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First demonstration of a sub-keV electron recoil energy threshold in a liquid argon ionization chamber

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ABSTRACT

We describe the first demonstration of a sub-keV electron recoil energy threshold in a dual-phase liquid argon time projection chamber. This is an important step in an effort to develop a detector capable of identifying the ionization signal resulting from nuclear recoils with energies of order a few keV and below. We obtained this result by observing the peaks in the energy spectrum at 2.82 keV and 0.27 keV, following the K- and L-shell electron capture decay of ^{37}Ar respectively. The ^{37}Ar source preparation is described in detail, since it enables calibration that may also prove useful in dark matter direct detection experiments. An internally placed ^{55}Fe x-ray source simultaneously provided another calibration point at 5.9 keV. We discuss the ionization yield and electron recombination in liquid argon at those three calibration energies.

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1. Introduction

Dual-phase noble liquid detectors have become a popular choice for WIMP dark matter experiments thanks to their target mass scalability, low background, and low threshold. More recently, they have been also proposed to search for coherent neutrino–nucleus scattering (CNNS). In both applications, the only signature in the detector is a low-energy nuclear recoil. For the most common WIMP detection scenarios, nuclear recoil energies between 10 and 100 keVr in liquid Ar or Xe are expected [1]. For CNNS, detection sensitivity to nuclear recoils of a few hundred eVr is needed, especially if reactor neutrinos are employed [2]. Energy thresholds of 5–10 keVr are commonly obtained in dark matter experiments with liquid xenon or argon. The XENON10 experiment recently showed that an energy threshold as low as 1 keVr, corresponding to only a handful of ionized electrons, might be obtained [3] in liquid xenon. This result was obtained from extrapolation of the model described in Ref. [4]. It is essential to measure the low-energy response of noble gas detectors to allow their use for CNNS, and to probe broader ranges of light-mass WIMPs.

Here we report the first demonstration of sub-keV electron-recoil spectroscopy in a dual-phase argon detector. This is achieved by detecting the proportional scintillation produced in the gas phase of the detector by ionization electrons after they have been extracted from the liquid phase. Specifically, we observed the 270 eV cascade following L-shell electron capture in ^{37}Ar. The signal detected from spurious single electrons in the liquid is used as an absolute calibration for the ionization channel. We then suggest that low energy electron recoils can be modeled within an existing framework. The results shown here are a first step toward providing detector capability to measure the ionization yield of nuclear recoils at few keVr and below, as well as for enhancing the reach of axion search via the axio-electric effect.

In liquified noble gas detectors, the energy transferred to the medium by a particle results in ionization, scintillation and heat [5]. The fraction lost to each channel depends on both the incident particle type and energy. Indeed, electron recombination rate varies with ionization density along the track as well as the electric field. A discussion of the mechanism and yields of energy transfer in liquefied noble gases lies outside the scope of this paper. Extensive prior work has been done on this subject (see for example [6] and references therein). However, experimental data are still scarce at low energies for both electron and nuclear recoils. In addition, the measurements have mostly focused so far on scintillation yields alone, rather than ionization.

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2. Detector and calibration sources

We have built a prototype dual-phase liquid argon time-projection chamber in the context of our program to detect coherent neutrino–nucleus scattering [7]. Our detector emphasizes high-sensitivity measurement of the ionization signal by means of secondary scintillation in the gas region. A particle interaction in the liquid phase produces primary scintillation (S1) and ionization [5]. The electrons are drifted away from the interaction site by an electric field and extracted into the gas where they create secondary scintillation (S2) that is detected by photomultiplier tubes (PMTs). Light collection was optimized for the S2 rather than S1 signal, and as a result the detection of S1 is limited to above approximately 10 keV.

A schematic view of the detector is provided in Fig. 1. It consists of ~100 g of liquid argon as the active volume surrounded on the bottom and sides by ~1 kg of inactive liquid. A gaseous region extends on top of the liquid and is kept at a constant pressure of ~ 820 torr. The temperature of the gas is that of the Ar vapor at that pressure. The active volume is 3.65 cm high and 5 cm in diameter. A set of four copper rings delimits this active volume and shapes the electric field needed to drift the electrons in the liquid. An extraction grid is placed 5–10 mm below the liquid level, while the anode is located 2.5 cm above the extraction grid. Electric fields up to 4 kV/cm in the drift region and up to 10 kV/cm in the gas region were achieved. At the operating fields indicated in Fig. 1, the electrons speed is 2.85 mm/μs and 0.7 cm/μs in the drift and gas region respectively [8,9]. The S2 signal decays with the characteristic 3.2 μs decay constant of argon triplet states in gas [10].

The argon scintillation light is transmitted through a fused silica window and detected by four 1 in. Hamamatsu R8520 PMTs modified for cryogenic operation and arranged into a square array. A 0.05 mg/cm^2 coating of tetraphenyl butadiene (TPB) deposited on the silica window acts as a wavelength shifter for the Ar UV scintillation light [11]. The signals produced by PMTs provide a trigger and are digitized at 500 MHz using a LeCroy Waverunner 104MXi-A 8 bit digital oscilloscope.

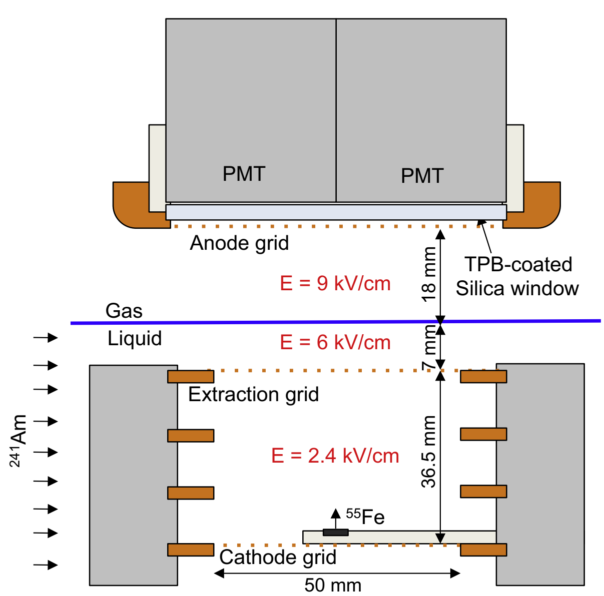

Fig. 1. Schematic drawing of the vertical cross-section of the detector central region. The four copper rings are negatively biased and shape the electric field in the drift region. The anode is at ground potential. A SS mesh (50 mesh/in., 30 μm dia wire, 88% optical transparency) is used for the anode and cathode grids. The extraction grid is obtained using 15 μm SS wire with 1 mm spacing. The scintillation light is collected by four 1 in. PMTs through a TPB-coated silica window. The electric fields used to obtain the data reported here are also shown. For calibration, a vertical beam of gamma rays from a collimated ^{241}Am source entered the active region from the side. A ^{55}Fe source is mounted facing upward on a movable teflon arm extending in the detector volume just above the cathode grid.

The detector response was studied using the 59.54 keV gamma rays from a 5 cm diameter electroplated ^{241}Am source (18.5 MBq). To minimize peripheral events, the source was vertically collimated to produce a ~2 mm width beam passing through the center of the detector and spanning the entire drift region of the detector (see Fig. 1). The decrease in S2 amplitude of photoelectric events (59.54 keV) with event depth facilitates measurement of electron lifetime in the liquid. The event depth is calculated using the time delay between the S1 and S2 scintillation signals. For the measurements reported here, the electron lifetime was ~12 times longer than the electron drift time through the active region. The ^{241}Am purity data were taken at a drift field of 3.0 kV/cm.

Two radioactive sources, ^{55}Fe and ^{37}Ar, were used for calibration of the detector to low energy electron recoils. A 5 mm diameter electroplated ^{55}Fe bare source provided 5.90 keV and 6.49 keV x-rays with ~1 kBq activity. The source was mounted on a movable arm located just above the cathode inside the liquid argon active volume.

In addition, for the first time in a dual-phase detector, we used ^{37}Ar as a diffused source throughout the active region. ^{37}Ar was obtained from neutron irradiation of ^{nat}Ar at McClellan Nuclear Research Center, similarly to what described in Ref. [12]. ^{nat}Ar is composed of ^{40}Ar (99.6%), ^{36}Ar (0.34%) and ^{38}Ar (0.06%). The irradiation therefore produces mainly ^{41}Ar that quickly decays with a half-life of 110 min, leaving ^{37}Ar as the only significant radioactive product. ^{37}Ar decays by electron capture (EC) to the ground state of ^{37}Cl with a half life of 35 days. The atomic shell cascade processes result in a total energy release of 2.82 keV for K-shell capture and 0.27 keV for L-shell capture [13]. For production of ^{37}Ar used in our experiment, 1 l of ^{nat}Ar at a pressure of 11 bar was irradiated in a nuclear reactor for 4 h to obtain 30 μCi of ^{37}Ar. The activity was verified by measuring gamma emission from ^{41}Ar shortly after irradiation. The gas was then cryogenically extracted, transferred to a small gas cylinder and pressurized with ^{nat}Ar to 90 bar. The activated argon is injected in the detector through a purifier (SAES MC1500-903) in a similar way as the ^{nat}Ar. In order to reach the desired activity in the detector, a fixed volume of gas at known pressure was introduced several time. We demonstrate that an ^{37}Ar source is useful for calibration of low-energy electromagnetic recoils in dual-phase detectors.

3. Results

We report the results of our first measurements with ^{37}Ar. These measurements were taken with $E_{drift} = 2.4$ kV/cm applied electric field across the active region, and 6.0 kV/cm across the 7 mm of liquid argon in the extraction region, which ensures ~100% transmission of electrons from the liquid into the gas phase [14]. The electric field in the gaseous amplification region was 9.0 kV/cm.

The waveform of each PMT was independently digitized and stored for off-line analysis. The trigger was set to acquire all four PMTs signals when signals from two selected PMTs exceed the hardware threshold set just above the baseline noise within 5 μs. Each waveform is 100 μs long and includes a 35 μs pre-trigger.

The analysis of PMTs signals is performed following a gate-time algorithm similar to the one outlined in Ref. [15]. From each triggered waveform, the baseline is first computed for each channel; software thresholds are then set based on the single photo-electron (s.p.e.) response of each PMT. All digitized points above threshold are grouped into a single event if their time gap is less than a given gate time across all four channels. A gate time of 3.5 μs is used for the analysis of the data reported here. Varying