Neutrino Backgrounds to Dark Matter Searches and Directionality

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Abstract. Neutrino-nucleus 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 several orders of magnitude smaller. With large target masses and few keV recoil energy detection thresholds, coherent scattering of solar neutrinos becomes an irreducible background. Directional dark matter detection can discriminate against such backgrounds in a second observable: nuclear recoil angle. The motion of our solar system around the galactic center should produce an apparent dark matter wind. With this signal, directional detection of dark matter can provide an unambiguous observation of dark matter interactions even in the presence of backgrounds, from neutrinos and other sources. The DM-TPC collaboration and others are developing recoil direction-sensitive dark matter detectors with very promising results.

1. Introduction

The nature of dark matter is one of the key questions today in physics and astrophysics. Many experiments seek to detect dark matter particles via their elastic scattering interactions with detector nuclei [1]. Current experiments set upper limits on the dark matter scattering cross section based on the observation of zero signal events. With 10 kg-scale detectors, the scattering cross section upper limit is approximately 10^{-43} cm^2 [2]. This corresponds roughly to one background event per kilogram of detector fiducial mass per day of detector live time. Spanning the plausible range of predicted interaction cross sections will require multi-ton scale target masses [3].

Direct detection dark matter experiments search for $\chi N \rightarrow \chi N'$ scattering, a very rare signal process which is identified by observing recoiling nuclei N' with kinetic energies as low as 2 keV [2]. Many backgrounds can fake this signature, including photon-electron scattering, neutron scattering, and radioactive decays of detector nuclei. It has recently been pointed out that neutrino-nucleus coherent elastic scattering is also a background to direct dark matter detection [4]. The $\nu N \rightarrow \nu N'$ cross section can be as large as 10^{-39} cm^2 [5], producing nuclear recoils with kinetic energies up to tens of keV. It is impossible to veto or shield a detector from incident neutrinos, and so for experiments with large target masses and few-keV recoil energy detection thresholds, coherent neutrino scattering represents an irreducible background.

However, even in the presence of backgrounds, directional detection can provide an unambiguous observation of dark matter interactions. The motion of the sun, and therefore our solar system, around the galactic center should produce an apparent dark matter wind.

This wind is detectable as diurnal modulations of the magnitude and direction of a dark matter interaction signal in a terrestrial detector. In contrast, backgrounds are expected to be relatively isotropic. In this way, directional detection can discriminate against backgrounds, including those from neutrino-nucleus scattering. It is very challenging experimentally to measure the direction of a low energy nuclear recoil. Several groups are now working to develop a detector with the capability of directional dark matter detection.

2. Neutrino Backgrounds to Direct Dark Matter Detection

Neutrino interactions are an irreducible source of background since no detector can be shielded from the ambient flux of incident neutrinos. This flux of 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, and supernova relic anti-neutrinos. Of these, solar neutrinos from the ^8B fusion chain ($\Phi \sim 5 \times 10^6\ \nu/cm^2/s$) are the dominant source of background for direct dark matter detection experiments, because of their high energies, up to 12 MeV, and large abundance.

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 $\nu - N$ 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 [6]. The maximum recoil electron kinetic energy can be as large as a few hundred keV, but the cross section is 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, of order 10^{-39} cm^2.

Neutrino-nucleus coherent scattering, $\nu N \to \nu N'$, can produce a signal with an identical final state to a dark matter scattering interaction, $\chi N \to \chi N'$, since neither the neutrino nor the dark matter particle are observable in the detector, leaving only the recoiling nucleus N'. The maximum recoil kinetic energy in $\nu - N$ coherent scattering is

$$T_{max} = \frac{2E_\nu^2}{M + 2E_\nu}. \tag{1}$$

where E_ν is the incident neutrino energy, and M is the mass of the target nucleus. For neutrino energies below 20 MeV and nuclear targets from ^{12}C to ^{132}Xe, the maximum recoil kinetic energy ranges from 50 keV down to 2 keV. As for dark matter scattering, the coherent $\nu - N$ cross section is enhanced by a factor of $\sim A^2$, where A is the number of target nucleons. The coherent cross section is suppressed by a nuclear form factor as $F(Q)^2$, where $F(Q)$ falls off steeply with momentum transfer Q. For estimating backgrounds to direct detection dark matter experiments, we use form factors calculated for ^{12}C, ^{19}F, ^{40}Ar, ^{76}Ge, and ^{132}Xe from [8]. The suppression of the cross section by the nuclear form factor is 5-10%.

Even before direct dark matter detection experiments existed this process was anticipated as a background [7]. With the neutrino fluxes and the $\nu - N$ coherent scattering cross section described above, we calculate numbers of events per ton-year exposure as a function of recoil nucleus kinetic energy, for target materials relevant to current dark matter searches. We find that the only significant contribution comes from the solar ^8B neutrino flux. The 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 targets in table 1. 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 $\nu - N$ coherent scattering. This source of background is an order of magnitude smaller, for the same threshold, in heavier target nuclei owing to lower allowed maximum recoil kinetic energies. In

Table 1. Rate of ^{8}B solar $\nu - N$ 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

a counting analysis, using only the measured recoil energy, these events would be mistaken for a signal. Following [9], one would expect 5-25 dark matter signal events per ton-year if the cross section were 10^{-46} cm^2. If signal and background cannot be distinguished, this $\nu - N$ background sets a lower bound of approximately 10^{-46} cm^2 on the experimental sensitivity to the true dark matter scattering cross section.

This $\nu - N$ coherent background could be easily eliminated by requiring recoil energies greater than the allowed values for coherent $\nu - N$ scattering. However, the expected kinetic energy distribution of recoiling nuclei from dark matter interactions is exponential, and therefore direct dark matter detection experiments gain significantly in sensitivity with lower thresholds. A more promising discriminant is scattering angle. The coherent scattering cross section depends on scattering angle as $d\sigma/d\cos(\theta) \sim \cos(\theta)$, which means that solar neutrino elastic scattering events will, unlike dark matter interactions, point back to the sun. To take advantage of this, a dark matter detector needs directional sensitivity.

3. Directionality and DM-TPC

A recent development in direct dark matter detection has been the pursuit of detector sensitivity in a second dimension: the nuclear recoil angle. The WIMP-nucleus interaction signal is expected to be highly anisotropic in recoil direction because of the earth's motion with respect to the WIMP halo [14]. In contrast, the backgrounds of most WIMP experiments are fairly isotropic in recoil angle in the detector coordinate system, and therefore this experimental approach provides increased discrimination against backgrounds. Most importantly, directional detection can positively identify the dark matter origin of a nuclear recoil signal through correlation with the astrophysical source.

Directional detection has the potential for significant impact on direct dark matter search sensitivity. In the absence of a dark matter signal, but in the presence of backgrounds, two-dimensional detection (recoil energy and direction) can potentially improve upon a one-dimensional (recoil energy only) limit by an order of magnitude for WIMP masses below 100 GeV [15]. This occurs largely because of the power of the angular distribution to discriminate between a dark matter signal and an isotropic background angular distribution. In the event of a positive signal, the recoil direction should exhibit 30-100% diurnal modulations, in contrast to the 2-10% annual modulation accessible to experiments which measure only recoil energy [14]. It is estimated that a 90% confidence level detection of anisotropy in the dark matter sky requires 5-100 events; the range corresponds to various assumptions about detector configuration [16].

Several groups are developing directional dark matter detectors [10, 11, 12, 13]. In all of these, the target medium is a low pressure gas, inside a time projection chamber with drift and proportional amplification regions, instrumented with finely segmented readout. The motivation for this type of detector design is to reconstruct the full track of the nuclear recoil. This requires very low density targets; for example, in 100 $torr$ of CF_4, a 40 keV nuclear recoil travels only 1 mm before ranging out. In contrast, current experiments with liquid or solid targets can detect only total energy deposition because nuclear recoils travel $< \mu m$ distances. Reconstructing the direction of a low-energy nuclear recoil track requires readout segmented at the scale of ~100 μm to get sufficient resolution; a variety of readout schemes are employed, including MWPC charge and time readout [10], micro-pattern pads with GEM amplification [11], micromegas [12], and CCD imaging of scintillation photons created in a wire-mesh amplification region [13].

R&D towards directional dark matter detection has recently made great progress. The DM-TPC collaboration has demonstrated direction and energy reconstruction of low-energy nuclear recoils, from a ^{252}Cf source, with 10% and 15% resolution respectively at 100 keV [13]. With this level of detector performance, it is possible to correlate a dark matter candidate signal with its astrophysical source [16]. The NEWAGE collaboration has set a spin-dependent dark matter limit using directionality, with an unshielded detector on the surface, which is now operating underground [**?**]. DRIFT [10], NEWAGE, and DM-TPC have all measured electron background rejection at the level of 10^{-6}, using range vs. deposited energy to discriminate. This is a strength of gas detectors relative to current experiments, for which electron backgrounds are a limiting factor in sensitivity. However, gas requires much larger detectors to achieve large target mass. For spin-dependent dark matter scattering sensitivity, several groups project that a 1 m^3 directional CF_4 detector could achieve the world's best $\sigma_{\chi-p}$ limit, at $\sim 10^{-1}$ pb [**?**, 13]. For competitive sensitivity in the spin-independent channel, 10^{-8} pb, a DM-TPC detector would occupy ~200 m^3 [13]. To probe the full range of theoretically favored cross sections, a directional dark matter detector would be of the scale of current large neutrino detectors.

4. Conclusions

The next generation of dark matter experiments may be able to observe neutrino-nucleus coherent elastic scattering of solar neutrinos. While exciting, because this process has never been seen, it would be indistinguishable from dark matter interactions and therefore a limiting background, at the level of $\sim 10^{-46}$ cm^2. However, these events should point back to the sun, and therefore directional dark matter searches could uniquely reject neutrino backgrounds. There has been great progress recently in developing directional dark matter detectors, with the goal of positively identifying a dark matter candidate signal by correlation with its astrophysical source.

References

[1] R. J. Gaitskell, *Ann. Rev. Nucl. Part. Sci.* **54** 315 (2004)
[2] J. Angle *et al.*, [arXiv:0706.0039] (2007), Z. Ahmed *et al.*, [arXiv:0802.3530] (2008)
[3] J. R. Ellis, K. A. Olive, Y. Santoso, V. C. Spanos, *Phys. Rev. D* **71** 095007 (2005)
[4] J. Monroe, P. Fisher, *Phys. Rev. D* **76** 033007 (2007)
[5] D. Z. Freedman, D. N. Schramm, D. L. Tubbs, *Annu. Rev. Nucl. Sci.* **27** 147 (1977)
[6] J. N. Bahcall, M. Kamionkowski, A. Sirlin, *Phys. Rev. D* **51** 6146 (1995)
[7] A. K. Drukier, K. Freese, D. N. Spergel, *Phys. Rev. D* **33** 3495 (1986)
[8] C. J. Horowitz, B. D. Serot, *Nucl. Phys. A* **368** 503 (1981)
[9] J. D. Lewin, P. F. Smith, *Astropart. Phys.* **6** 87 (1996)
[10] S. Burgos *et al.*, *Astropart. Phys.* **28** 409 (2007)
[11] K. Miuchi *et al.*, *Phys. Lett. B* **654** 58 (2007)
[12] D. Santos *et al.*, *J. Phys. Conf. Ser.* **65** 012012 (2007)
[13] D. Dujmic *et al.*, *Astropart. Phys.* **30** 58 (2008)
[14] D. N. Spergel, *Phys. Rev. D* **37** 1353 (1988)
[15] S. Henderson, J. Monroe, P. Fisher, *Phys. Rev. D* **78** 015020 (2008)
[16] A. M. Green, B. Morgan, *Astropart. Phys.* **27** 142 (2007)