A combined energy scale for WIMP searches in LAr with the DarkSide-50 detector

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on the behalf of the DarkSide collaboration

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DarkSide-50 detector overview

- **Water Cherenkov** detector (1,000 tons of ultra pure water): active veto for $\mu$ and passive shield for external radiation

- **Liquid scintillator** detector (30 tons of PC+PPO+TMB): active $\gamma$s and neutron detector ($^{10}$B loading)

- **LAr TPC** detector (current phase $\sim$50 kg of Ar fiducial): inner detector for WIMP searches
Scintillation in noble liquids

A particle interaction produces excited (excitons) and ionized (ions) and heat (soft elastic recoils which dominant for NRs - visible light quenched by factor ~3-5 in LAr - while negligible for ERs)

- Excitons produced either directly or through recombined electrons
  - Excitons → Excited dimer decay producing photons ($\lambda=128$nm for Ar)
  - If electric field $\neq 0$, electrons can avoid recombination and collected

Energy deposition - $E_{\text{dep}}$

Excitation - $N_{\text{ex}}$

Ionization - $N_1$

Scintillation

- $\text{Ar}^*$
- $\text{Ar}^{*2}$
- $\text{Ar}^+$
- $\text{Ar}^{+2}$
- $\text{Ar}^{**}$

Ionization
Two-phase Argon TPC

- S1 (primary scintillation) and S2 (ionization signal) give:
  - Energy estimation
  - 3D position of the event ($t_{\text{drift}} \rightarrow z$ and light pattern on PMTs $\rightarrow xy$)
  - Particle discrimination: PSD and S2/S1 can distinguish between electron (ERs - $\beta/\gamma$) and nuclear recoils (NRs - n/WIMPs)
A combined energy frame

- Why? WIMP’s interactions will deposit only small amounts of energy and dR/dE exp falling - **IMPORTANT:** understand energy scale since directly maps WIMP sensitivity

- How? Exploit anti-correlation between S1 and S2 signals → energy scale independent from recombination ([Doke et al. (2002)](https://doi.org/10.1086/340319))

  - \( E_{\text{dep}} = W (N_{\text{ex}}+N_i) = W (S_1/\varepsilon_1+S_2/\varepsilon_2) \)

- Being \( S_1 = \varepsilon_1 (N_{\text{ex}}+r N_i) \) \( S_2 = \varepsilon_2 (1-r) N_i \), \( N_{\text{ex}}/N_i=0.21 \) (ERs - [Doke et al. (2002)](https://doi.org/10.1086/340319)) and \( W=19.5\text{eV} \) ([Doke et al. (2002)](https://doi.org/10.1086/340319) and [Takahashi et al. (1975)](https://doi.org/10.1086/182830)) is average work function to create electron-ion pair and \( r \) is recombination prob.

- Unknowns: \( \varepsilon_1, \varepsilon_2 \) and \( r=r(E_{\text{dep}},E_d) \) being \( E_d \) the strength of the drift field

- Combined energy has access to micro-physics parameter to better understand detector response: light and charge yield (\( L_y, Q_y \)) and recombination (\( r \))
Calibration data

- Idea: since $r=r(E_{\text{dep}}, E_d)$, then $\varepsilon_1$ and $\varepsilon_2$ can be determined looking at S1 and S2 from different calibration sources with data taken at different drift fields

<table>
<thead>
<tr>
<th>E [keV]</th>
<th>type</th>
<th>Edrift [V/cm]</th>
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<tbody>
<tr>
<td>$^{57}\text{Co}$</td>
<td>122.1 (86%)</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>136.5 (11%)</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>$^{83\text{m}}\text{Kr}$</td>
<td>9.1+32.4</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>$^{37}\text{Ar}$</td>
<td>2.82</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td></td>
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<td>100</td>
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<td>50</td>
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</table>
Data selection criteria and corrections

• Data quality cuts are applied (check sanity of the detector in terms of performances and completeness of information)

• Single scatter events (S1+S2) considered only

• **3D fiducial** (~0.5cm top and bottom and events radius <13.5cm)

• Corrections: 3D correction for both S1 and S2
S1 corrections

- $S1=S1(t_{drift})$ - bottom PMTs see more light than top (total internal reflection liquid-gas interface, grid not transparent) - effect up to ~14%

- $S1=S1(x,y)$ - parts have better light collection (cylindrical shape, different QE PMTs, non uniformity of TPB) - effect up to ~3% (less severe)
S2 corrections

- **S2=S2(x,y)** - central PMT sees x3 more light than corners (possible cause is anode sagging or grid deflection) - effect up to ~300%

- **S2=S2(t_{drift})** - impurities can “eat” electrons during drift: survival probability \( \sim \exp(-t_{drift}/T_e) \) where \( T_e \approx 5\text{ms} \) is electron lifetime - effect up to \( \sim 7\% \)
Data analysis

- Each mono-energetic source generates a fixed mean amount of light and charge: signals appear as elliptical overdensities in (S1,S2)-space.

- Measurements of the light and charge yields follow directly from Gaussian fits (1D and 2D) for the mean S1 and S2.
Results

Total error: $\sigma_{\text{stat}} + \sigma_{\text{sys}}$ where $\sigma_{\text{sys}}$ is obtained propagating uncertainties of the various corrections on S1 and S2
Combined energy spectra

- Spectra taken at different $E_d$ overlap $\rightarrow$ energy scale is independent from recombination probability

- Improvement in the peak resolution ($\sigma/\mu$): e.g. for $^{37}$Ar from 24% for S1 to 17% for E

- New energy scale is in good agreement with reference $\gamma$-lines at low energy. At high energy (>40keV) discrepancy of ~5%
PARIS model (I)

• Several models developed to describe recombination probability as function of energy and drift field

  • NEST approach combines Thomas-Imel and Doke-Birks models by constraining associated parameters using exp. data. Data set abundant for Xe but for Ar limited at some energies

• Other approach: Precision Argon Response Ionization (and) Scintillation

• Simplify embedding an effective model to parametric effects inducing S1 and S2 signals:

  • Empirical parametrization:
    \[ r(E) = \text{erf}(E/p_0) \left( p_1 \exp(-E/p_2) + p_3 \right) \]

  • \( p_i \) i=0,...3 tuned on DarkSide-50 data @ \( E_d=200\) V/cm

See reference JINST 12 P10015
Energy [keV]
0 50 100 150 200 250

Recombination Probability
0.5 0.6 0.7 0.8 0.9 1

- Extraction of the recombination probability from comparing DS50 data vs. G4DS and considering only single scatter events

- Determine \( r(E) \) by simultaneous fit of S1 spectra of:
  - endpoint of \(^{39}\text{Ar}\) spectrum (565 keV)
  - \(^{37}\text{Ar}\) peak (2.82 keV) peak
  - \(^{83m}\text{Kr}\) (9.4+32.1 keV) peak
PARIS model (III)

- Recombination probability from PARIS - cross check with external calibration $\gamma$ sources ($^{57}$Co and $^{133}$Ba)

- Very good agreement between data and Monte Carlo G4DS, both for single-scatter and multiple-scatters events
Combined Energy Scale vs. PARIS model

- Light yield ($L_y$) for electron increases at low energy where there is more recombination (due to higher stopping power). Complementary behavior for charge yield ($Q_y$).

- Good agreement between $L_y$ derived with combined energy scale and PARIS.

- ~5-10% discrepancy at high energy (>40keV) for recombination probability: expected since PARIS is 1) tuned only on S1 signal and not on both S1 and S2 and 2) full recombination is assumed at zero field.
Conclusions and future development

• Conclusions:
  
  • New energy framework allows better energy resolution at low energy and agrees with PARIS model
  
  • Combined energy frame used to achieve recent results in arXiv 1802.07198: useful for detailed studies of ER backgrounds (See G. Giovanetti’s talk)

• Future:
  
  • Investigate NR
  
  • Compare results with NEST
  
  • Study fluctuation in the recombination