Things that go bump in the dark

Outline of (this component of) the course:

• Brief introduction to low-background techniques
• What do we expect from WIMPs and axions?
  (what do we think we know about them, basic phenomenology)
• Detailed discussion of direct search methods
• Have we found them yet?
• What will it take to call it “dark matter”?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technology</th>
<th>$\beta\gamma$ rejection</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMS</td>
<td>Cryo Ge/Si</td>
<td>ionization/phonon</td>
<td>surface $\beta$s, timing helps</td>
</tr>
<tr>
<td>Edelweiss</td>
<td>Cryo Ge</td>
<td>ionization/thermal</td>
<td>surface $\beta$s, NbSi helps</td>
</tr>
<tr>
<td>CRESST, Rosebud</td>
<td>Cryo CaWO$_4$</td>
<td>scintillation/thermal</td>
<td>low light for WIMP on W</td>
</tr>
<tr>
<td>Zeplin, XENON,</td>
<td>LXe 2-phase</td>
<td>charge/scintillation</td>
<td>low light, PMT radioactivity</td>
</tr>
<tr>
<td>WARP, ArDM,</td>
<td>LAr 2-phase</td>
<td>charge/scintillation</td>
<td>scint, self-shielding, No E-field, good scaling</td>
</tr>
<tr>
<td>XMASS</td>
<td>LXe</td>
<td>scint, pulse shape disc</td>
<td>also solar $\nu$, no E-field</td>
</tr>
<tr>
<td>CLEAN</td>
<td>LAr/LNe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Majorana, Gerda</td>
<td>HPGe</td>
<td></td>
<td>primarily $\beta$-decay, extreme purity, stat. subtraction</td>
</tr>
<tr>
<td>Genius, GEDEON</td>
<td>HPGe</td>
<td></td>
<td>large mass, ann. mod.</td>
</tr>
<tr>
<td>CuoRcino</td>
<td>Cryo TeO$_2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAMA/LIBRA, ANAIS</td>
<td>NaI scint.</td>
<td></td>
<td>large mass, ann. mod., also $\beta$-decay</td>
</tr>
<tr>
<td>Picasso, COUPP</td>
<td>bubble chambers</td>
<td></td>
<td>large mass, alpha bgd</td>
</tr>
<tr>
<td>DRIFT</td>
<td>drift chmb (gas)</td>
<td></td>
<td>directionality/low density</td>
</tr>
</tbody>
</table>

DM Direct Search Progress Over Time (2009)

P. Cushman

R. Gaitskell
We live in a radioactive medium
(and one day, "dark matter" will be regarded as just another source of natural radioactivity)

Many sources:
• Primordial (U, Th, K)
• Cosmogenic
• Man-made

"Equilibrium" not always there
(chemical affinities, mobility)

\[
N_B = \frac{\lambda_A}{\lambda_B} N_A
\]

2.6 MeV = "Thallium limit"
We live in a radioactive medium
(and one day, "dark matter" will be regarded as just another source of natural radioactivity)

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- Primordial (U, Th, K)
- Cosmogenic
- Man-made

Fig. 7.3. A schematic description of the production and fate of cosmic ray particles in the atmosphere and upper layer of the Earth.

Cosmogenics in CoGeNT

Not a stationary situation!
(atm depth, solar activity)
We live in a radioactive medium
(and one day, "dark matter" will be regarded as just another source of natural radioactivity)

Many sources:
- Primordial (U, Th, K)
- Cosmogenic
- Man-made

Fig. 3. Background spectra obtained using GEANT4 simulation for the 8 × 8 × 30 cm³ CsI(Tl) crystal with 10 mBq/kg $^{137}$Cs contamination, 30 mBq/kg $^{134}$Cs contamination, and 10 ppb $^{87}$Rb contamination: (a) spectrum of $^{137}$Ba; (b) beta-ray spectrum of $^{137}$Cs; (c) $^{134}$Cs spectrum; (d) $^{87}$Rb spectrum; and (e) total summed spectrum.

Chemical affinity: a real pain in the tuckus

Simulated for increasing thickness of absorbing layer made of radio-pure lead. The numbers at arrows indicate the layer thicknesses in mm. The uppermost spectrum was obtained without any layer of radio-pure lead.
Low-background techniques

Problem for early C-14 counters:

Background rates ~100c/min regardless of shielding:
Birth of the anticoincidence veto

Cosmogenic origin: \( n_{th} + ^{14}\text{N} \rightarrow ^{14}\text{C} + \text{H} \)

Fixed by plants via photosynthesis

Pioneered at UC by W. Libby
(tradition continued by J. Simpson, T. Turkevich, etc.)

Fig. 1.1. Low-level counting started with this system. Libby’s radiocarbon system with which he and his co-workers established the radiocarbon dating technique in 1947–1949.
Low-background techniques

Pure science apps
- The atmosphere
- The oceans
- Cross sections
- Meteorites
- Lunar studies
- Astronaut studies

H. Miley
**Low-background techniques**

<table>
<thead>
<tr>
<th>detector + coincidence condition</th>
<th>total count rate [cpm] (≥ 100 keV)</th>
<th>no anticoinc.</th>
<th>with anticoinc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>half of 10&quot;Ø x 9&quot;</td>
<td>537</td>
<td>167</td>
<td></td>
</tr>
<tr>
<td>6&quot;Ø x 4&quot;</td>
<td>201</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>2 fold coinc. 1a + 1b</td>
<td>214</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>3 fold coinc. 1a + 1b + 2</td>
<td>1.6</td>
<td>0.16</td>
<td></td>
</tr>
</tbody>
</table>

$T_{2\alpha} = 7.2 \pm 1.2 \text{ My}$

$T_{4\alpha} = 0.31 \pm 0.07 \text{ My}$

Prof. Ouyang
Low-background techniques

LASR basement lab: a remnant of this era
Low-background techniques

- Hanford Works environmental surveillance
- Early high-sensitivity radiation detection using NaI underground
- Methodical bkg reduction & sensitivity increase for environmental samples

Lots to clean up after Manhattan project... (e.g., watch “Deadly Deception”)
Low-background techniques

Techniques not restricted to Dark Matter searches (by now common to most non-accelerator particle physics)

G. Heusser
Low-background techniques

Techniques have reached a sobering level of maturity (in this example, state-of-the-art radioassay)

G. Heusser

Peruse if you want:
http://kicp.uchicago.edu/~collar/Heusser.pdf
http://kicp.uchicago.edu/~collar/martoff.pdf
Low-background techniques
(as applied to DM searches)

Bag-of-tricks:
• Depth
• Shielding (active & passive)
• Radiopurity
• Background rejection
• Special detector properties

Four sources of neutrons to control:
• secondaries (modest overburden)
• environmental (hydrogenated shielding)
• \((\mu,n)\) in detector and shield (active veto)
• “punchthrough” (depth, massive moderator)
Low-background techniques
(as applied to DM searches)

Bag-of-tricks:
- Depth
- Shielding (active & passive)
- Radiopurity
- Background rejection
- Special detector properties

“muon telescope”
Not everything known in this area yet.

FIG. 15: The muon-induced neutron production rate predicted for some common detector shielding materials. Note that minor variations due to neutron back-scattering have been neglected in these calculations. Mei + Hime

Long-term concerns:
“punchthrough” neutrons (also (α,n) reactions)
Low-background techniques
(as applied to DM searches)

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• Depth
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(as applied to DM searches)

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<table>
<thead>
<tr>
<th>Sets properties</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of moderator (cm)</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Statistics time (days)</td>
<td>17</td>
<td>118</td>
<td>97</td>
<td>41</td>
</tr>
<tr>
<td>Counts/(keV kg day)</td>
<td>0.74(6)</td>
<td>0.39(2)</td>
<td>0.22(1)</td>
<td>0.24(2)</td>
</tr>
</tbody>
</table>

Cosmogenic tritium a limiting factor

G. Luzon
Low-background techniques
(as applied to DM searches)

Bag-of-tricks:
• Depth
• Shielding (active & passive)
• Radiopurity
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Fig. 2. A 3-Cell Zone Refiner.

Fig. 3. A Zone-Refined Ingot.

Ge zone refinement

Fig. 4. Electroformed Cu cryostat

Impurities \( \sim 1 \times 10^{-13} \text{ g/g} \)

Fig. 1. Improvements in low-background technology.

...and yet not enough per se to catch a WIMP...
Low-background techniques
(as applied to DM searches)

Bag-of-tricks:
• Depth
• Shielding (active & passive)
• Radiopurity
• Background rejection
• Special detector properties

DISCRIMINATION
STRATEGIES

CRESST ROSEBUD
CaWO₄, BGO
ZnWO₄, Al₂O₃ ...

CRESST I
TeO₂, Al₂O₃, LiF

Phonons
10 mcV/ph
100% energy

Scintillation
~ 1 keV/γ
few % energy

Ionization
~ 10 eV/e
20% energy

CUORE

CDMS
EDELWEISS
Ge, Si

ZEPLIN II, III
XENON, LUX
WARP, ArDM
SIGN

Xe, Ar, Ne

DEAP
CLEAN
XMASS

NAIAD
DAMA

Depth vs. Y-Axis

0 Å - Target Depth - 550 Å
Low-background techniques
(as applied to DM searches)

Bag-of-tricks:
- Depth
- Shielding (active & passive)
- Radiopurity
- Background rejection
- Special detector properties

E.g., COUPP's choice of target
CoGeNT's dynamic range and E resolution

Ridiculous or sublime?

**DISCRIMINATION STRATEGIES**

- Phonons
  - 10 meV/ph
  - 100% energy
- CDMS
  - EDELWEISS
  - Ge, Si
- Scintillation
  - ~1 keV/γ
  - few % energy
- Ionization
  - ~10 eV/e
  - ~20% energy
- Nuclear Recoils
  - 100 GeV WIMP
  - 1 eV-47 cm²
  - 8B solar ν E res. conv.
  - 100 GeV WIMP
  - 1 eV-48 cm²
  - 8B solar ν
A few words about your project

• 5-page “white paper” (i.e., a pre-proposal) + references + “Quad chart”
• Usual sections: motivation, implementation, projected sensitivity, deliverables (reach). Skip funding...
• Will adapt to your finals schedule (deadline flexible)
• Show some creativity!!! (grading DARPA-style)
• GET STARTED NOW

Particle dark matter? The number of candidates is comparable to the ~30 experiments out to detect it.

• Standard model neutrinos
• Sterile neutrinos
• Axions
• Supersymmetric dark matter (neutralinos, sneutrinos, gravitinos, axinos)
• Light scalar dark matter
• Little Higgs dark matter
• Kaluza-Klein dark matter
• Superheavy dark matter (wimpzillas)
• Q-balls
• CHArged massive particles (CHAMPS)
• Self-interacting dark matter
• D-matter
• Cryptons
• Superweakly interacting dark matter (SWIMPS)
• Brane-world dark matter
• Heavy 4th generation neutrinos
• Mirror particles
• Etc., etc.
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Proposal Title: Compact, moderately-superheated bubble chambers: the most sensitive fast neutron detector?

**Proposed technical Approach:**

**PHASE I TASKS (1st year, medium risk):**
- Development of 4 kg CF3 prototype
- Proof-of-principle tests at Sandia and LLNL, using SNMs and a variety of simulated cargo configurations. Use of optimal Li-7(p,n) 60 keV neutron generator (LLNL) as the interrogating source.
- Demonstration of insensitivity to $(\gamma,\nu)$ and $(\gamma,\alpha)$ $E \geq 12$ MeV gammas.
- Using simulations validated in previous tests, generate accurate predictions of expected sensitivity in a variety of cargo configurations
- Development of fastest possible cycling of the chambers (less than present 5 s) to minimize dead time.
- Development of triggering schemes compatible with the above
- Development of 2 to 4 large portal monitors (chambers ~2 m tall)

**PHASE 3 TASKS (3rd year, low risk):**
- Continued development of 2 to 4 large portal monitors (chambers ~2 m tall)
- Installation and tests within a “nuclear car wash” context.

**Operational capability to be provided:**
- Low-cost, moderately superheated bubble chambers can be built with sufficient stability and design simplicity to permit use as portal monitors.
- Prototype chambers have demonstrated a predictable neutron energy threshold below which neutrons cannot take place. A gamma rejection factor of $>10^4$ and total insensitivity to therma $\gamma$s has also been shown. This allows the chamber in the presence of a low-energy interrogating neutron source, responding only to fast neutrons from smuggled SNMs escaping with energies higher than that of the source.
- Simulations show that the ability to detect the low prompt fission neutrons able to reach the chamber with excellent efficiency, while being insensitive to source-induced backgrounds, leads to an unparalleled sensitivity to SNMs, even in the worst possible shielding conditions (a cargo container full of hydrogenated moderator). Use of a low-energy neutron source and the short exposures required also results in a negligible activation of cargo, safe operation and fast screening.

**Cost & Schedule:**
- Total project cost: $899,000 (1st year $291,000, 2nd year $350,000, 3rd year $258,000)
- Highest risk involved during first task (first year). Demonstration of total insensitivity to interrogating source with a low-enough threshold for sufficiently high-efficiency detection of escaping fission $n$'s is crucial. The decision to proceed with phases 2 & 3 will be taken after prototype tests at Sandia/LLNL during task 1.

**Deliverables:**
- A tested bubble chamber design ready for transfer to industry by the third year. A complete demonstration portal monitor with sensitivity to 0.1 (100g) smuggled HEU, even in the worst-case shielding scenarios.

**Contact Information:**
- Asst. Prof. Juan I. Collar, Enrico Fermi Institute, University of Chicago, 5640 S. Ellis Ave., LASR 214, Chicago IL 60637.
- Phone: (773) 702 4253, Fax: (773) 834 4279
- E-mail: jjcollar@uchicago.edu  www: collargroup.uchicago.edu
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OTHER MYTHICAL BEASTS: Monopoles, Nuclearites, Q-balls, D (all HEAVILY ionizing)

Fig. 5. Energy losses of SECS versus $\beta$ in the earth mantle; $Z_0$ is the electric charge of the Q-ball. The dashed parts of the lines indicate interpolations.


Can be enormous for Nuclearites: $dE/dx \approx (1 \times 10^{-8}) A^2 (\beta^2 B)$... A up to $10^{26}$ !!!

"ASTROBLOTS" (de Rujula & Glashow) "LINEAR EARTHQUAKES"

Faux meteorites?

Read about these “Aborigines of the nuclear desert” (usual path+)
alvaro1.pdf <- Beauty!
alvaro2.pdf
vigdor1.pdf
vigdor2.pdf <-!!
vigdor3.pdf <- ho-hum (let that be a lesson...)

Many other ways to look for these, e.g., fullerene.pdf, MACRO detector, macro.pdf
http://www.bo.infn.it/macro/pub_refi.htm etc.
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![Chart of nuclides, hopefully incomplete.](image)

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Many other ways to look for these, e.g., fullerene.pdf, MACRO detector, macro.pdf
http://www.bo.infn.it/macro/pub_refi.htm
etc.

True threshold “detector”: natural radioactivity cannot produce enough (if any) fullerenes due to short tracks and feeble dE/dx.

C-60 takes a beating and keeps on ticking: it does survive over geological ages once formed (in rocks known to have undergone episodes of intense heating). Extremely stable.

Fullerenes absent from “middle-of-the-road” carbonaceous rocks (good sensitivity immediately possible)
A few words about your project

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Geochemical approach
To WIMP detection
(Exposure = Nt)

Snowden-Ifft et al. PRL 74 (1995) 4133
Collar & Avignone NIM B95 (1995) 349
Collar PRL 76 (1996) 331

FIG. 1. An illustration of the etching technique. (a) If WIMPs exist they would cause the constituent atoms of muscovite mica, mainly $^{16}$O, $^{27}$Al, $^{28}$Si, and $^{39}$K, to recoil across a cleavage plane. (b) When both halves of the cleavage plane are etched matching pits will appear. The illustration also shows the development of $\alpha$-recoil tracks and that these tracks will have longer summed depths than WIMP-recoil tracks.

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