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Coherent Neutrino Scattering in Dark Matter Detectors

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Coherent elastic neutrino- and WIMP-nucleus interaction signatures are expected to be quite similar. This paper discusses how a next generation ton-scale dark matter detector could discover neutrino-nucleus coherent scattering, a precisely-predicted Standard Model process. A high intensity pion- and muon-decay-at-rest neutrino source recently proposed for oscillation physics at underground laboratories would provide the neutrinos for these measurements. In this paper, we calculate raw rates for various target materials commonly used in dark matter detectors and show that discovery of this interaction is possible with a 2 ton-year GEODM exposure in an optimistic energy threshold and efficiency scenario. We also study the effects of the neutrino source on WIMP sensitivity and discuss the modulated neutrino signal as a sensitivity/consistency check between different dark matter experiments at DUSEL. Furthermore, we consider the possibility of coherent neutrino physics with a GEODM module placed within tens of meters of the neutrino source.

I. INTRODUCTION

Coherent elastic neutrino-nucleus scattering is a well-predicted Standard Model interaction that is of widespread interest. Characterizing the process can provide a probe of beyond the Standard Model physics, such as through non-standard neutrino interactions [1], and can contribute to our understanding of supernova dynamics. Although experiments have been proposed to search for this channel [2–5], neutrino-nucleus coherent elastic scattering has never been observed. This paper shows that, for existing proposed layouts of neutrino sources and ton-scale dark matter detectors, discovery of coherent neutrino scattering can occur with a 2 ton-year exposure under an optimistic detection scenario. Along with coherent neutrino physics, the observation of rare, WIMP-like events with a well predicted flux (shape and absolute normalization) and cross section in a well-known time window can provide a cross-check of the sensitivity and efficiency of dark matter detectors. Furthermore, in the case that a substantial event sample is collected with a dedicated experiment close to the neutrino source, sensitivity to physics beyond the Standard Model and a unique probe of $\sin^2 \theta_W$ can be obtained through a coherent neutrino scattering cross section measurement.

We discuss the physics importance of the coherent neutrino interaction in the next section and detection methods in Section III. Section IV provides our assumptions for a few example experiments and the raw rates in these detectors with various exposures and as a function of envisioned energy thresholds and baseline lengths. The effect of coherent events as a background for WIMP interactions is also considered. Then, we consider the scenario in which a detector module is brought within tens of meters of the neutrino source and used to obtain a high statistics sample of events for coherent neutrino physics (Section V).

II. COHERENT NEUTRINO SCATTERING

The coherent scattering cross section, $\sigma$, depends on the number of neutrons, $N$, and protons, $Z$, of the target material with mass $M$. If $T$ is the recoil energy of the interaction and the incoming neutrino has energy $E_{\nu}$,

$$\frac{d\sigma}{dT} = \frac{G_F^2 Q_W^2 M}{4\pi} \left(1 - \frac{MT}{2E_{\nu}^2}\right) F(Q^2)^2. \quad (1)$$

In this equation, $G_F$ and $Q_W$ are the precisely known Fermi constant and weak charge $|Q_W = N - (1 - 4 \sin^2 \theta_W) Z|$, respectively. The form factor, $F(Q^2)$, dominates the $\sim 5\%$ cross section uncertainty [6].

As the cross section is well predicted, coherent elastic neutrino-nucleus scattering is an ideal source to search for new physics in the neutrino sector. A cross section measurement with $\sim 10\%$ uncertainty will result in an uncertainty on $\sin^2 \theta_W$ of $\sim 5\%$ [1]. While this uncertainty is large compared to existing and planned precision atomic parity violation and Møller scattering measurements, a discrepancy from the Standard Model prediction already observed in the neutrino sector by the NuTeV experiment [7] motivates more neutrino-based measurements.

Notably, a $\sin^2 \theta_W$ measurement with coherent neutrino-nucleus scattering would be at $Q \sim 0.04 \text{ GeV/c}$, well away from all previous neutrino scattering measurements (including NuTeV’s at $Q \sim 4 \text{ GeV/c}$).

A coherent neutrino-nucleus scattering cross section measurement agreement within 10% uncertainty of the Standard Model prediction will result in limits on non-standard neutrino interactions (NSI) which improve on the present ones by more than an order of magnitude [1, 8, 9]. The low-$Q$ existing and planned precision measurements mentioned above are not sensitive to new physics unique to neutrino interactions. NSI terms can enter the Standard Model Lagrangian through an extra term,

$$\mathcal{L}^\text{NSI} = -\bar{\nu}_\alpha P \gamma^\mu G F (\bar{\nu}_\alpha \gamma_\mu L \nu_\beta)(\bar{\nu}_\beta \gamma^\mu P f) \quad (2)$$
where \( f \) is a first generation Standard Model fermion, \( e, u, \) or \( d \) and \( P = L \) or \( R \) [10]. These \( \varepsilon^{f}_{\alpha\beta} \) terms can appear due to a range of sources, including incorporating neutrino mass into the Standard Model [11] and supersymmetry [12]. The \( \varepsilon_{ee} \) and \( \varepsilon_{e\tau} \) terms, in particular, are poorly constrained by existing measurements. Measuring a coherent scattering cross section in disagreement with the Standard Model expectation could be an indication of NSI. In the case that a cross section discrepancy is observed, multiple nuclear targets could be employed in order to disentangle effects from NSI, a sin\(^2\)\( \theta_W \) anomaly (e.g. consistent with NuTeV), and/or nuclear physics.

Characterizing neutrino coherent scattering is also essential to the understanding of supernova evolution as the energy carried away by neutrinos comprises \( \sim99\% \) of the supernova’s total energy and the coherent channel’s cross section exceeds all others by at least an order of magnitude in the relevant energy region. In a stellar core collapse, the density of the electron/nucleus plasma at the core can reach \( \sim10^{12} \) g/cm\(^3\). At these densities, a 20 MeV neutrino’s mean free path is on the order of 0.5 km [13] with the opacity in nucleus-rich regions dominated by coherent scattering. Along with being relevant for supernova evolution in general, the coherent cross section may also affect the supernova neutrino signals expected on Earth.

The coherent process is important for supernova burst neutrino detection as well, providing information about all flavors of neutrinos—not just \( \nu_e/\bar{\nu}_e \). For coherent neutrino-nucleus scattering specifically, unlike other channels of flavor-blind neutral current interactions, the nuclear recoil energy is proportional to neutrino energy due to the elastic nature of the interaction. Such information could be combined with charged current \( \nu_e/\bar{\nu}_e \) interaction information from other sources to develop a complete picture of oscillations with supernova neutrinos.

Note that approximately seven neutrino-nucleus coherent events in one ton of Ar during a ten second window for a galactic core-collapse supernova at 10 kpc are expected with a recoil energy threshold of 5 keV [6]. Although the detectors discussed below are probably too small to provide a sizable sample of supernova burst neutrino-nucleus coherent scatters (unless the supernova is very close), an accelerator-based measurement to confirm the predicted interaction cross section would prove valuable to a next-generation coherent neutrino scattering experiment’s supernova burst neutrino measurement.

III. DETECTION

The coherent neutrino-nucleus cross section favors very low recoil energies, in the few-to-tens of keV range. This is well below the threshold of the most sensitive recent and existing large-scale low energy neutrino detectors, like SNO [14], Borexino [15], and KamLAND [16], which explains why this relatively high cross section process has not yet been observed. Dark matter detectors, on the other-hand, have energy thresholds in the \( \sim10 \) keV range and lower. As such, these detectors are potentially ideal coherent neutrino scattering detectors if given a sufficiently large target mass and neutrino flux. A ton-scale dark matter detector at its nominal depth underground of 1-2 km, in combination with an intense decay-at-rest (DAR) neutrino source, could discover the coherent neutrino scattering process.

It is worth noting that dark matter detectors could observe \(^8\)B solar neutrino coherent events, as has been pointed out in Ref. [17]. The \(^8\)B rate depends on the detector threshold and material, with more events for lighter target nuclei and lower thresholds. This solar neutrino signal becomes negligible for high-A targets when the low-energy recoil threshold of the experiment is between 5 and 10 keV or more. There are zero solar coherent events expected with a 5/10 keV threshold for the targets (Xe, Ge/Ar) and exposures considered here. In contrast, the DAR accelerator source described in Section IV will produce a significant number of events within a well-defined time window when the accelerator is on. These events can therefore only be considered a WIMP background during those times (see Sec. IV B). In terms of a coherent neutrino physics measurement, the accelerator-based case has the luxury of an in-situ background measurement (when the source is off) in addition to the higher-energy, above-threshold nuclear recoils.

IV. RATES AND TIME TO DISCOVERY

In order to be reasonably concrete, we study a set of experimental designs inspired by proposals for the Deep Underground Science and Engineering Laboratory (DUSEL). We note that the detector designs are not very different from those under consideration at other underground laboratories and that the results can be easily scaled. For the neutrino source, we assume a DAR configuration produced by high intensity cyclotrons which are now under development [18][19] and proposed for DUSEL [20].

DAR neutrinos are known to be an excellent source for neutrino-nucleus coherent scattering experiments [2, 3]. The neutrinos are produced with relatively low energies (<52.8 MeV), a range where coherent neutrino scattering dominates all other cross sections by about an order of magnitude. Ref. [20] calls for a design with 800 MeV protons, accelerated via high intensity cyclotron(s), which impinge on a carbon target and facilitate the production and eventual decay of pions: \( \pi^+ \rightarrow \mu^+\nu_\mu \), followed by \( \mu^+ \rightarrow e^+\bar{\nu}_e\nu_\mu \). A DAR source flux profile is shown in Fig. 1.

High intensity DAR sources are being proposed for CP violation searches involving Gd-doped ultra-large water Cerenkov detectors at underground science laboratories [21–23]. The design for this search [20] calls for multiple accelerator sites at varying distances from ultra-large water Cerenkov detector(s). The DAE\(\delta\)ALUS cyclotron-
**Table 1:** Coherent neutrino scattering events/ton/year (with the accelerator running at 1 MW with a 13% duty factor) for various detector layouts and thresholds. The rates are obtained by summing Eq. 1 in bins of recoil energy $T$, starting at $T_{\text{min}}$. For the aforementioned targets, we find the rates given in Table I, where we assume 100% detection efficiency.

![Recoil energy distributions for coherent scattering](image1)

**Fig. 2:** Recoil energy distributions for coherent scattering 1.5 km from a DAR neutrino source for Ne, Ar, Ge, and Xe. The rates reported assume 100% detection efficiency.
A. Detection at a Ton-Scale Dark Matter Experiment

Next, we consider one of the nuclear targets mentioned above ($^{76}$Ge) in more detail. GEODM is a proposed ton-scale dark matter detector [27] based on the cryogenic Ge crystal technology used in the CDMS experiment [31]. The target design for GEODM is an array of 300 ~5 kg Ge crystals operated at 40 mK with a total target mass of ~1500 kg. Interaction events in an individual crystal produce populations of athermal phonons and electron-hole pairs which are measured by various phonon and ionization sensors lithographically patterned on the crystal surfaces. The ratio of ionization to phonon signals for an event is a powerful discriminator between electron and nuclear recoils. The signals also enable precise determination of the position and energy of each event, which allow volume and energy cuts. This information is used to set the number of electron recoils that can pass the cuts and pose as nuclear recoils. This electron recoil “leakage” into the nuclear recoil band constitutes one source of background events. There is also a background from muon- and radiogenic-induced neutrons, which is controlled through the use of radio-pure materials and passive and active shields to be < 0.15 events/ton/year.

The efficiency of GEODM depends critically on the cuts used to achieve a target leakage background. This is largely a function of the future detector’s performance, which we need to estimate. In light of this, we consider a “baseline” scenario and an “optimistic” scenario for the detector parameters, summarized in Table II. Fig. 3 shows the recoil energy distribution in a detector with two hypothetical efficiency curves as a function of recoil energy. The baseline scenario has a 10 keV nuclear recoil energy threshold with the efficiency rising linearly to 0.3 at 20 keV. We additionally assume an energy resolution near threshold of 300 eV and a fiducial mass uncertainty of 5%. These parameters are consistent with the performance of the Ge detectors used in the CDMS II experiment [32]. The optimistic scenario assumes that refinement of the detectors improves all of these parameters. In the optimistic scenario, we assume a 5 keV nuclear recoil energy threshold and an efficiency that rises linearly to 0.6 at 20 keV. We also assume an energy resolution near threshold of 50 eV and a fiducial mass uncertainty of 1%. The optimistic scenario parameters are anticipated to be achieved by detectors in the SuperCDMS experiment. In all cases, unless otherwise specified, we assume a raw exposure of 4.5 ton-year before the efficiency curve is applied. We also assume a leakage background of 1 event per 4.5 ton-year raw exposure with a spectrum of $e^{-E_{recoil}/10 \text{ keV}}$, and a neutron background of 0.15 events per ton-year of exposure with a spectrum of $e^{-E_{recoil}/50 \text{ keV}}$ before the efficiency curve is applied. Events are required to have recoil energies less than 100 keV to be considered nuclear recoils, so we do not use any background events with energies exceeding 100 keV. This neutron spectrum is convolved with each efficiency curve and scaled by the exposure to obtain the expected distribution of neutron events for each scenario. For the baseline scenario we expect 0.13 total neutron events, and for the optimistic scenario we expect 0.29 total neutron events with a 4.5 ton-year exposure.

Using the baseline efficiency and energy threshold, we find that a coherent neutrino rate of 0.8 events/ton/year is expected in a $^{76}$Ge-based detector at a baseline of 2.3 km. GEODM expects an overall leakage rate of about 1 background surface leakage event with a 4.5 ton-year exposure, obtained by adjusting efficiency/fiducial volume cuts to get to that number. In addition, there is a neutron-induced nuclear recoil background (absolute rate convolved with detection efficiency) of 0.13 events/(4.5 ton-year) and 0.29 events/(4.5 ton-year) for the baseline and optimistic scenarios, respectively. The total expected background rate during the 13% of beam-on time would therefore be 0.15 events/(4.5 ton-year) for the baseline and 0.17 events/(4.5 ton-year) for the optimistic scenario. The assumptions for GEODM as a coherent neutrino detector are shown in Table III. Based on these considerations and assuming no WIMP “background”, one can see that an experiment like GEODM could find evidence for coherent scattering in a ~4.5 ton-year exposure with 3–4 signal events above a background expectation of 0.15 events. The probabil-

![Recoil energy distribution for coherent neutrino scattering on Ge at 2.3 km from a DAR neutrino source, before and after the effect of two hypothetical efficiency curves.](image)

**TABLE II:** The GEODM detector scenarios considered. The neutron background expectation is after efficiency corrections.
TABLE III: The assumptions used in the text for coherent neutrino detection with GEODM deep underground.

<table>
<thead>
<tr>
<th>Scenarios considered</th>
<th>GEODM Assumptions</th>
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</thead>
<tbody>
<tr>
<td>ν source</td>
<td>“Baseline” and “Optimistic”</td>
</tr>
<tr>
<td>ν flux uncertainty</td>
<td>4 × 10^22 ν/ flavor/year w/ 13% duty factor</td>
</tr>
<tr>
<td>Distance from ν source</td>
<td>2%</td>
</tr>
<tr>
<td>Exposure</td>
<td>2.3 km</td>
</tr>
<tr>
<td></td>
<td>4.5 ton/year</td>
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It is worth noting that the absolute (100% efficiency and 100% on-time) solar coherent neutrino interaction rate on a 76Ge target above 5 keV is expected to be 0.079 events/ton/year [33]. In either efficiency scenario and with 13% beam-on time, the solar coherent “background” rate is negligible.

B. The effect of the coherent background on WIMP sensitivity

Since coherent neutrino scattering is an irreducible background for WIMP searches, the presence of a neutrino source near a dark matter experiment will reduce the sensitivity of the experiment. In calculating a WIMP-nucleon cross section limit, one can either use data from only the 87% of the time when the neutrino source is off or data from the 87% beam-off time and the 13% beam-on time. Since background events reduce the sensitivity of a limit in the optimum interval method [34], using the combined exposure may result in a worse limit than using only the beam-off exposure. Fig. 4(a) and Fig. 4(b) present a comparison of limits for the baseline and optimistic GEODM detector scenarios. The limits assume a GEODM-style detector with a raw exposure of 4.5 ton/year before efficiency cuts and the same assumptions as in the previous section. In particular, we use the hypothetical efficiency curves shown in Fig. 3, a neutron rate of 0.15 events/ton/year before efficiency cuts and convolution, and a total surface-event leakage of 1 event per 4.5 ton-year raw exposure. We use the recoil energy distribution from Fig. 3 for neutrino events in the 13% beam-on time and a detector at 2.3 km from a DAR neutrino source.

Using these parameters, we randomly generate 100 realizations of the background events and compute the average of the upper limits on the WIMP-nucleon cross section for each. In this study, the beam-off data actually has greater sensitivity than the combined beam-on and beam-off data. Using the beam-off data with 87% exposure only, the mean upper limit at maximum sensitivity is 4.0 · 10^{-47}cm² (baseline) or 1.9 · 10^{-47}cm² (optimistic). The combined data give a limit of 5.5 · 10^{-47}cm² (baseline) or 3.6 · 10^{-47}cm² (optimistic). The results for the 87% exposure obviously also have worse sensitivity than 100% exposure without any beam-on time. If there were no beam-on time, the upper limit at maximal sensitivity would be 3.3 · 10^{-47}cm² (baseline) or 1.7 · 10^{-47}cm² (optimistic).

Note that when the number of background events is zero, the sensitivity to WIMPs scales as the reciprocal of the exposure. This occurs because the expected number of events in an experiment is proportional to the product of the cross section σ and the exposure E,

$$\mu \propto \sigma E.$$  (3)

A limit at confidence level C is obtained by determining the expected number of events μ such that there is a probability C of observing zero events. Assuming Poisson statistics the expected number of events is μ = −log(1 − C). It is thus apparent from Eq. (3) that the cross section limit σ corresponding to confidence level C, scales as the reciprocal of the exposure E. In the presence of a nonzero background that is proportional to exposure, the limit will scale more slowly than the reciprocal of the exposure. Fixed backgrounds set by fiducial cuts may produce more complicated scaling behavior.

V. PHYSICS WITH A DETECTOR CLOSE TO THE NEUTRINO SOURCE

A suitable detector within tens of meters of the stopped pion source could gather a rather large sample of elastic neutrino coherent scatters for physics studies. The 300 ft adit at DUSEL could provide direct tunnel access to an envisioned experimental site for such a detector. The cyclotron would then be located just outside the tunnel in a building against the cliff face. As discussed earlier, a coherent cross section measurement is sensitive to a number of physics possibilities. For simplicity, we consider a flux-integrated total cross section measurement as our figure of merit. However, the shape of the cross section as a function of energy is also interesting, especially in the case that a measured total cross section is inconsistent with expectation.

Although many low-threshold nuclear-recoil-sensitive detector technologies could work (including a noble liquid detector [2, 3] or other dark matter detector technology), for concreteness we consider the specific example of a set of GEODM-derived detectors with 16.7 kg raw
mass, 20 m away from the stopped-pion neutrino source. With the optimistic efficiency estimate (Figure 3) and a fiducial mass of 10 kg, we expect a detected coherent rate of 0.74 events/(10 kg·day) within the 13% beam-on time window. The background rate design goal for such an experiment would be <0.1 events/(10 kg·day) within the same window. This rate seems reasonable with ~300 ft of rock shielding along with modest passive/active shielding immediately surrounding the detector for prompt cosmic-ray-induced background attenuation/tagging. The radiogenic background is assumed negligible, at a rate consistent with GEODM deep underground. The uncertainty on the non-beam related background estimate will easily be statistics-dominated with an in-situ background measurement during beam-off. We also assume that there are no background events from neutrons produced by the DAR neutrino source at a 20 m baseline with 17 m rock and 3 m Fe shielding. This assumption was justified by performing a Geant4 [35] simulation of an isotropic neutron source along a 20 m baseline, fitting the flux at various distances from the neutron source to the functional form

\[ F(z) = \frac{A e^{-z/\lambda}}{z^2}, \]

where \( A \) and \( \lambda \) are fit parameters and \( z \) is the distance along the baseline. The rate from this fit was extrapolated to 20 m distance and a 50 kg-year exposure, and the number of neutron events was found to be negligible. The neutron flux and spectrum used were taken from the SNS source, which is similar to the DAR source discussed here [36].

A 50 kg-year exposure with the previously described experimental design would yield about 1350 coherent events, assuming a coherent cross section consistent with the Standard Model. With an optimistic 1% uncertainty on the target mass, 0.1 background events/(10 kg·day) with statistical-only error, 2% absolute flux normalization uncertainty, and a 0.5% uncertainty on the energy resolution near threshold, a flux-averaged total cross section measurement with <5% (statistical and systematic) uncertainty would be achieved. The assumptions that went into the event rate and cross section measurement uncertainty estimates are summarized in Table IV.
VI. CONCLUSIONS

Coherent elastic neutrino-nucleus scattering has never been observed. Relevant for supernova evolution, supernova-burst neutrino detection, probing non-standard neutrino interactions, and measuring $\sin^2\theta_{13}$ with neutrinos at low-$Q$, among other topics [39], the process is very well predicted by the Standard Model and confirmation of the $\sim 5\%$ precision theoretical cross section prediction is needed.

Dark matter detectors can double as coherent neutrino scattering experiments as the products of WIMP and coherent scattering interactions are predicted to be nearly identical. In the case of a decay-at-rest neutrino source and a suite of dark matter experiments at the same site, the deep underground detectors would have merely need to receive a beam timing signal in order to participate in the coherent search. Furthermore, these detectors would receive a free dark matter detection consistency check in the form of non-WIMP rare events in a well-known time window—all with a modest cost to the WIMP analysis/exposure. The power of this consistency check is strongly dependent on the number of coherent neutrino events collected, a value which is expected to be fairly low in most configurations. In both optimistic and baseline detection scenarios, the best limit on the WIMP-nucleon cross section uses only data from the period when the DAR source is off. In the optimistic scenario, the cross section limit is only about 12% weaker than if no neutrino source were present.

A coherent neutrino interaction discovery in GEODM could be achieved with a 2 ton-year exposure. About 20 detected coherent neutrino events/ton/year over a background of 0.03 events/ton/year are expected in a GEODM-style detector at a 2.3 km baseline, given optimistic assumptions for energy threshold and detection efficiency. Even in a conservative (baseline) scenario, with energy threshold and efficiency reasonably consistent with CDMS II, evidence for coherent neutrino scattering could be obtained with a 4.5 ton-year exposure. In addition, a 10 kg fiducial mass GEODM-derived detector brought within 20 m of the neutrino source could collect about 1350 events with a 50 kg-year exposure. Such a sample would be good for a $<5\%$ flux-averaged total cross section measurement uncertainty and significant tests of the Standard Model.

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Coherent scattering has even been envisioned as a nuclear reactor monitoring tool [37][38].