Search for Dark Matter with bubble chambers

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For the PICO Collaboration at DPF 2015
The PICO Dark Matter search

• PICO: merger of **PICASSO** and **COUPP** Collaborations
• In addition to various test and calibration chambers, PICO includes two main bubble chambers at SNOLAB
  – **PICO-2L**: a 2-liter bubble chamber currently operating with $\text{C}_3\text{F}_8$
  – **PICO-60**: a 60-liter bubble chamber undergoing a switch from $\text{CF}_3\text{I}$ to $\text{C}_3\text{F}_8$
PICO fast compression bubble chambers

Pressure expansion puts fluid ($\text{CF}_3\text{I}$ or $\text{C}_3\text{F}_8$) in superheated state

- I for spin-independent
- F for spin-dependent

- Particle interactions nucleate bubbles
- Cameras capture stereoscopic bubble images
- Acoustic sensors capture bubble sound
- Chamber recompresses after each event
- Pressure & temperature define minimum energy, $\text{dE/dx}$ threshold
The new PICO collaboration has also recently launched the PICO which is trapped on the flake, forming a nano currents in the target fluid. The flakes react with the CF current hypothesis is that these events are coming from chemically reactive signal relative to nuclear recoils and a markedly increased rate during periods of thermal instability. The COUPP free. We have confirmed the presence of a non absence of multi $^{35}$ The COUPP PICO bubble chambers, and roughly 1 in 4 neutron events in COUPP multiple (Fig. 3) from a direct detection experiment (Fig. 2). The first deep underground bubble chamber that began taking dark matter data on Oct. 28, 2013, operating in the same location as the COUPP bubble events confirms that the steps taken since COUPP holds. The resulting spin dependent WIMP decays and gamma interactions. Data come from the COUPP ber data came from the COUPP PICASSO collaboration in superheated droplets [23], and has since been confirmed in COUPP bubble chambers [24][8]. The discovery of acoustic alpha discrimination has transformed the bubble chamber PICASSO – a product of the recent merger between COUPP and PICASSO – uses superheated fluids to search for WIMP dark matter. The baseline PICO detector at SNOLAB at 15 days at 8 $^{222}$ Rn and its daughters. The WIMP search data at 15 keV threshold [9]. The Acoustic Parameter (AP) is a corrected measure of the intensity of the ultra-sonic emission from a growing bubble. The blue position limits are the most stringent to require the chamber re adjusts from the state of having produced a bubble to the superheated state, arming for the next event. Despite this reset period, the primary trigger on bubble nucleation and the second settling of the liquid target (C $^{3}$ F $^{8}$ or CF $^{4}$) and run in a moderately superheated state where it is sensitive to the low energy nuclear recoils from WIMP decays and gamma interactions. The data come from the COUPP PICASSO, and roughly 1 in 4 neutron events in COUPP multiple (Fig. 3) from a direct detection experiment (Fig. 2).

**Background Rejection**

**Gamma/Beta do not produce bubbles**

![Gamma/Beta bubble events](image)

**Neutron multiples**

![Neutron multiple events](image)

**Alpha-decay**

> 99.3% Rejection

![Alpha-decay events](image)
PICO-60

Scale-up of COUPP-4 chamber

- 37-kg CF$_3$I target operated in SNOLAB from June 2013 to May 2014
- Collected >3000 kg-days of dark matter search data between 8 and 25 keV threshold
PICO-60

- Large background of unknown origin (>1000 events)
- Possible impurity/particle contamination
  - Addressable via cleaning/hardware/filtration/chamber-design
- Background can be discriminated against
  - Acoustics, timing, position

Louder than nuclear recoils

```
Counts

0 50 100 150 200 250 300 350 400 450 500
-0.5 0 0.5 1 1.5 2
```

```
In(AP_{high})
```

```
AmBe source data
WIMP search data
```

```
Unknown background
```

```
Alphas
```

Position dependent

Time dependent

```
Rate
```

```
Expansion time
```

```
R^2/R_{jar} [mm]
```

```
Z [mm]
```

```
18
16
14
12
10
8
6
4
2
0
```
PICO-60 Final event selection

- Cut-setting method similar to the optimum interval method
  One-sided cuts on: AP, expansion time, bubble distance from wall/surface
  - Keeps 48% exposure, 0 candidates
  - Cut choice results in a statistical penalty of 1.8
PICO-2L

A 2 liter $C_3F_8$ detector replacing COUPP-4 ($CF_3I$)

- Twice the F density
- Lower threshold
- Improved efficiency
- Lower background hardware

Oct 2013-May 2014:
>200 kg-day exposure with thresholds between 3-8 keV
PICO-2L
Acoustic discrimination

• Two distinct alpha peaks, clearly separated from nuclear recoils
• Timing of events in high AP peaks consistent with radon chain alphas, and indicate that the higher energy $^{214}\text{Po}$ alphas are significantly louder

→ “Acoustic calorimetry”

Radon chain alphas

$^{222}\text{Rn}$  
$\alpha(5.6 \text{ MeV})$  
3 minutes

$^{218}\text{Po}$  
$\alpha(6.1 \text{ MeV})$  
55 minutes

$^{214}\text{Po}$  
$\alpha(7.9 \text{ MeV})$
PICO-2L results

• 12 candidate events in 211.6 kg-days of exposure

<table>
<thead>
<tr>
<th>Seitz threshold, $E_T$ (keV)</th>
<th>Livetime (d)</th>
<th>WIMP exposure (kg-d)</th>
<th>Candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.2 \pm 0.2$ (exp) $\pm 0.2$ (th)</td>
<td>32.2</td>
<td>74.8</td>
<td>9</td>
</tr>
<tr>
<td>$4.4 \pm 0.3$ (exp) $\pm 0.3$ (th)</td>
<td>7.5</td>
<td>16.8</td>
<td>0</td>
</tr>
<tr>
<td>$6.1 \pm 0.3$ (exp) $\pm 0.3$ (th)</td>
<td>39.7</td>
<td>82.2</td>
<td>3</td>
</tr>
<tr>
<td>$8.1 \pm 0.5$ (exp) $\pm 0.4$ (th)</td>
<td>18.2</td>
<td>37.8</td>
<td>0</td>
</tr>
</tbody>
</table>

• Expected $\sim$1 background event (neutrons)
However:

- Post-run samples show evidence of particulate contamination
- Candidate events have timing correlations inconsistent with WIMPs or neutrons
- Timing becomes a cut variable, method similar to optimum interval of Yellin, PRD 66.032005 (2002)
Spin-independent limits (low mass)
Spin-independent limits (high mass)

- PICO-60 (prelim.)
- XENON100
- CDMS-II
- COUPP-4 (2012)
- DarkSide-50
- PICO-60 (prelim.)
- LUX

SI WIMP-nucleon cross section [cm$^2$] vs. WIMP mass [GeV/c$^2$]
Spin-dependent limits

SD WIMP–proton cross section [cm²]

Preliminary

PICASSO (2012)
COUPP–4 (2012)
XENON100
SIMPLE
SK (soft)
PICO–60 (prelim.)
PICO–2L
SK (hard)
PICO–60 (prelim.)

WIMP mass [GeV/c²]

ICE CUBE
SK (hard)

CMS
ATLAS

10⁻³⁶
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10¹
10²
10³
10⁴
Summary

• PICO-60 is a 37 kg bubble chamber using CF₃I
  – Good acoustic rejection of alphas, as well as acoustic discrimination against unknown background
  – PICO-60 has a new world-best SD WIMP-proton limit

• With a brand new target fluid (C₃F₈) PICO-2L has demonstrated:
  – Successful operation at 3keV nuclear recoil threshold
  – No neutron background observed
  – Good acoustic rejection of alphas
  – Detailed Fluorine and Carbon-recoil efficiency calibrations (no time in this talk!)
  – PICO-2L has a new world-best SD WIMP-proton limit
Dark matter direct detection

- Interaction rate depends on how the dark matter couples to quarks/gluons in target nuclei
  - Z, higgs, squark exchange, ...
- Model dependent
  - Eg SUSY: is lightest neutralino more bino-like, higgsino-like, what is the sparticle spectrum, etc
Dark matter direct detection

• WIMP-nucleus interaction could be
  – Spin-Independent (SI) (scalar/vector coupling)
    • Coherent scattering
      → enhancement for heavy nuclei: Ge, Xe, I, ...
      → higher sensitivity to WIMP-nucleon cross-section
    • Nonetheless depending on the model the SI cross-section could be small and another type of coupling could dominate...
Dark matter direct detection

- WIMP-nucleus interaction could be
  - Spin-Dependent (SD) (axial-vector coupling)
- Couples to nuclear spin
  → requires unpaired nucleon, enhancement depends on nuclear shell structure

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Spin</th>
<th>Unpaired</th>
<th>$\lambda^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Li}$</td>
<td>3/2</td>
<td>p</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{19}\text{F}$</td>
<td>1/2</td>
<td>p</td>
<td>0.863</td>
</tr>
<tr>
<td>$^{23}\text{Na}$</td>
<td>3/2</td>
<td>p</td>
<td>0.011</td>
</tr>
<tr>
<td>$^{29}\text{Si}$</td>
<td>1/2</td>
<td>n</td>
<td>0.084</td>
</tr>
<tr>
<td>$^{73}\text{Ge}$</td>
<td>9/2</td>
<td>n</td>
<td>0.0026</td>
</tr>
<tr>
<td>$^{127}\text{I}$</td>
<td>5/2</td>
<td>p</td>
<td>0.0026</td>
</tr>
<tr>
<td>$^{131}\text{Xe}$</td>
<td>3/2</td>
<td>n</td>
<td>0.0147</td>
</tr>
</tbody>
</table>

Fluorine is ideal
(Well, multiple targets is ideal!)
Acoustic discrimination

• Discovery of acoustic discrimination against alphas (Aubin et al., New J. Phys.10:103017, 2008)
  – Alphas deposit their energy over tens of microns.
  – Nuclear recoils deposit theirs over tens of nanometers.

• In PICO bubble chambers alphas are several times louder.

Observable bubble ~mm

~40 μm

~50 nm

Daughter heavy nucleus
(~100 keV)

Helium nucleus
(~5 MeV)
Threshold and efficiency

- Threshold based on theory of Seitz, Phys. of Fluids I, 2 (1958)
- Energy deposition $E_{th}$ within length $R_c$ will nucleate a bubble
- Seitz model assumes step function above threshold, but the track dependence is not fully specified

\[ p_v - p_l = \frac{2\sigma}{r_c} \]

\[ E_{th} = 4\pi r_c^2 \left( \sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3}\pi r_c^3 \rho_v h \]

- Surface energy
- Latent heat
Understanding efficiency of F, C recoils

SRIM simulation of 15keV F recoils.
23 bubble AmBe neutron event

High multiplicity is a result of high bubble nucleation efficiency; 60% of neutron calibration events are multiples (compared to 25% in CF$_3$I).
C$_3$F$_8$ Sensitivity Calibrations

In addition to in-situ AmBe we calibrate the nuclear recoil response of C$_3$F$_8$ with 61 & 97 keV neutrons at U. of Montreal → probe very low energy recoils (12 & 20 keV max)

The shape of the efficiency curve is constrained at low energy, with agreement across calibrations.

Conservative approach: choose least sensitive pair of eff curves 1σ consistent with calibrations

Preliminary

Systematic uncertainty on neutron flux

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Preliminary

Systematic uncertainty on neutron flux
CF$_3$I Sensitivity Calibrations

In addition to in-situ AmBe and test chamber calibrations, direct measurement through pion scattering

Projected limits
SI projections