Discovery of underground reservoir of argon with low level of $^{39}\text{Ar}$

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Cristiano Galbiati, on behalf of …

Discovery of underground argon with low level of radioactive $^{39}\text{Ar}$ and possible applications to WIMP dark matter detectors
• Part of research program funded by NSF
• Motivation for exploration of underground argon
• Status and development of analytical techniques
• Sample collection and preparation
• Discovery of first source with low level of $^{39}\text{Ar}$
• Next step: massive collection of low background argon for large WIMP detector
Liquid argon excellent material for WIMP and neutrino detection:

- Copious scintillation
- Excellent target for ionization detector
- Best beta/recoil discrimination among energy-sensitive detectors. See next slide with last WARP records

Large-scale argon WIMP detectors under development

- WARP 3.2-kg delivered first Ar-limit on WIMP detection (2006)
- WARP 140-kg operating next year at LNGS
Recent WARP Results on Discrimination

After recent electronics upgrade, pulse shape discrimination between m.i.p. and nuclear recoils better than $3 \times 10^{-7}$ for $>35$ photoelectrons, better than $10^8$ for $>50$ photoelectrons. Shape of distribution does not change by applying S2/S1 cut (reduction $5 \times 10^2$). Two discriminations independent within statistics collected.
Why is underground argon desirable?

- Radioactive $^{39}\text{Ar}$ produced by cosmic rays in atmosphere
  - decays betas, $Q = 565$ keV, $t_{1/2} = 269$ years
- In atmospheric argon:
  - $^{39}\text{Ar}/\text{Ar}$ ratio $8 \times 10^{-16}$
  - specific activity 1 Bq/kq
- Limits size and sensitivity of argon detectors
Why is underground argon desirable?

• $^{39}$Ar-depleted argon available via centrifugation or thermal diffusion, but expensive at the ton scale!

• $^{39}$Ar production by cosmic rays strongly suppressed underground

• Shielding of hydrocarbons in deep underground reservoirs results in low cosmogenic $^{14}$C, important for solar neutrino detection

• Borexino just reported measurement of solar $^7$Be neutrinos

• Background from $^{14}$C defeated through use of scintillator from petrochemicals

• In petrochemicals $^{14}$C/$C\sim10^{-18}$, six orders of magnitude lower than in atmospheric carbon ($^{14}$C/$C\sim10^{-12}$)
• $^{39}$Ar also produced underground by neutron activation, from fission and ($\alpha$,n) neutrons

• $^{39}$K(n,p)$^{39}$Ar

• $^{39}$Ar content depends on local content of U, Th, and K, and on rock porosity

• In some groundwater samples $^{39}$Ar/Ar ratio measured up to a factor $20\times$ (2000%) of the atmospheric ratio

• Cannot rely on $^{39}$Ar simply being low. Pre-scan of $^{39}$Ar activity on small samples necessary for program.
Analytical techniques to measure $^{39}$Ar

- Three main techniques:
  - Counting of argon gas in low-background proportional detectors
  - Accelerator Mass Spectrometry (AMS)
  - Counting of argon in low-background liquid-phase detectors
Counting of argon gas in low-background proportional counters

- First established (Loosli 1969) and still today standard method for $^{39}\text{Ar}$ determination
- Collaborators Loosli and Purtschert run in Bern underground Lab dedicated facility for $^{39}\text{Ar}$ measurements since 1969
- Small samples (1-2 liters STP) of argon and limited depth (100 m.w.e.) required to measure $^{39}\text{Ar}$ at or below atmospheric level
- $^{39}\text{Ar}$ sensitivity limited by detector background. Detector background must be carefully characterized by measurement with reference argon gas depleted in $^{39}\text{Ar}$
- Current limit on sensitivity at 5% of atmospheric level
Accelerator Mass Spectrometry (AMS)

- Requires special Electron Cyclotron Resonance (ECR) ion source to create positive ions in multiple (7+,8+) ionization states
- Combination of ECR source and ATLAS linear accelerator unique facility at Argonne National Labs
- In 2002 campaign, reached a sensitivity for $^{39}\text{Ar}/\text{Ar}$ equivalent to 5% of atmospheric level
- Most flexible tool: measurement requires few ml of STP argon
ATLAS at Argonne National Labs

ECR Ion Source

ATLAS Linear Accelerator

Spectrograph
AMS: 2002 Test

$^{39}$Ar-spiked argon at 3000% of atm. activity

Deep ocean argon at 30% of atm. activity

Sensitivity limited by presence of $^{39}$K background from ion source walls, intrinsic to aluminum
AMS: 2007 Test

- 1 week run in June 2007, ECR source upgraded with addition of high purity aluminum liner

- Reduction of K background by factor 13

- Sensitivity potentially increased to 0.5% of atmospheric level

- Next step:
  - request of additional 2 weeks of time
  - measurement of large pool of samples at 0.5% atm. level
Counting in Liquid-phase detectors

- WARP 3.2-kg reached accuracy of 10% of atmospheric level
- Specially designed low background detector with 10-kg mass could reach below 0.1% of atmospheric level
- Requires first large batch of argon from underground reservoir
Sample Preparation

- Challenge: Ar in subsurface gases typically at few hundred ppm concentration. Needs large quantities with purity >50%
- 1+yr R&D program in Princeton run by graduate student Ben Loer, senior Daniel Marks, freshman Daniel Acosta-Kane
- Resulted in construction of two stages separation plant, deployable on the field
- Chromatographic plant removes strongly adsorbing components (methane, ethane, heavy hydrocarbons, nitrogen, carbon dioxide)
- Cold trap removes helium, hydrogen
- Achieves production of argon samples with purity exceeding 80%
## Discovery of low $^{39}\text{Ar}$ from underground reservoirs

<table>
<thead>
<tr>
<th></th>
<th>Count Rate [$\mu\text{Bq}$]</th>
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<tbody>
<tr>
<td>Underground Ar</td>
<td>2036±43</td>
</tr>
<tr>
<td>$^{39}\text{Ar}$-Depleted Reference</td>
<td>2035±49</td>
</tr>
<tr>
<td>Atmospheric Ar</td>
<td>3625±77</td>
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<tr>
<td>$(\text{Under. Ar}) - (\text{Ref.})$</td>
<td>1±65</td>
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<tr>
<td>$(\text{Atm. Ar}) - (\text{Ref.})$</td>
<td>1589±91</td>
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<tr>
<td>$(\frac{^{39}\text{Ar/Ar}}{\text{und}}/\frac{^{39}\text{Ar/Ar}}{\text{atm}})$</td>
<td>0.00 ±0.05</td>
</tr>
</tbody>
</table>

Conclusions

• Discovery of underground reservoir with argon low in radioactive $^{39}$Ar! Depletion factor at least 20 relative to atmospheric argon.

• No $^{39}$Ar detection, represents only upper limit. Motivates development of new, more sensitive techniques.

• Reservoir able to supply argon target for multi-ton WIMP/neutrino detector.

• Collaboration developing with industry infrastructure for massive collection and underground storage of depleted argon.
WARP Update
Cryostat for 140-kg detector in Hall B, assembly started
Operating 2008