Dark matter searches with the PICO bubble chambers

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Overview

• Dark matter direct detection: spin-independent (SI) vs. spin-dependent (SD) WIMP-nucleon couplings

• Bubble chambers for direct detection: the PICO program

• The PICO-60 C₃F₈ detector; Run-1 WIMP-search results

• Next chamber: PICO-40L
  Design/background goals, timeline, physics reach

• Future ton-scale chamber: PICO-500
• Bubble chambers \textbf{don’t} use the typical direct detection channels

(exception: scintillating LXe BC - see slides from J. Zhang’s talk, TeVPA 2017, Mon 7 Aug, 5:15pm)

Zornoza, NIM. A 742 130-138 (2014)
Direct detection: channels

- Bubble chambers don’t use the typical direct detection channels
- They’re threshold detectors
- No direct measurement of recoil energy, however...
- **Acoustic** signals do enable both spectroscopy and discrimination (arguably fits in the “heat” category)
Two primary interactions considered by experimentalists:

**Spin-independent (SI):** couples to all nucleons

- $A^2$ enhancement for large nuclei (coherent scattering)

**Spin-dependent (SD):** couples to the spin of the nucleus, i.e. unpaired spin of one nucleon

- "SDp" and "SDn" are similar but not directly comparable

($^{19}$F, $^{73}$Ge, $^{129/131}$Xe, ...)

SI vs. SD (vs. nuclear physics/EFT)

- Spin-independent searches have received the most attention due to the $A^2$ rate enhancement (>15,000 for xenon)

- But the actual mechanism is unknown, and may be more complicated

SD vs. SI cross section predictions for different models (Barger, PRD, 78 056007)

Sensitivity of different p-coupling operators to various nuclear targets (L. Fitzpatrick, INT Workshop, 2014)
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Fluorine’s great for proton spin! (SDp)

Sensitivity of different p-coupling operators to various nuclear targets (L. Fitzpatrick, INT Workshop, 2014)
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Why is SD interesting?

- PICO-500’s SD-proton sensitivity is very similar to LZ’s SD-neutron sensitivity

- So: given typical SD/SI cross-section ratios, a first discovery by PICO-500 is plausible

- The CEνNS floor is much lower for F than for Xe: we actually want to **minimize SI** sensitivity in order to **maximize SD reach**
Complementarity w/ xenon, colliders

- A more model-independent comparison: bubble chamber (fluorine) results constrain effective proton coupling in a complementary way to xenon TPC constraints on effective neutron coupling

- Complementarity with LHC: limit from simplified collider production model for CMS, following recommendations of LHC Dark Matter Working Group
Why bubble chambers?

- High density of $^{19}$F means great SDp sensitivity
- Intrinsic rejection of electron recoil backgrounds
- Low energy recoil sensitivity (< 5.5 keV)
- Large, monolithic (self-shielding) target mass - ton-scale next generation
- **Multiple target nuclei**: ability to test scattering rate dependence on atomic number, nuclear spin, etc.
- Disadvantages: no measurement of recoil energy; threshold calibrations may be difficult; recompression dead-time requires very low overall event rate
Target: superheated fluid

Lower pressure in 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)
Gamma rejection

Set temp. & pressure for sensitivity to nuclear recoils ($\alpha$, $n$, nuclei, WIMPs), and **insensitivity to electron recoils** ($\gamma/\beta$) [protobubble immediately collapses]
We can set the threshold on $dE/dx (E/T/c)$

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<tr>
<th>Threshold (keV)</th>
<th>Probability of Nucleation</th>
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Aim for this level for 1-year exposure

Gamma Rejection by Chamber

Various PICO Detectors

(Dan Baxter, Conference on Science at SURF, May 14, 2017)
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”)

Observed bubble ~mm

- ~50 nm
- ~40 μm

Daughter heavy nucleus (~100 keV)
- Helium nucleus (~5 MeV)
- Multiple radiating bubbles
Neutron background

• 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 PICO-60 C₃F₈ Run-1: **0.25 ± 0.09** (0.96 ± 0.34) single- (multiple)-bubble events
Cameras as a “neutron veto”

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

Four views of a neutron event from an AmBe source
Multiply-scattering neutrons won’t be mistaken for WIMPs (3:1)

Cameras as a “neutron veto”

26 bubbles in the small 2L chamber!
Backgrounds checklist

• Gammas/betas:
  • $dE/dx$ threshold in superheated detectors affords “intrinsic” rejection $\sim 10^{-11}$ for typical PICO energy thresholds in C$_3$F$_8$

• Alpha decays:
  • large acoustic signals allow discrimination at $>99.4\%$ (stats. limited)

• Neutrons:
  • reject multiple scatters visually, veto detector-adjacent cosmogenics, minimize other sources (extensive material screening, shielding)
The PICO program

- **PICO** - 2012 merger of the **PICASSO** and **COUPP** collaborations

- Small surface test chambers at Université de Montréal, Queen’s University, Northwestern, Drexel, NEIU (for threshold calibration, etc.)

- PICO-2L C$_3$F$_8$ (2014-17)
  C. Amole *et al.*, PRL 114, 231302 (2015)
  C. Amole *et al.*, PRD 93, 061101 (2016)

- PICO-60 CF$_3$I (2013)
  C. Amole *et al.*, PRD 93, 061101 (2016)

- PICO-60 C$_3$F$_8$ (2016-17)
  C. Amole *et al.*, PRL 118, 251301 (2017)

- PICO-40L (2017-19)

- PICO-500 (~2018+)
The PICO-60 detector

- Deployed 2 km underground at SNOLAB
- C\textsubscript{3}F\textsubscript{8} target: 52 kg total (45.7 ± 0.5 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
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
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
PICO-60 Run-1: blinded

- Following “pre-physics” background and calibration data, detector performance was assessed good enough to allow a blind analysis.
- Acquired acoustically blinded background data from 28 Nov 2016 to 13 Jan 2017 (no power outages, remarkably stable running).
- Saw 106 bulk singles in WIMP-search dataset: consistent with Rn decay rate seen in unblinded pre-physics data.
- Saw 3 multiples, so given 3:1 multiples to-singles ratio from n calibration and simulation, expected 0-3 bulk n singles.
PICO-60 Run-1: unblinding

- 30 live-day run at 3.3 keV threshold, published in PRL*: a background-free 1167 kg-day WIMP-search exposure
- Factor of 17 improvement in upper limit on spin-dependent WIMP-proton cross-section
- Additional blinded exposure acquired at lower thresholds
- Now decommissioning, as any additional exposure would be expected to be background limited

**Nearly competitive in SI at low mass**

...additional reach available at lower threshold?

![Graph showing the SI WIMP-nucleon cross section vs. WIMP mass for various experiments.](image-url)
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 were projected to produce <5 events over a 30 live-day exposure, now acquired.

Analysis is wrapping up, results soon…
Why end PICO-60?

• Only published 30 live days, with ~30 more on the way…

• After over a year commissioning, why acquire so little data?

• Short answer: 3 multiple-scatter neutron events in Run-1 meant expectation of 1 single-scatter neutron (which we didn’t see)

• That rate now appears to have been a slight upward fluctuation, but the full (3.3, 2.4) keV dataset (~60 days) will almost certainly be background limited: very slow gains if we’d continued

• More pressing need: build the next chamber!
PICO-40L Goals

• **Science:** acquire one-year background-free exposure
  • Order of magnitude improvement on PICO-60 limits

• **Engineering:** demonstrate background reduction and technology improvements for PICO-500
  • Focus on (neutron) background reduction
  • Confirm “RSU” design used in prototype chambers

*Note:* where the “L” again indicates, approximately, “demonstrator for next, bigger chamber”
PICO-60 $\rightarrow$ PICO-40L

- Pressure vessel
- Bellows
- Water (Buffer)
- Acoustic Sensors (Piezos)
- Propylene Glycol (hydraulic fluid)
- C$_3$F$_8$ (Target)
- Cameras

- Pressure vessel
- C$_3$F$_8$/freon (target)
- Hydraulic fluid (mineral oil)
- Heating element
- Thermal gradient (no water buffer)
- Bellows
- Thermal insulation
PICO-40L detector design

- To be deployed 2 km underground at SNOLAB ("ladder labs" area)
- Target: ~40L C₃F₈, (proj. >90% fiducial)
- Synthetic fused silica inner vessel and piston (no more "water piston")
- **Larger** stainless steel pressure vessel, 20t water tank, muon veto - all minimize neutron backgrounds
PICO-40L detector design

• Inversion eliminates potential sources of background:
  • water droplets
  • surface tension effects
  • particulates – would now fall out of active region into cold annulus

• No buffer: allows wider choice of target fluid, wider range of operating temperatures; directly enables full target recirculation and purification
Many upgraded systems

- Optics/DAQ: much better Basler cameras using new Sony IMX174 CMOS sensor
  - running on newer USB3 Vision interface for more programming flexibility
  - better lenses (higher resolution, reduced barrel distortion, etc.)
  - better stereoscopic viewing angles and camera mounts
  - better retroreflector and improved LED lighting rings
- Hydraulic system control: brought into alignment with new designs used on several test chambers; will enable continuous active recirculation/filtration
- Piezo acoustic sensors: better physical coupling, and improved longevity in different hydraulic fluid (mineral oil rather than propylene glycol)
PICO-40L timeline

- Pressure vessel arrived to SNOLAB surface 18 May 2017
- Clean surface commissioning ongoing presently
- Full detector assembly to be shipped underground to SNOLAB Dec 2017
- First data January 2018
- End of physics data in 2019
PICO-500

- Planned ton-scale detector
- Intended to begin surface commissioning as soon as late 2018
- Goal is to begin data-taking in 2019
PICO-500

- Designed to have an additional order of magnitude sensitivity beyond PICO-40L
- Could run C$_3$F$_8$ and/or several other targets (i.e. CF$_3$I or hydrocarbons: C$_2$H$_2$F$_4$, etc.) to probe higher/lower mass or reduce a WIMP signal in a predictable way
PICO-500

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Summary and outlook

- **PICO-40L** commissioning now, data in **early 2018**
  - One year background-free run - order of magnitude improvement on PICO-60 result
  - Demonstrate background reduction advances enabling ton-scale PICO-500
- **PICO-500** could begin data taking as early as **2019**
  - Sensitivity to additional order of magnitude in SDp beyond PICO-40L, covering significant new well motivated parameter space
  - Could check itself/signals from other detectors with a **target change**
- PICO detectors are relatively cheap and flexible, with very quick turnaround time
- SD WIMP interactions are arguably just as promising as SI! Imagine a first signal in 2019?
Extra slides
Direct Detection Rates

\[ \frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \]

- DM density component
- Unknown cross section – what we set upper limits on
- Nuclear form factor: \( F^2 \propto \exp(-Q/Q_0) \) where \( Q_0 \sim (80 \text{ MeV})/A^{5/3} \)
- Velocity distribution of dark matter in the galactic halo
Comparing SD limits

SD WIMP-nucleus cross-section at $q=0$

$$\sigma_A = \frac{32}{\pi} G_F^2 \mu_A^2 \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2 \frac{J + 1}{J}$$

WIMP-nucleon cross-sections (in limiting cases $a_{n,p}=0$)

$$\sigma_{p,n}^{\text{lim}(A)} = \frac{3}{4} \frac{J}{J + 1} \frac{\mu_{p,n}^2}{\mu_A^2} \sigma_A \langle S_{p,n} \rangle^2$$

from experiment
LHC comparison method

4.1.2 SD case: Axial-vector mediator

For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as

$$\sigma_{\text{SD}} = \frac{3 f^2(g_q) g_{\text{DM}}^2 \mu_{nX}^2}{\pi M_{\text{med}}^4}.$$  \hspace{1cm} (4.7)

In general $f_{p,n}^p(g_q)$ differs for protons and neutrons and is given by

$$f_{p,n}^p(g_q) = \Delta_u^{(p,n)} g_u + \Delta_d^{(p,n)} g_d + \Delta_s^{(p,n)} g_s,$$ \hspace{1cm} (4.8)

where $\Delta_u^{(p)} = \Delta_d^{(n)} = 0.84$, $\Delta_d^{(p)} = \Delta_u^{(n)} = -0.43$ and $\Delta_s = -0.09$ are the values recommended by the Particle Data Group [50]. Other values are also used in the literature (see e.g. [51]) and differ by up to $\mathcal{O}(5\%)$.

Under the assumption that the coupling $g_q$ is equal for all quarks, one finds

$$f(g_q) = 0.32 g_q,$$ \hspace{1cm} (4.9)

and thus

$$\sigma_{\text{SD}} \simeq 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left( \frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left( \frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left( \frac{\mu_{nX}}{1 \text{ GeV}} \right)^2.$$ \hspace{1cm} (4.10)

(arXiv:1603.04156)