Two-Phase Emission Detector for Measuring Coherent Neutrino-Nucleus Scattering

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Abstract—Coherent scattering is a flavor-blind, high-rate, as yet undetected neutrino interaction predicted by the Standard Model. We propose to use a compact (kg-scale), two-phase (liquid–gas) argon ionization detector to measure coherent neutrino scattering off nuclei. In our approach, neutrino-induced nuclear recoils in the liquid produce a weak ionization signal, which is transported into a gas under the influence of an electric field, amplified via electroluminescence, and detected by phototubes or avalanche diodes. This paper describes the features of the detector, and estimates signal and background rates for a reactor neutrino source. Relatively compact detectors of this type, capable of detecting coherent scattering, offer a new approach to flavor-blind detection of man-made and astronomical neutrinos, and may allow development of compact neutrino detectors capable of nonintrusive real-time monitoring of fissile material in reactors.

Index Terms—Argon, electroluminescence, gas detectors, neutrinos, nuclear fuels, xenon.

I. INTRODUCTION

COHERENT neutrino-nucleus scattering is a famous but as yet untested prediction of the Standard Model [1]. The process is mediated by neutral currents (NC), and hence is flavor-blind. Despite having relatively high rates, neutrino-nucleus scattering is difficult to observe because its only signature is a small nuclear recoil of energy \( \sim \text{keV} \) (for MeV neutrinos), requiring a low detector threshold. Over the past two decades, a number of authors have suggested low-temperature calorimeters [1], [2], gas detectors [3], and germanium ionization detectors [4] for measuring neutrino-nucleus scattering. In this paper, we study a two-phase (gas-liquid) ionization detector, which combines low energy threshold with large event rates.

Coherent neutrino-nucleus scattering has the cross section [1] \( \sigma \sim 0.4 \times 10^{-44} N^2 (E_\nu/\text{MeV})^2 \text{cm}^2 \), where \( N \) is the neutron number, and \( E_\nu \) is the neutrino energy. This formula is valid for neutrino energies up to about 50 MeV, and thus applies to reactor, solar, and supernova neutrinos. For a fixed neutrino energy, the recoil spectrum falls linearly. The average energy is

\[
\langle E_r \rangle = \frac{1}{3} E_r^\text{max} = 716 \text{ eV} \left( \frac{E_\nu}{\text{MeV}} \right)^2 \left( \frac{A}{A} \right)
\]

(1)

where \( A \) is the atomic number of the target nucleus.

It is well known however, that recoiling atoms are less effective in producing primary ionization or scintillation than electrons of the same energy. The ratio of the ionization (and/or scintillation) yield from atomic projectiles to that from electrons, referred to as the quench factor \( q \), generally decreases with energy and is material dependent. For example, measured \( q \) factors in silicon [5] decrease from 0.41 to 0.26, for recoil energies of 21 keV and 3.3 keV, respectively. An even smaller quench factor of \( q = 0.15 \) was reported for germanium [6], at a recoil energy \( E_r = 254 \text{ eV} \).

A signal consisting of only a few electrons or photons is below threshold for conventional solid or liquid state detectors without internal amplification. Hence we propose a two-phase (gas-liquid) argon emission detector with an electroluminescence gap in the gas to provide gain. This scheme combines a large target density in the liquid with the capability of sensing single electrons. Its moderate cost and scalability, as compared to calorimetric detectors, make this technology a promising approach to NC based detection of reactor and astronomical neutrinos.

II. RECOIL RATE AND IONIZATION YIELD

An attractive attribute of neutrino coherent scattering is its relatively large cross section compared to inverse beta decay. For reactor neutrinos \( [\psi \sim 6 \times 10^{12} \text{ cm}^{-2} \text{s}^{-1} \sim 25 \text{ m}] \) from a 3-gigawatt thermal (GWt) core, the expected event rates before detection efficiencies are 56 kg\(^{-1}\)day\(^{-1}\) for coherent scattering off argon, compared to 2.8 kg\(^{-1}\)day\(^{-1}\) for the inverse beta decay reaction in (CH)\(_2\). Here we assumed a typical fuel mix of 61.9% 235U, 6.7% 238U, 27.2% 239Pu, and 4.2% 241Pu, with neutrino spectra and mix parameters taken from [7], [8]. Fig. 1 shows the expected argon recoil spectra, obtained by convoluting the reactor neutrino spectrum [7] with the theoretically predicted nuclear recoil energy distribution [1]. Although the average recoil energy in argon is \( \sim 200 \text{ eV} \), the majority of the recoil events do not produce primary ionization or excitation because of quenching.

In order to estimate the amount of ionization produced by recoils, we performed a Monte Carlo simulation of the atomic collision cascade. Our computer calculations are based on the transport of ions in matter (TRIM) code [9], which models the collisions as a series of binary events separated by a path length \( L = n_r^{-1/3} \) (= 3.6 \( \times 10^{-8} \) cm in liquid argon), where \( n_r \) is the atomic number density. For each collision step, the impact parameter is sampled by randomly choosing a point within a disk of area \( A_{\text{max}} = n_r^{-2/3} \). The scattering angle and hence the elastic energy transfer is determined by a Molière inter-atomic potential. Inelastic interactions were modeled by sampling the

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measured Ar–Ar ionization and excitation cross sections for each collision with probabilities $p_{\text{ion}} = \sigma_{\text{ion}}/\sigma_{\text{geo}}$ and $p_{\text{exc}} = \sigma_{\text{exc}}/\sigma_{\text{geo}}$. Fig. 2 depicts the inelastic argon cross sections compiled by Phelps [10]. The inelastic energy losses were accounted for in the energy budget of each cascade as follows. For collisions energies $< 1$ keV, ionization is primarily produced via the creation of the auto-ionizing state $(1s^22s^22p^63s^13p^64s^1)$ with excitation energy $\sim 25$ eV, leading to the subsequent emission of an Auger electron of energy $\sim 9.4$ eV [11]. The exiting Ar$^+$ projectile neutralizes quickly by charge exchange ($\sigma_{\text{exc}} \sim 10^{-15}$ cm$^2$), with its energy reduced by the ionization potential of liquid argon ($I_p = 14.3$ eV [12]). The inelastic excitation energy loss ($\Delta E \sim 25$ eV) is shared evenly between the colliding bodies, while the energy loss due to charge exchange ($\Delta E = I_p$) is randomly assigned to one of the outgoing projectiles. Excited argon atoms (Ar$^+$) are assumed to be created in state $(1s^22s^22p^63s^23p^54s^1)$ with energy $\Delta E \sim 12$ eV. The primary projectile and all energetic secondary particles produced in the cascade are followed till their energies drop below the inelastic reaction threshold ($\sim 25$ eV in the laboratory frame).

The Monte Carlo code allowed us to calculate the average ionization and excitation yields as a function of recoil energy $E$, and thus determine the Ar quench factor (shown in Fig. 3), defined here as

$$q(E) \equiv \frac{N_{\text{ion}}(E) + N_{\text{exc}}(E)}{N_{\text{ion}}^{\text{elec}}(E) + N_{\text{exc}}^{\text{elec}}(E)}$$

(2)

where $N_{\text{ion}}$ and $N_{\text{exc}}$ are the energy-dependent average ionization and excitation numbers. Kubota et al. [13] measured the yields from electron recoils

$$N_{\text{ion}}^{\text{elec}}(E) + N_{\text{exc}}^{\text{elec}}(E) \approx 1.21 \frac{E}{W}$$

(3)

and related them to $W$, the average electronic energy required to produce an electron-ion pair. In liquid argon, $W$ has a value of $\sim 23$ eV [14], [15].

We obtained the reactor neutrino ionization spectrum, depicted in Fig. 4, by convolving the ionization efficiency with the recoil spectrum. About 29% of all recoils produce at least a single electron-ion pair. In addition, a similar number of Ar$^+$ excitons are created with an identical number spectrum. Some of the excitation can be converted into ionization via doping with xenon. Since the Ar$^+$ exciton energy exceeds the ionization potential of xenon in liquid argon ($I_p(\text{Xe}) \sim 10.6$ eV), the secondary ionization process (Ar$^+$ + Xe $\rightarrow$ Ar + Xe$^+$ + e$^-$) is energetically allowed. Experimentally [13], the probability for this Penning mechanism to occur is

$$P_{\text{Penning}} = \frac{1.44 f_{\text{Xe}}[\%]}{1 + 1.44 f_{\text{Xe}}[\%]}$$

(4)
where $f_{Xe}$ is the xenon concentration in liquid argon. The number of free electrons created in argon is consequently enhanced to

$$N_e = N_{\text{ion}} + p_{\text{drift}} N_{\text{exc}}.$$  

Table I summarizes the expected recoil and ionization rates.

III. DETECTOR SCHEME

Our proposed detector is similar to those currently being developed for WIMP dark matter experiments [16]–[20]. Emission detectors house two phases (liquid-gas or liquid-solid) of a noble element in a single cell [21]. They may combine a large detector mass with a low detection threshold, and are ideally suited for measuring rare events in the kiloelectronvolt range. The primary ionization event most likely takes place in the condensed phase of the detector, where free electrons are produced. An applied electric field causes the electrons to drift toward the phase boundary and cross into the gas, where the charge signal is converted to an ultraviolet light signal via proportional scintillation. Geminate recombination and capture on electronegative impurities, such as $O_2$, may lead to electron loss. The rate of the former is proportional to the product of the positive and negative charge densities, and thus small for weak ionization events. The latter process can be made negligible by keeping the transfer time smaller than the free electron lifetime. Bakale et al. [22] measured an attachment lifetime of

$$\tau_a \approx \frac{10^{-11}}{\sqrt{O_{2}}} \text{s}$$  

and lifetimes of a few ms are routinely achieved using commercially available purification systems.

The electron transfer time (between primary event time till detection in the gas region) is usually dominated by the drift time $\tau_d$ (in the liquid), and the phase boundary crossing time $\tau_x$. The electron drift velocity in liquid argon is electric field dependent. For the range $10^2 \text{ V/cm} < \varepsilon < 10^3 \text{ V/cm}$, the drift time $\tau_d$ over a distance $L_d$ (in cm) is approximately given by [12]

$$\tau_d \approx 10^{-5} L_d \left( \frac{\varepsilon}{300 \text{ cm}} \right)^{0.64} \text{s}.$$  

The electronic potential barrier height of the liquid-gas interface in argon is $\sim 0.2 \text{ V}$, and the electrons are transferred into the gas by field-assisted thermionic emission. Borghesani et al. [21] determined a crossing time of

$$\tau_x \approx 0.1 \frac{1}{\varepsilon} e^{-0.06 \varepsilon^{1/2}} \text{s}.$$  

where $\varepsilon$ has units of $\text{V/cm}$.

Once in the gas phase, the electrons traverse an electroluminescence gap defined by two parallel grids with an applied potential of a few kilovolts. Inelastic collisions create $Ar_2^+$ molecules which decay radiatively, emitting UV photons of energy $\sim 10 \text{ eV}$. Both singlet and triplet states are created, with lifetimes of 4 ns and 3 is respectively [24]. Dias et al. [25] have extensively modeled the scintillation efficiency as a function of the reduced field $\varepsilon/r$. The light conversion efficiency, i.e., the fraction of electric potential energy converted into scintillation energy, rises from the threshold value $\left(\varepsilon/r_n\right)_0 = 3 \times 10^{-17} \text{ Vcm}^2$ roughly linearly to $\sim 50\%$ at $\left(\varepsilon/r_n\right) = 7 \times 10^{-17} \text{ Vcm}^2$. Gain values of a few hundred photons per electron with a cm scale gap are typical. Lastly the UV light needs to be collected with high efficiency to enable detection of single electrons. Both large-area, UV-sensitive phototubes and windowless avalanche diodes are attractive options. Fig. 5 shows a schematic of the detector we envisage for this experiment.
for low electron energies [28]. Here \( F(Z, E) \) is the Fermi function, \( Z \) is the charge number of the daughter nucleus, and \( \Phi(E) \) is the statistical factor of beta decay. Using this expression, we estimate a differential beta activity of \( \sim 5 \text{ mBq/(keV} \cdot \text{kg)} \) at the low energy end. Fig. 6 shows the estimated background rates in a bare detector and for a dual-shield configuration.

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