Latest Updates from the AlCap Experiment

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on behalf of the AlCap collaboration

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Lawrence Berkeley National Laboratory
Muon-to-Electron Conversion Searches

The next generation of muon-to-electron conversion experiments will search for the $\mu \rightarrow e$ conversion process, with a single event sensitivity of $\sim 10^{-17}$.

$$R_{\mu \rightarrow e} = \frac{\mu^- + N(Z, A) \rightarrow e^- + N(Z, A)}{\mu^- + N(Z, A) \rightarrow \nu_e + N(Z - 1, A)}$$

COMET @ J-PARC

Experimental Method: Stop $O(10^{10})$ muons per second in Al
Muon-to-Electron Conversion Searches

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Experimental Method: Stop $O(10^{10})$ muons per second in Al
What happens when a muon is stopped by an atom?

A **muonic atom** is formed:

- the muon instantly falls down to the 1s orbital → **X-rays**
- after some time the muon will undergo one of the following processes:
  - $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ (decay-in-orbit)
  - $\mu^- + N(Z, A) \rightarrow \nu_e + N(Z - 1, A)$ (nuclear muon capture) → **γ-rays, heavy charged particles, neutrons**

Cartoon of the $\mu - e$ conversion process
Why do we care?

**Heavy Charged Particles**
- proton with kinetic energy 5 MeV has momentum 100 MeV/c
  - will enter the detectors → hit background
  - are highly ionising → damage
- need a proton absorber → how thin can we make it?

**Neutrons**
- will leave the experiment and hit the cosmic ray vetos and mimic a cosmic ray → additional deadtime

**Photons**
- can be used to count the number of captured muons

We want to know the rate and spectrum of these emission products!
What do we know about the nuclear capture decay products?

Heavy Charged Particles:
- for Al: only know the high energy region (> 40 MeV)
- for low energy: only known for Si
- composition (p, d, t etc.) not measured

Neutrons:
- rate has been measured

Photons:
- X-rays and γ-rays are known
- any background lines? are delayed γ-rays strong enough?

<table>
<thead>
<tr>
<th>Material</th>
<th>Transition</th>
<th>Intensity [%]</th>
<th>Energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>2p − 1s</td>
<td>79.8 ± 0.8</td>
<td>346.828 ± 0.002</td>
</tr>
<tr>
<td></td>
<td>3p − 1s</td>
<td>7.62 ± 0.15</td>
<td>412.87 ± 0.05</td>
</tr>
<tr>
<td>Si</td>
<td>2p − 1s</td>
<td>80.3 ± 0.8</td>
<td>400.177 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>3p − 1s</td>
<td>7.40 ± 0.20</td>
<td>476.80 ± 0.05</td>
</tr>
</tbody>
</table>

(S. E. Sobottka and E. L. Wills Phys.Rev.Lett. 20 (1968) no.12, 596)

(B. Macdonald et.al. Phys.Rev. 139 (1965) B1253)

The AlCap experiment is a joint venture between the Mu2e and COMET collaborations to measure the rate and spectrum of individual charged particles, neutrons and photons after nuclear muon capture.

Three runs at PSI:

- 2013: charged particles and photons (Al, Si (passive))
- 2015a: neutrons and photons (Al, Ti, Pb, SS, Water and Mylar)
- 2015b: charged particles and photons (Al, Si (active), Ti)

I will focus on the charged particle analysis.
Experimental Setup

Run 2013 Setup
Experimental Setup

- Ge
- μ
- p,d,t
- γ
- Right Detector System
- Left Detector System
- Collimator
- Back Wall
- Muon Counter
- Veto
- Scintillator
- Right Detector System
- Ge
Particle ID

With the layered silicon detectors, we can **identify the different particle types** because $dE/dx$ rises sharply when going to lower energies:

![Graph showing particle identification]
Particle ID

Easy to **extract individual emission products** using simple cuts and check the arrival times are **consistent** with the muonic atom lifetime

- Si: 767 ns

EvdE Plot for Si dataset with cut to select protons

Arrival times for the selected protons

Currently **evaluating efficiency and purity of cuts using MC.**
Unfolding

Once we’ve extracted the particle band, we need to correct for energy lost in the target → **unfolding**.

Energy Loss of Protons in Target

Folded and Unfolded Spectra

Currently **investigating systematic effects of unfolding** (e.g. assumed stopping depth)
Normalisation

When muon stops it emits X-rays as it transitions between atomic energy levels. Specifically we look for the $2p - 1s$ transition.

$^{152}$Eu Source

Active Target

Currently resolving this $\sim 10\%$ discrepancy
Other Datasets

Analysis of other datasets going well:

Al 50 µm

Al 100 µm

Ti 50 µm
Conclusion

AlCap was formed to determine the rate and spectrum of charged particles, neutrons and photons after nuclear muon capture for the next generation of muon-electron conversion experiments.

Expect to finish the charged particle analyses in the next few months:

- band extraction efficiency and purity
- unfolding systematics
- resolve normalisation discrepancy (or live with it)
Thanks for listening!

And thanks to our respective funding agencies for their support!
Backup slides
Charged Lepton Flavour Violation

SM Prediction
\[ R_{\mu \rightarrow e} \propto \left( \frac{\Delta m_{\nu}^2}{M_W^2} \right)^2 < 10^{-52} \]

BSM Predictions
\[ R_{\mu \rightarrow e} \sim 10^{-17} - 10^{-15} \]

Current 90% UL: \[ B(\mu N \rightarrow eN \text{ on Au}) < 7 \times 10^{-13} \text{ (SINDRUM II)} \]
Full X-Ray Spectrum

Si16b Dataset, Full X-Ray Spectrum

AlCap Preliminary

Energy [keV]
200
400
600
800
1000
1200
Counts / 2 keV
0
10000
20000
30000
40000
50000

Si 2p-1s X-Ray

2p-1s
(400.177 keV)
Si16b MC, Right Arm, Proton Response Matrix

AlCap Monte Carlo