

Technique for direct detection of weakly interacting massive particles using scintillation time discrimination in liquid argon

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Abstract

Discrimination between electron and nuclear recoil events in a liquid argon scintillation detector has been demonstrated with simulations by using the differences in the scintillation photon time distribution between these classes of events. A discrimination power greater than 10^8 is predicted for a liquid argon experiment with a 10 keV threshold, which would mitigate electron and γ -ray backgrounds, including β decays of ^{39}Ar and ^{42}Ar in atmospheric argon. A dark matter search using a ~ 2 kg argon target viewed by immersed photomultiplier tubes would allow a sensitivity to a spin-independent WIMP-nucleon cross-section of $\sim 10^{-43} \text{ cm}^2$ for a 100 GeV WIMP, assuming a one-year exposure. This technique could be used to scale the target mass to the tonne scale, allowing a sensitivity of $\sim 10^{-46} \text{ cm}^2$.

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It is now well established that a significant part of the matter present in our universe is non-baryonic dark matter. A currently favored hypothesis is that the dark matter is comprised of WIMPs, weakly interacting massive particles, which have so far remained undetected. Direct searches place limits on the interaction cross-section and mass of these particles, with the current best limit from the cryogenic dark matter search (CDMS) experiment [1]. Scaling up the current-generation experiments to large masses (on the order of a tonne) is of current interest and there are several proposed methods for achieving this goal. Much effort has been placed on the study of noble liquids as detectors for WIMP particles in the past few years, since many of these have high photon scintillation yields, can be cleaned to very low levels of radioactivity, and can be used to provide a large target mass for WIMP searches. A large part of

the experimental effort is in separating the ubiquitous backgrounds from γ -rays and electrons which enter the sensitive detector region. The XENON [2], ZEPLIN [3] and WARP [4] collaborations are attempting to discriminate against these backgrounds by drifting and subsequently detecting the energetic electrons which result from ionization in the detector, using liquid xenon and argon targets. It has recently been shown that differences in scintillation photon time distributions between electron and nuclear recoils could be exploited for effective background discrimination in liquid neon [5]. This discrimination capability, together with the potential to purify liquid neon using conventional cold traps, makes possible a dual purpose detector for low-energy solar neutrinos and WIMP dark matter. Final evaluation of the discrimination achievable in neon awaits accurate determination of the scintillation parameters. In this paper, we follow the approach detailed in Ref. [5] and realize the opportunity to exploit scintillation time discrimination to reject backgrounds in a dedicated WIMP search using a liquid argon target. The small difference between the singlet and triplet time constants in liquid

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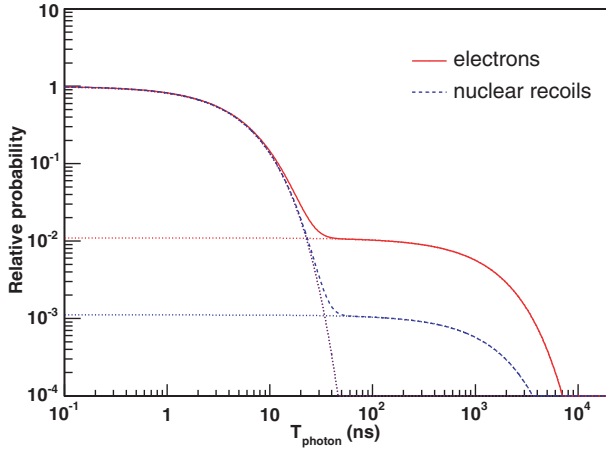


Fig. 1. Scintillation time distribution for electrons and nuclear recoils in liquid argon from Ref. [8]. The dotted lines show the contributions from the singlet (prompt) and triplet (late) components separately.

xenon precludes discrimination at the levels achievable in neon and argon based on timing alone. Consequently, a dedicated WIMP detector based on liquid argon can be

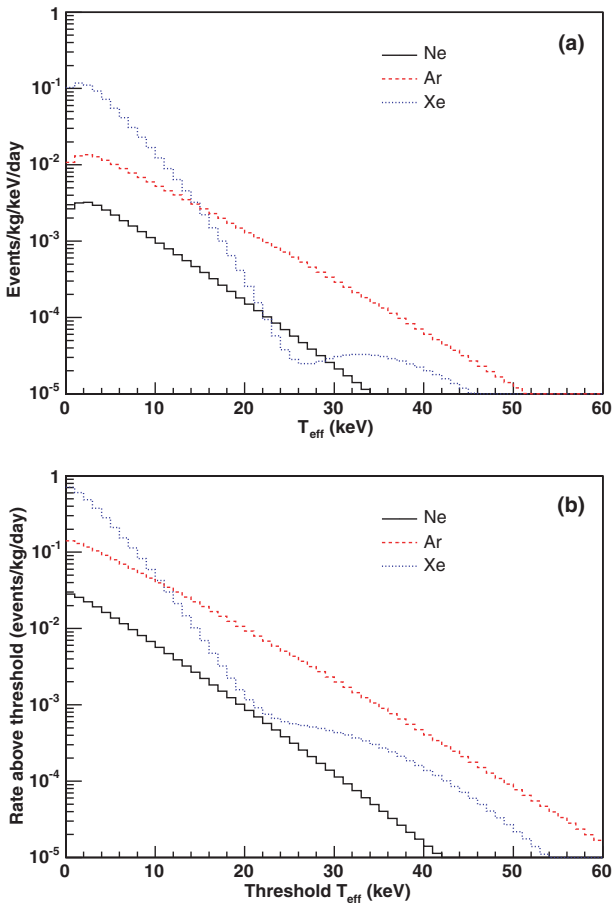


Fig. 2. Predicted rates for WIMP scatters on Ne, Ar, and Xe assuming a WIMP-nucleon spin-independent cross-section $\sigma_p = 10^{-42} \text{ cm}^2$ and a 100 GeV WIMP mass. (a) Predicted rates in effective (observed) kinetic energy assuming 25% quenching for nuclear recoils. (b) Integrated rates above threshold.

realized that is conceptually simple and that does not require the complication associated with high-field drift of electrons.

In general, a WIMP particle (χ) can be detected through elastic scattering from a target nucleus (N),

$$\chi + N \rightarrow \chi' + N', \quad (1)$$

by measuring the kinetic energy imparted to the recoiling nucleus (N'). The distributions of observed kinetic energies from WIMP scatters on neon, argon, and xenon are shown in Fig. 2, for a WIMP-nucleon spin-independent cross-section of 10^{-42} cm^2 , a 100 GeV WIMP mass, and with the standard assumptions for the distribution of WIMPs in our galactic halo [6,7]. It is interesting to note that the integral rates in argon are equal to those in xenon for a threshold near $\sim 10 \text{ keV}$, due to the increased form factor suppression in xenon at higher nuclear recoil energies. If the material in which the nucleus recoils is a scintillator, the generated scintillation photons can be used to measure this energy. Shown in Table 1 are the scintillation parameters for liquid neon, argon, and xenon (see Refs. [8–13]) for nuclear recoil events (inferred from measurements with fission fragments) and for electrons. Experimental determination of the scintillation parameters in liquid neon is currently being performed in support of the CLEAN [14] experiment.

In general, ionizing radiation in noble liquids will lead to the formation of dimers in either singlet or triplet states. These states will have characteristic lifetimes (τ_1 and τ_3) and are produced with different amplitudes (I_1 and I_3), depending on the liquid and the ionizing radiation. Here we exploit these differences to separate electron from nuclear recoil events in liquid argon.

To estimate experimental sensitivity, a detector with a photosensitive coverage of 75% has been assumed. Nominal photomultiplier tube (PMT) properties assumed are shown in Table 2, which have been extrapolated from properties of PMTs used in the XENON [2] experiment. The conceptual experimental design is shown in Fig. 3. six PMTs, each with a 4 in. sensitive diameter are immersed in liquid argon, and view an inner sensitive region, which is opaqued from activity in the outer region using an optical

Table 1
Scintillation parameters for electrons and nuclear recoils in noble liquids from Refs. [8–13]

Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
Prompt time constant τ_1 (ns)	2.2	6	2.2
Late time constant τ_3	2.9 μs	1.59 μs	21 ns
I_1/I_3 for electrons		0.3	0.3
I_1/I_3 for nuclear recoils		3	1.6
$\lambda(\text{peak})$ (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30

Quenching for nuclear recoils has been assumed to be 25% for all materials. The ratio of prompt to late photons (I_1/I_3) provides the background discrimination.

Table 2
PMT and wavelength shifter (WS) properties assumed in the simulation

PMT diameter	4 in.
U content	28 mBq
Th content	16 mBq
K content	240 mBq
PMT efficiency	20%
PMT time resolution	5 ns
PMT noise rate	1500 Hz
WS efficiency (4π)	1
WS time constant	15 ns

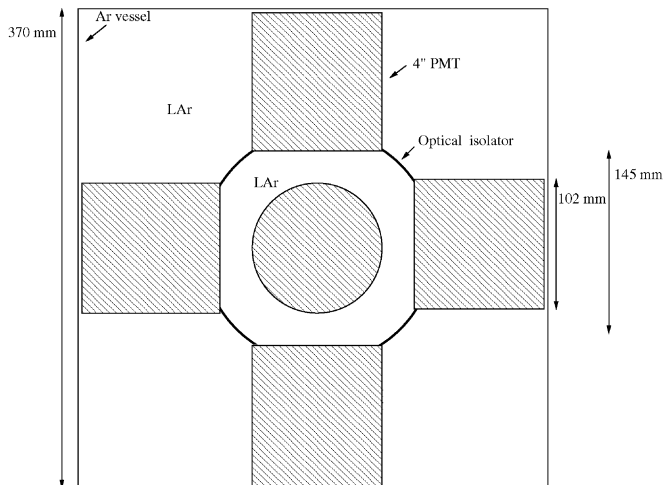


Fig. 3. Conceptual design of 2 kg liquid argon experiment. Six PMTs immersed in argon provide a photocathode coverage of approximately 75%. The PMT faces are coated with wavelength shifter to provide sensitivity to the 128 nm scintillation photons.

isolator. Each PMT is coated with a wavelength shifting film to shift the 128 nm photons into a region where the PMTs are sensitive. It is assumed that the PMT pulses are digitized so that the photon arrival times are known to within the time resolution of the PMTs. The ICARUS collaboration has constructed a large (600 ton) liquid argon experiment, and the PMTs and wavelength shifter have been demonstrated to work in liquid argon [15]. In this study the optical isolator is assumed to be a simple photon absorbing surface; it may be advantageous to include a reflective foil coated with wavelength shifter to increase the detector acceptance and photon yield, or equivalently to decrease the required number of PMTs. The time distributions for events with reconstructed energies of 10 keV have been simulated by sampling the scintillation distributions for liquid argon (shown in Fig. 1) and applying the detection response of Table 2. We have estimated the sensitivity here assuming a photon yield of six photoelectrons per keV in liquid argon, corresponding to a photocathode coverage of 75% with a 20% photon detection efficiency. From the simulated time distributions, the ratios of prompt to total hits (F_{prompt}) have been constructed for electron and nuclear recoil events by taking the ratio of the number of hits in a prompt 100 ns window

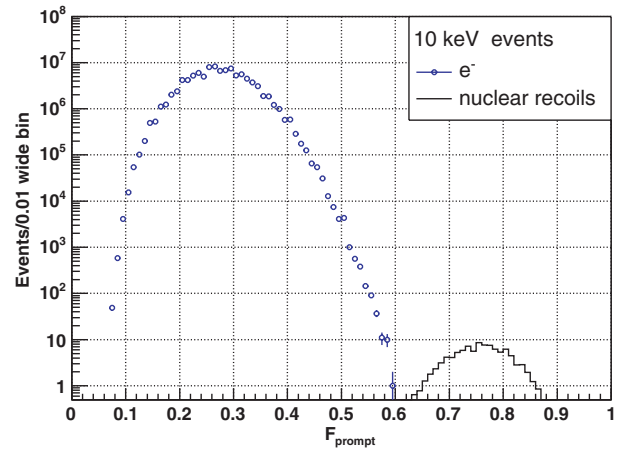


Fig. 4. Discrimination of nuclear recoils from electrons in liquid argon. Shown are the F_{prompt} distributions from 10^8 simulated electron events and for 100 simulated nuclear recoil events, with effective energies of 10 keV.

to those in a 15 μs window. A simulated hardware trigger was used to determine the start time of the scintillation pulse, which is found by determining the time at which the number of hits in a sliding 100 ns window is maximized. The trigger details would be optimized in an actual experiment with calibration sources. The resulting F_{prompt} distributions are shown in Fig. 4. We find that there is an essentially background-free region where the nuclear recoil events are expected, even in the presence of 10^8 electron events. Projected sensitivities are shown in Table 3.

The largest source of background expected in liquid argon is from ^{39}Ar , produced through cosmogenic activity in the atmosphere. The ratio of ^{39}Ar to natural argon is $8.1 \pm 0.3 \times 10^{-16}$ [16]. The concentration of ^{42}Ar in the atmosphere is much lower, 6×10^{-21} [17], and it is not expected to be a significant source of background. ^{39}Ar is a β emitter with a Q -value of 565 keV, and a lifetime of 388 years [18]. The results presented here assume an analysis window between 10 and 25 keV, where the threshold energy of 10 keV would correspond to 60 PMT hits. The number of background events in this window for 2 kg of liquid argon, and from the six PMTs is shown in Table 4. The discrimination shown in Fig. 4 is thus adequate to mitigate this level of background, and may be feasible for an experiment with several orders of magnitude larger mass. We note the difference from the approach presented in Ref. [5] where a fiducial volume is defined to remove external-source background events. In the approach presented

Table 3

Detector configurations and projected sensitivity to the WIMP-nucleon spin-independent cross-section (σ_p) with liquid argon for a one year exposure

Sensitive mass (kg)	Detector radius (cm)	No. PMTs	σ_p sensitivity (cm^2)
2	7.25	6	$\sim 10^{-43}$
100	26	79	$\sim 10^{-45}$
1000	56	365	$\sim 10^{-46}$

Table 4
Estimated backgrounds for the 2 kg, six PMT liquid argon experiment

Source	Rate (events/year)
^{39}Ar	1.26×10^6
^{42}Ar	76
U in PMTs	2.65×10^5
Th in PMTs	1.51×10^5
K in PMTs	4.54×10^5
Total	2.13×10^6

The dominant source of background is from decays of ^{39}Ar . Shown are the estimated event rates per year in the 10–25 keV analysis window.

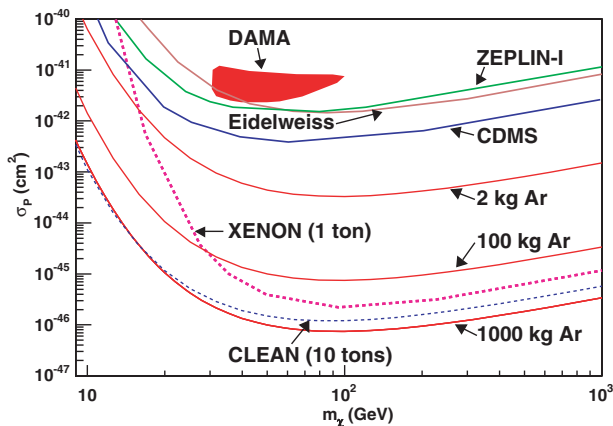


Fig. 5. Projected sensitivity to the WIMP-nucleon spin-independent cross-section versus WIMP mass. A 2 kg argon experiment would improve current experimental limits, and could be scaled to large target masses. The limits for argon are for a one year background-free exposure, and a 10 keV threshold. Projected sensitivity for CLEAN is from Ref. [5]. Data from other experiments adapted from Gaitskell and Mandic [21].

here all of the volume viewed by the PMTs is fiducial. The 2 kg experiment could also be useful as a prototype for the design of a larger scale neon experiment (such as CLEAN), where similar scintillation time discrimination could be used in a dual-purpose experiment with WIMP and solar neutrino sensitivity [5]. The ultimate sensitivities to the spin-independent WIMP-nucleon cross-section for 2 kg, 100 kg, and 1000 kg experiments using liquid argon are shown in Fig. 5. It is found that the 2 kg experiment has a good sensitivity to the WIMP-nucleon cross-section, and larger scale argon experiments could increase the sensitivity significantly.

The PMT background rates are assumed to be equivalent to the those in the R9288 PMT manufactured by Hamamatsu, scaled to 4 in. in diameter, and are shown in Table 4. The experiment could equivalently use a larger number of the 2 in. diameter R9288 PMTs, and Hamamatsu has agreed to provide a version of this PMT with a platinum underlay which should allow the PMT to function at liquid argon temperature [19]. With these assumed background rates, the total neutron background from (α, n) reactions

in the PMTs is expected to be negligible [20]. Other potential sources of neutron backgrounds to the WIMP search lead to similar requirements for cosmic-ray and neutron shielding, and materials selection as for a xenon dark matter experiment, described in Ref. [20].

In summary, we have explored the possibility of using the differences in scintillation photon times for electrons and nuclear recoils in liquid argon for discrimination of backgrounds in a WIMP search. The level of discrimination should allow suppression of electron and γ -ray backgrounds required for a sensitive WIMP search. A small-scale experiment using liquid argon, which would demonstrate this discrimination and lead to improved WIMP sensitivity is presented. This technique could be extended to a tonne-scale experiment, which would be competitive with a xenon-based experiment, but with a conceptually simpler design.

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