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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 ${}^7\text{Be}$ 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.

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 ~ 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 ${}^8\text{B}$ 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 , ${}^7\text{Be}$, 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 $\sim 10^{-45} \text{ cm}^2$ [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 compo-

nents 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: $p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$ (pp), $p + e^- + p \rightarrow {}^2\text{H} + \nu_e$ (pep), ${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$ (${}^8\text{B}$), and ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$ (${}^7\text{Be}$). 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 ${}^7\text{Be}$ (${}^8\text{B}$) fluxes directly measure the respective contributions from the $pp\text{II}$ ($pp\text{III}$) chains. The spectrum of pep neutrinos is a thermally-broadened line at 1.44 MeV. There are two thermally-broadened lines associated with ${}^7\text{Be}$ 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 ${}^7\text{Be}$ 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 $(2.79 \pm 0.13) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ [18]. Assuming the MSW solution for ν_e transition to other flavors, corresponding to a survival probability of $P_{ee} = 0.524$, the deduced SSM flux is $(4.43 \pm 0.22) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$. This measurement is consistent with the high- Z SSM, which predicts a 0.86 MeV ${}^7\text{Be}$ flux of $4.47(1 \pm 0.07) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ [14], and disfavors the low- Z prediction of $4.08(1 \pm 0.07) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ [13]. The uncertainties on these theoretical fluxes are due to variations of the SSM parameters. Taking as an assumption the high- Z SSM, the measured ν_e -electron flux corresponds to a survival probability of $P_{ee} = 0.51 \pm 0.07$.

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 $(1.00 \pm 0.22) \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$. Assuming the MSW solution for ν_e transition to other flavors, corresponding to a survival probability of $P_{ee} = 0.514$, the deduced SSM flux is $(1.63 \pm 0.35) \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$. The pep flux measured by Borexino is consistent with both

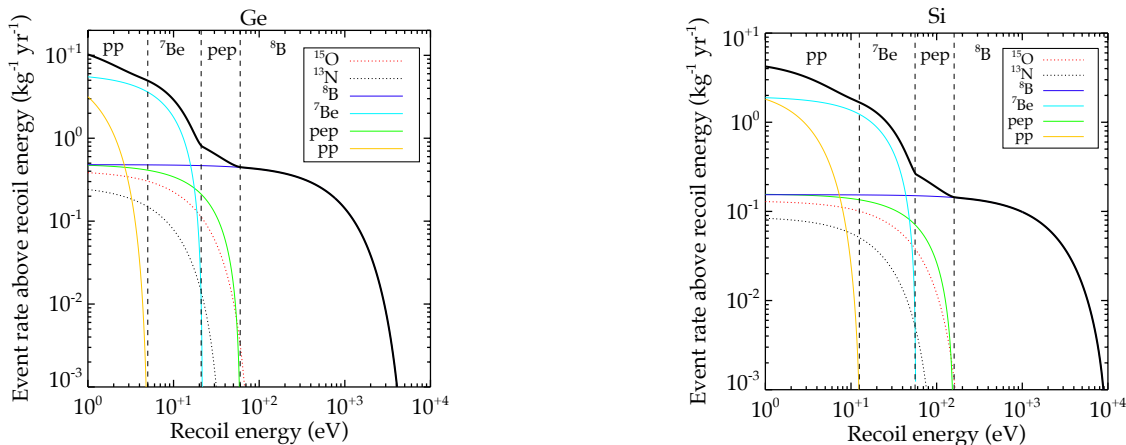


FIG. 1: Integrated number of events above a nuclear recoil threshold energy from coherent scattering due to solar neutrinos in a Ge (left) and Si (right) detector. The black solid curve is the sum of all components. The vertical dashed lines indicate the energy regions over which a particular flux component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

the high and low- Z SSMs, though the predicted pep flux is relatively insensitive to solar metallicity. Because 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 . Taking as an assumption the high- Z SSM, the measured ν_e -electron flux corresponds to a survival probability at 1.44 MeV of $P_{ee} = 0.62 \pm 0.17$.

Borexino has recently reported the first direct measurement of the pp neutrino spectrum [20]. Assuming the MSW solution, the deduced SSM flux is $(6.6 \pm 0.7) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$. This is in agreement with the predictions of both the high- Z ($5.98 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$) and low- Z SSM ($6.03 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$). 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 ${}^7\text{Be}$, pep , and pp measurements, Borexino has placed an upper bound of $< 7.7 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ 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 ${}^8\text{B}$ flux [21].) We assume pure Standard Model (SM) contributions to the CNS cross sec-

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

$$F_{\alpha\beta} = \sum_{i=1}^n \frac{T_{exp}^2}{N_i^{tot}} \frac{R_{\alpha i}}{f_{\alpha}} \frac{R_{\beta i}}{f_{\beta}}, \quad (1)$$

where the sum is over n recoil energy bins, $R_{\alpha i}$ is the predicted rate in the i^{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 $\alpha = pp, {}^7\text{Be}, pep, CNO$ and ${}^8\text{B}$. The total number of events from all flux components is N_i^{tot} , and the exposure, T_{exp} , is the mass of the detector times the run

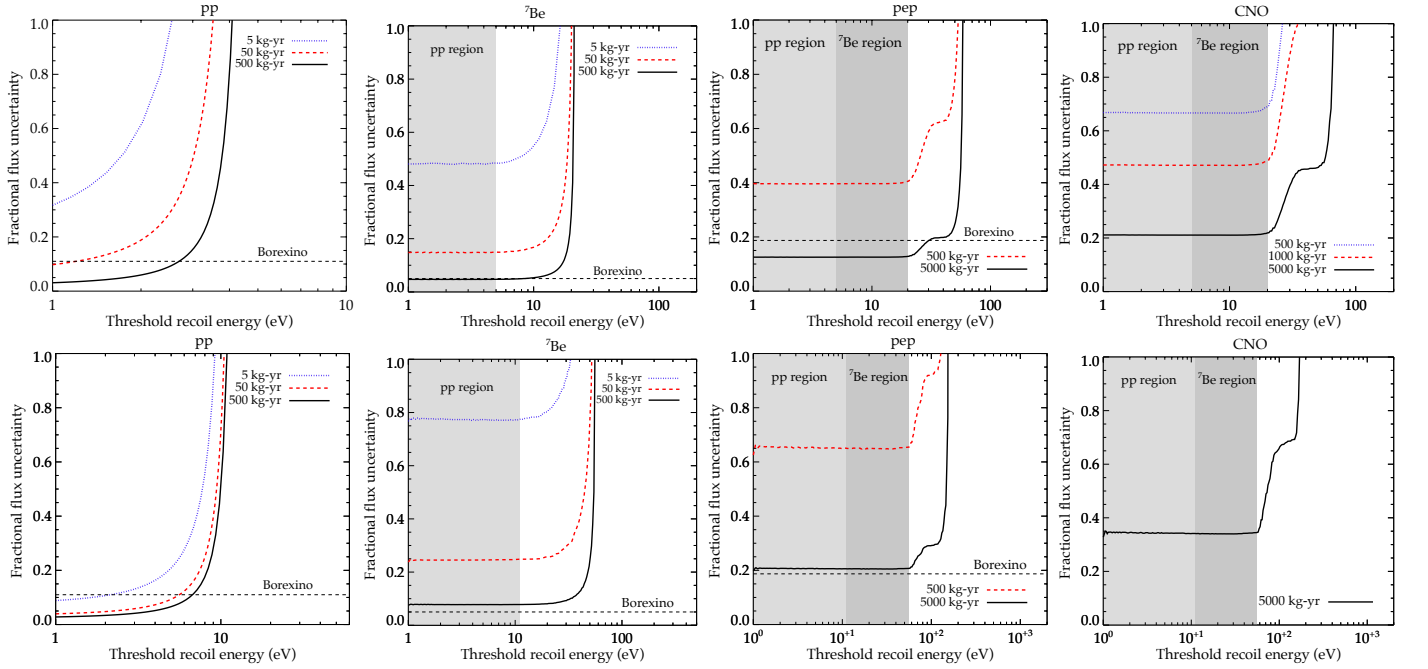


FIG. 2: Fractional flux uncertainty (Δf) on the pp , ${}^7\text{Be}$, pep , and CNO components as a function of threshold nuclear recoil energy. The top row is for Ge, and the bottom row is for Si. For the pp , ${}^7\text{Be}$, and pep panels, the Borexino sensitivity is indicated. In the ${}^7\text{Be}$, 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 ${}^7\text{Be}$ 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.

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 in nuclear recoil energy bins of width $\sim \text{eV}$. 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 theoretical simplicity we do not consider experimental backgrounds, amounting to the assumption that they can be reduced and understood experimental analysis. A background of relevance for this region is the residual gamma background from radioactivity, which may be handled as discussed in Ref. [12].

For our fiducial model we assume the high- Z SSM for the flux normalizations. Figure 2 shows Δf for the pp , ${}^7\text{Be}$, 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 $\lesssim 3 \text{ eV}$ and an exposure $\sim 5 \text{ kg-yr}$, while a Ge detector reaches the Borexino sensitivity for the same threshold and an exposure $\sim 500 \text{ kg-yr}$. It should be emphasized that the Borexino mea-

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

The pep and CNO fluxes are prominent at energies lower than ${}^8\text{B}$, but higher than ${}^7\text{Be}$. 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 $\sim 500 \text{ kg-yr}$ Ge exposure with $\sim 10 \text{ eV}$ 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 \sim 50 kg-yr, a threshold of \sim 10 (30) eV in Ge (Si) will measure the ${}^7\text{Be}$ solar neutrino flux. Approximately an order of magnitude larger mass detectors will be sensitive to pp 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. Combining with the Borexino measurement will establish 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 that alters the shape of the measured event spectrum [26].

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 [27].

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. [28].) The major sensitivity is to pp neutrinos, for which the integrated event rate above 1 keV electron recoil energy is \sim 4 $\text{kg}^{-1}\text{yr}^{-1}$, and the rate remains constant down to eV energies. Over this same electron recoil energy region, the rate due to ${}^7\text{Be}$ 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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