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 in a LAr-TPC. A liquid scintillation counter was arranged to detect and identify neutrons scattered in the LAr-TPC target and to select the energy of the recoiling nuclei.

We report the observation of a significant dependence on drift field of liquid argon scintillation from nuclear recoils of 11 keV. This observation is important because, to date, estimates of the sensitivity of noble liquid 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 [1–5]. 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.

Two measurements of the nuclear recoil light yield in LAr, both performed in absence of a drift field, have been reported [6, 7]. For Liquid Xenon (LXe), several measurements in absence of a drift field are in the literature [8–17]; two measurements [18, 19] showed a small effect due to drift field, almost independent of the field strength.

We have observed a strong dependence on drift field of the scintillation from nuclear recoils in LAr.

Nuclear recoils were produced using a neutron beam at the University of Notre Dame Institute for Structure and Nuclear Astrophysics. Protons from the Tandem accelerator [20] struck a 0.20 mg/cm^2 thick LiF target mounted in the beamline vacuum, generating a neutron beam through the reaction ^{7}Li(p,n)^{7}Be. For the study reported here, the proton beam energy was set to (2.353±0.001) MeV. The proton beam was bunched and chopped to provide pulses 1 ns wide, separated by 101.5 ns, with the accelerator pulse selector set to allow one of every two proton bunches to strike the LiF target, giving one neutron beam pulse every 203.0 ns. The energy width at zero degrees was ∼2 keV FWHM [21].

The average energy of neutrons hitting the LAr-TPC was 581 keV. Scattered neutrons were detected in two commercial liquid scintillator counters [22], N1 and N2, 12.7×12.7 cm cylinders, 71 cm from the LAr target. These detectors provide timing information and pulse shape discrimination, both of which suppress background from γ-ray interactions. The scattering angle to the neutron detector was 50.6°, defining the nuclear recoil energy of 11 keV (4 keV FWHM, see Fig. 1). Cylinders of polyethylene (25.4×25.4 cm) shielded the neutron detectors from direct view of the LiF target.

The design of the LAr-TPC target and of the beam was influenced by a set of Monte Carlo simulations performed with the GEANT4 framework [23], including all the materials in the SCENE LAr-TPC, a realistic detector geometry, particle kinematics, and interactions.

The design of the detector closely mirrors that of the DarkSide-10 LAr-TPC [4]. The active

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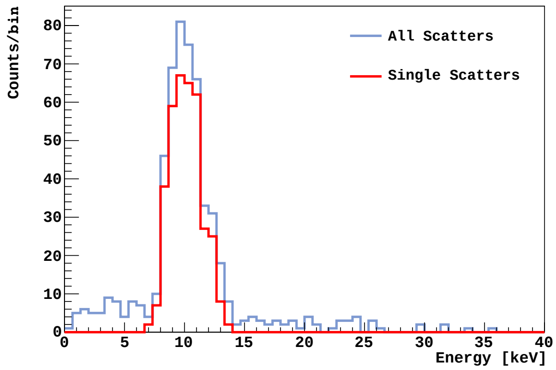

FIG. 1: GEANT4-based simulation of the SCENE detector: the lines represent actual energy deposition, not broadened by the detector resolution. Blue: all scatters in the LAr-TPC producing coincidences in either neutron detector and surviving the timing cuts discussed in the text. Red: single elastic scatters surviving the same cuts.

volume is contained within a 68.6 mm diameter, 76.2 mm tall, right circular cylinder lined with 3M Vikuiti enhanced specular reflector [24], viewed by two 3″ Hamamatsu R11065 PhotoMultiplier Tubes (PMTs) [25]. All internal surfaces of the detector were coated with the wavelength shifter TetraPhenylButadiene (TPB).

To monitor the scintillation yield from the LAr scintillation, ^{83m}Kr was continuously injected into the detector by passing the argon gas through a ^{83}Rb trap [26–28]. ^{83m}Kr has a half life of 1.82 hours and decays via two sequential electromagnetic transitions with energies of 9.4 and 32.1 keV and a mean separation of 222 ns. In the LAr, we observe the two decays as a single event. The decay rate of ^{83m}Kr in the LAr-TPC was about 1.2 kBq.

Scattered neutron events were triggered by a coincidence of either of the two LAr-TPC PMTs with either neutron detector. In addition, we recorded data triggered by the LAr-TPC only trigger, prescaled by a factor of 100, permitting the collection of ^{83m}Kr events at a rate of 12 Hz. The trigger thresholds of the LAr-TPC PMTs were set to $\sim$0.2 PhotoElectrons (PE). The LAr-TPC trigger efficiency, measured using positron annihilation radiation from a ^{22}Na source detected in the LAr-TPC in coincidence with the neutron detector, was above 90% for prompt scintillation pulses of 1 PE and greater.

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 was continuously determined using pulses in the tails of scintillation events and was stable to $\pm$2.5% over the length of the run. The long term stability of the entire chain was assessed throughout the data taking by ^{83m}Kr runs in the absence of drift field. The position of the ^{83m}Kr peak was measured to be 277$\pm$7 PE and varied by less than $\pm$3%. 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.

We exploited Čerenkov events from γ-ray interactions in the windows of the LAr-TPC and the PMTs (see Fig. 2(a)) to study any dependence of the apparatus response on the drift field. Čerenkov interactions produce fast 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 [29]). The Čerenkov event spectrum 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 [30], which recorded signals from the LAr-TPC and neutron detectors and the accelerator RF signal. The digitizer records were 16 μs long including 5 μs before the hardware trigger (used largely to establish the baseline). We computed the following quantities:

TPCtof: the neutron time of flight from the LiF target to the LAr-TPC (modulo an arbitrary offset; start defined by the immediately preceding RF pulse).

S1: the integral of the LAr-TPC PMTs digitizer records within a 7 μs window from the start of the LAr-TPC pulse.

$\mathtt{f}_{90}$: the fraction of the LAr sum pulse integral occurring in the 90 ns following the start of the LAr-TPC pulse. (Nuclear recoils in LAr have $\mathtt{f}_{90}$ in the range 0.45-0.85 while γ-ray interactions have $\mathtt{f}_{90}$ in the range 0.2-0.3 [29]).

Ntof: the neutron time of flight from the LiF target to the neutron detector (modulo an arbitrary offset; start defined by the immediately preceding RF pulse).

Npsd: the pulse shape discrimination parameter for the neutron detector, defined as the maximum pulse amplitude divided by the pulse integral.

Fig. 2(a) shows an uncut scatterplot of $\mathtt{f}_{90}$ vs. TPCtof for a sample of events collected in absence of drift field. Beam-associated events with γ-like and neutron-like $\mathtt{f}_{90}$ are clustered near 10 and 75 ns respectively. Čerenkov events are characterized

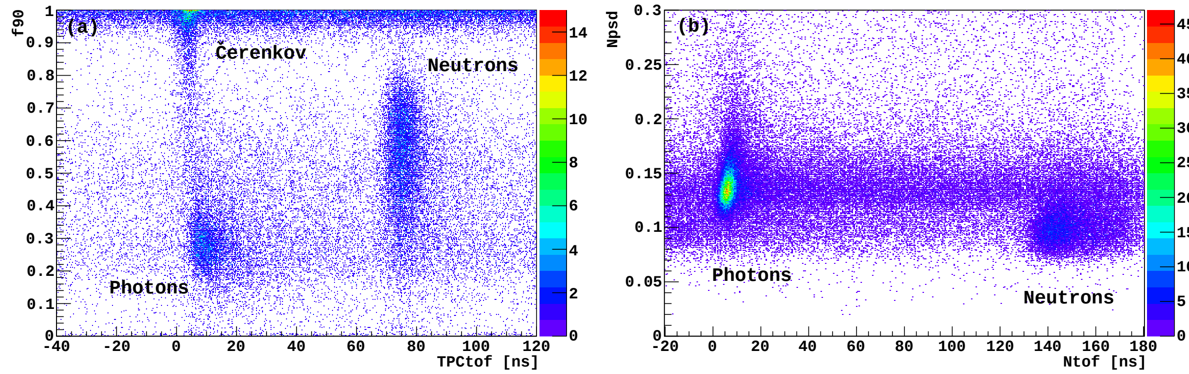

FIG. 2: Uncut distributions of pulse shape discrimination vs. time of flight. Panel (a) refer to the LAr-TPC and panel (b) to the neutron detectors. Data were collected in absence of drift field.

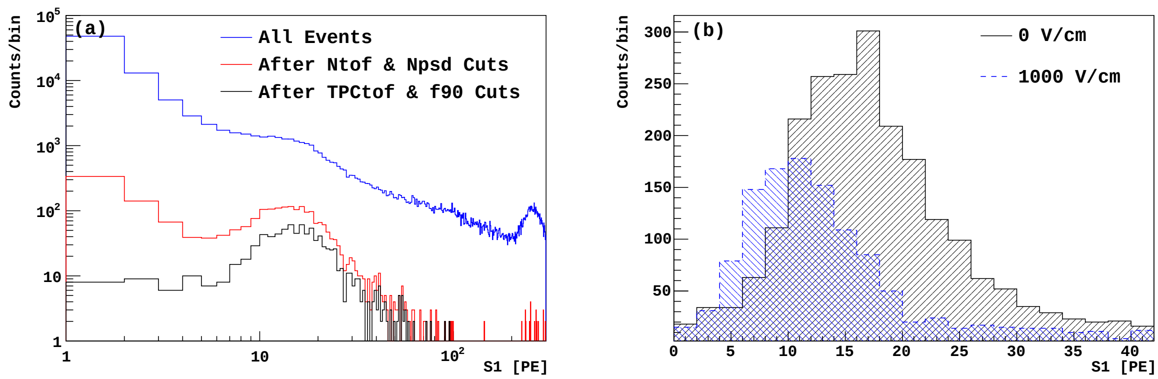

FIG. 3: (a) Surviving S1 distributions as the neutron selection cuts described in the text are imposed sequentially. Data were collected in absence of drift field. The high energy peak is from the ^{83m}Kr source in use for continuous monitoring of the detector. (b) Final S1 distributions for the 11 keV nuclear recoils as function of drift field.

by $\mathtt{f}_{90}$ close to 1.0 and γ-like timing. The ^{83m}Kr events form a band with γ-like $\mathtt{f}_{90}$ evenly distributed in TPCtof. We derive cuts $0.40<\mathtt{f}_{90}<0.80$ and 72 ns<TPCtof<78 ns to select scattered neutron events. Fig. 2(b) shows an uncut scatterplot of Npsd vs. Ntof for the same events. Scattered neutron events cluster near a Ntof of 140 ns and a Npsd of 0.09, while β/γ events cluster near a Ntof of 5 ns and a Npsd of 0.13. Random background is visible at intermediate times. We derive cuts 138 ns<Ntof<144 ns and 0.06<Npsd<0.12 to select scattered neutron events.

Fig. 3(a) shows the S1 scintillation spectra as the cuts are imposed in sequence. The final spectra obtained as function of drift field, shown in Fig. 3(b), are fitted to a gaussian and the centroid of the gaussian peak represents our measurement of the yield. The relative light yield vs. drift field, normalized to the value obtained in absence of drift field, is shown in Fig. 4. At a field of 1 kV/cm, the light yield is reduced by 35%.

In summary, we have presented a new technique for measuring the scintillation yield for nuclear recoils in LAr, using a dedicated LAr-TPC exposed to a pulsed, narrowband, neutron beam. Using this technique we have measured the light yield from 11 keV nuclear recoils in LAr and find a marked dependence of the yield on drift field. Such a significant dependence on field has not been previously reported. Past and current estimates of sensitivity for noble liquid TPC dark matter searches assume the light yield for nuclear recoils is only slightly affected by the presence of a drift field.

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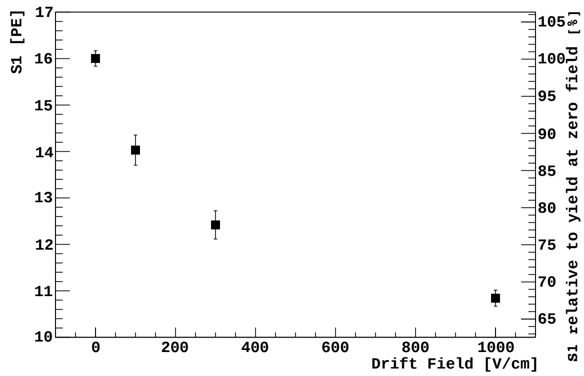

FIG. 4: Variation of the S1 scintillation yield for 11 keV nuclear recoils as a function of drift field.

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