electron events, using 100% efficiency in each case is 200 per day for the pion source and 26 for the...
FIG. 5: Electron Spectrum, Pion Source: The lines are the same as in Fig. although only electrons associated with two neutrons are shown. Most of the electrons are produced from the forbidden 0-, 1- and 2- transitions.

FIG. 6: Electron Spectrum, $\gamma = 5$: Same as Fig. except for ions accelerated to smaller energy. Most of the electrons are produced from allowed nuclear transitions.

beta beam at $\gamma = 10$. For this table, the numbers of electron events for the beta beam can be roughly scaled as

$$ N = \left( \frac{N_\nu}{10^{13} s^{-1}} \right) \left( \frac{900 m}{L} \right) \left( \frac{M}{10 \text{ tons}} \right) N_{\text{table}}, $$

where $M$ is the mass of the target, $L$ is the total length of the ring and $N_\nu$ is the number of neutrinos emitted per second in the ring. However, changing the cross sectional area of the detector and the distance of the detector from the beam is a nonlinear effect since it alters the spectra through the angular dependence of the Lorentz boost.

In both of Figs 4 and 5 we show the contribution from various parts of the nuclear response, allowed ($0^+ + 1^+$) and different parts of the forbidden. As can be seen, different parts contribute with different weight at different energies to the signal. Understanding which pieces contribute with which weight is an important aspect of the theoretical interpretation of the signal. It is necessary in order to be able to accurately calculate supernova neutrino-nucleus scattering where the spectra are different still and will help to understand such theoretical questions as which underlying force fits the response best.

Although any electron spectrum produced from neutrino-lead scattering would be a great improvement on the current experimental situation, to understand which nuclear transitions are producing given electrons would be better still. Although there is no way to determine experimentally whether a particular electron was produced by way of a particular nuclear matrix element, there are several ways to obtain more information in this direction. One way is to separate out the electrons that are emitted in coincidence with zero, one or two neutrons. Another way would be to compare a stopped pion signal to a beta beam signal and fit both simultaneously. Finally, one could run a beta beam at different energies, boosting for example to $\gamma = 10$ and then to $\gamma = 15$ or $\gamma = 5$.

In Fig. 5 we show the electron energy spectrum for only those electrons emitted with two neutrons, for the pion decay at rest source, although the same can be done for the beta beam. There are 66 events per day associated with two neutrons for the pion source and 10 events per day associated with two neutrons for the beta beam with $\gamma = 10$. In Fig. 4 the majority of the electrons, 80%, are produced by the $0^-, 1^-$ and $2^-$ part of the signal. In a similar way, the electrons associated with one neutron can be shown to come primarily, 75%, from the allowed part of the cross section. As can be seen from a comparison with Fig. 4 much more information can be obtained if the electrons can be identified as being produced with either one or two neutrons, than from the aggregate spectrum alone. Such a two neutron analysis would also be particularly useful when applied to a lead based supernova neutrino detector such as OMNIS or LAND, since supernovae electron neutrinos will oscillate with the muon and tau type neutrinos, and the two neutron signal will consist primarily of electron neutrinos that were originally produced as muon neutrinos. If electron neutrinos and muon neutrinos from the supernova are widely separated in energy, then observing the two neutron signal would be an effective way to “measure” the original muon or tau spectrum.

In Fig. 6 we show the electron spectrum associated with a beta beam boosted to $\gamma = 5$ instead of $\gamma = 10$. For the lower energy spectrum there are 1.1 total electron events per day, and only 0.05 electrons associated with two neutrons.
The majority of electrons are produced by way of allowed transitions in the nucleus. Some information about these allowed transitions can be inferred from (p,n) reaction data [27]. However, a beta beam of this energy would provide a first nearly direct measurement of these transitions, without the need to decompose the signal by coincident number of neutrons. It can also provide information about the relative strength of the 0+ or Fermi transition (governed by $g_V$) and the 1+ or Gamow-Teller transitions (governed by $g_A$). If it were possible to take data at a boost factor of both $\gamma = 5$ and $\gamma = 10$, then the information obtained by the $\gamma = 5$ measurement could be used to calculate the allowed part (long dashed line in Fig. 4) of the $\gamma = 10$ signal, thereby enabling a better interpretation of the rest of the signal. Higher multipoles continue to contribute more strongly at even larger boost factors. For example, at $\gamma = 15$ for these calculations that terminate at the fourth multipole, the 2+, 3+, 3−, 4+ and 4− multipoles contribute 38% to the total signal. Therefore such a third measurement would be beneficial in understanding this piece, which is the most uncertain part of the response that would contribute to neutrino-nucleus scattering by supernova neutrinos.

IV. CONCLUSIONS

We have discussed the electron spectrum produced from a lead target for two different sources of neutrinos. Any future measurements of neutrino-nucleus cross sections are much anticipated. However, if possible it would be desirable to have more than one electron spectrum with which to calibrate theory. We have illustrated the relative nuclear contribution to the electron energy spectra for various beta beam energies and compared this with the pion source. We have also considered the contributions of the one neutron and two neutron spectrum. One could maximize the information with which to compare theory calculations by separating the spectra into parts associated with zero, one and two neutrons, by running the beta beam at more than one energy such as at $\gamma = 5$, $\gamma = 10$ and $\gamma = 15$, or by using the electron spectra produced by both sources.

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TABLE I: For various electron neutrino sources, this table shows for $^{208}\text{Pb}$ the flux averaged charged current cross sections, the average energy of the electrons, and compares numbers of events per day in the detector. The event rates are for 100% efficiency, a detector with a 4m² cross sectional area, and a straight section of beta beam track of 90m that ends 10m from the detector. Also assumed are that there are $10^{13}$ decays per second in the ring, and that 90m takes up 10% of the track. Some electrons will be produced in coincidence with one or two neutrons and these numbers are also shown.