Preliminary Results from the AlCap Experiment

John Quirk on behalf of AlCap Collaboration
Boston University
PSI 2019
Muon to Electron Conversion Experiments

Mu2e and COMET are looking:

1. For a rare $\mu$Al interaction $(R_{\mu e}^{(Au)} < 7 \times 10^{-13})^\text{[*]}$
2. Through a lot of $\mu$Al ($>10^{18}$) generated noise, background, and damage

Consequently, must understand muon-aluminum interactions

Muonic Atoms

Atomic Capture

Atomic Cascade

Decay In Orbit  Nuclear Capture

\[ \Delta E_{2p \rightarrow 1s}^{\text{Al}} \approx 347\text{keV} \]

\[ Br_{2p \rightarrow 1s}^{\text{Al}} \approx 80\% \]
Nuclear Capture

\[ \mu^- + _{13}^{27}\text{Al} \rightarrow \nu_\mu + \frac{A}{Z}N + \ldots (n, p, \gamma) \]
Issues for Mu2e

Heavy Charged Particles:

- Protons in momentum acceptance (>70 MeV/c) cause tracker hits
- Proton absorber: reduces hits → reduced $\Delta p_{\text{conv. e}}$
- Tradeoff: conversion $e^-$ resolution ↔ proton hits

Neutral Particles:

- $X$-rays used for counting muon stops
- $\gamma$s pair-produce, create backgrounds
- Neutrons highly penetrating → accidental cosmic ray veto triggers

M. MacKenzie Mu2e Internal 2018

Conversion $e^-$: 105 MeV
Detected Proton: 5.8 MeV
Undetected Proton: $\leq 2.6$ MeV
Work Packages

WP1: Charged Particles

- Proton emission rate of $\mu$Al
  - Assess noise hits
- Previous spectrum >40 MeV
  - No use to Mu2e

Previous measurement:

WP2: Photons

- $\mu$Al Capture/activation $\gamma$s
  - Muon counting
- X-rays from candidate target and structures
  - Muon counting
  - Noise hits

Previous measurement:

WP3: Neutrons

- Spectrum from target and structures
  - Noise hits
  - Previous measurement had no neutron energy information

Previous measurement:
Macdonald et al., Phys. Rev. 139, B1253 (1965)
Work Packages

WP1: Charged Particles
- Proton emission rate of $\mu$Al
- Assess noise hits
- Previous spectrum >40 MeV
- No use to Mu2e

WP2: Photons
- $\mu$Al Capture/activation $\gamma$s
  - Muon counting
- X-rays from candidate target and structures
  - Muon counting
  - Noise hits

WP3: Neutrons
- Spectrum from target and structures
  - Noise hits
  - Previous measurement had no neutron energy information

Previous measurement:

Previous measurement:

Previous measurement:
Macdonald et al, Phys. Rev. 139, B1253 (1965)
Difficulty in Proton Energy Measurement

$E_0 = 3 \text{ MeV}$

$dx = 25 \mu \text{m}$

$E_{\text{loss}} = 900 \text{ keV}$

$E_{\text{meas}} = 2.1 \text{ MeV}$

Requirements:
- Vacuum
- Thin target
- Tight beam

AlCap Setup

**Key**
- Plastic Scintillator
- Silicon Detector
- Wire Chamber
- Liquid Scintillator
- Germanium Detector
- Lead Shielding
- Stainless Steel

**Chamber**
- Cylindrical
- Stainless steel
- Under vacuum
- 30cm $\varnothing \times 60$ cm

**Particle Identification Package**
- $E$
- $dE$
- Veto

Lead shielding kills scattered muons: $t_{\mu \text{Pb}} < t_{\mu \text{Al}}$

John Quirk PSI 2019
AlCap Setup

SiL  SiR

John Quirk PSI 2019
Proton Measurement

- X-ray Count
- Muon count
- Charged Particle Measurement
- Particle Identification
- Measured Proton Energies
- True proton energy spectrum and rate
- Beam measurement
- Simulation
- Stopping distribution
- Response Matrix
- X-ray Count
- Muon count
- Charged Particle Measurement
- Particle Identification
- Measured Proton Energies
- True proton energy spectrum and rate
- Beam measurement
- Simulation
- Stopping distribution
- Response Matrix
Muon Count from X-rays

\[ N_\mu = \frac{N_{2p-1s}}{\epsilon_{2p-1s} \times I_{2p-1s}} \]

<table>
<thead>
<tr>
<th>2p-1s X-rays</th>
<th>84215(510)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge Efficiency @ 347 keV</td>
<td>6.6(2) × 10^{-4}</td>
</tr>
<tr>
<td>X-ray Intensity (/μ-stop)</td>
<td>79.8(8)%</td>
</tr>
<tr>
<td>Stopped Muons</td>
<td>160(5) × 10^6</td>
</tr>
</tbody>
</table>

X-Ray Spectrum (Al50 Target) ±200ns

- \( x^2 / \text{ndf} = 428.2 / 52 \)
- Bkg \( y \)-int = 7343 ± 304.4
- Bkg Slope = -19.2 ± 0.9
- Al Amp = 1.219 ± 0.04 ± 5.784 × 10^{-1}
- Al Energy = 345.4 ± 0.6
- Pb Amp = 2452 ± 28.4
- Pb Energy = 349.6 ± 0.6
- Sigma = 0.9418 ± 0.0035

John Quirk PSI 2019
Particle Identification: dE/dx Method

1. Particles lie on distinct dE vs. E bands
2. Fit transformed bands to gaussians
3. Cut on particle species

Classify by transformed (Log-Log, rotation) energies:

\[(E, dE) \rightarrow \left( \frac{\log(E) - \log(dE)}{\sqrt{2}}, \frac{\log(E) + \log(E)}{\sqrt{2}} \right)\]
Measured Proton Energy

Selection:
- $\lambda_{\mu \text{Pb}} = 80\text{ns} \rightarrow 400\text{ns} < t_p$
- $dt_{\text{Si1-Si2}} < 200\text{ns}$
- $T_{\text{neighboring } \mu} > 10\mu\text{s}$
- Protons only

Left/Right Differences Understood:
- Target stopping distribution pushes SiR energies lower
- SiR is a larger detector; $\Omega_{\text{SiR}} > \Omega_{\text{SiL}}$
- Thin SiL higher threshold $\rightarrow$ high $E$ difference
Unfolding

\[ E_{\text{meas}} = M \times E_{\text{true}} \]

- Response matrix:
  \[ M \ni \{ \varepsilon_{\text{geom}}, \varepsilon_{\mu\text{-stop}}(E_{\text{true}}) \} \]
- Obtained from MC
- BayesUnfold\((M, E_{\text{meas}}) = E_{\text{true}}\)
- \(M\) relatively linear, simplifying unfolding

\[
D'\text{Agostini, 2010, arXiv:1010.0632}
\]

John Quirk PSI 2019
## Systematics: 3.5-10 MeV

<table>
<thead>
<tr>
<th>Backgrounds and Efficiencies</th>
<th>PID (Energy Cut) Acceptance</th>
<th>3.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pb Contamination</td>
<td>0.87%</td>
</tr>
<tr>
<td>Calibration</td>
<td>Si ECal</td>
<td>0.4%</td>
</tr>
<tr>
<td>Geometry</td>
<td>Target Position</td>
<td>0.75%</td>
</tr>
<tr>
<td></td>
<td>Detector Position</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam &amp; Stopping Distribution</th>
<th>Stopping Depth</th>
<th>2.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfolding</td>
<td>Iterations</td>
<td>0.17%</td>
</tr>
<tr>
<td></td>
<td>Bin width</td>
<td>0.17%</td>
</tr>
<tr>
<td></td>
<td>Energy Bound</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

| Total                        | Statistical    | 3.2% |
|                             | Systematic     | 7.1% |
Proton Emission in Aluminum

Proton Emission
\((3.5-10 \text{ MeV})\)
per \(\mu\)-capture

\(0.0207(7)_{\text{stat}}(15)_{\text{syst}}\)
Impact for Mu2e

Inner proton absorber:

- Reduces proton detector hit rate
  - Decrease noise hit rates
- Degrades conversion $e^-$ signal
  - Degrades signal momentum resolution
  - Reduces signal energy

Actual proton rate factor of $\sim 3$ lower than expected $\rightarrow$ Mu2e thinner proton absorber, COMET removed absorber $\rightarrow$ less degradation of signal energy resolution.
Neutron Status

- Used 2 neutron detectors (BC501a)
- Preliminarily report 0.44(3) $n/\mu$-capture in 2-11.5 MeV

### Detector 1 Raw n Count

<table>
<thead>
<tr>
<th>Element</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>289026</td>
</tr>
<tr>
<td>Ti</td>
<td>295309</td>
</tr>
<tr>
<td>Pb</td>
<td>80521</td>
</tr>
</tbody>
</table>

### Detector 2 Raw n Count

<table>
<thead>
<tr>
<th>Element</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>337627</td>
</tr>
<tr>
<td>Ti</td>
<td>349783</td>
</tr>
<tr>
<td>Pb</td>
<td>94698</td>
</tr>
</tbody>
</table>
X/γ-rays

- Data taken on: Al, Ti, W, Pb
- Analysis in progress
- Al/Ti for normalization
- W/Pb for backgrounds

<table>
<thead>
<tr>
<th>Photon</th>
<th>Energy [keV]</th>
<th>Emission rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (26Mg*)</td>
<td>1808.7</td>
<td>0.51 ± 0.05</td>
</tr>
<tr>
<td>Ti (2p-1s)</td>
<td>931.0</td>
<td>0.90 ± 0.04</td>
</tr>
<tr>
<td>W (4f-3d)</td>
<td>761.0</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>783.6</td>
<td>0.19 ± 0.01</td>
</tr>
</tbody>
</table>
AlCap Status

- AlCap reports preliminary results for proton emission (3.5-10 MeV) per muon capture in aluminum of $0.0207(7)_{\text{stat}}^{(15)}_{\text{syst}}$
  - TWIST recently reported (arXiv:1908.06902) $0.0322(7)_{\text{stat}}^{(22)}_{\text{syst}}$ over 3.4 MeV
- Additional aluminum datasets still being analyzed
- Further results forthcoming on deuteron and triton, as well as on Si and Ti targets
- Photon and neutron analyses from a number of targets are in progress
THANK YOU!

COMET

Imperial College London

大阪大学

OSAKA UNIVERSITY

Institute of High Energy Physics

Chinese Academy of Sciences

Funding provided in part by DOE

John Quirk PSI 2019
While the effects on the individual detector arms is significant, averaging them cancels this out. Ideally, the unfolded rates would agree in the left and right arms.
R13 Setup

- Plastic Scintillator
- Silicon Detector
- Wire Chamber
- Liquid Scintillator
- Germanium Detector
- Lead Shielding
- Stainless Steel

**Detector**

- Beam counter
- Collimator (Stainless Steel)
- PID Package
- Target
- Punch through veto detector
- Ge Detector

**Chamber**
- Stainless steel
- Under vacuum
- Diameter ~30 cm
## Campaigns

<table>
<thead>
<tr>
<th>Campaign</th>
<th>R13</th>
<th>R15a</th>
<th>R15b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Packages</td>
<td>WP 1, 2, 3</td>
<td>WP 2, 3 (Neutral particles)</td>
<td>WP 1 (Charged particles)</td>
</tr>
<tr>
<td>Beamline</td>
<td>πE1</td>
<td>πE5</td>
<td>πE1</td>
</tr>
<tr>
<td>Targets</td>
<td>Al, Ti, Si (Passive)</td>
<td>Al, Ti, H2O, Pb, Steel</td>
<td>Al, Ti, Si</td>
</tr>
</tbody>
</table>
Paul Scherrer Institut (PSI)

- Highest current, highest power proton accelerator (2.2mA, 590MeV cyclotron)
- Most intense muon beam
- Number of DC muon beamlines to choose from to balance rate and momentum bite
### Beamlines at PSI

#### (Some) Collaborators

Experiments
- Mu2e
- COMET

---

#### Beamline

<table>
<thead>
<tr>
<th>Beamline</th>
<th>πE1</th>
<th>πE5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campaign</td>
<td>R13, R15b</td>
<td>R15a</td>
</tr>
<tr>
<td>Ω (msr)</td>
<td>13</td>
<td>150</td>
</tr>
<tr>
<td>Momentum Resolution (FWHM)</td>
<td>0.26%</td>
<td>2%</td>
</tr>
</tbody>
</table>

---

[Diagram showing beamlines and Collab]
Sanity Check: Lifetime = 864ns
1. Pulse passes preset threshold, triggering data taking in that channel (each channel is self-triggered)
2. Number of presamples before trigger used to calculate pedestal, preset number of samples taken
3. Maximum height from pedestal taken as energy
4. Interpolated clock tick where pulse hits 10% of maximum taken as time
Charged Lepton Flavor Violation: $\mu \rightarrow e$

New Physics

$$R_{\mu e}^{Au} = \frac{\Gamma_{\text{conv}}(\mu Au \rightarrow e Au)}{\Gamma_{\text{capt}}(\mu Au)} < 7 \times 10^{-13}$$

AlCap: The Aluminum Capture Experiment

Mu2e

COMET

AlCap @ Paul Scherrer Institut (PSI)
The beam counter (SiT) was placed as close as possible to the target; greatly improved muon stopping fraction.
Pileup protection rejects 4.9% of muons
Muon Count from X-rays

\[ N_\mu = \frac{N_{2p-1s}}{\epsilon_{2p-1s} \times I_{2p-1s}} \]
Energy Loss in Target

A proton’s energy loss in the target is dependent on stopping location and initial energy.

John Quirk PSI 2019
Unfolded Spectrum

- Poorer statistics at lower energies
- Some structure seems to appear, but will disappear after considering systematics

Includes only proton statistical error