Observation of the Dependence of Scintillation from Nuclear Recoils in Liquid Argon on Drift Field

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We have exposed a dual-phase Liquid Argon Time Projection Chamber (LAr-TPC) to a low energy pulsed narrowband neutron beam, produced at the Notre Dame Institute for Structure and Nuclear Astrophysics, to study the scintillation light yield of recoiling nuclei. Liquid scintillation counters were arranged to detect and identify neutrons scattered in the LAr-TPC and to select the energy of the recoiling nuclei.

We report the observation of a significant dependence (up to 32%) on drift field of liquid argon scintillation from nuclear recoils of energies between 10.8 keV and 49.9 keV. The field dependence is stronger at lower energies. The first measurement of such an effect in liquid argon, this observation is important because, to date, estimates of the sensitivity of LAr-TPC dark matter searches are based on the assumption that electric field has only a small effect on the light yield from nuclear recoils.

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Noble liquid TPCs are in widespread use to search for WIMP dark matter by detecting low energy nuclear recoils that would be produced by WIMP interactions [1–6]. A precise understanding of the scintillation light yield from nuclear recoils and its dependence on energy and drift field are key to the interpretation of results from present experiments and to estimates of sensitivity of future detectors.

Measurements of the nuclear recoil light yield in liquid argon (LAr) have been performed in absence of a drift field with monoenergetic neutrons and reported in [7, 8]. For liquid xenon (LXe), several measurements have been performed with and without an applied electric field using both monoenergetic and broad spectrum neutron sources [9–20]. These measurements in LXe report that the applied electric field has a < 10% effect on the nuclear recoil light yield that is independent of energy, although the uncertainty increases as the recoil energy decreases.

We have used a monoenergetic neutron beam to observe the light produced by nuclear recoils between 10.8 and 49.9 keV in a LAr time projection chamber (LAr-TPC) with and without an applied electric field. We report a strong dependence on drift field of the scintillation yield, a dependence that increases with decreasing energy.

The experiment was performed at the University of Notre Dame Institute for Structure and Nuclear Astrophysics. Protons from the Tandem accelerator [22] struck a 0.20 mg/cm² thick LiF target deposited on a 1-mm-thick aluminum backing, generating a neutron beam through the reaction ⁷Li(p,n)⁸Be. For this study, the proton beam energy was 2.376 or 2.930 MeV, depending on the desired nuclear recoil energy. The proton beam was bunched and chopped to provide pulses 1 ns wide, separated by 101.5 ns, with an average of 6.3 × 10⁴ protons per pulse. The accelerator pulse selector was set to allow one of every two proton bunches to strike the LiF target, giving one neutron beam pulse every 203.0 ns.

The design of the LAr-TPC closely follows that used in DarkSide-10 [5]. The active volume is contained within a 68.6 mm diameter, 76.2 mm
TABLE I: Run parameters for the data presented in this letter.

| Proton energy (MeV) | Neutron energy (MeV) | Scattering angle (°) | Nuclear recoil energy (keVr) |
|---------------------|----------------------|----------------------|-----------------------------|
| 2.376               | 0.604                | 49.9                 | 10.8                        |
| 2.930               | 1.168                | 42.2                 | 15.2                        |
| 2.930               | 1.168                | 49.9                 | 20.8                        |
| 2.930               | 1.168                | 59.9                 | 29.0                        |
| 2.930               | 1.168                | 82.2                 | 49.9                        |

FIG. 1: A schematic of the experiment setup. The zoomed-in view of the TPC shows the PMTs, field shaping rings and PTFE support structure. It does not include the inner reflector.

FIG. 2: GEANT4-based simulation of the energy deposition in the SCENE detector at the 10.8 keV setting. Blue: all scatters in the LAr-TPC producing coincidences in either neutron detector and surviving the timing cuts discussed in the text. Red: single elastic scatters surviving the same cuts.
FIG. 3: Distributions of pulse shape discrimination vs. time of flight for data taken in the 10.8 keV configuration at 1000 V/cm. All variables are defined in the text. Panel (a) refers to the LAr-TPC and panel (b) to the neutron detectors.

FIG. 4: (a) Surviving primary scintillation light (S1) distributions for 10.8 keV nuclear recoils as the neutron selection cuts described in the text are imposed sequentially. Data were collected with a field of 1000 V/cm. The high energy peak is from the $^{83m}$Kr source in use for continuous monitoring of the detector. (b) Final S1 distributions for the 10.8 keV nuclear recoils at null field at 1000 V/cm.

of 1 PE and greater using positron annihilation radiation from a $^{22}$Na source placed between the LAr-TPC and the neutron detector in a manner similar to that described in [19].

The stability of the complete light collection and conversion system is of critical importance to our measurements and was monitored in several ways. The single PE response of each PMT, determined using pulses in the tails of scintillation events, was continuously monitored and showed a slow decline of about 15% in the top PMT and 10% in bottom PMT over the course of the 6 day run. The stability of the entire system was assessed throughout the data taking by $^{83m}$Kr runs in the absence of drift field. The position of the $^{83m}$Kr peak was measured to be 260 PE and varied by less than $\pm 2.5\%$ for the data presented here. The short term stability during a run in presence of a drift field was checked with $^{83m}$Kr spectra accumulated every 15 minutes; these show negligible variations during a given run.

Our data include a collection of prompt events characterized by narrow pulses in the LAr-TPC PMTs with timing slightly earlier than photon-induced scintillation events (the LAr fast scintillation component has a decay time of $\sim 6$ ns [30]), and data taken with no liquid in the TPC have a similar collection of events. We take these signals to be Cerenkov radiation and therefore independent of scintillation processes in the argon and examine them to study any dependence of the apparatus response on the drift field. The spectrum of these events shows a peak at $\sim 80$ PE which is stable within $\pm 2.5\%$ over all the electric field settings.

The data acquisition system was based on 250 MSPS waveform digitizers [32], which recorded signals from the LAr-TPC and neutron detectors and the accelerator RF signal. The data were recorded using the “Daqman” data acquisition and analysis software [31]. The digitizer records were
FIG. 5: Distributions of pulse shape discrimination vs. time of flight for data taken in the 49.9 keV configuration at 1000 V/cm. All variables are defined in the text. Panel (a) refers to the LAr-TPC and panel (b) to the neutron detectors. For these data, the polyethylene cylinders blocking the line-of-sight between the LiF target and the neutron detectors were removed due to geometric constraints. Accidental direct neutron coincidence events appear as the first "Neutron" blob around 80 ns in panel (b).

FIG. 6: (a) Surviving S1 distributions for 49.9 keV nuclear recoils as the neutron selection cuts described in the text are imposed sequentially. Data were collected with a field of 1000 V/cm. The high energy peak is from the $^{83m}$Kr source in use for continuous monitoring of the detector. (b) Final S1 distributions for the 49.9 keV nuclear recoils at null field at 1000 V/cm.

16 µs long including 5 µs before the hardware trigger (used to establish the baseline).

Figure 3(a) shows a scatterplot of the discrimination parameter $f_{90}$ [33], defined as the fraction of light detected in the first 90 ns of an event, vs. the time difference between the proton-beam-on-target and the TPC signal (TPCtof) for all events taken in the 10.8 keV configuration at 1000 V/cm. Beam-associated events with γ-like and neutron-like $f_{90}$ are clustered near 10 and 75 ns respectively, as expected given a speed of approximately 0.1c for 604 keV neutrons. Cerenkov events are characterized by $f_{90}$ close to 1.0 and γ-like timing. The $^{83m}$Kr events appear with γ-like $f_{90}$ uniformly distributed in TPCtof. For the same events, Fig. 3(b) shows a scatterplot of the neutron pulse shape discriminant (Npsd), defined as peak over area in the neutron detectors, vs. the time difference between the proton-beam-on-target and the neutron detector signal (Ntof). Neutron events scattering in the LAr-TPC cluster near a Npsd of 0.09 and a Ntof of 140 ns, while β/γ events cluster near a Npsd of 0.13 and a Ntof of 5 ns. Random coincidences from environmental backgrounds are visible at intermediate times.

We exploit the pulse-shape discrimination and timing information available to define a series of cuts. Figure 4(a) shows the primary scintillation, or S1, spectra as these cuts are imposed in sequence. The final spectrum at each drift field and recoil energy is fit to a Gaussian and the mean value in the fit represents our measurement of the yield. Fig. 4(b) shows final spectra at the 10.8 keV configuration for 0 V/cm and 1000 V/cm. For comparison, Figs. 5 and 6 show the same information for the 49.9 keV data point. In this configuration,
the polyethylene cylinders blocking the direct line of sight between the target and the neutron detectors were absent, resulting in a population of direct neutron events visible near 80 ns in Fig. 5(b). Because the neutron beam energy was higher to produce these data (see Table I), good scattering events cluster at shorter times of flight relative to the 10.8 keV point (53 and 110 ns in Figs. 5(a) and (b) versus 75 and 140 ns in Figs. 3(a) and (b)).

The light yield normalized to the value at null field is shown as a function of drift field in Fig. 7 for five different recoil energies. As can be seen, the signal yield decreases significantly as a function of the applied electric field, and this effect is more pronounced for lower energy recoils. At a field of 1 kV/cm, the light yield is reduced by 32% (14%) for 10.8 (49.9) keV recoils. Such a significant dependence on field has not been previously reported.

The presence of an external electric field can reduce the light yield by recoils in noble liquids largely because the external field reduces the probability of ion-electron recombination and subsequent de-excitation, one of the processes that ultimately produces light. The size of the effect can be expected to depend on the relative strengths of the external field and the field due to the ionization of the medium, the latter being determined by the total ionization energy loss and the density of the ionization along the path of the recoil. In general, low density tracks are more likely to feel the influence of an external electric field. For electrons, the reduction of light-yield by an external field in both argon and neon is well-known [14, 34]. For our energies of interest (< 50 keV), we note that the argon nuclei are on the decreasing side of the Bragg peak (see Fig. 4 in [8] for example), and therefore lower energy nuclear recoils have lower dE/dx. The simplest interpretation of our data is that a modest external electric field reduces the recombination probability, and this reduction increases as the argon recoil energy decreases.

To date, estimates of the sensitivity of LAr-TPC dark matter searches are based on the assumption that electric field has only a small, energy-independent effect on the light yield from nuclear recoils. Our result has important implications for the sensitivity estimates of LAr-TPC dark matter experiments and on the choice of operating parameters of those experiments. While our results do not necessarily transfer to xenon, the quality of the data enabled by this technique may prompt similar investigations in liquid xenon.

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[1] E. Aprile et al. (XENON Collaboration), Phys. Rev. Lett. 109, 181301 (2012).
[2] D. S. Akerib et al. (LUX Collaboration), Nucl. Inst. Meth. A 704, 111 (2013).
[3] C. Amsler et al. (ARDM Collaboration), J. Inst. 5, P11003(2010).
[4] R. Brunetti et al. (WARP Collaboration), Astropart. Phys. 28, 495 (2008).
[5] T. Alexander et al. (DarkSide Collaboration), Astropart. Phys. 48, in press (2013).
[6] H. Gong, K. L. Giboni, X. Ji, A. Tana, and L. Zhao, J. Inst. 8, P01002 (2013).
[7] D. Gastler, E. Kearns, A. Hime, L.C. Stonehill, S. Seibert, J. Klein, W. H. Lippincott, D. N. McK-
insey, and J. A. Nikkel, Phys. Rev. C 85, 065811 (2012).
[8] C. Regenfus, Y. Allkofer, C. Amsler, W. Creus, A. Ferella, J. Rochet, and M. Walter, J. Phys.: Conf. Ser. 375, 012019 (2012).
[9] F. Arneodo et al., Nucl. Inst. Meth. Phys. Res. A 449, 147 (2000).
[10] A. Gokalp et al., Eur. Phys. J. C 3, 1 (2001).
[11] D. Akimov et al., Phys. Lett. B 524, 245 (2002).
[12] E. Aprile et al., Phys. Rev. D 72, 072006 (2005).
[13] V. Chepel et al., Astropart. Phys. 26, 58 (2006).
[14] E. Aprile, C. E. Dahl, L. de Viveiros, R. Gaitskell, K.-L. Giboni, J. Kwong, P. Majewski, K. Ni, T. Shutt, and M. Yamashita, Phys. Rev. Lett. 97, 081302 (2006).
[15] P. Sorensen et al. (XENON Collaboration), Nucl. Inst. Meth. Phys. Res. A 601, 339 (2009).
[16] V. N. Lebedenko et al. (ZEPLIN-III Collaboration), Phys. Rev. D 80, 052010 (2009).
[17] E. Aprile et al., Phys. Rev. C 79, 045807 (2009).
[18] A. Manzur, A. Curioni, L. Kastens, D. N. McKinsey, K. Ni, and T. Wongjirad, Phys. Rev. C 81, 025808 (2010).
[19] G. Plante, E. Aprile, R. Budnik, B. Choi, K.-L. Giboni, L. W. Goetzke, R. F. Lang, K. E. Lim, and A. J. Melgarejo Fernandez, Phys. Rev. C 84, 045805 (2011).
[20] M. Horn et al. (ZEPLIN-III Collaboration) (2011), Phys. Lett. B 705, 471 (2011).
[21] E. Aprile et al., Phys. Rev. D 88, 012006 (2013).
[22] Model FN from High Voltage Engineering Corporation.
[23] Vikuiti enhanced specular reflector by 3M, Inc., 3m.com.
[24] hamamatsu.com.
[25] EJ301 liquid scintillator from Eljen, Inc., eljentechology.com.
[26] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Inst. Meth. A 506, 250 (2003).
[27] L. W. Kastens, S. B. Cahn, A. Manzur, and D. N. McKinsey, Phys. Rev. C 80, 045809 (2009); L. W. Kastens, S. Bedikian, S.B. Cahn, A. Manzur and D. N. McKinsey, J. Inst. 5, P05006 (2010).
[28] W. H. Lippincott, S. B. Cahn, D. Gastler, L. W. Kastens, E. Kearns, D. N. McKinsey, and J. A. Nikkel, Phys. Rev. D 81, 045803 (2010).
[29] A. Manalaysay, T. Marrodan Undagoitia, A. Askin, L. Baudis, A. Behrens, A. D. Ferella, A. Kish, O. Lebeda, R. Santorelli, D. Venos, A. Vollhardt, Rev. Sci. Inst. 81, 073303 (2010).
[30] A. Hitachi, T. Takahashi, N. Funayama, K. Masuda, J. Kikuchi, and T. Doke, Phys. Rev. B 27, 5279 (1983).
[31] Daqmman software, github.com/bloer/daqman.
[32] V1720B digitizers by CAEN S.p.A., caen.it.
[33] W. H. Lippincott, K. J. Coakley, D. Gastler, A. Hime, E. Kearns, D. N. McKinsey, J. A. Nikkel, and L. C. Stonehill, Phys. Rev. C 78, 035801 (2008).
[34] S. Kubota, A. Nakamoto, T. Takahashi, T. Hamada, E. Shibamura, M. Miyajima, K. Masuda, and T. Doke, Phys. Rev. B 17, 2762 (1978).