WIMP Search at Low Energy Threshold with PICO-60 C$_3$F$_8$

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Overview

• The PICO-60 C$_3$F$_8$ detector


• Energy threshold constraints and gamma background

• Second physics run, with lowered energy threshold

• Potential physics reach; impact on future chambers
The PICO-60 detector

• Deployed 2 km underground at SNOLAB

• $C_3F_8$ target: 52 kg total
  $(45.7 \pm 0.5 \text{ kg fiducial, 87.7\%})$

• Synthetic fused silica inner vessel, stainless steel pressure vessel, water tank, muon veto

• Bellows allow expansion to superheated state with typical per-event cycle of 800s, >80% live-fraction

• Four cameras monitor for bubble nucleation using LED illumination

• Eight piezoelectric acoustic sensors monitor sound of bubble nucleation
Target: superheated liquid

Lower pressure in the target liquid until it is in metastable superheated state
Energy deposition nucleates small bubble that grows to visible size
Cameras watch for visible bubble and issue the primary trigger

(plots by Eric Dahl)
Acoustic discrimination

- Alphas deposit their energy over tens of μm
- Nuclear recoils deposit energy over tens of nm
- In PICO, alphas are several times louder than recoils
- For a WIMP-search run, the acoustic signals are blinded in order to set an unbiased cut on this “acoustic parameter” (“AP”)

![Diagram showing observable bubble size and acoustic spectroscopy](image)

Dendrogram showing:
- Observable bubble ~mm
- ~40 μm
- ~50 nm
- Daughter heavy nucleus (~100 keV)
- Helium nucleus (~5 MeV)
- Multiple radiating bubbles

Graph showing:
- Counts vs. In(AP)
- Alpha-rejection in PICO-2L
- Sensitivity of the experiment to dark matter detection

Values shown:
- Rn
- Po
- Po

Livetime (d) and efficiency for detecting low energy carbon.

Additional notes:
- The sensitivity of the experiment to dark matter detection can be improved by using acoustic discrimination.
- Alphas deposit energy over tens of micrometers, while nuclear recoils deposit energy over tens of nanometers.
- In PICO, alphas are several times louder than recoils.
- For a WIMP-search run, acoustic discrimination is blinded to set an unbiased cut on the acoustic parameter (AP).

Graph showing distributions for neutron calibration with two distinct peaks at high threshold. Note that the x-axis shows ln(AP) for data with an uncertainty of 0.3.

Table showing:
<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>222Rn</td>
<td>5.5</td>
</tr>
<tr>
<td>218Po</td>
<td>6.0</td>
</tr>
<tr>
<td>214Po</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Additional details:
- Alphas from the decay chain can be identified by their time signature and populate the two peaks in the graph.
- Spontaneous fission from nearby Ba source forms a detailed Monte Carlo simulation of the detector acceptance band in that data set, confirming that acoustic power events leak into the nuclear recoil band.
- With no candidate events in the WIMP search data, providing a 90% C.L. upper limit of 0.008 cts/kg/day, consistent with the background.
- The 4.4 keV threshold comes from uncertainties on the temperature (0.3°C) and pressure (0.7 psi) of the data.
- The 214Po is primarily the radon chain with no candidate events.
- For an AmBe source, 222Rn decays with a half-life consistent with that of the 218Po. A steady state of about 4 events/day is reached.
- None of the events are from the third event in the chain.
- The high energy alphas that produce fewer than 0.05 events in the PICO-2L WIMP search data.
Additional data stream: optics

Multiply-scattering neutrons won’t be mistaken for WIMPs either (3:1)

Four views of a neutron event from an AmBe source
Fast camera trigger

• Primary trigger: “image entropy”

\[ S_I = - \sum_i P_i \log_2 P_i \]

• Calculate absolute difference of successive frames, searching for changes in information content

• Images initially acquired at 200 Hz - increased to hardware maximum 340 Hz for low threshold run - fast trigger ensures stable operations at very low pressures
First physics run

- **30 live-day run at 3.3 keV** threshold, accepted for pub. in PRL: a *background-free 1167 kg-day* WIMP-search exposure
- **Factor of 17** improvement in upper limit on spin-dep. WIMP-proton cross-section
- See session R3-3 (Thurs. 14:00), talk by G. Giroux, for details
- Can we probe lower masses?
Gamma rejection

Gamma Rejection by Chamber

Hard background turns on very quickly at low energy

Various PICO Detectors

C$_3$F$_8$

CF$_3$I

PICO-60

(Dan Baxter, Conference on Science at SURF, May 14, 2017)
Decreasing pressure scan

• Following the blind physics run at 3.3 keV (14°C, 30 psi), raised temperature to 16°C, scanned in pressure (to 21 psi)

• Goals:
  1. Measure background appearance at low threshold
  2. Test detector stability at much lower pressures

minimum: 1.8 keV
Decreasing pressure scan

Incidental benefit: improved acoustic signal-to-noise → potential for more powerful discrimination

(plots by Guillaume Giroux)
Gamma rejection

- PICO-60 at 3.3 keV exposed to 1 mCi $^{133}$Ba source + Geant4 Monte Carlo yields rejection factor: $(1.80 \pm 0.38) \times 10^{-10}$

- Combining MC with estimate of local gamma flux, expect 0.026 electron recoil events in Run-1 (90% CL upper limit)

- Extrapolating nucleation probability down to 1.8 keV
  - expected: 27 gamma events per day
  - observed: <5 per day (90% CL) over 7.5 live-days

- Revised estimate suggests physics reach available at thresholds below 3.3 keV
Gamma rejection

PICO-60 C₃F₈: bulk rate in ⁶⁰Co calibration data

\[ \lambda = 5.02 \]

Fiducial low-AP event rate (counts/live-hr)

Seitz threshold (keV)

chosen low-thresh. point

Measured event rates with ⁶⁰Co gamma source
Low threshold physics run

• Second physics run prompted by observation of far fewer recoil events than expected at lower thresholds

• Decided on a threshold of 2.4 keV, where backgrounds are projected to produce <5 events over a 30 live-day exposure
Potential reach: spin-dep. $\rho$

Ultimate plan: use data at 1.8 keV, 2.4 keV, and 3.3 keV to produce combined limit.
Outlook

• Next chamber already on the way: PICO-40L in early commissioning; tonne-scale PICO-500 proposed

• Ability to run stably at much lower pressures, thresholds now demonstrated

• Gamma backgrounds measured to be significantly lower than initially predicted

• Opens up possibility to run background-free at lower energy thresholds with PICO-40L and/or PICO-500, for significantly improved sensitivity to low-mass WIMPs
Extra slides
Setting the threshold

Choose thermodynamic parameters for sensitivity to nuclear recoils, and not electron recoils.
Backgrounds: Neutrons

- Single-scatter neutrons are indistinguishable from WIMPs in these detectors
- Can’t discriminate against them, so minimize them
- Two neutron sources for PICO-60:
  - **Cosmogenic:** spallation in rock near detector by high energy cosmic ray muons (veto present for C₃F₈ Run-1, saw no muons)
  - **Radiogenic:** natural radioactivity in rock and detector apparatus (alpha-n and spontaneous fission)
- Total neutron background estimate for C₃F₈ Run-1: 
  \[0.25 \pm 0.09\] (0.96 ± 0.34) single- (multiple)-bubble events
Event cycle

Expand to target pressure, begin counting live-time after 25s stability
Primary trigger: changes in image information content (bubble appearance)
Time-out trigger set to 2000s - regular cycling improves detector stability

(plot by Dan Baxter)