Neutrino Backgrounds to Dark Matter Searches

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Neutrino coherent scattering cross sections can be as large as 10^{-39} cm^2, while current dark matter experiments have sensitivities to WIMP coherent scattering cross sections five orders of magnitude smaller; future experiments plan to have sensitivities to cross sections as small as 10^{-48} cm^2. With large target masses and few keV recoil energy detection thresholds, neutral current coherent scattering of solar neutrinos becomes an irreducible background in dark matter searches. In the current zero-background analysis paradigm, neutrino coherent scattering will limit the achievable sensitivity to dark matter scattering cross sections, at the level of 10^{-46} cm^2.

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I. INTRODUCTION

Dark matter comprises approximately 25% of the mass of the universe [1], yet its particle properties are unknown. Dark matter is observed to interact gravitationally, from which its density is inferred to be between 0.4 and 0.7 (GeV/c^2) per cm^3, and its average velocity $<v> \simeq 230$ km/s [2]. The leading dark matter particle candidate is the lightest predicted supersymmetric particle, the LSP. Supersymmetry predicts that the LSP interacts weakly with atomic nuclei, that the LSP mass is in the range of 10 to 10^4 GeV/c^2, and that the cross section lies in the range of 10^{-42} to 10^{-48} cm^2 [3]. Collider experiments have mostly excluded masses below 80 GeV/c^2 and cross sections larger than $\sim 10^{-42}$ cm^2 in minimal supersymmetric models [3].

Direct detection experiments search for dark matter particles using the coherent elastic scattering process. Ordinary neutrinos of energy around 10 MeV also interact coherently with atomic nuclei, causing the nucleus to recoil with energies up to tens of keV. Such recoils would be indistinguishable from dark matter interactions. The scale of the ambient neutrino flux in this energy range is 10^6 per cm^2 per second, and the coherent neutrino-nucleus cross section is of order 10^{-39} cm^2.

In this paper, we estimate background rates in dark matter detectors caused by coherent neutrino-nucleus elastic scattering of ambient neutrinos. We find that ν-A coherent scattering produces 10-100 background events in experiments with few keV thresholds and ton-year exposures. In the prevalent zero-background analysis method, this translates into a fundamental lower bound of roughly 10^{-46} cm^2 on the dark matter cross section sensitivity achievable by direct detection experiments.

II. DARK MATTER DETECTION

Many experiments seek to detect dark matter particles via their elastic scattering interactions with detector nuclei [4]. The current experimental method is to set upper limits on the dark matter scattering cross section based on the observation of zero signal events, using the Yellin gap technique [5]. This statistical procedure optimizes the upper limit an experiment can set, at a given confidence level, by finding the largest possible region of parameter space which contains zero background events. In a statistically unbiased way, this method effectively turns any experiment with low background rates into a "zero-background" experiment, albeit over a restricted region of the experiment's acceptance. The more background events an experiment has, the smaller the "gap" between events, and the worse the sensitivity. Using this approach, recent observations [6, 7] limit the magnitude of the scattering cross section to be less than approximately 10^{-43} cm^2. This corresponds roughly to one background event per kilogram of detector fiducial mass per day of detector live time.

Dark matter experiments search for a very rare signal process which is detected via the observation of recoiling nuclei with kinetic energies as low as 2 keV [6]. Current experiments with masses of 10 kg have zero-background cross section sensitivities of 10^{-44} cm^2, and project that spanning the predicted range of LSP interaction cross sections requires 1 ton target masses. The expected kinetic energy distribution of recoiling nuclei is exponential, falling from zero to about 100 keV. Direct dark matter detection experiments gain significantly in sensitivity with lower recoil energy detection thresholds.

Neutrino-nucleus coherent scattering can also produce nuclear recoils with kinetic energies of a few keV, and, though coherent ν-A scattering has never been observed, the process is theoretically well understood. The calculated Standard Model cross section is relatively large, of order 10^{-39} cm^2 [8, 9]. There has been interest in

using this process to make precision weak interaction measurements at the SNS [10], to search for supernova neutrinos [11] and to measure neutrinos produced in the sun [12]. Even before direct dark matter detection experiments existed this process was anticipated as a background [13]. Here we calculate the background rates caused by ν-A coherent scattering in target materials relevant to current dark matter searches. We consider the recently-measured solar and geo-neutrino fluxes, and include the nuclear form factors in the coherent cross section calculation.

III. NEUTRINO BACKGROUNDS

Neutrino interactions are an irreducible source of background since no detector can be shielded from the ambient flux of incident neutrinos. Direct dark matter detection experiments have pushed the energy threshold frontier to a few keV, and achieved background levels of approximately 1 event/kg/keV/day. In such an environment, ν-A coherent scattering becomes observable, and a source of background to direct detection dark matter searches.

A. Neutrino Fluxes

The flux of ambient neutrinos and anti-neutrinos is large, with contributions from many sources. These include neutrinos produced in fusion reactions in the sun, anti-neutrinos produced in radioactive decays in the earth's mantle and core, atmospheric neutrinos and anti-neutrinos produced by the decays of cosmic ray collision products in the upper atmosphere, supernova relic anti-neutrinos, and man-made anti-neutrinos produced in fission processes at nuclear reactors. The fluxes of ambient sources of neutrinos and their approximate energy ranges are shown in table I. Of these, we consider solar, geo-neutrino, and atmospheric fluxes. The energy distributions of the fluxes used in our calculation are shown in figures 1, 2, and 3.

The ^{8}B solar neutrino flux is well understood. The measured normalization of the total ^{8}B solar neutrino flux agrees with the predicted flux, shown in table I, to 2% [19]. Although the predicted flux normalization has an uncertainty of 16% [14], the measured flux, including neutrino oscillations, has an uncertainty of 3.5% [20]. The geo-neutrino flux is less well known. The flux from ^{238}U and ^{232}Th decays has been measured to be approximately 4 times the predicted magnitude shown in table I, with a measurement uncertainty of 76% [21]. The atmospheric neutrino flux is measured by a number of experiments to be consistent with predictions including neutrino oscillations; the estimated normalization uncertainty is 10% for neutrino energies below 100 MeV [22]. The atmospheric flux extends over a large energy range, but only the lowest energy neutrinos are interesting here

TABLE I: Ambient sources of neutrinos. Fluxes are given in number per cm^2 per second.

Source	Predicted Flux	Energy (MeV)
[14] Solar ν pp	5.99×10^{10}	<0.4
[14] Solar ν CNO	5.46×10^{8}	<2
[14] Solar ν ^{7}Be	4.84×10^{9}	03, 0.8
[14] Solar ν ^{8}B	5.69×10^{6}	<12
[14] Solar ν h.e.p.	7.93×10^{3}	<18
[15] Geo $\overline{\nu}$ ^{238}U	2.34×10^{6}	<5
[15] Geo $\overline{\nu}$ ^{232}Th	1.99×10^{6}	<2.5
[15] Geo $\overline{\nu}$ ^{235}U	$\sim4\times10^{3}$	<2
[15] Geo $\overline{\nu}$ ^{40}K	$\sim1\times10^{7}$	<2
[16] Atmospheric $\nu+\overline{\nu}$	$O(1/E(GeV)^{2.7}))$	0-10^3
[17] Reactor $\overline{\nu}$	$O(1\times10^{20}/\text{distance}^2)$	<10
[18] Supernova Relic $\overline{\nu}$	$O(10^1)$	<60

since the coherent scattering process occurs for energies below roughly 50 MeV. The normalization of the low energy component of the atmospheric neutrino flux depends strongly on latitude because of the geo-magnetic cutoff; for example, the flux at the SNO experiment is approximately 50% larger than at Super-Kamiokande. We use the atmospheric neutrino flux prediction at Super-Kamiokande [23].

The calculations here use the predicted solar, geo, and atmospheric neutrino fluxes, without including neutrino oscillations. The coherent scattering process is neutrino-flavor independent to leading order, and we assume no sterile neutrino participation in oscillations, thus the oscillated and un-oscillated predicted neutrino fluxes are in practice equivalent for our calculation.

B. Neutrino Scattering Cross Sections

Dark matter experiments are potentially sensitive to two kinds of neutrino interactions: ν-e^- neutral current elastic scattering, where the neutrino interacts with the atomic electrons, and ν-A neutral current coherent elastic scattering, where the neutrino interacts with the target nucleus. The former process has been considered as a method for solar neutrino detection in low-threshold detectors [24]. The maximum recoil electron kinetic energy can be as large as a few hundred keV, and the cross sections are of order 10^{-44} cm^2. The latter process has never been observed since the maximum nuclear recoil kinetic energy is only a few tens of keV, however, the cross section is relatively large, approximately 10^{-39} cm^2. This work focuses exclusively on coherent ν-A scattering.

The maximum recoil kinetic energy in ν-A coherent scattering is

$$T_{max} = \frac{2E_\nu^2}{M + 2E_\nu}.$$

where E_ν is the incident neutrino energy, and M is the mass of the target nucleus. The four-momentum transfer

is related to the recoil kinetic energy by $Q^2 = 2MT$, and the three-momentum transfer q is approximately $\sqrt{2MT}$. For neutrino energies below 20 MeV and nuclear targets from ^{12}C to ^{132}Xe, the maximum recoil kinetic energy ranges from approximately 50 down to 2 keV, and therefore the maximum possible q is quite small, <1 fm^{-1}. Typical nuclear radii, R, are 3-5 fm, and therefore the product $qR < 1$. In this regime, the neutrino scatters coherently off of the weak charge of the entire nucleus, which is given by

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

where N and Z are the number of target nucleons and protons respectively, and θ_W is the weak mixing angle. Through the dependence on Q_W, coherence enhances the scattering cross section with respect to the single nucleon cross section by a factor of N^2.

The ν-A coherent scattering cross section is given by [8, 9]

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 E_\nu^2 (1 + \cos\theta) F(Q^2)^2$$

where G_F is the Fermi coupling constant, Q_W is the weak charge of the target nucleus, E_ν is the projectile neutrino energy, $\cos\theta$ is the scattering angle in the lab frame of the recoil nucleus with respect to the incoming neutrino direction, and $F(Q^2)$ is a nuclear form factor that describes the distribution of weak charge within the nucleus. In this work, we use form factors calculated for ^{12}C, ^{19}F, ^{40}Ar, ^{76}Ge, and ^{132}Xe [25]. The suppression of the cross section by the nuclear form factor is 5-10%.

The dependence of the cross section on scattering angle means that solar neutrino elastic scattering events will, in principle, point back to the sun. However, the majority of dark matter detectors do not have directional sensitivity, and so it is most useful to calculate event rates as a function of recoil nucleus kinetic energy. The scattering angle and the recoil kinetic energy are related via 2-body kinematics and the cross section can be expressed in terms of the kinetic energy, T, of the recoiling nucleus as

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

The theoretical uncertainty on the coherent ν-A scattering cross section comes from nuclear modelling in the form factor calculation; for neutrino energies of the order of 10 MeV the uncertainty is expected to be less than 10% [11].

C. Background Rates

With the neutrino fluxes and the ν-A coherent scattering cross section described above, we calculate the numbers of events per ton-year exposure as a function of recoil

TABLE II: Rate of ^{8}B solar ν-A coherent scattering events per ton-year as a function of minimum nuclear recoil kinetic energy detection threshold.

Target	T>0 keV	T>2 keV	T>5 keV	T>10 keV
^{12}C	235.7	191.8	104.1	36.0
^{19}F	378.0	204.4	88.8	13.3
^{40}Ar	804.8	231.4	21.0	<1.0
^{76}Ge	1495.0	111.5	<1.0	<1.0
^{132}Xe	2616.9	14.7	<1.0	<1.0

nucleus kinetic energy. These are shown for a ^{12}C target in figures 1, 2, and 3 for solar, geo, and atmospheric neutrinos respectively. The recoil energy spectra and integrated numbers of events over threshold as a function of recoil energy threshold are compared for ^{12}C, ^{19}F, ^{40}Ar, ^{76}Ge and ^{132}Xe in figure 4. The only significant source of events above recoil energies of 1 keV comes from ^{8}B solar neutrinos. For this source, we summarize the number of ν-A coherent scattering events per ton-year exposure for several target nuclei used in current direct detection dark matter experiments in table II. For lighter target nuclei, above a 2 keV threshold, we find that there will be a few hundred background events to dark matter searches from ν-A coherent scattering. This source of background is smaller, for the same threshold, in heavier target nuclei owing to lower allowed maximum recoil kinetic energies.

IV. DISCUSSION

For any detector medium, with a ton-year exposure and few keV recoil energy threshold, solar ν-A coherent scattering will be an irreducible background to dark matter searches, at the level of 10-100 events depending on the detector energy threshold. Under the zero-background assumption, in a counting-only analysis, these events would be mistaken for a signal. Following [2], one would expect 5-25 signal events per ton-year if the cross section were 10^{-46} cm^2. If signal and background cannot be distinguished, a background of 10-100 ν-A events per ton-year sets a lower bound on the experimental sensitivity to the true dark matter scattering cross section. Thus, there is a fundamental limit of 10^{-46} cm^2 achievable with the zero-background counting-only method.

This ν-A coherent background could be easily eliminated by requiring recoil energies greater than the allowed values for coherent ν-A scattering. Imposing a cut of $T>30$ keV for light targets, or $T>5$ keV for heavier targets, would suffice; however, this approach would reduce the sensitivity of dark matter searches approximately as $exp(-\Delta E_{th}/E_0 r)$ [2], where ΔE_{th} is the change in the recoil energy threshold, E_0 is the kinetic energy of the dark matter particle, and r is $(4m_D m_{target})/(m_D + m_{target})^2$. For example, in a ^{12}C detector, increasing the threshold from 5 to 30 keV would reduce the sensitivity by a factor

of 6 for a dark matter particle of mass $m_D = 100 \, \text{GeV/c}^2$.

Abandoning the zero-background paradigm, it may be possible to discriminate statistically against ν-A coherent scattering events using the angular distribution, or the recoil kinetic energy spectrum. An important caveat is that the sensitivity of experiments with background events increases with exposure time as $\sqrt{t}$, whereas without backgrounds the sensitivity is proportional to t. A standard technique is to search for an excess above a background expectation; in this case, the uncertainties on the rate and kinematics of solar ν-A coherent scattering become very important. If there is a sizeable signal, a fit to the recoil energy spectrum could distinguish between the slopes expected from coherent neutrino scatter-ing and a dark matter signal excess. Further, a detector with directional sensitivity and tens of events could fit in two dimensions: recoil kinetic energy vs. recoil track angle with respect to the sun.

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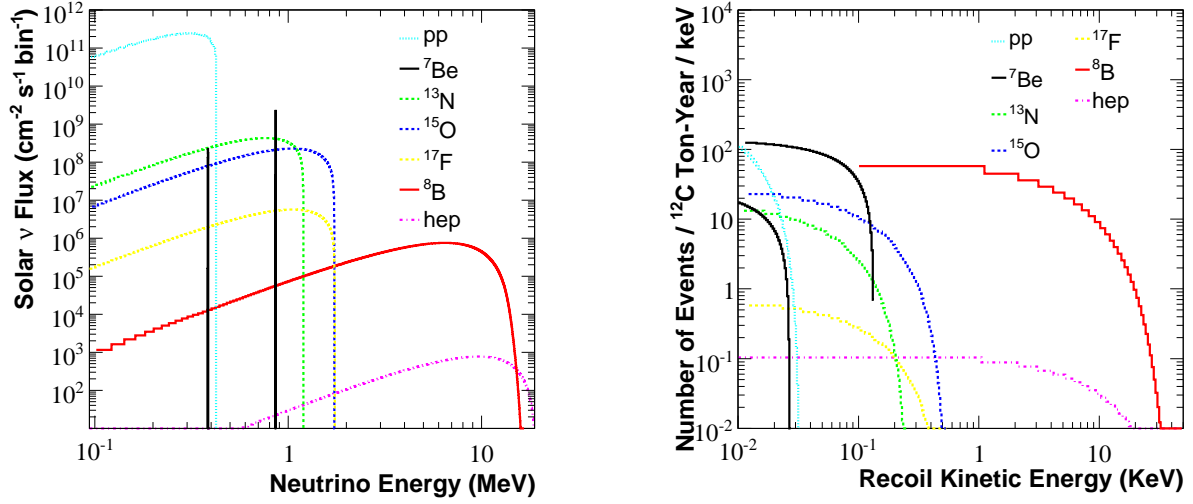
FIG. 1: Left: number of solar neutrinos per cm^2 per second per energy bin vs. neutrino energy (MeV). Right: number of solar neutrino-nucleus coherent scattering events per ^{12}C ton-year exposure, normalized per keV, vs. recoil kinetic energy (keV).
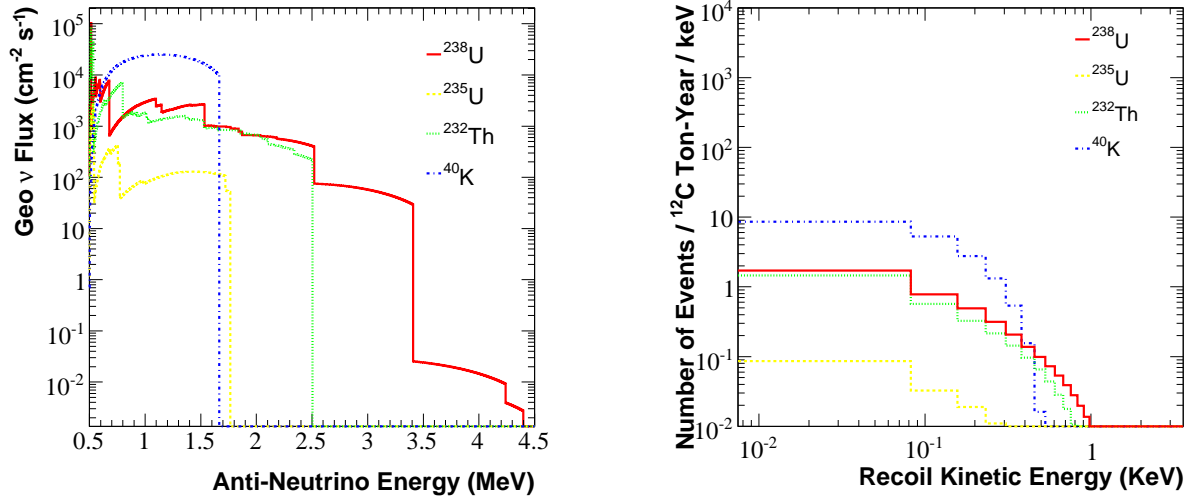

FIG. 2: Left: number of geo anti-neutrinos per cm^2 per second vs. neutrino energy (MeV). Right: number of geo neutrino-nucleus coherent scattering events per ^{12}C ton-year exposure, normalized per keV, vs. recoil kinetic energy (keV).
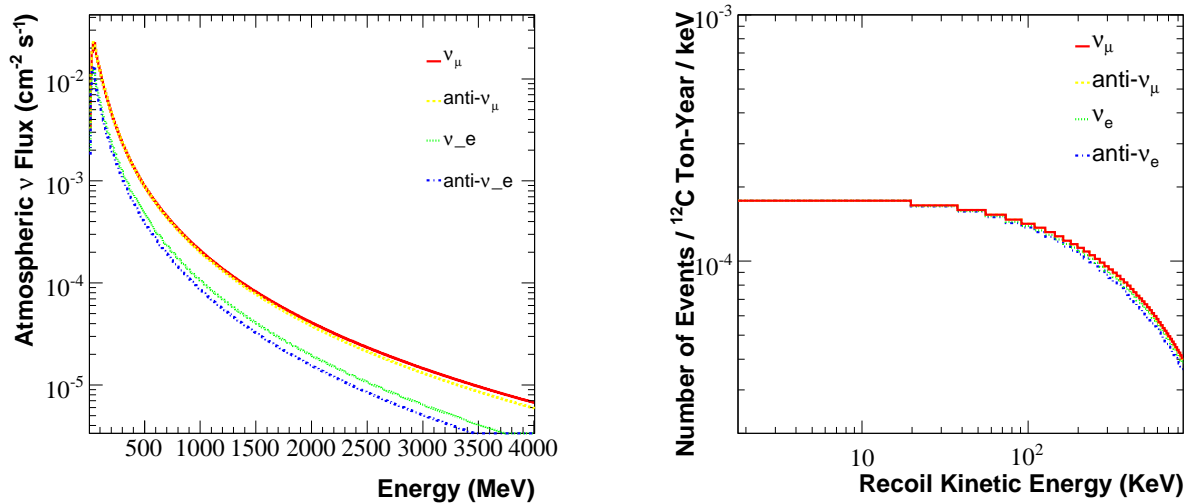

FIG. 3: Left: number of atmospheric neutrinos per cm^2 per second vs. neutrino energy (MeV). Right: number of atmospheric neutrino-nucleus coherent scattering events per ^{12}C ton-year exposure, normalized per keV, vs. recoil kinetic energy (keV).
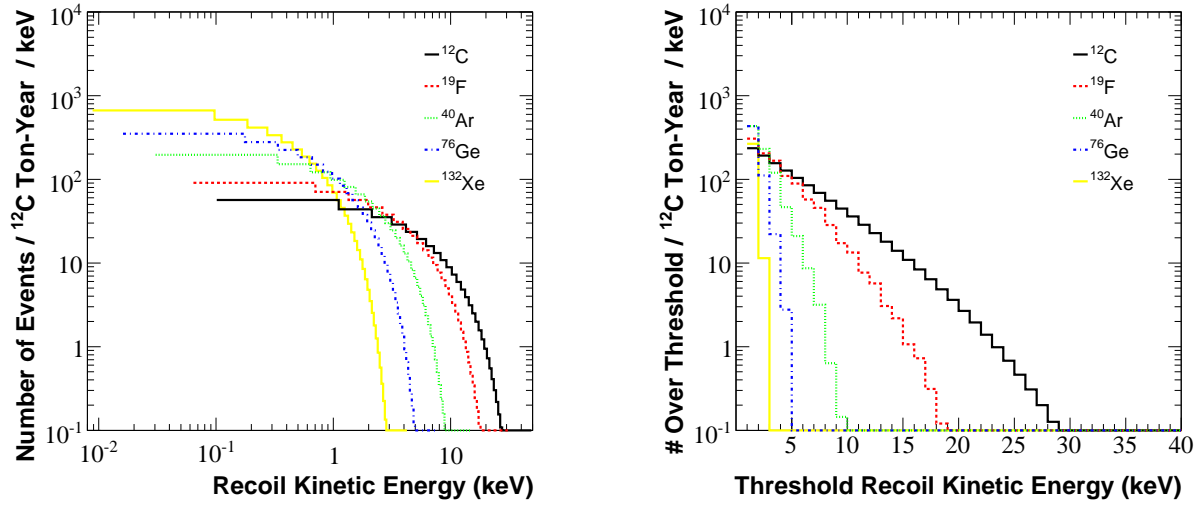
FIG. 4: Left: number of ^8B solar neutrino-nucleus coherent scattering events per ton-year exposure in various detector media, normalized per keV, vs. recoil kinetic energy (keV). Right: integrated number of neutrino-nucleus coherent scattering events above threshold per ton-year exposure in various detector media per keV vs. recoil kinetic energy threshold (keV) for ^8B solar neutrinos.