# Argon Recoil Ionization and Scintillation (ARIS)

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**Abstract**

We propose to measure the liquid argon scintillation and ionization responses to nuclear recoils (NRs) with monoenergetic directional neutrons, as functions of different applied electric fields using a dual-phase argon Time Projection Chamber (TPC). Neutrons are produced with the LICORNE neutron source and 13.25 MeV $^{7}$Li beam from the TANDEM accelerator of the ALTO facility. Information on the scintillation and ionization energy scales, quenching factor, recombination probability, and time response will deeply impact the results of current and future liquid argon based experiments designed for direct detection of dark matter particles, such as DarkSide [1, 2], ArDM [3], and Deap-3600 [4]. In addition, the liquid argon response may depend on the NR direction with respect to the electric field. In case this effect will be observed, liquid argon based experiments will benefit from an unambiguous signature for the direct dark matter detection. We request 20 UT for this experiment.

## 1 Motivation and Goals

The existence of gravitational effects that do not arise from normal matter is well established, even if their source is a deep mystery. One possibility, motivated by considerations in elementary particle physics, is that the mysterious effects are due to "Dark Matter", consisting of undiscovered elementary particles. A leading candidate explanation is that Dark Matter is composed of Weakly Interacting Massive Particles (WIMPs), formed in the early universe and gravitationally clustered together with standard baryonic matter.

The present leading technology in the direct search for dark matter employs instrumented volumes of noble liquids to look for WIMP elastic scattering on atomic nuclei. Liquid argon (LAr) is among the most favorable choices because it guarantees excellent radio-purity, high stopping power for penetrating radiation, and high ionization and scintillation yields. Furthermore, LAr provides exceptional discrimination power for separating the nuclear recoils (NRs) expected from WIMP elastic scatters from the abundant electron recoil (ER) backgrounds resulting from gamma and electron interactions.

The current leading LAr based dark matter experiment is DarkSide-50 [1, 2], which uses a dual-phase (liquid-gas) argon Time Projection Chamber (TPC). In a dual-phase LAr TPC, recoiling nuclei cause argon excitation and ionization. Each scatter is detected by looking for both the primary scintillation light signal (S1), from argon de-excitation, and the signal from free ionization electrons. As shown in Fig. 1 (left), the latter are drifted towards the top of the TPC, thanks to a vertical electric field, and extracted into the argon

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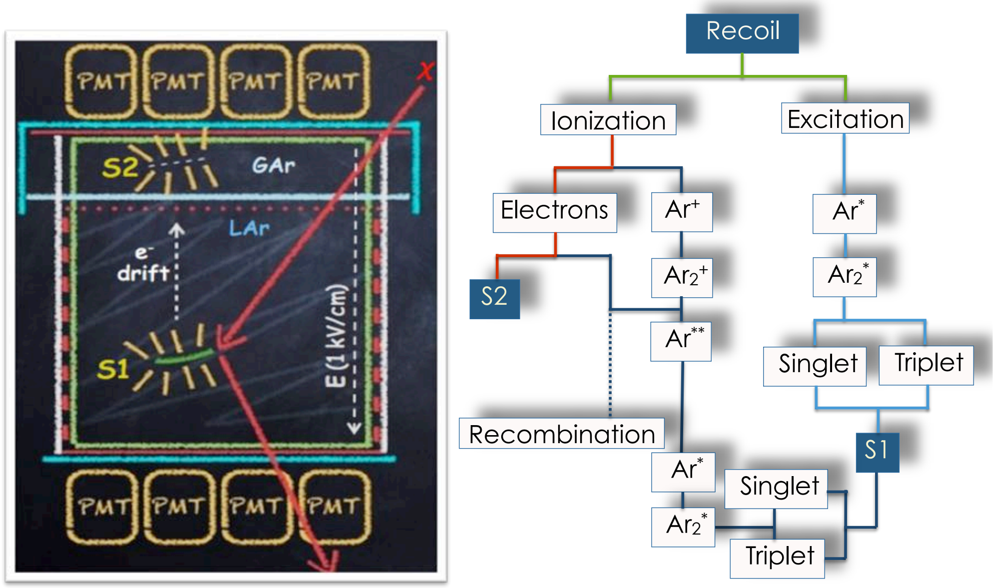


Figure 1: (Left) Schematic of a LAr TPC. (Right) Scheme for the ionization and scintillation branches.

gas phase, close to the top array of photo-sensors. Accelerated electrons produce, by electroluminescence in the gas pocket, a secondary light pulse (S2). A fraction of free electrons, however, recombine with ions in the ion-electron cloud produced by the ionizing track itself, forming short-lived excited diatomic argon "molecules". These directly contribute to the S1 light pulse, as shown in Fig. 1 (right).

The time profile of the S1 pulse is characterized by two time constants, one associated with de-excitation from the singlet state and the other with the triplet state. The ratio of singlet to triplet states produced in the track from a NR is different from the ratio in the track from a ER, providing an extremely powerful discrimination (pulse shape discrimination, PSD) between the two types of recoils. In addition, the ratio of ionization to excitation differs in NR vs. ER, providing an additional discrimation parameter.

A critical aspect to LAr TPC dark matter search experiments is the limited knowledge of the LAr response for recoil energies below 100 keV, in both the scintillation and ionization channels, and as function of the drift electric field. It is mandatory to improve the knowledge of the mechanisms at the basis of the S1 and S2 pulses, since the recombination effect is non-linearly energy dependent. To achieve this, we plan to measure the LAr response at different NR energies, especially in the 10 keV to 100 keV range, and with different intensities of the electric field, which also affects the electron-ion recombination probability. Also the scintillation time pulse shape is affected by the recombination effect, since the dimer produced by the ion-electron recombination de-excites in a different way with respect to an argon molecule directly excited by particle interactions.

Furthermore, columnar recombination [5] models suggest that the magnitude of the recombination effect should, in some circumstances, vary with the angle between the field and the track direction. A difference in the electron-ion recombination effect is, in fact, expected when the ionizing track is either parallel or perpendicular to the electric field. In the first case, the electrons cross a "column" of ion-electron pairs produced by the ionizing track, maximizing the recombination probability. In the second case, the crossed "column" volume is strongly reduced, and the recombination probability is minimized. The net effect of the electron-ion recombination is the reduction of the ionization signal (S2), and the consequent enhancing of the primary scintillation pulse (S1). An accurate measurement of the sum (S1 + S2) and the ratio (S1/S2) of the two signals may provide an indication on the track direction.

**We propose to expose a small-scale dual-phase LAr TPC, capable of 3D position reconstruction, in front of the LICORNE beam to fully characterize the LAr response and to search for directional effects.** The neutrons will be observed in coincidence by the LAr TPC and by neutron detectors (NDs), placed at several angles with respect to the beam-TPC axis to kinematically constrain the NR energy. Such measurements are nearly impossible to do in full-scale dark matter detectors, where nuclear recoils are very rare; it is cumbersome and unwieldy to install neutron sources; and the fields and other TPC parameters cannot be readily changed.

Similar measurements were performed in 2013 and 2014 by the SCENE experiment [6, 7] with a TANDEM accelerator at Notre Dame Institute for Structure and Nuclear Astrophysics. The reaction $^{7}$Li(p,n)$^{7}$Be used by SCENE generates an isotropic neutron flux which strongly limited the statistics and increased the background. The exceptional collimation reachable with the LICORNE source, in association with the quasi-monoenergetic regime, makes the IPNO beam the ideal and unique facility to perform such a measurement. To make a comparison, full simulations of the proposed setup in front of the LICORNE source (assuming 13.25 MeV $^{7}$Li energy, a neutron rate of 245 kHz, and including the full kinematics) demonstrated that we will reach a signal rate >100 higher than the SCENE one with similar or better signal to background ratios.

The dual-phase TPC that we intend to expose in front of LICORNE is already built and characterized at UCLA. It is equipped with seven 1-inch photomultiplier tubes (PMTs) on the top and one 3-inch PMT on the bottom, strongly increasing the energy resolution relative to SCENE and making accessible the 3D position reconstruction of each scatter. In comparison, the SCENE TPC was equipped with only one 3-inch PMT on the top, which does not allow reconstruction of the xy-position of the interaction.

## 2 Proposed Measurement

We propose to characterize several aspects of the LAr response. In particular, the physics program is aimed to reach the following goals:

1. **Precision measurement of the relative scintillation efficiency of NRs as function of the energy, in the range 16 keV to 130 keV.** As shown in Fig. 2, results present in literature are controversial especially below 50 keV [8].
2. **Map of the PSD estimator (f90) as function of the energy and the drift field.** The f90 variable is defined as the number of detected primary scintillation photons in the first 90 ns with respect to the total number of detected photons in S1. This parameter is used to discriminate the ER background in WIMP search experiments. In particular, the precise measurement of its distribution is critical to define the acceptance region of the expected WIMP candidates.
3. **Measurement of recombination probability as a function of the energy and drift field.** We will derive its behavior by combining S1 and S2 scintillation signals. The result will be compared with a model developed at APC for the DarkSide experiment, working for electron recoils but never tested on a NR data set.
4. **Measurement of recoil directionality.** We will measure the scintillation and ionization yields, at fixed NR energies, for perpendicular and (almost) parallel NR directions with respect to the drift field. As already mentioned, we expect an enhancement of the recombination effect for parallel NR tracks with respect to the orthogonal ones, which should result in a difference of the yields. This measurement has the potential to deeply impact the future of direct dark matter experiments, extending their sensitivities to extremely small WIMP elastic scattering cross sections, where also astrophysical neutrinos are expected.

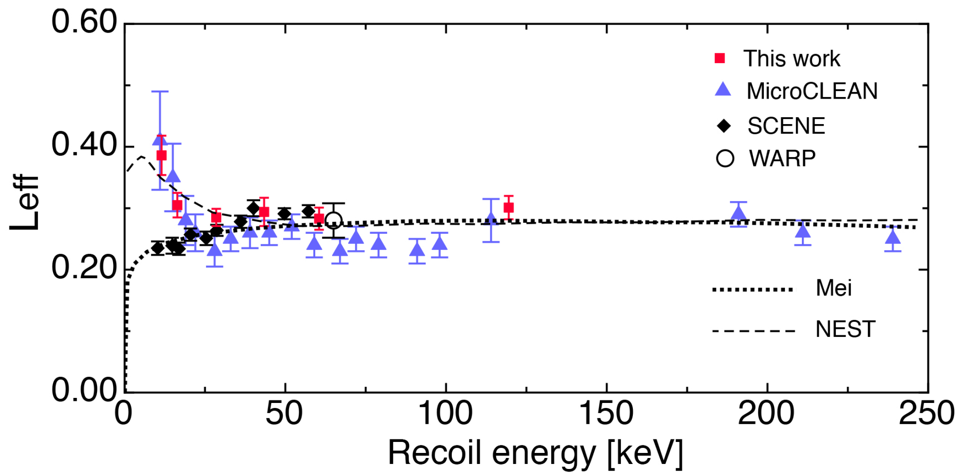


Figure 2: Previous measurements of relative scintillation efficiency ($\mathcal{L}_{\rm eff}$) in other experiments. Red squares ("This work") refer to Ref. [8].

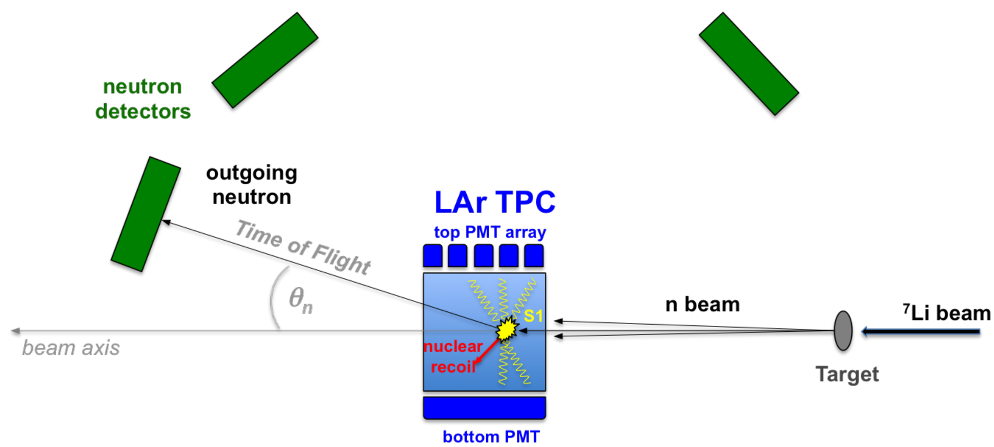


Figure 3: Schematic of the LAr TPC in the neutron beam with neutron detectors (green) at various angles.

## 3 Experimental Setup

The neutrons produced by the IPNO Tandem $^7$Li pulsed beam on the LICORNE source first interact with the liquid argon target in the TPC and then, in coincidence, with a neutron detector, as shown in Fig. 3. There are four neutron detectors currently available at the Licorne facility.

The LAr TPC has a design that closely follows the one used in DarkSide-50 [1, 2]. The diameter and height of the LAr target are chosen to limit contamination from multiple neutron scattering to an acceptable level. The active volume is contained within a 7.6 cm diameter, 7.6 cm tall, right circular Poly-Tetra-Fluoro-Ethylene (PTFE, or Teflon) cylinder and capped by quartz windows. The LAr is viewed through the windows by one 3-inch Hamamatsu R11410 PMT on the bottom and an array of seven 1-inch Hamamatsu R8520 PMTs on the top. The windows are coated with indium tin oxide (ITO), a transparent conductor, which constitute the anode and cathode surfaces. Copper rings embedded in the PTFE cylinder maintain field uniformity. All internal surfaces of the detector are coated with the wavelength shifter Tetra-Phenyl-Butadiene (TPB), which converts the LAr scintillation light from the vacuum UV range (128 nm) into the blue range (420 nm).

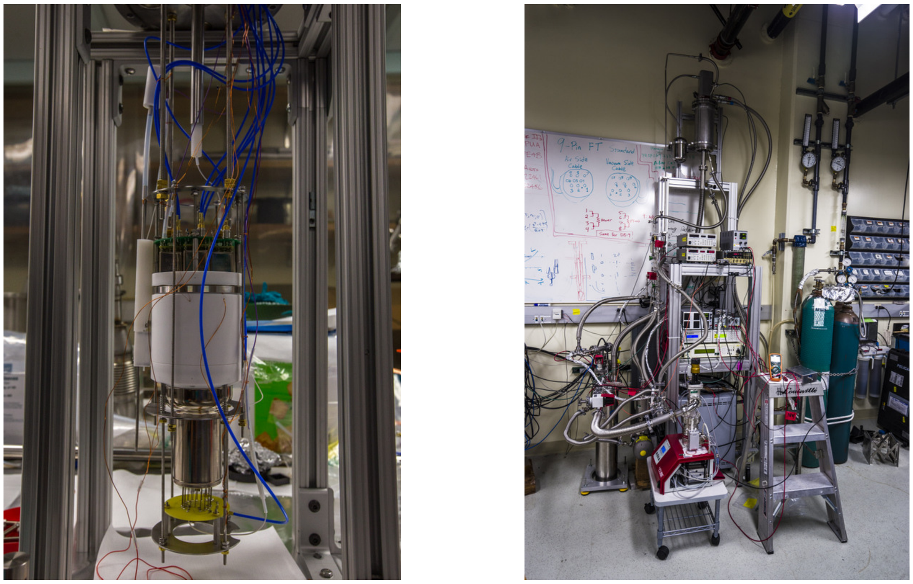

Figure 4: (Left) Fully assembled LAr TPC at UCLA. (Right) TPC installed within cryostat and integrated into full cryogenics, high voltage, and data acquisition systems.

A stainless steel mesh grid is positioned 8 mm below the anode and defines the top of the active volume. The gas pocket is designed to be 5 mm thick, so the grid is below the liquid surface. The grid, anode, and cathode surfaces can be tuned to set the drift field up to 1 kV/cm and the extraction field above the grid up to 4 kV/cm. The TPC is mounted on a stainless steel flange which sits on top of a vacuum jacketed stainless steel cryostat. As can be seen in Fig. 4, the LAr TPC has been fully built and tested at UCLA.

Operation of the TPC requires a variety of supporting subsystems for high voltage, Ar liquefaction, gas recirculation, online Ar purification, data acquisition, and system monitoring. High voltage (HV) is passed into the cryostat via custom made feedhthroughs. The maximum HV needed for this experiment is 12 kV, which is passed into the cryostat through a feedthrough that has been tested to 20 kV. A Cryomech PT90 Cryocooler condenses Ar into liquid, which is transferred to the cryostat via a vacuum jacketed transfer line. Argon gas is recirculated using a Q-drive pump in a closed loop from the cryostat through a SAES MonoTorr getter (to remove impurities) and back to the condenser. The cryostat pressure, gas flow rate, and various temperatures are monitored by a LabView slow control. The PMT signals are read by an Acqiris 8-bit 8-channel 500 MHz DAQ. The DAQ software is also written in LabView and is fully functional.

In November 2015, the TPC was commissioned at UCLA. The main goal was to test the ability to produce S2 signals, which requires nearly all subsystems to be functional. We successfully produced S2 signals, as shown in Fig. 5, while holding 5 kV on the grid and 9 kV on the cathode.

The EDEN NE213 liquid scintillator neutron detectors have cylindrical shape with 2 cm diameter surface and 5 cm height. The neutron energies are determined with a time-of-flight (TOF) measurement where the start is given by the RF accelerator signal. Typical neutron energy resolution is about 60 keV for 1 MeV neutrons with an efficiency of about 50%.

The angle defined by the beam axis and the ND, in association with the known energy of the emitted neutron, allows to kinematically constrain the NR energy with good accuracy. The precision will be improved by exploiting the neutron TOF technique. The time coincidence between the beam pulse, the TPC, and the ND will strongly increase the signal-to-background ratio. In particular, the trigger condition will include a TOF cut of $\pm 10$ ns around the peak value measured at the ND distance.

Ideally, we want to select events scattering only once in the liquid argon target and at least once in the ND,

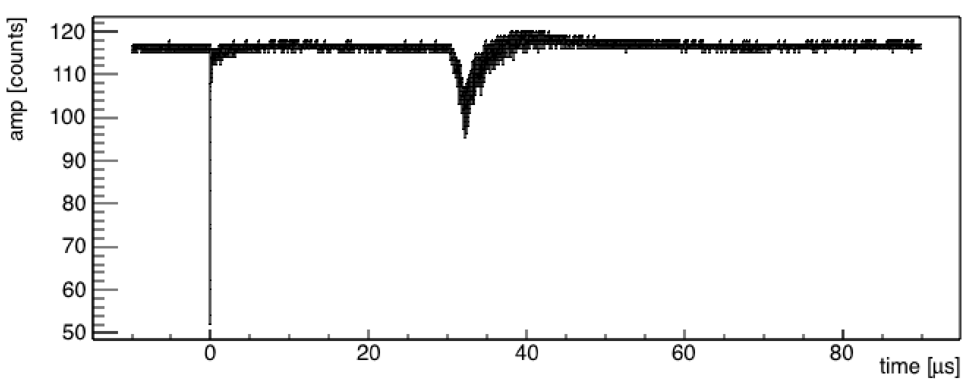


Figure 5: Example event showing the S1 and S2 signals.

without other scatters in passive materials, like the steel of the cryostat or the Teflon used for mechanical support and light reflector in the TPC. The background can be classified as following:

- neutron multiple scattering in liquid argon and/or in the detector materials;
- multiple neutrons scattering in liquid argon in the same acquisition gate;
- accidental coincidences with gamma background generated by the LICORNE source itself;
- accidental coincidences with neutrons scattering off the hall walls and floor.

A full GEANT4 Monte Carlo simulation of the described setup has been implemented to study the optimal parameters in order to minimize the background and maximize the signal rate. The main physics constraint is due to pile-up during the time of the acquisition gate: the slow component of the scintillation pulse has a characteristic time of 1.6 µs, which implies that the full S1 signal is contained in a 8 µs gate. The maximum drift time, assuming the minimum drift field of 200 V/cm (drift velocity ∼1 mm/µs) and the TPC height (∼7.6 cm) is ∼76 µs. Conservatively, an acquisition gate of the order of 100 µs is needed to fully contain both S1 and S2 signals. Each waveform is acquired with 2 ns sampling. The maximum TPC DAQ acquisition rate is ∼100 Hz.

The distance between the source target and the TPC is defined by requiring a mean number of gamma interactions in liquid argon per gate equal to or lower than 0.1. A first estimation of the gamma background was obtained by comparing measurements performed at IPNO, with a ND placed on-axis at 2.25 m of distance from the beam, and simulations. The isotropic 478 keV gamma flux generated at the beam target is of the order of 10 MHz. Assuming such a rate, the condition for a maximum of 0.1 gamma event in 100 µs gate is satisfied at a target-TPC distance of 2 m. Assuming to work with the S1 pulse only, regardless of the S2 one, the background condition is satisfied for a 8 µs gate at a distance of ∼80 cm.

The planned ND configuration that we will use allows for more favourable background conditions. The actual distance of the TPC from the target will be defined after onsite measurement of the actual gamma background, which will be performed with a standalone setup composed by two $BaF_2$ detectors and a digital oscilloscope (LECROY WaveRunner 625Zi) with a bandwidth of 2.5 GHz and a maximum trigger rate of 1 MHz waveform/second (same setup as in reference [9]).

In order to reach the physics goals of the experiment, we propose to run the setup in 3 phases:

- **Phase 1** will be dedicated to the S1 signal only, with a “short” acquisition gate of 8 µs, able to acquire very large statistics and to explore a large number of points in the NR energies vs drift field parameter space.

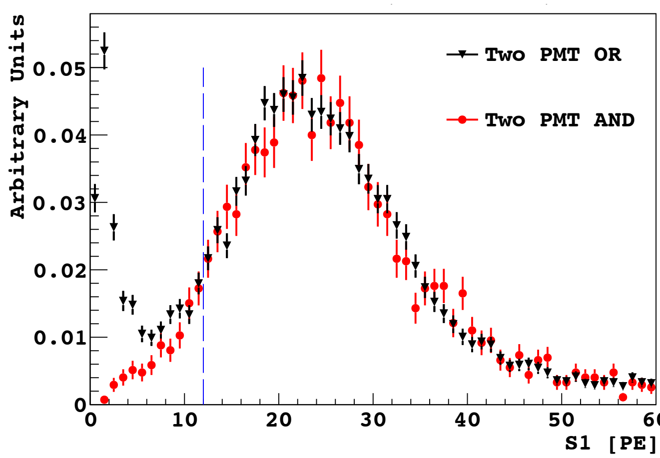


Figure 6: Example spectrum measured by SCENE for the NR energy of 20.5 keV and a field of 970 V/cm [7].

- **Phase 2** will be dedicated to the S1+S2 measurement with a "long" gate (∼100 µs) and a large target-TPC distance to avoid gamma background. The number of steps in the parameter space will be reduced with respect to the previous phase.
- **Phase 3** will be dedicated to the measurement of directionality effects.

In the first two phases, the beam will be tuned to reach the highest collimation in order to focus the neutron scatters into the TPC center, improving the kinematic constraint of the NR energy. The collimation condition is satisfied by the lowest achievable $^{7}$Li energy (∼6 MeV), which is particularly convenient because it corresponds to the neutron energy regime closest to the monochromatic one.

In order to improve the accuracy in the scintillation and ionization yield measurements reached by SCENE and, taking into account the detector resolution and the non-linearity of the LAr response, we estimated the necessity of statistical samples of tens of thousands of events, an order of magnitude larger than in SCENE. Fig. 6 shows an example spectrum measured by SCENE for the NR energy of 20.5 keV and a field of 970 V/cm.

The goal of phase 1 is to operate with a trigger rate of ∼20 Hz per ND configuration (1 hr runs). Simulations have demonstrated that this is achievable with a ND distance from the TPC at 1 m, a neutron flux of 245 kHz, and a beam-TPC distance of 80 cm. The signal rate corresponds to about half of the trigger one, after applying cuts to reject electron recoil background, multiple scattering neutrons, and interaction of multiple neutrons. In the phase 1 we will scan 12 NR energies (16 keV to 130 keV) and 8 fields (0 V/cm to 1000 V/cm), which corresponds to 24 runs of 1 hour with 4 NDs.

Phase 2 is expected to operate at a few Hz rate assuming a distance of 1.7 m. In this phase, we will scan 4 NR energies (16, 25, 40, and 130 keV) and 8 fields (0 V/cm to 1000 V/cm), corresponding to 8 runs of 5 hours with 4 NDs.

The last goal, the directionality, requires a different configuration (Phase 3). Since the beam cannot be vertically oriented and the TPC cannot be tilted, the beam direction is always orthogonal to the electric field. This prevents selection of NR tracks parallel to the field in the energy region of interest (>40 keV, where the effect is expected). To avoid this problem, we will exploit the maximum energy of the $^{7}$Li beam (∼22 MeV), which corresponds to the largest cone opening angle (∼40°). At the border of the beam cone, the quasi-monoenergetic condition is still satisfied. The TPC will be then placed about 60 cm below the beam z-position (∼170 cm) and 50 cm in the forward direction. This geometrical configuration allows selecting, for the same NR energy, different track orientations by means of the 4 available NDs. The low neutron flux, crossing the TPC at large angles, and the large gamma background associated to the high energy of the beam, will oblige us to limit the acquisition to only one NR energy, with 4 different track orientations. The electric field values will be set first at 200 V/cm (which corresponds to the operational field of DarkSide) and at 400 V/cm. The expected rate is of the order of 0.1 Hz. The two runs will be then long enough (24 hour each) to acquire enough statistics for observing a difference in the LAr response at a few percent level.

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