COUPP Iodine Recoil Threshold Experiment
T1017

Hugh Lippincott for the COUPP Collaboration

July 26, 2012

IDM 2012
Chicago
With support from:

COUPP

M. Ardid¹, E. Behnke², T. Benjamin², M. Bou-Cabo¹, S.J. Brice³, D. Broemmelsiek¹, J.I. Collar⁴, P.S. Cooper³, M. Crisler³, C.E. Dahl⁵, E. Grace², J. Hall³, C. Harnish², I. Levine², W.H. Lippincott³, D. Maurya⁶, T. Nania², R. Neilson⁴, S. Priya⁶, E. Ramberg³, A.E. Robinson⁴, A. Sonnenschein³, and E. Vázquez Jáuregui⁷

¹Politecnica Valencia
²Indiana University South Bend
³Fermi National Accelerator Laboratory
⁴KICP - University of Chicago
⁵Northwestern University
⁶Virginia Tech
⁷SNOLAB

With support from:
Bubble nucleation theory (Seitz, Phys. of Fluids, 1, 2 (1958))

- Bubbles form from proto-bubbles with radius \( r > r_c \)
- Requires energy deposition greater than \( E_{th} \)
- Recoil path length less than some length scale, \( R_c \), related to critical radius

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

\( \sigma = \) surface tension

\( P_l = \) liquid pressure

\( P_v = \) vapor pressure

\( p_v - p_l = \frac{2\sigma}{r_c} \)

Surface energy

Latent heat
Threshold and efficiency

- Calibration remains necessary to validate the Seitz model and measure any threshold softness
- Complicated by the three different types of recoils in CF$_3$I, with very different track length scales
Threshold and efficiency of iodine

- Iodine provides main sensitivity to spin-independent interactions
- Use AmBe and $^{252}$Cf neutron sources for calibrations
  - However, iodine recoils comprise only $\sim 15\%$ of these events, with very few directly at threshold

![AmBe induced recoils graph]

<table>
<thead>
<tr>
<th>Energy threshold (keV)</th>
<th>Event fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
</tr>
<tr>
<td>15</td>
<td>0.7</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
</tr>
<tr>
<td>25</td>
<td>0.5</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- Carbon
- Fluorine
- Iodine
Threshold and efficiency iodine

- Use radon daughters as proxy for iodine
- Consistent with 100% nucleation efficiency near threshold
- Needs explicit confirmation
Nuclear recoil calibrations

- Common problem in dark matter experiments
  - One method uses elastic scattering of monoenergetic neutrons (e.g. $L_{\text{eff}}$ in noble liquids or calibrations of superheated droplet detectors by Picasso)

\[ E_{\text{recoil}} \approx \frac{2m_N m_r E}{(m_N + m_r)^2} (1 - \cos \theta) \]
Alternate approach

- Superheated fluids are unique among dark matter detectors - they are insensitive to MIPs
  - Allows for elastic scattering of high momentum charged particles - can be tracked with very high precision

\[ T = E_{\text{recoil}} = \frac{(p\theta)^2}{2m_r} \]
Pion elastic scattering

- For 12 GeV $\pi$, 15 mrad $\rightarrow$ 125 keV iodine recoils
  - Can measure 0-125 keV recoils at the same time - impossible with tagged neutron scattering (particularly with bubble chambers)
- Tracking gives us event by event energy information which bubble chambers normally cannot provide

\[
T = E_{\text{recoil}} = \frac{(p\theta)^2}{2m_r}
\]
How does this address iodine recoils

- Neutron calibrations give us integral spectra dominated by carbon and fluorine
- With pion beam, we can measure energy event by event and explicitly at threshold
- Moreover, iodine is dominant at low recoil energies because C and F are diluted by the mass ratio \( E_r \propto \frac{1}{m_r} \)
What do we need

- A tunable beam - Fermilab Test Beam Facility (http://www-ppd.fnal.gov/FTBF/)
What do we need

- Resolution - only significant instrumental uncertainty is on scattering angle $\theta$
  
  $$\frac{\sigma_{E_r}}{E_r} = \frac{2\sigma_\theta}{\theta}$$

- For 12 GeV $\pi$, $E_r = 15$ keV $\rightarrow \theta = 5$ mrad. We’d like $\sigma_\theta \approx 0.5$ mrad

- Scattering angle uncertainty determined by Multiple Coulomb Scattering (MCS) in combination with angular resolution of tracker
Multiple Coulomb Scattering

- Multiple Coulomb Scattering affects all charged particles traversing a medium

Approximated by a Gaussian with width \( \theta_{MCS} \approx \frac{13.6}{\rho} \sqrt{\frac{x}{R}} \) where \( x \) is path length and \( R \) is radiation length of the medium.

- \( R_{CF_3I} = 5.8 \text{ cm} \), so for 12 GeV \( \pi \), 1 cm of CF\(_3\)I, \( \theta_{MCS} = 0.5 \text{ mrad} \)
Spatial resolution

- Ideally below MCS - For a 50 cm long tracker, measuring an angle with uncertainty of 0.5 mrad requires ~250 micron resolution
- Fermilab/CMS has a lot of experience with silicon pixel technology
- FTBF offers the use of a silicon pixel detector telescope (about 90 cm long) with ~10-100 micron resolution (courtesy of Computing Division Detector Instrumentation Group and CMS)

Beam profile on the FTBF pixel telescope display
FTBF Pixel Telescope

- Pixel pitch is 100 $\mu$m x 150 $\mu$m
- Chips of pixels are combined into either 20 mm x 30 mm or 20 mm x 40 mm plaquettes
- Plaquettes are movable and rotateable (up to about 90 cm maximal separation along the beam axis)
- For this experiment, plaquette overlap is about 15 mm x 15 mm
A test tube bubble chamber

- Small path length to minimize MCS ($\sim 5 \text{ ml CF}_3\text{I in 1 cm test tube}$)
- Hydraulics for pressure control
- Water bath for temperature control
- Beam tube penetrations in bath
- Acoustic sensor for timing
  - To align bubbles with tracks in the pixel telescope
- Small overall package to fit inside the telescope
A test tube bubble chamber

- First bubbles observed Jan. 28, 2012
- Short beam run from Feb. 7-9
  - Tested timing and physical integration of system
  - Led to improved design of water bath
- Run from March 14-28 at 15 keV Seitz threshold, before year-long accelerator shut down
An example good scattering event

Example event -10 mrad, 56 keV
Track to bubble correlation

- Reconstruction and track matching looks very good
- Strong correlation between bubble position from the cameras and telescope vertex position
March 14-28 run

- Data collection rate is fairly low - final data will only have several hundred good scattering events
- 1 beam spill/minute means at most 1 event/minute
- Significant losses to beam down time, commissioning, alignment etc. - collected over 9000 spills with good run conditions
- 80\% of bubbles correlated with spill (efficiency losses to backgrounds, water bubbles)
- Large fraction of events contain multiple bubbles (inelastic scattering, poor beam bunching)
- 1/3 of single bubbles scatter out of the telescope (i.e. no downstream track)
- Another half of bubble induced particles miss the telescope entirely
Analysis ongoing

- Use passive target data from a test run in December and target full and target empty data to validate MC models
- For example, comparing the scattering angle distribution for the CF$_3$I target
Analysis ongoing

- Use MC to isolate iodine component of data

- Final fit to a ratio of bubble-correlated tracks to all tracks in a given scattering angle
  - Minimize track reconstruction and acceptance systematics
  - In this ratio, correct for multiple bubble tracks and scatters in the water bath and quartz tube using data-validated Monte Carlo
Preliminary results for 15 keV Seitz threshold

- Premature to perform an actual fit
- Plot compares the data to our published exponential efficiency model applied to MC, with no other parameter tuning
Conclusion

- Successfully operated a test tube bubble chamber in the existing pixel telescope at the FTBF

- Two week run in March collected several hundred good, single bubble events

- Analysis ongoing, and preliminary results for iodine recoils are encouraging