ReD for liquid argon nuclear recoil directionality

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On behalf of the ReD collaboration

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Objective:

Determine the angular resolution of dual phase liquid argon TPC by measuring the directional modulation in recombination.

SCENE, Phys Rev D. 91.092007

FIG. 21. Scintillation yield relative to null field (left panels) and ionization yield with non-zero drift field (right panels) of nuclear recoils at 16.9, 36.1 and 57.3 keV. Black: momentum of nuclear recoil is perpendicular to \( E_d \). Red: momentum of nuclear recoil is parallel to \( E_d \). Sources of systematic uncertainties common to both field orientations are not included in the error bars.

Directional dark matter detection sensitivity of a two-phase liquid argon detector

“... using the angular information alone, 100 (250) events are sufficient to reject the isotropic hypothesis at 3 sigma level for a perfect (400 mrad) angular resolution. ... at 200 GeV WIMP mass”
The ReD TPC

Active volume 5*5*5 cm³, 0.7cm gas pocket. Full SiPM coverage on top (24 channels to improve X-Y resolution) and bottom (24 SiPMs grouped into 4 channels). Fused silica window + ITO + TPB Acrylic-3M foil reflector + TPB ~200V/cm drift field.
Performance of the ReD TPC

Performance of the ReD TPC, a novel double-phase LAr detector with Silicon Photomultiplier Readout

For more details, please see arxiv 2106.13168
Submitted to Eur. Phys. J. C

A detailed characterization of the TPC performance.

A thorough study of 50-500 keV electron recoil signal yield in liquid argon from null field to 1000 V/cm. A phenomenological parameterisation of the recombination probability in LAr is presented

High S1 light yield ($g_1$) and S2 gain ($g_2$) achieved.

$$g_1 = (0.194 \pm 0.013_{\text{stat+sys}}) \text{ PE/photon}$$

$$g_2 = (20.0 \pm 0.9_{\text{stat+sys}}) \text{ PE/e}^-.$$
The neutron beam setup

INFN, Laboratori Nazionali del Sud, Catania

Target chamber
LAr cryostat
End of $^7$Li beamline

Neutron detector (LSci)
TPC
Silicon $E\Delta E$ detector (SiTel)
CH$_2$ target

$^7$Li + H $\rightarrow$ n + $^7$Be

28 MeV $^7$Li from TANDEM $\rightarrow$ 7.4 MeV neutron (Energy tunable). $^7$Be tagged by SiTel.

Neutron scatters at 36.8° $\rightarrow$ 74.5±7.8 keV nuclear recoil. The energy spread is due to kinematics and the finite detector sizes.

Neutron detectors (LSci) looking at recoils at 0°, 20°, 40°, 90° relative to the drift field.

Looking for triple coincidence signal.
$^7\text{Li} + \text{H} \rightarrow n + ^7\text{Be}$

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The recombination model

Question:
What is the aspect ratio $R$ for a 70keV nuclear recoil in LAr?

V. Cataudella et al 2017 JINST 12 P12002
https://iopscience.iop.org/article/10.1088/1748-0221/12/12/P12002
What signal are we looking for?

**Contours:** detector response from mono-energy NRs.

**Black dots:** centers of contours.
- Center: \( R=1 \)
- Up: \( R=2, 90° \)
- Down: \( R=2, 0° \)

\( g_1 \) and \( g_2 \) are arbitrary, comparable to ReD.

S2 variance more significant than S1, if it is recombination modulation.
First look at the signals

↑ All TPC - $^7\text{Be}$ tagging double coincidence events
↓ All triple coincidence NR events.

↑ Independent Gaussian fit to the peaks in each recoil direction channel. Pink box indicate the RMS of the peaks. Error bars indicate the uncertainties of the mean positions.
Detailed analysis

Gamma from TPC neutron capture

Neutrons with Be*, 63.5keV recoils.

Neutrons with multi-scattering in cryostat.

Signal

Simulation

Pulse finding → SiPM calib. → Clustering & Pos rec → Pos based correction → Event selection → Set limit on R

Laser runs

241Am runs

Neutron production from 28MeV Li

Be

Be*
Global likelihood fit

Unbinned likelihood: \[ \mathcal{L}(X | \delta R, \nu) = \prod_{i=0}^{5} \mathcal{L}_i(X_i | \delta R, \theta_i, \nu) \times \mathcal{L}_{\text{cali}}(X_{\text{cali}} | \nu) \times \mathcal{L}_{\text{prior}}(\nu) \]

The model includes:
- NR band shape. Lindhard + Mei, et. al. (SCENE, Phys Rev D. 91.092007)
- The modified Thomas-Imel box model. The aspect ratio \( R \) is the parameter of interest.
- Geant4 simulation of signal and background energy spectrum

5 sig ch  Calibration  Prior of nuisance parameters:
\[ \nu = \{C_{\text{box}}, g_1, g_2, \sigma_{\text{S1}}, \sigma_{\text{S2}}\} \]

Blue: All.
Pink: multiscatter backgrounds
Red: random coincidence.

\( R = 1.036 \pm 0.024 \) (Preliminary!)
Conclusion

We have measured the LAr response to NRs around 70 keV under 200V/cm with great precision.

The directional modulation of charge recombination in 70 keV NR in LAr is measured to be very weak.
The aspect ratio of the ionized charge cloud is constrained to be < 1.1.

The final polishing of the analysis is underway. Stay tuned!
Back up
(a) Mesh structure

(b) $S^2$ distribution
Analysis - Event reconstruction

- Pulse finding
- SiPM calib.
- Clustering & Pos rec
- Pos based correction

Laser runs  Am241 runs

SiPM PE response

3D position-based correction.

Electron lifetime

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Nuclear recoil band shape

TPC-SiTel double coincidence
Shape of the NR band.
Multi-scattering backgrounds

Geant4 simulation

gs: 72.5keV NR
1st: 63.5keV NR
Colli: Beam collimator, removed during beam time to increase signal rate.

Top: Recoil direction vs. recoil energy. With coincidence cut.

Bot: Timing spectra. With NR direction and energy cut.

Irreducible!!
Multi-scattering backgrounds

Geant4 simulated energy spectrum of signal and backgrounds.

Rates are not to scale -- later estimated from data and simulation.
Geometrical effects

If we use independent Gaussians to fit the signal peaks in different directions...

Same behaviour as in SCENE:
Large directional dependence in S1
Small directional dependence in S2

Recombination modulation
Total energy modulation
(geometrical effect)

Corrected with Geant4 simulation.

Red shade: ±1 sigma of the peaks
Geometrical effects

Geometrical effects in the NR kinematics. The recoil angle has different dependence on scattering Z position at different directions.
Geometrical effects

Simulation, Z dependence in recoil energy.