COUPP500: a 500kg Bubble Chamber for Dark Matter Detection

Eric Vázquez Jáuregui
SNOLAB

Identification of Dark Matter 2012
Chicago IL, USA; July 26, 2012
The COUPP collaboration

- KICP - University of Chicago
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  R. Neilson, Alan E. Robinson

- Indiana University South Bend
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- Fermi National Accelerator Laboratory
  Steve J. Brice, Dan Broemmelsiek,
  Peter S. Cooper, Mike Crisler, Jeter Hall,
  W. Hugh Lippincott, Erik Ramberg,
  Andrew Sonnenschein, Fermilab Engineers and Technicians

- Northwestern University
  C. Eric Dahl

- Politecnica Valencia
  M. Ardid, M. Bou-Cabo

- SNOLAB
  Eric Vázquez-Jáuregui

- Virginia Tech
  D. Maurya, S. Priya
COUPP bubble chambers

- Target material: superheated $CF_3I$ spin-dependent/independent
- Particles interacting evaporate a small amount of material: bubble nucleation
- Cameras record bubbles
- Piezo sensors detect sound
- Recompression after each event
COUPP bubble chambers

- The ability to reject electron and gamma backgrounds by arranging the chamber thermodynamics such that these particles do not even trigger the detector
COUPP bubble chambers

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- The ability to suppress neutron backgrounds by having the radioactively impure detection elements far from the active volume and by using the self-shielding of a large device and the high granularity to identify multiple bubbles.
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- Sensitivity to spin-dependent and spin-independent WIMP couplings.
COUPP-4kg and COUPP-60kg

- Running at SNOLAB since 2010
- World leading spin dependent limits

  (Michael B. Crisler talk)

- Engineering run at Fermilab in 2011
- Moving to SNOLAB
- Physics run in late 2012

  (Andrew Sonnenschein talk)
COUPP at SNOLAB

SNOLAB

deepest and cleanest large-space international facility in the world

• 2 km underground near Sudbury, Ontario

• ultra-low radioactivity background environment Class 2000

• Physics programme focused on neutrino physics and direct dark matter searches
Calibrations

• $\gamma$ and neutron calibrations
  – AmBe and $^{252}$Cf
  – $^{60}$Co and $^{133}$Ba

• COUPP Iodine Recoil Threshold Experiment

• Low energy Iodine recoils

• $\pi$ beam and silicon trackers
  (Hugh Lippincott talk)

• $^{88}$Y/Be calibration chamber

• Monochromatic low energy neutrons
  (Alan E. Robinson talk)
- A tonne scale detector
- Spin-independent sensitivity $9 \times 10^{-47} cm^2$, background-free year running
- Beyond next generation (G2) device
- <9M total cost (R&D funded by NSF, waiting on DOE)
- Possible to use alternative fluids ($C_4F_{10}$)

**R&D phase**
COUPP-500kg design

- **Target fluid:** CF$_3$I
  - $\text{C}_4\text{F}_{10}$ at 15keV:
    - SI rate $\times 17 \downarrow$
    - (WIMP mass $\sim$100 GeV)
  - $\text{C}_4\text{F}_{10}$ at 15(10)keV:
    - SD rate $\times 4(18) \uparrow$
    - (WIMP mass $\sim$10 GeV)

- **Inner vessel assembly:**
  ultra-high-purity synthetic fused silica jar

- **Outer vessel:**
  Stainless steel ($\phi = 60$ inches)

- **Acoustics sensors:**
  piezoelectric acoustic transducers
COUPP-500kg design

- **Outer neutron shielding:**
  - neutron moderator
  - muon veto
  - temperature control

- **Pressure control unit:**
  - expand and recompress the chamber
  - regulate chamber pressure

- **Data acquisition:**
  - T and P sensors
  - machine vision cameras
  - acoustic transducers
R&D and calibrations

- Calibration of low energy nuclear recoil response
  - CIRTE, $^{88}$Y-Be, ...

- Calibration of gamma rejection

- In-situ source for alpha calibration

- Bubble acoustics and acoustic sensors

- Extensive background simulation!
COUPP-500kg simulations

- **External backgrounds:**
  - Rock neutrons
  - Muon induced neutrons
  - $(\gamma,n)$ reactions

- **Internal backgrounds:**
  - U and Th: fission and $(\alpha,n)$
    on light elements
  - $^{238}$U direct decay
  - *Materials: SS, quartz,...
  - *Fluids: water, glycol, CF$_3$I
  - *Radon
  - *Mine dust
  - *veto PMTs
  - *Acoustic transducers

GEANT4 model
COUPP-500kg: external neutrons

Fast neutrons from norite:
4000 n/m²/day

Muon induced neutrons in:
rock, water, stainless steel

Water tank dimensions:

- $\phi = 6.8$ m
- $L = 7.4$ m

$\sim 67$ muons/day

Neutron energy for $(\alpha, n)$ reaction in norite

Eric Vázquez-Jáuregui
IDM 2012
July 26, 2012
COUPP-500kg: fission and ($\alpha$,n)

Stainless steel, quartz
Water (buffer and tank), propylene glycol

- $^{238}\text{U}$, $^{232}\text{Th}$, $^{235}\text{U}$

Other backgrounds:
- Mine dust
- veto PMTs
COUPP-500kg: gammas, betas and $(\gamma,n)$ reactions

Gamma and beta decays:

Interact by Compton scattering, photoelectric absorption, and pair production

Rejection factor:
\[ \sim 10^{-10} - 10^{-12} \]

COUPP-4kg at SNOLAB measured:
\[ < 3 \times 10^{-11} \text{ at } 15 \text{ keV} \]

COUPP-500kg expected:
\[ 10^{-6} \text{ events/kg-day} \]

$(\gamma,n)$ reactions:

\[ 1^{27}\text{I}(\gamma,n)^{126}\text{I}: \]
\[ 4 \times 10^{-8} \text{ events/kg-day} \]

SNOLAB: \[ 4 \gamma/\text{cm}^2/\text{yr} > 9\text{MeV} \]

Other reactions:
\[ < 7 \times 10^{-10} \text{ events/kg-day} \]
COUPP-500kg: acoustic transducers

Two positions simulated:

$$10 \text{ ppb } ^{238}\text{U and } ^{232}\text{Th}$$
$$0.1 \text{ ppb } ^{235}\text{U, 10 Bq/kg } ^{210}\text{Pb}$$

- side only, 25g
  $$2 \times 10^{-8} \text{ events/kg-day}$$
- bottom only, 25g
  $$3 \times 10^{-7} \text{ events/kg-day}$$

Acoustic simulation in progress for design optimization

screening for salts used in the manufacture of piezoelectric transducers around 15 samples (high purity germanium detector at SNOLAB)
COUPP-500kg: CF$_3$I purity

$\alpha$ decays and neutrons from ($\alpha$,n):

- 0.0159 ppt $^{238}$U
- 0.0488 ppt $^{232}$Th
- 0.0025 ppt $^{235}$U
- 25 $\mu$Bq/kg $^{222}$Rn
- 25 $\mu$Bq/kg $^{210}$Pb

$6 \times 10^{-6}$ events/kg-day

vetoable: alpha + neutron

COUPP-500kg: radon

Radon deposition and emanation on all surfaces

Radon diffusion in all fluids
## Background Summary

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>Rate</th>
<th>Single evts/yr</th>
<th>Multiple evts/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock</td>
<td>$4000 \pm 1000 \text{ n/m}^2/\text{d}$</td>
<td>$O(10^{-11})$</td>
<td>$O(10^{-11})$</td>
</tr>
<tr>
<td>Muon induced from rock</td>
<td>$5.4 \times 10^{-11} \text{ n/cm}^2/\text{s}$</td>
<td>$0.0904 \pm 0.0131$</td>
<td>$0.2544 \pm 0.0219$</td>
</tr>
<tr>
<td>Muon induced from shield or detector</td>
<td>$67.11 \pm 1.85 \text{ \mu/d}$</td>
<td>$0.493 \pm 0.014$</td>
<td>$1.050 \pm 0.030$</td>
</tr>
<tr>
<td>U and Th in detector materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>steel only</td>
<td>$1 \text{ppb } ^{238}\text{U and } ^{232}\text{Th}$</td>
<td>$0.0504 \pm 0.0030$</td>
<td>$0.1242 \pm 0.0068$</td>
</tr>
<tr>
<td>quartz only</td>
<td>$10^{-2} \text{ppb } ^{238}\text{U and } ^{232}\text{Th}$</td>
<td>$0.0360 \pm 0.0026$</td>
<td>$0.0922 \pm 0.0062$</td>
</tr>
<tr>
<td>Radon deposition onto and diffusion into outer surface of quartz jar</td>
<td>Dep. Rate $= 10^{-3}/\text{m/y}$</td>
<td>$0.0198 \pm 0.0015$</td>
<td>$0.0415 \pm 0.0030$</td>
</tr>
<tr>
<td>Radon in water tank</td>
<td>$S=0.25, 100 \text{ Bq/m}^3 \text{Rn}$</td>
<td>$(1.83 \pm 0.28) \times 10^{-3}$</td>
<td>$(5.17 \pm 0.60) \times 10^{-3}$</td>
</tr>
<tr>
<td>Radon in heat exchange pipes</td>
<td>$S=0.25$</td>
<td>$0.0230 \pm 0.0021$</td>
<td>$0.0572 \pm 0.0052$</td>
</tr>
<tr>
<td>Radon emanation from quartz and steel</td>
<td>$A=34.81 \text{m}^2/100 \text{ \mu Bq/m}^2 \text{Rn}$</td>
<td>$(1.39 \pm 0.13) \times 10^{-3}$</td>
<td>$(2.93 \pm 0.26) \times 10^{-3}$</td>
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<td>Mine dust on top surfaces</td>
<td>0.01 g/m², 2.21 m² 1.11 ppm $^{238}$U 5.56 ppm $^{232}$Th</td>
<td>$0.0127 \pm 0.0011$</td>
<td>$0.0286 \pm 0.0026$</td>
</tr>
<tr>
<td>$^{127}$I($\gamma,n)^{126}$I</td>
<td>$4.0 \gamma/cm²/yr &gt; 9$MeV</td>
<td>$&lt; 0.0069$</td>
<td></td>
</tr>
<tr>
<td>other photonuclear</td>
<td></td>
<td>$&lt; 1.3 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Piezoelectric acoustic transducers, 50g</td>
<td>10 ppb $^{238}$U</td>
<td>$0.0577 \pm 0.0031$</td>
<td>$0.142 \pm 0.008$</td>
</tr>
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<td>¶ side only, 25g</td>
<td>10 ppb $^{232}$Th</td>
<td></td>
<td></td>
</tr>
<tr>
<td>¶ bottom only, 25g</td>
<td>0.1 ppb $^{235}$U</td>
<td>$0.0036 \pm 0.0002$</td>
<td>$0.0072 \pm 0.0004$</td>
</tr>
<tr>
<td>¶ bottom only, 25g</td>
<td>10 Bq/kg $^{210}$Pb</td>
<td>$0.0541 \pm 0.0031$</td>
<td>$0.134 \pm 0.008$</td>
</tr>
<tr>
<td>CF$_3$I U and Th ($\alpha,n$)</td>
<td>0.0159 ppt $^{238}$U</td>
<td>$1.078 \pm 0.061$</td>
<td>$4.37 \pm 0.25$</td>
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<tr>
<td>Other radon induced backgrounds</td>
<td>0.0488 ppt $^{232}$Th</td>
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<td>Other radon induced backgrounds</td>
<td>6mo. deposition on steel</td>
<td>$8.0 \pm 0.5 \times 10^{-6}$</td>
<td>$2.00 \pm 0.12 \times 10^{-5}$</td>
</tr>
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<td>Other radon induced backgrounds</td>
<td>92.6$\mu$Bq/m³ in IV</td>
<td></td>
<td></td>
</tr>
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<td>Other radon induced backgrounds</td>
<td></td>
<td>$1.84 \pm 0.06$</td>
<td>$6.08 \pm 0.25$</td>
</tr>
<tr>
<td>Other radon induced backgrounds</td>
<td></td>
<td>$0.264 \pm 0.014$</td>
<td>$0.663 \pm 0.025$</td>
</tr>
</tbody>
</table>

4-page table, each $\sim 10^5 - 10^6$ years simulated
COUPP-500kg expected sensitivity at SNOLAB

![Graph showing expected sensitivity for WIMP masses and spin-dependent proton cross-sections for various experiments including COUPP, SIMPLE, IceCube, Super-K, and PICASSO. The graph includes different sensitivity bands for different mass ranges and cross-sections, highlighting the expected sensitivities for COUPP experiments with different mass and background controls.]
COUPP-500kg expected sensitivity at SNOLAB

Spin-independent cross-section (cm$^2$)

COUPP (Jan. 2011)
CDMS (SUF)
COUPP (Apr. 2012)
CDMS
XENON10
COUPP−4, 4 mo, 0 bg
XENON100
COUPP−60, 4 mo, 0 bg
COUPP−60, 1 yr, 0 bg
COUPP−500, 1 yr

cMSSM

WIMP Mass (GeV)

$10^{-40}$ $10^{-39}$ $10^{-38}$ $10^{-37}$ $10^{-36}$ $10^{-35}$ $10^{-34}$ $10^{-33}$ $10^{-32}$ $10^{-31}$ $10^{-30}$ $10^{-29}$ $10^{-28}$ $10^{-27}$ $10^{-26}$ $10^{-25}$ $10^{-24}$ $10^{-23}$ $10^{-22}$ $10^{-21}$ $10^{-20}$ $10^{-19}$ $10^{-18}$ $10^{-17}$ $10^{-16}$ $10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$
Schedule

• 2013:
  – Finish mechanical design of all major components
  – Order Outer Vessel
  – Prototype hydraulic system
  – Test pressure control at full scale
  – First tests of 3rd generation acoustic sensors
  – Select SNOLAB installation location

• 2014:
  – Water tank construction at SNOLAB
  – Inner Vessel prototype testing at Fermilab
  – High purity fluid system construction
  – Control system and DAQ testing
2015:

- Construction of final Inner Vessel
- Installation of all equipment at SNOLAB
- Commissioning

Ready for Physics data taking in 2016!
Conclusions

COUPP family of detectors making huge improvements:

- COUPP-4kg currently running at SNOLAB
- COUPP-60kg running by the end of the year
- Calibrations, calibrations and calibrations:
  CIRTE, $^{88}\text{Y}/\text{Be}$, gamma, neutron, ...

COUPP-500kg is the following target:

- a tonne scale detector
- spin-independent sensitivity:
  $9 \times 10^{-47} \text{cm}^2$ (background-free year running)
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More great and beautiful physics from COUPP just around the corner!