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Dark Matter Detection With Electron Neutrinos in Liquid Scintillation Detectors

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We consider the prospects for liquid scintillation experiments (with a focus on KamLAND) to detect the flux of electron neutrinos arising from dark matter annihilation in the core of the sun. We show that, with data already taken, KamLAND can provide the greatest sensitivity to the dark matter-proton spin-dependent scattering cross-section for dark matter lighter than 20 GeV. It is also possible to probe the dark matter-nucleon spin-independent scattering cross-section for isospin-violating dark matter lighter than 10 GeV. KamLAND can thus potentially confirm the dark matter interpretation of the DAMA and CoGeNT signals, utilizing data already taken.

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Introduction. Neutrino detectors search for the neutrino flux arising from dark matter annihilating in the sun's core. It has been argued recently that liquid scintillator (LS) neutrino detectors can be used for dark matter searches [1, 2]. The key is the ability of LS detectors to reconstruct a charged lepton track from the timing of the first scintillation photons to reach the PMTs. If a charged lepton is produced from a neutrino from the sun through a charged-current interaction, then a measurement of the direction and energy of the fully-contained charged lepton track is sufficient to reconstruct the neutrino energy. The measured energy spectrum can then be compared to the expected atmospheric neutrino background.

This analysis is typically performed utilizing muon tracks, where the track direction is determined from the Cerenkov cone. The difficulty with this method is that, unless the muons are of relatively low energy or the detector is extremely large, the muon track will not be contained within the detector. This makes it impractical to measure the energy of the muon, and thus impossible to determine the energy of the original ν_μ . Instead, one must compare the event rate of muons which pass entirely through the detector ("throughgoing muons") to the event rate expected from atmospheric neutrinos. Since the atmospheric neutrino background falls sharply with energy, the throughgoing muon background is dominated by low-energy neutrinos which produce muons just energetic enough to pass through the fiducial volume.

There are two significant advantages to dark matter searches for $\nu_e, \bar{\nu}_e$, producing e^- or e^+ via charged-current interactions. First, the atmospheric neutrino flux for electron neutrinos is smaller than that of $\nu_\mu, \bar{\nu}_\mu$ by a factor which varies from ~ 2 to ~ 10 in the energy range of interest. More importantly, unlike muons, electrons and positrons produce showers which attenuate very quickly. Even a very energetic ν_e will produce a shower which can be fully-contained within a reasonably sized LS detector. For such a shower, the timing of the first detected photons can be used to reconstruct the direction of the produced electron/positron with $\lesssim 1^\circ$ uncertainty [1]. With the direction and energy of the electron/positron, as well as total calorimetry, one can reconstruct the energy of the neutrino to within $\lesssim 1\%$ [1]. On

the other hand, water Cerenkov (WC) detectors such as Super-Kamiokande have greater difficulty in accurately measuring the direction or energy of electron showers, making it difficult for them to base dark matter searches on electron neutrinos.

This suggests that electron neutrinos are an ideal channel for neutrino-based dark matter searches, and are the channel for which LS detectors are uniquely well-suited. We will demonstrate that KamLAND, using data already collected, can place bounds on the spin-dependent dark matter-proton scattering cross-section (σ_{SD}^p) which are competitive with current bounds. We will also show that KamLAND can probe the dark matter-nucleon spin-independent scattering cross-section (σ_{SI}) at a level competitive with other experiments for $m_X \lesssim 10$ GeV.

Dark Matter Detection with $\nu_e, \bar{\nu}_e$. Dark matter is gravitationally captured by the sun through elastic scattering from solar nuclei: when dark matter loses enough energy through nuclear recoil, it falls below the sun's escape velocity and is captured, eventually settling in the core. The capture rate depends on the dark-matter-nucleon scattering cross-section (σ_{XN}), the dark matter mass (m_X), the local dark matter density and velocity distribution, and on the composition of the sun [3, 4].

For dark matter in the range of masses considered here, the sun would be in equilibrium [5], with the capture rate Γ_C related to the annihilation rate Γ_A by $\Gamma_C = 2\Gamma_A$. Given any choice of the dark matter annihilation channel, Γ_A determines the magnitude of the neutrino flux at earth, while m_X determines the neutrino energy spectrum. These together determine the lepton interaction rate at any neutrino detector. Since Γ_C is determined by m_X and σ_{XN} , a measured event rate at a neutrino detector constrains the (m_X, σ_{XN}) parameter-space.

KamLAND. KamLAND is an LS detector with an approximately spherical inner detector ($V \sim 1000 \text{ m}^3$). The KamLAND scintillator density is $\sim 80\%$ that of water. We consider a "fully-contained" electron event to be an e^+ or e^- shower which starts within the detector and travels for at least 4.3 m before leaving the inner detector. This corresponds to ~ 10 radiation lengths, ensuring a light yield sufficient to accurately determine the energy of the e^+ , e^- initiating the shower. The volume for this

analysis is the portion of the inner detector in which a track pointing from the sun could originate and travel at least 4.3 m without leaving the inner detector. Our analysis volume is $\sim \frac{1}{2}$ the volume of the inner detector.

Analysis. The fully-contained charged lepton rate at a neutrino detector can be written as

$$R_{l(\bar{l})} = \Gamma_A \times \frac{\sigma_{\nu(\bar{\nu})N}(m_X) \times N_A}{4\pi R^2} \times \langle Nz \rangle_{\nu(\bar{\nu})} \quad (1)$$

where $z = E_\nu/m_X$, N_A is the number of target nucleons within the analysis volume, $R = 1.5 \times 10^{11}$ m is the earth-sun distance, and $\sigma_{\nu(\bar{\nu})N}$ are the (anti-)neutrino-nucleon scattering cross-sections. In the range $E_\nu \sim 2 - 1000$ GeV, these can be approximated as [6, 7]

$$\begin{aligned} \sigma_{\nu N}(E_\nu) &= 6.66 \times 10^{-3} \text{ pb } (E_\nu/\text{GeV}) \\ \sigma_{\bar{\nu} N}(E_{\bar{\nu}}) &= 3.25 \times 10^{-3} \text{ pb } (E_{\bar{\nu}}/\text{GeV}) \end{aligned} \quad (2)$$

This cross-section is thus proportional to $\langle Nz \rangle_{\nu(\bar{\nu})}$, where

$$\langle Nz \rangle = \frac{1}{m_X} \int_0^{m_X} dE \left[\frac{dN}{dE} E \right] \quad (3)$$

is the first moment of the neutrino spectrum.

E_ν is determined by the electron energy (E_e) and the angle θ between the electron shower and the neutrino:

$$E_\nu = m_N E_e [m_N - E_e(1 - \cos \theta)]^{-1}, \quad (4)$$

where m_N is the nucleon mass. Since KamLAND can measure the energy and direction of fully-contained leptons precisely, it can determine E_ν event by event for a neutrino assumed to be arriving from the direction of the sun. Our analysis counts only events where the electron shower is within an analysis cone of half-angle

$$\theta_{\text{cone}} = 20^\circ \sqrt{10 \text{ GeV}/E_\nu} \quad (5)$$

from the direction from the sun; $\sim 2/3$ of electrons arising from the charged-current interaction of an electron-neutrino originating in the sun will lie within this cone.

Note that this analysis can be refined significantly if the direction and energy of the recoiling nucleon can also be measured from scintillation light, as has been argued in [1]. This measurement would permit the neutrino energy and direction to be reconstructed independently, greatly reducing the background from atmospheric neutrinos. However, for an analysis at KamLAND, the number of background events is so small that this further step is not required.

The atmospheric electron neutrino flux can be determined from Honda *et al.* [8]. For a search for dark matter with mass m_X , we count events with reconstructed E_ν between $E_{thr} = 1.5$ GeV and m_X ; for a 2135 live-day search for $m_X = 5 - 1000$ GeV, there will be fewer than $5 e^\pm$ events arising from atmospheric neutrinos within the analysis cone given in eq. 5 (averaging over zenith angle, azimuthal angle and solar cycle). KamLAND can be considered to be sensitive to models which would produce 10 signal events in 2135 live-days.

Γ_C and $\langle Nz \rangle$ are determined as functions of m_X and σ_{XN} by DarkSUSY [9], including the effects of neutrino oscillations in vacuum and matter [10, 11] on the neutrino spectra. Dark matter local density is taken to be $0.3 \text{ GeV}/\text{cm}^3$ with a Maxwell-Boltzmann velocity distribution with dispersion $\bar{v} = 270 \text{ km/s}$. The neutrino spectra have been computed for b , τ , W and $\nu_{e,\mu,\tau}$ annihilation channels. It is assumed that the W^\pm polarization is isotropic. If the dark matter is a Majorana fermion, then W 's will be transversely polarized [12]. However, the assumption of an isotropic polarization will have only a negligible effect on $\langle Nz \rangle$, assuming $E_{thr} \ll m_X$ [13].

Bounds from KamLAND. Fig. 1 shows the sensitivity to σ_{SD}^p which KamLAND can achieve assuming 2135 live-days of data and dark matter annihilation entirely to the b , τ , W or ν (flavor-blind) channels. This bound arises from dark matter captured by the sun through spin-dependent scattering off hydrogen. Also reported in Fig. 1 are bounds on σ_{SD}^p from PICASSO, COUPP, SIMPLE, Super-Kamiokande (Super-K), Amanda, and IceCube/DeepCore and a projection for a 50 kT future LS detector (e. g. LENA [14] or Hanohano [15]). The 50 kT LS detector projection assumes 1800 live-days of data.

Even for $m_X > 80$ GeV, detection prospects for annihilation through the τ channel are better than for the W channel. This is not the case for Amanda or IceCube, due to several effects. The hardest ν spectrum arises from transversely-polarized W bosons, which are heavily peaked at large and small values of z . For detectors searching for fully-contained muons, the event rate is proportional to $\langle Nz^2 \rangle$, thus weighting transversely polarized W 's more heavily. This is especially true for detectors whose energy threshold is comparable to the dark matter mass; since they are only sensitive to ν s with $z > E_{thr}/m_X$, the best detection prospects arise from spectra peaked at large z . For KamLAND, the analysis threshold is always much lower than m_X , and the event rate for fully-contained events is proportional to $\langle Nz \rangle$.

Note that, if dark matter couples to quarks through heavy mediators, then an effective operator analysis can permit the Tevatron to place current exclusion bounds in the $\sigma_{SD}^p \sim 10^{-3} - 10^{-4}$ pb range for $m_X \lesssim 10$ GeV [21].

Fig. 2 shows the sensitivity to the dark matter-nucleon spin-independent scattering cross-section (σ_{SI}^N) which KamLAND can achieve with 2135 live-days of data and dark matter annihilation to τ s. The spin-independent (SI) capture rate is dominated by scattering off heavier nuclei; though heavy nuclei are rare in the sun, dark matter-nucleus scattering receives an A^2 coherent scattering enhancement. Bounds on σ_{SI} are thus tighter than those on σ_{SD}^p . But since direct detection experiments are so much more sensitive to σ_{SI} , the bounds from KamLAND are only relevant for $m_X \lesssim 10$ GeV, when direct detection experiments begin to lose sensitivity.

This region of parameter-space is especially interesting, since the DAMA and CoGeNT experiments have reported signals which are potentially consistent with a

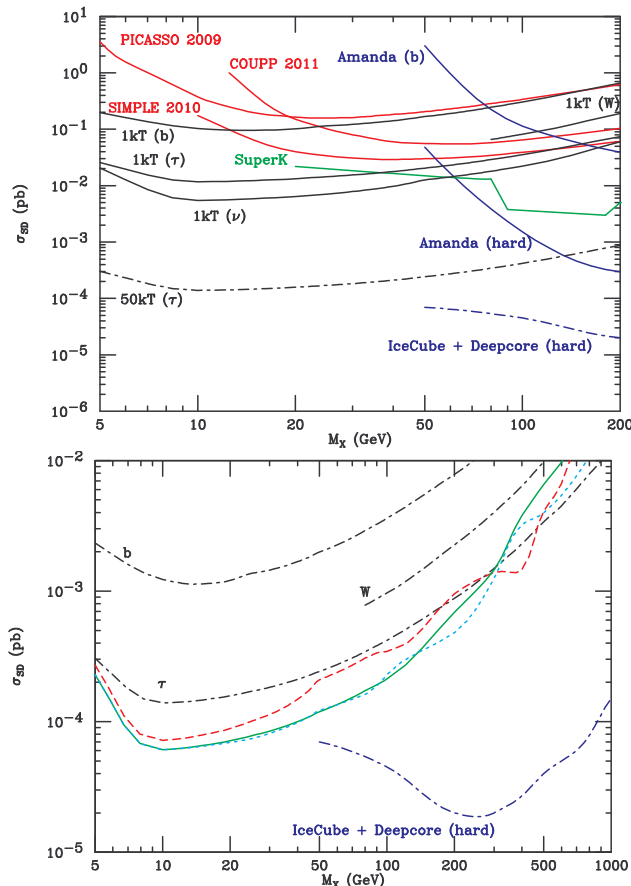


FIG. 1. (Top panel) Sensitivity of a 1 kT LS detector (such as KamLAND) to σ_{SD}^p , using 2135 live-days of data, assuming annihilation to the b , τ , W or ν (flavor-blind) as labeled. Also plotted are current bounds from Super-Kamiokande [16], PICASSO [17], COUPP [18], SIMPLE [19], Amanda and IceCube, as well as prospective bounds from IceCube/DeepCore with 1800 live-days of data [20] and prospective bounds for a 50 kT LS detector with 1800 live-days of data. The hard channel for Amanda and IceCube is the τ channel for $m_X < 80$ GeV and the W channel for $m_X > 80$ GeV. (Bottom panel) Sensitivity of a 50 kT LS detector with 1800 live-days of data, assuming annihilation to the b , τ , W and ν_e (dashed), ν_μ (solid) and ν_τ (dotted) channels as labeled.

dark matter candidate with $m_X \lesssim 10$ GeV and $\sigma_{\text{SI}} \sim 10^{-3-5}$ pb [22, 23]. CRESST has also reported preliminary data [24] which is consistent with the DAMA and CoGeNT signals. However, exclusion bounds from the XENON100 [25] and CDMS [26] collaborations are in tension with a dark matter interpretation of DAMA, CoGeNT and CRESST. Reanalyses of Xenon10 data are also in tension with these signals [27, 28]. There is much controversy regarding both the reported signals and the exclusion bounds, in particular regarding the sensitivity of these direct detection experiments at low mass [29]. There is thus great interest in testing these results with a different experimental method. Super-K can potentially probe this region of parameter-space with data already taken [2, 30] utilizing muon tracks, though this

analysis of the data has not yet been performed. Assuming equal dark matter couplings to proton and neutrons, KamLAND can probe part of the DAMA-preferred region, but not CoGeNT (top panel, Fig. 2).

But it has recently been noticed that the data from DAMA and CoGeNT and the bounds from CDMS and Xenon10/100 can be brought into better agreement if one considers isospin-violating dark matter (IVDM) [32, 33]. IVDM couples differently to protons and neutrons; if we parameterize these couplings by $f_{p,n}$, the data seem to be brought into closest agreement for $f_n/f_p \sim -0.7$. Since dark matter coupling to protons and neutrons interfere destructively, direct detection experiments which rely on coherent scattering suffer a great loss of sensitivity. But for $m_X \sim 10$ GeV, $\sim 3\%$ of dark matter capture is due to scattering from hydrogen [34], where there is no destructive interference. As such, KamLAND may be more sensitive to IVDM models which can explain DAMA and CoGeNT than are other direct detection experiments.

A conservative estimate of KamLAND's sensitivity is to assume that IVDM only scatters against the hydrogen. The sensitivity of KamLAND to σ_{SI}^p in this limit is the same as to σ_{SD}^p . Taking $f_n/f_p \sim -0.7$, DAMA and CoGeNT could be consistent with an IVDM particle with a SI cross-section for scattering off a proton given by $\sigma_{\text{SI}}^p \sim 2 - 3 \times 10^{-2}$ pb for $m_X \sim 10$ GeV [33]. If the IVDM candidate has a significant annihilation branching fraction to τ 's, it can be probed by data already taken at KamLAND (see bottom panel of Fig. 2).

Comparison to Water Cerenkov Detectors. Water Cerenkov neutrino detectors can also search for electron neutrinos produced by dark matter annihilating in the sun. However, for large exposures, LS detectors are expected to have much smaller backgrounds.

In addition to precise measurement of the charged lepton energy and direction, LS detectors can independently measure the neutrino energy to within $\sim 1\%$ accuracy [1] using the total light yield (including scintillation from the recoiling nucleon). The direction of the electron neutrino can thus be reconstructed to within 1° accuracy [1]. This analysis should be able to reject most atmospheric background within the analysis cone of eq. 5, leaving only background events from atmospheric neutrinos arriving within $\sim 1^\circ$ of the sun. This method of background rejection cannot be used by WC detectors, which cannot independently measure the neutrino energy and can only reconstruct it under the assumption the neutrino came from the sun.

As a specific example, we may compare the sensitivity of a 50 kT LS detector to a putative 200 kT WC detector (the estimated size of LBNE [35]), assuming a run-time of 1800 live-days. Given the larger exposure, one would expect ~ 1144 electron events due to atmospheric neutrinos within the analysis cone (eq. 5) at the WC detector. The WC detector can be considered sensitive (2σ) to dark matter models producing ~ 68 signal events within the cone over this run-time. For the 50 kT LS detector, assuming 1° uncertainty in neutrino direction resolution,

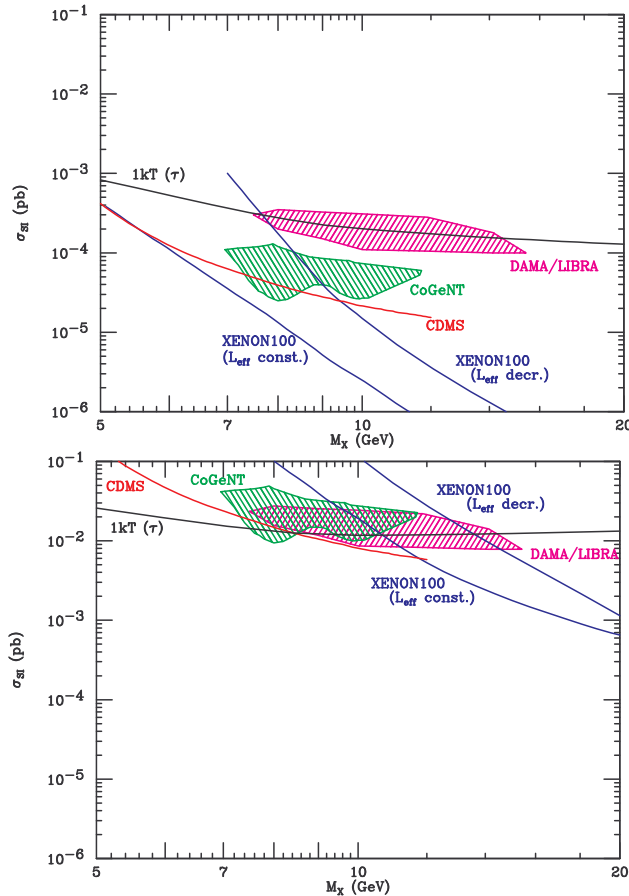


FIG. 2. Sensitivity of a 1 kT LS detector (such as KamLAND) to σ_{SI}^N (black), using 2135 live-days of data and assuming annihilation in the τ channel. Also plotted are the preferred region for the CoGeNT signal (green) at 90% CL [23], the preferred DAMA region (magenta) at 3σ CL (no channeling) [27, 31], and exclusion bounds from CDMS Soudan (red) [26] and Xenon100 (blue) [25], with either \mathcal{L}_{eff} either constant or decreasing with energy. The top panel assumes no isospin violation ($f_n = f_p$). The bottom panel is for an IVDM model with $f_n/f_p = -0.7$.

one would expect less than 2 background events; this detector would be sensitive to models which would produce

~ 10 signal events over the run-time. Accounting for the larger volume of the WC detector, one would still expect the LS detector's sensitivity to be greater than the WC detector's sensitivity by a factor ~ 1.7 . It should be emphasized, however, that the ability to independently reconstruct the neutrino direction depends crucially on the ability to measure the scintillation light of the recoiling nucleon; the efficiencies and uncertainties in the measurement must be understood for a designed detector before firm conclusions about sensitivity can be made.

Conclusion. We have studied the dark matter detection prospects for KamLAND, using the 2135 live days of running which are already available. KamLAND can provide the world's best sensitivity to the σ_{SD}^p for $m_X \sim 4 - 20$ GeV. Moreover, KamLAND's sensitivity to dark matter is not as heavily suppressed by isospin-violating destructive interference as that of other direct detection experiments for $m_X \sim 10$ GeV. If the τ annihilation channel dominates, KamLAND's sensitivity to IVDM is competitive with other direct detection experiments, and can potentially test recent hints of low-mass dark matter from DAMA, CoGeNT and CRESST. Though KamLAND is a smaller detector than Super-K, this disadvantage is compensated by the ability to search for dark matter in the $\nu_e, \bar{\nu}_e$ channel.

Recently, it was argued that a light dark matter candidate which could potentially explain the DAMA and CoGeNT signals could also be responsible for a possible photon excess from the Galactic Center, provided the candidate annihilates primarily to τ 's [36]. LS detectors can thus provide an interesting way of testing this model.

Future large LS detectors such as Hanohano and LENA can improve sensitivity by perhaps $\times 100$. But a complete analysis must include a simulation of acceptances and efficiencies of a particular detector, including energy and angular resolution, e/μ discrimination, nucleon recoil measurement, and cosmic ray μ rejection. These issues are beyond the scope of this work.

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