The neutrino floor at ultra-low threshold

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By lowering their energy threshold direct dark matter searches can reach the neutrino floor with experimental technology now in development. The ^7Be flux can be detected with ~ 10 eV nuclear recoil energy threshold and 50 kg-yr exposure. The *pep* flux can be detected with ~ 3 ton-yr exposure, and the first detection of the CNO flux is possible with similar exposure. The *pp* flux can be detected with threshold of $\sim$ eV and only $\sim$ kg-yr exposure. These can be the first pure neutral current measurements of the low-energy solar neutrino flux. Measuring this flux is important for low mass dark matter searches and for understanding the solar interior.

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I. INTRODUCTION

Particle dark matter with mass near the weak scale has long provided a compelling and testable cosmological paradigm [1]. Direct dark matter searches have especially strong bounds on particles of mass $\sim$ 10 GeV - 1 TeV [2, 3], with expected improvement from various experiments in the near future. In addition to improving sensitivity for dark matter in this mass range, there is ample theoretical and experimental motivation to expand the search window. Of particular interest is dark matter with mass $\lesssim 10$ GeV, below which experimental limits have recently improved [4–6] and there has been renewed theoretical emphasis [7, 8].

Direct dark matter searches will sooner or later be confronted by the "neutrino floor," which is due to interactions of astrophysical neutrinos [9–11]. In particular, a $\lesssim 10$ GeV particle induces a signal in an energy regime that overlaps with the solar neutrino signal. Indeed a major focus of recent discussion is the ^8B component of the solar neutrino flux, which mimics an ~ 6 GeV dark matter particle in future detectors [9]. As detectors further lower their thresholds and become sensitive to even lighter dark matter, lower energy components of the solar neutrino flux, such as *pp*, ^7Be, *pep* and *CNO*, will become detectable. Dark matter searches with thresholds low enough to be sensitive to these solar neutrino flux components will see a "raised" neutrino floor, corresponding to dark matter with spin-independent cross section $\sim 10^{-45}$ cm^2 [9].

Identifying the neutrino floor is important not only for low mass dark matter searches, it is independently important for understanding the solar metallicity problem and in searches for new physics [12]. Recent modeling suggests a lower abundance of metals in the solar core, i.e. a low-Z Standard Solar Model (SSM) [13], in comparison to the previously established high-Z SSM [14]. Though some solar neutrino experiments favor a high-Z SSM, a global analysis of all solar neutrino fluxes remains inconclusive [15, 16].

In this paper we discuss the prospects for reaching the neutrino floor with ultra-low threshold dark matter detectors sensitive to nuclear recoils $\sim$ eV. We calculate the detector mass required to measure the low-energy components of the solar neutrino flux, and discuss the complementarity with existing measurements of solar neutrinos.

II. LOW ENERGY SOLAR NEUTRINOS

Four components of the solar neutrino flux have now been directly measured: $p + p \rightarrow {}^2H + e^+ + \nu_e$ (*pp*), $p + e^- + p \rightarrow {}^2H + \nu_e$ (*pep*), $^8B \rightarrow {}^8Be^\star + e^+ + \nu_e$ (^8B), and $^7Be + e^- \rightarrow {}^7Li + \nu_e$ (^7Be). The *pp*/*pep* components provide a direct measure of the solar energy generated from the fusion chain, which accounts for $\sim$ 99% of the solar energy output. The ^7Be (^8B) fluxes directly measure the respective contributions from the ppII (ppIII) chains. The spectrum of *pep* neutrinos is a thermally-broadened line at 1.44 MeV. There are two thermally-broadened lines associated with ^7Be neutrinos, one at 0.86 MeV with $\sim$ 90% branching fraction and a one at 0.38 MeV with $\sim$ 10% branching fraction.

The rate of elastic neutrino-electron interactions from the 0.86 MeV ^7Be line was measured by the solar neutrino spectroscopy experiment Borexino [17, 18]. The equivalent ν_e-electron flux, which is calculated assuming that the observed rate is due only to electron neutrino interactions, is $(2.79 \pm 0.13) \times 10^9$ cm^{-2} s^{-1} [18]. Assuming the MSW solution for ν_e transition to other flavors and the high-Z SSM, this corresponds to a survival probability of $P_{ee} = 0.51 \pm 0.07$, and the deduced SSM flux is $(4.43 \pm 0.22) \times 10^9$ cm^{-2} s^{-1}. This measurement is consistent with the high-Z SSM, which predicts a 0.86 MeV ^7Be flux of $4.47(1 \pm 0.07) \times 10^9$ cm^{-2} s^{-1} [14], and disfavors the low-Z prediction of $4.08(1 \pm 0.07) \times 10^9$ cm^{-2} s^{-1} [13]. The uncertainties on these theoretical fluxes are due to variations of the SSM parameters.

Borexino has also measured the flux from the *pep* reaction, again from elastic neutrino-electron interactions [18, 19]. For *pep* neutrinos the equivalent ν_e-electron flux is $(1.00 \pm 0.22) \times 10^8$ cm^{-2} s^{-1}. Assuming the MSW solution for ν_e transition to other flavors, the survival probability at 1.44 MeV is $P_{ee} = 0.62 \pm 0.17$, and the deduced SSM flux is $(1.63 \pm 0.35) \times 10^8$ cm^{-2} s^{-1}. The *pep* flux measured by Borexino is consistent with both the high and low-Z SSMs, though the predicted *pep* flux is relatively insensitive to solar metallicity. Because

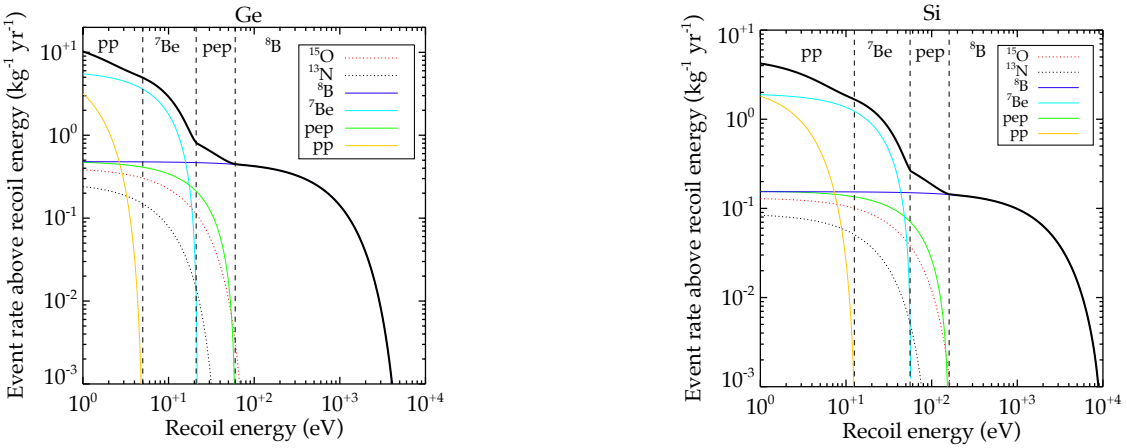

FIG. 1: Integrated number of events above a nuclear recoil threshold energy from coherent scattering due to solar neutrinos in a Ge (left) and Si (right) detector. The black solid curve is the sum of all components. The vertical dashed lines indicate the energy regions over which a particular flux component is dominant.

the *pep* flux is closely related to the solar luminosity and to the *pp* flux, there is a low theoretical uncertainty on the *pep* flux of ~ 0.01.

Borexino has recently reported the first direct measurement of the *pp* neutrino spectrum [20]. Assuming the MSW solution, the deduced SSM flux is $(6.6 \pm 0.7) \times 10^{10}$ cm^{-2} s^{-1}. This is in agreement with the predictions of both the high-Z (5.98×10^{10} cm^{-2} s^{-1}) and low-Z SSM (6.03×10^{10} cm^{-2} s^{-1}). Again the small variation in these predictions is because the *pp* flux is directly related to the solar luminosity and has a theoretical uncertainty of only ~ 0.006.

In addition to the ^{7}Be, *pep*, and *pp* measurements, Borexino has placed an upper bound of $< 7.7 \times 10^{8}$ cm^{-2} s^{-1} on the sum of all components that contribute to the CNO flux. This corresponds to a ratio of the flux with respect to the high-Z SSM prediction of < 1.5. There is a relatively large theoretical uncertainty (~ 0.15) on the CNO neutrino flux, and it is very sensitive to the solar metallicity.

III. ANALYSIS

In this paper we are interested in detecting solar neutrinos via coherent neutrino-nucleus scattering (CNS) using direct dark matter detection experiments. Because it is a neutral current interaction, the detection of CNS would provide the first direct measurement of the SSM flux and thus a direct measurement of the survival probability for the low-energy solar neutrino spectrum. (Recall that the SNO experiment was sensitive to neutral current interactions of the high-energy ^{8}B flux [21].) We assume pure Standard Model (SM) contributions to the CNS cross section (see Refs. [22, 23] for discussions of beyond the SM contributions to the cross section). We further assume the standard three neutrino flavors, which implies that we do not need to account for flavor mixing. We specifically consider ultra-low threshold Ge and Si detectors, whose feasibility has been recently discussed elsewhere [24].

Figure 1 shows the nuclear recoil energy spectrum from solar neutrinos, highlighting the ultra-low threshold regime down to $\sim$ eV. Going from high to low nuclear recoil energy threshold, the event rate is dominated by ^{8}B, then *pep*, ^{7}Be, and finally *pp* solar neutrinos. The most prominent rise in the event rate occurs when the ^{7}Be window opens up, corresponding to a nuclear recoil energy threshold of $\sim$ 20 eV in Ge, and $\sim$ 50 eV in Si. Smaller increases arise in the transition from the ^{8}B to *pep*-dominated recoil energy region, and the ^{7}Be to the *pp*-dominated recoil energy region. The CNO flux, which we take as the sum of the ^{15}O and ^{13}N components, contributes as a subdominant component in an energy region overlapping with *pep* neutrinos. (Note that we do not consider the ^{17}F component of the CNO flux, which makes a negligible contribution to the event rate.)

Since several flux components contribute to the energy regions in Figure 1, a multi-component spectral analysis is required to detect a particular flux component. To determine the detection prospects, we define a poisson likelihood function in the recoil energy bins and have

$$F_{\alpha\beta} = \sum_{\imath=1}^{n} \frac{T_{exp}^{2}}{N_{\imath}^{tot}} \frac{N_{\alpha\imath}}{f_{\alpha}} \frac{N_{\beta\imath}}{f_{\beta}}, \qquad (1)$$

where the sum is over n recoil energy bins, $N_{\alpha\imath}$ is the predicted rate in the $\imath^{th}$ energy bin from a flux component, and f_{α} are the flux normalizations for each component of the solar neutrino spectrum, so that in our case $\alpha = pp, {}^{7}Be, pep, CNO$ and ^{8}B. The total number of events from all flux components is $N_{\imath}^{tot}$, and the exposure, T_{exp}, is the mass of the detector times the run time of the experiment. The one-sigma uncertainty on the flux normalization f_{α} is $\sqrt{(\mathbf{F}^{-1})_{\alpha\alpha}}$.

Motivated by developing detector technology with excellent energy resolution [24], we examine the event rate

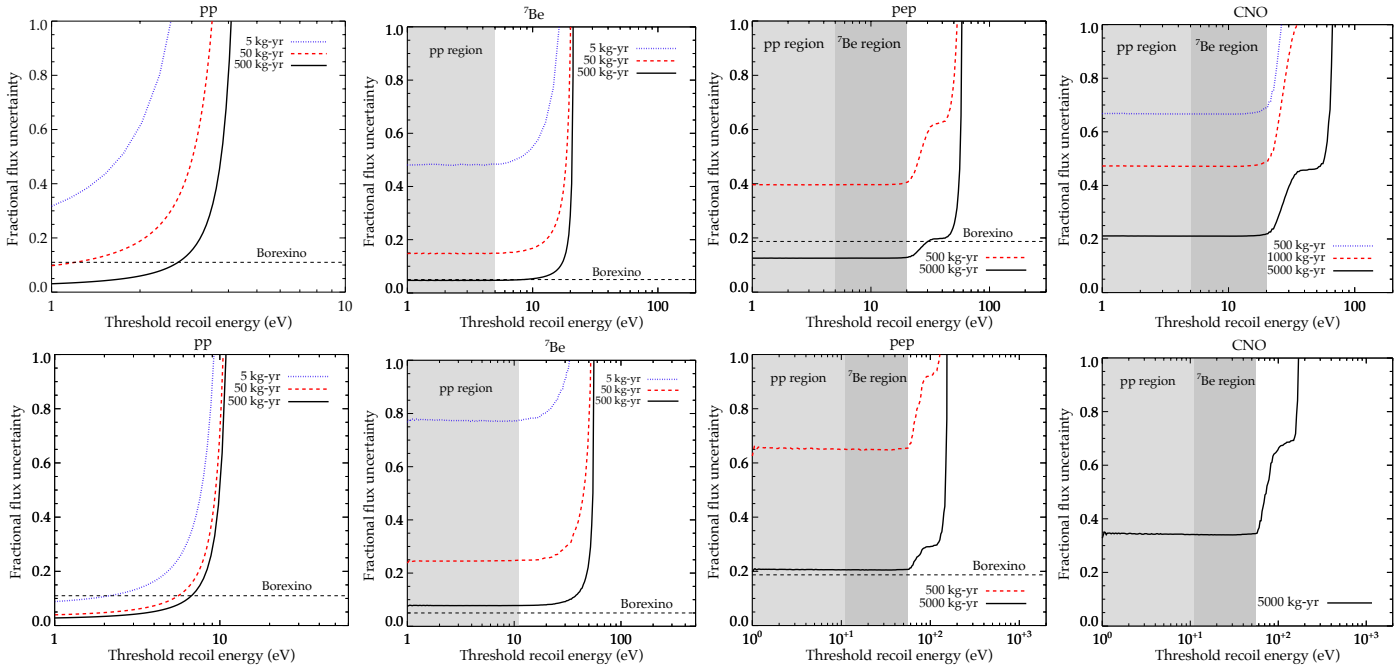

FIG. 2: Fractional flux uncertainty (Δf) on the *pp*, ^7Be, *pep*, and *CNO* components as a function of threshold nuclear recoil energy. The top row is for Ge, and the bottom row is for Si. For the *pp*, ^7Be, and *pep* panels, the Borexino sensitivity is indicated. In the ^7Be, *pep*, and *CNO* panels, energy regions where the *pp* signal dominates is shaded light grey. In the *pep* and *CNO* panels, energy regions where the *pp* signal dominates is shaded light grey, and energy regions where the ^7Be signal dominates is shaded dark grey. Note the difference in energy ranges between the panels, and the different curves in each panel correspond to different exposures.

in nuclear recoil energy bins of width $\sim$ eV. We quote results in terms of the fractional uncertainty on the flux normalization, Δf, and quantify how the measurement of Δf for each component improves with decreasing nuclear recoil energy threshold and increasing exposure.

For our fiducial model we assume the high-Z SSM for the flux normalizations. Figure 2 shows Δf for the *pp*, ^7Be, *pep*, *CNO* fluxes as a function of threshold nuclear recoil energy for different exposures T_{exp}. In all cases there is a dramatic improvement in the measurement of Δf as the threshold is dropped into the regimes where each respective flux component dominates (Figure 1). For *pp* neutrinos, a Si detector reaches the Borexino sensitivity for a threshold $\lesssim 3$ eV and an exposure ~ 5 kg-yr, while a Ge detector reaches the Borexino sensitivity for the same threshold and an exposure ~ 500 kg-yr. It should be emphasized that the Borexino measurement is neutrino-electron scattering, which is due mostly to charged-current interactions. A CNS measurement would thus represent the first pure neutral current detection of these flux components.

For the ^7Be flux, a ~ 50 kg-yr Ge exposure with ~ 10 eV threshold will result in a detection with $\Delta f \simeq 0.15$. At this same threshold, ~ 500 kg-yr exposure with Ge will match the Borexino sensitivity, $\Delta f \simeq 0.05$. For Si, ~ 50 kg-yr exposure with a ~ 30 eV threshold will result in a detection with $\Delta f \simeq 0.25$, and a $\gtrsim 500$ kg-yr exposure matches the Borexino sensitivity. Thus for $\gtrsim 1$ eV threshold, a Si detector is most sensitive to the *pp* flux, while a Ge detector is most sensitive to the ^7Be flux.

The *pep* and *CNO* fluxes are prominent at energies lower than ^8B, but higher than ^7Be. Though the *pep* and *CNO* spectral shapes are different, their flux normalizations are correlated in a multi-component analysis. This is evident in Figure 1 which indicates a brief saturation as the threshold is lowered before Δf is ultimately minimized. For the *pep* flux, we find that a ~ 500 kg-yr Ge exposure with ~ 10 eV threshold will measure normalization to a fractional uncertainty of ~ 0.4. This exposure will provide a $\sim 2\sigma$ detection of the *CNO* flux. Increasing the exposure to 5 ton-yr will match the Borexino charged current sensitivity to the *pep* flux, and also attain $\Delta f \sim 0.2$ on the *CNO* flux.

IV. DISCUSSION AND CONCLUSION

We have examined the potential for direct dark matter searches to reach the neutrino floor with detector mass similar to those under development and with ultra-low energy thresholds, as low as $\sim$ eV. These detectors, such as e.g. SuperCDMS [4], will be sensitive to dark matter with mass $\sim$ GeV. For reasonable detector mass ~ 50 kg-yr, a threshold of $\sim 10\,(30)$ eV in Ge (Si) will measure the ^7Be solar neutrino flux. Approximately an order of

magnitude larger mass detectors will be sensitive to *pep* and CNO neutrinos. For a threshold of a few eV, the *pp* flux can be identified in both Si and Ge.

Identifying and measuring the neutrino floor in direct dark matter searches is of obvious importance for studying low mass dark matter. It also represents an important step in the continuing development of the solar neutrino program, dating back to over half of a century. The detector technology discussed in this paper will establish the first pure neutral current detection of all the low energy components of the solar neutrino flux, which will be the first direct and model independent measurement of the neutrino survival probability in the vacuum-dominated regime. The excellent energy resolution will in addition provide the first measurement of the energy dependence of the survival probability, which can have important implications in searches for new physics.

If the technology discussed here were to reach ton-scale mass, it will establish the first measurement of neutrinos from the CNO cycle. This is a long sought-after component of the solar neutrino spectrum that generates $\sim 1\%$ of solar energy. A measurement of CNO neutrinos will be important for understanding the solar abundance problem and for understanding the fusion process in main-sequence stars more massive than the Sun. Current scintillation detectors such as Borexino are limited in measuring the CNO flux because of muon induced backgrounds, though current designs may improve upon this present situation [25].

This analysis has focused on the detection of nuclear recoil events. Future direct dark matter searches will also be sensitive to dark matter and neutrino scattering off of electrons. (For ideas to detect electrons with even lower energies than discussed here see Ref. [26].) The major sensitivity is to *pp* neutrinos, for which the integrated event rate above 1 keV electron recoil energy is ~ 4 kg^{-1} yr^{-1}, and the rate remains constant down to eV energies. Over this same electron recoil energy region, the rate due to ^7Be electron scattering events is $\sim 1/3$ that of the *pp* rate. Thus for electron recoils there is no substantial gain to lower thresholds, unless the neutrino has a magnetic moment much larger than predicted in the SM.

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