PICO
Dark Matter Searches with Bubble Detectors

Tony Noble
Queens University

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The marriage of PICASSO and COUPP

PICASSO
- Complete PICASSO-32 and publish (Run Finished)
- Develop 100 kg Geyser prototype (underway)

PICO
- PICO-2L with $\text{C}_3\text{F}_8$ (Operational)

COUPP
- COUPP-4L Published Run 1 (Completed)
- COUPP-60 Kg CF$_3$I Detector (Operational)

PICO-250L
- 500 Kg Scale Bubble Chamber or Geyser
Two example events recorded

Single Bubble event

Neutron event
Bubble Chamber Data

- See Event with Stereo Cameras
- Record Pressure Rise
- Hear Acoustic Signal

A cosmic ray passing through chamber

A neutron bouncing around in chamber

A single bubble candidate

[Graph showing acoustic signal over time]
Bubble Chamber Thermodynamics

J. Willard Gibbs, “On the Equilibrium of Heterogeneous Substances” (1876)

Liquid-Vapour equilibrium when:

\[
\begin{align*}
P_\ell &= P_v \\
T_\ell &= T_v \\
\mu_\ell &= \mu_v
\end{align*}
\]

Pressure

Temperature

Chemical Potential
Bubble Chamber Thermodynamics

On saturation curve, two equal minima to Gibbs potential exist

- Gas Like (entropy)
- Liquid Like (enthalpy)

Liquid-Vapour equilibrium when:

\[
\begin{align*}
P_\ell &= P_v \\
T_\ell &= T_v \\
\mu_\ell &= \mu_v
\end{align*}
\]

Pressure

Temperature

Chemical Potential
Slightly off curve, still get two minima, one stable and one meta-stable.

We operate detectors in superheated meta-stable state. But a small disruption and the superheated liquid will vaporize.

Adjusting pressure/temperature allows the threshold to be tuned.
Bubble Nucleation Dynamics. What Controls Bubble Growth?

1. A small proto-bubble is produced.

2. The bubble begins to expand as the vapour is produced. Outward pressure $P_b$

3. This is opposed by the external pressure of the liquid $P_\ell$, and ...

4. It is opposed by the surface tension at the interface.

At equilibrium: $P_\ell + P_s = P_b$

Critical radius for (unstable) equilibrium:

$P_\ell + \frac{2\sigma}{r_c} = P_b$  \[ \begin{cases} \text{At larger radii, diff pressure is small, bubble grows easily .... Rapid boiling} \\ \text{At smaller radii, diff pressure is large, bubble can’t grow .... Collapse} \end{cases} \]
Particle detection with bubble chambers

- A bubble chamber is filled a superheated fluid in meta-stable state.

- Energy deposition greater than $E_{th}$ in radius less than $r_c$ from particle interaction will result in expanding bubble (Seitz “Hot-Spike” Model).

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

  Surface energy \quad Latent heat

- A smaller or more diffuse energy deposit will create a bubble that immediately collapses.

**Take away message:**

- To be sensitive, particle must deposit enough energy within a critical radius.
Bubble chambers as nuclear recoil detectors

- Thermodynamic parameters are chosen for sensitivity to nuclear recoils but not electron recoils.
- Better than $10^{-10}$ rejection of electron recoils (betas, gammas).
- Alphas are (were) a concern because bubble chambers are threshold detectors.

Take away message:

- Energy deposition depends on particle type. So can tune detector to be sensitive to certain types only. → Particle discrimination
Principle of Operation: Bubble Chamber

1. Lower the pressure to a superheated state.

2. See the bubble:
   • Cameras trigger, record position
   • Microphones record acoustic trace
   • Fast pressure transducer recording.

3. Raise pressure to stop bubble growth (100ms), reset chamber (30sec)
Backgrounds:

Require very low background environment to see rare events ….

- Go deep underground to escape cosmic rays.
- Provide local shielding
- Use materials with ultra-low levels of radioactivity
- **Develop particle discrimination techniques…**

- Neutrons
- Electrons/gammas
- Alpha
- Neutrinos
- Non-particle induced
Neutrons

- Go deep underground to escape cosmogenic neutrons.
- Provide local active & passive shielding for \((\alpha,n)\)
- Measure neutron rate independently
- Use fiducial volume cuts

COUPP-60 in neutron shielding tank.

Confirm neutron rate with multiples.
**Electron recoil rejection**

Bubble nucleation probability from gamma interactions in $C_3F_8$ and CF$_3$I

**Key Points:**

- Excellent electron/gamma rejection has been demonstrated.
- $C_3F_8$ can reach lower thresholds than CF$_3$I for same rejection.
- A lower threshold extends the sensitivity to lower mass WIMPs.
Alpha Acoustic Discrimination

• Discovery by PICASSO of acoustic discrimination against alphas (Aubin et al., New J. Phys.10:103017, 2008)
  – **Nuclear recoils** deposit their energy over tens of nanometers.
  – **Alphas** deposit their energy over tens of microns.
• In bubble chambers alphas are several times louder due to the expansion rate difference.

Observable bubble ~mm

~50 nm

Daughter heavy nucleus (~100 keV)

Helium nucleus (~5 MeV)

\[ I = \frac{\rho \vec{V}^2}{4\pi c} \]
COUPP 4

Dark matter search with CF\textsubscript{3}I

- Ideally has sensitivity to both spin-dependent (F) and spin-independent (I).


- Had issues with backgrounds. Had 20 anomalous recoil-like events in first run, but limits still good. Similar results in second run even after removing identifiable neutron sources.

- Some events clearly correlated with surface activity and not dark matter. But rate too small to study. Could be chemistry of CF\textsubscript{3}I?
COUPP-4
Spin-dependent results. Best results at that time.

Turns out that in CF$_3$I the F has low efficiency to trigger bubble ... less sensitivity...more uncertainty.

Spin-independent results. (I)

- Need to understand anomalous events
- Need detector large enough to study these while making good physics measurement.
  → COUPP 60 with CF$_3$I
COUPP 60

Dark matter search with CF$_3$I

• 2 main objectives…. a quality physics run and if they still persist, study the mystery events with larger sample.

• Still running, so not everything is public. > 4500 Kg-days collected.

• Good news: No multiple events have been seen, so source of neutrons has been removed. Large data set. Despite backgrounds a good limit will be set.

• Bad news: There are still some events that look/sound like recoils, but clearly are not dark matter.

  • Silver lining: Detector is large enough we can collect enough statistics to study them
COUPP-60
• Zero multiple bubbles
  – No neutron background.

• But, a population of events that sound similar to nuclear recoils but are clearly not WIMPs.
  – Non-istropic distribution.
  – Time dependence.
  – Appear louder on average than nuclear recoils.
  – This population is being studied in detail.
Also, some classes of events clearly correlated with the temperature of the water and glycol …. Correlation with pump, heaters, electrical noise, vibrations, *convection*…?
PICO 2L

Dark matter search with C\textsubscript{3}F\textsubscript{8}

- Objective 1…. a **quality physics run** (if background free and CDMS-Si had seen WIMPs, should get an event per day)

- Objective 2…. See how well C\textsubscript{3}F\textsubscript{8} works in bubble chamber. Can such a low threshold as was seen in PICASSO be achieved? → low mass sensitivity. It has potential to be a much better fluid.

- Still running, so not everything is public.

- **Good news:** Low thresholds can be achieved. Running at ~3 keV. Acoustic discrimination works well. Chamber looks to be working very well over all.

- **Bad news:** There was a mishap during the fill which appears to have contaminated the vessel. Will need to exchange flask.
PICO-2L

- Two liter active mass (same as COUPP-4):
  - Re-uses COUPP-4 location, neutron shield, other infrastructure.
- PICASSO inspired fluid
  - $\text{C}_3\text{F}_8$ instead of $\text{CF}_3\text{I}$.
  - Better fluorine sensitivity:
    - Twice the F density.
    - Lower threshold.
    - Improved efficiency.
    - More stable chemistry.
- New hardware:
  - Lower background.
  - Simpler controls.
  - Prototyping for ton-scale experiment.

New two-bellows design inner vessel assembly. Silica jar is an exact replica of COUPP-4 jar.
Simplified pressure vessel – $1/4$ the mass of steel as COUPP-4.
High neutron multiplicity implies high efficiency and means better rejection and measurement of neutron backgrounds.
Acoustic discrimination

• Alpha events are significantly louder than nuclear recoils (similar to CF$_3$I).

• Two distinct alpha peaks, and a valley with zero events between the alpha peaks and the signal region.

• No multiple bubble events in the low background data (would expect ~3 multiples so far if we had the neutron background observed in COUPP-4).
PICO-250L: ton-scale bubble chamber designed for CF$_3$I or C$_3$F$_8$ target
Sensitivity projections

Spin-Dependent

Spin-Independent

cMSSM model space from Roszkowski et. al., JHEP 0707:075 (2007).

PICO-2L projection based on 100 live-days of background free data.
Conclusions:

• Bubble Chambers for Dark Matter are coming of age.
• Background free potential.
• Should “own” the Spin-Dependent Sector with $C_3F_8$
• Should have world leading results for low mass WIMPS in SD and SI with $C_3F_8$
• With change to CF$_3$I, could be competitive in SI sector as well.
• Inexpensive, engineering understood, ...

Stay tuned!