The AlCap Experiment
Progress and Beam Request
Ed Hungerford
Univ. Houston

The Collaboration

COMET
Osaka University, IHEP China
Imperial College London
University College London

Mu2e
Argonne NL
Boston University
Brookhaven NL
INFN Frascati
University of Houston
University of Washington

One PhD awarded H. N. Tran
Four others in progress: D. Alexander, A. Edmomds, B. Krikler, J. Quirk
Muon-to-Electron (μ-e) Conversion
Lepton Flavor Violation

Lepton Flavor Changes by one unit
Coherent Conversion
\[ \mu^- + A \rightarrow e^- + A \]

\[ R_{\mu \rightarrow e} = \frac{\Gamma (\mu X \rightarrow eX)}{\Gamma (\mu X \rightarrow \nu_\mu X' \ldots)} \]

Muonic Atom

Nuclear Capture
\[ \mu^- + A \rightarrow \nu^+ \ [N + (A-1)] \]

μ Decay in Orbit (DIO)
\[ \mu^- \rightarrow e^- \nu \nu \]

Normalization
Mu2e/Comet Detector Components

- Detector Solenoid Cryostat
- Muon Stopping Target: 800 mm
- Outer Proton Absorber: 4275 mm
- Inner Proton Absorber: 1000 mm
- T Tracker: 3270 mm
- Calorimeter: 1400 mm
- Muon Beam Stop: 4086 mm

- Cosmic Ray Veto
- Tracking Solenoid
- Comet Cylindrical Drift Chamber
- Trigger Counter
- Muon Beam
- CDC Inner Wall
- CDC outer Wall
- Solenoid
Comet (Phase I)
The cylindrical drift chamber (CDC) is under construction
1) Inner wall to be completed and installed in 2015.

Mu2e
Successful DOE review in October 2014
1) Release to purchase long-lead items (Superconductor, Civil Construction to begin)
2) Permission to proceed to CD3 for other items - 2015

Open Questions
1) High Proton emission requires a Proton absorber – what thickness? Degrades resolution/ adds backgrounds
2) Neutron capture requires redesign of shields, e.g. high density concrete for Cosmic Ray Detector
3) Neutron single event upsets
4) Beam flash impacts choice of normalization detector
5) Normalization accuracy

Work Packages
1) Proton emission
2) Neutron emission
3) X-Ray and Gamma Ray
MC Simulation of Particle Emission from Al

FLUKA MC Neutron, Proton, Photon

Simulation Statistics
Al Target

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Value(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay/μ-stop</td>
<td>26</td>
</tr>
<tr>
<td>Capture/μ-stop</td>
<td>74</td>
</tr>
<tr>
<td>Proton/Neutron</td>
<td>24</td>
</tr>
<tr>
<td>0 Neutron/μ-stop</td>
<td>29</td>
</tr>
<tr>
<td>1 Neutron/μ-stop</td>
<td>39</td>
</tr>
<tr>
<td>2 Neutron/μ-stop</td>
<td>4.5</td>
</tr>
<tr>
<td>3 Neutron/μ-stop</td>
<td>0.18</td>
</tr>
<tr>
<td>4 Neutron/μ-stop</td>
<td>0.00072</td>
</tr>
<tr>
<td>5 Neutron/μ-stop</td>
<td>0.00003</td>
</tr>
<tr>
<td>Total Neutron/μ-stop</td>
<td>44</td>
</tr>
<tr>
<td>Avg. Neutron/μ-stop</td>
<td>*1.18</td>
</tr>
</tbody>
</table>

*Number not %
Table 2: Summary of the data that was collected during Run 2013.

<table>
<thead>
<tr>
<th>Target</th>
<th>Beam Momentum [×28 MeV/c]</th>
<th>Number of Muons</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si (1500 μm)</td>
<td>1.32</td>
<td>2.78 x 10^7</td>
<td>Active Target</td>
</tr>
<tr>
<td></td>
<td>1.30</td>
<td>2.89 x 10^8</td>
<td>Cross check with existing Si data</td>
</tr>
<tr>
<td></td>
<td>1.10</td>
<td>1.37 x 10^8</td>
<td></td>
</tr>
<tr>
<td>Si (62 μm)</td>
<td>1.06</td>
<td>1.72 x 10^7</td>
<td>Passive Target</td>
</tr>
<tr>
<td>Al (100 μm)</td>
<td>1.09</td>
<td>2.94 x 10^8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.07</td>
<td>4.99 x 10^7</td>
<td></td>
</tr>
<tr>
<td>Al (50 μm)</td>
<td>1.07</td>
<td>8.81 x 10^8</td>
<td></td>
</tr>
</tbody>
</table>
AlCap Geometry for Charged Particle Emission

- Geant4-based Monte Carlo simulation exists
- Used to obtain the response matrices of the silicon detectors

![Diagram of the AlCap Experiment setup]

- Vacuum Pump
- Lead shielding
- Muon Veto Scintillator
- Right Silicon Detector
- Target
- Neutron Detector
- Left Silicon Detector
- Germanium Detector
- Muon Triggers: MuSc, MuPC
- Collimator
- Ge Det
- Beam
- Si Det
- Veto
Charged Particle Emission Al-50

$\Delta E - E$ for PID
Time used to cut Pb background

ΔE vs E - Right

Charged particles from target

Charged particle spectra after muon capture
Preliminary Results

Normalization from recorded X-rays
Number of nuclear captures

\[ N \text{ stopped} = (1.57 \pm 0.05) \times 10^7 \]
\[ N \text{ cap.} = (9.57 \pm 0.31) \times 10^6 \]

Proton Emission 4MeV -8MeV

\[ R_p = 1.7 \times 10^{-2} \text{ (3.5\% total)} \]

Uncertainty 6.1\% with dominant sources unfolding process (5\%) and number of nuclear captures (3.2\%). Consistency between the data sets needs work to understand systematics.
Normalization for COMET/Mu2e

\[ R_{\mu \to e} = \frac{\Gamma (\mu X \to eX)}{\Gamma (\mu X \to \nu_\mu X')} \]

Error budget
10%

Prompt w/ Stop
- Instantaneous
- Near beam flash
- Low energy (BG)
- Radiation damage concerns
- High intensity
- Well known intensity

Prompt w/ Capture
- Time structure same as muon disappearance
- High energy
- Potentially moderate intensity
- Intensities not well known

Delayed
- Measurement during beam off
- High energy
- Equilibrium with beam required
- Lower intensity
- Intensities not well known

\[ ^{27}\text{Mg} \rightarrow ^{25}\text{Mg} \]

Branching Ratio of \(^{27}\text{Mg}\)
- Lit: 51(5)%
- Now: 53(5)%

Temple Thesis LBL-781
Neutron Emission (Preliminary)

-2 Neutron Detectors Borrowed from MuSun Experiment
5”x5” BC 501
-Pulse shape discrimination using fast/slow integral ratio.
  Slow integral defined as 30 to 200 ns after peak height.
  PSD separation good to an energy < 0.5 MeVee
Present folding-unfolding response simulated using RESP7. Applying software suite HEPROW using Gravel or Max. Entropy

<table>
<thead>
<tr>
<th>hNDet Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

Future will use 2 neutron detectors 5”x2.5” BC 501
500 MHZ Digitizer Readout – Pre-Calibrated at TUNL
More than Background and Rate Studies

Yad. Fiz. 14(1971)624
SJNP 14(1972)349
Yad. Fiz. 15(1972)154
SJNP 15(1972)639

See Raphael, et al; PL 24B(1967)15

Fig. 1. Spectra of giant multipole resonance states in $^{16}\text{O}$ and $^{16}\text{N}$, and neutron decay channels to $^{15}\text{N}$. 
1) Beam probe measurements at target location to better align beam on target
2) Improvements for measuring target position and target-detector geometry
3) Improved silicon detector preamp connections, shaping, and power to reduce noise
4) New commercial waveform Digitizer purchased to replace FADCs
5) Time resolution for Ge detector under investigation
6) Better Neutron detectors pre-calibrated and tested at TUNL
7) Gamma and Neutron runs using free standing target
8) Gamma and Neutron runs using higher momentum muons
9) Addition of a gamma LYSO detector for higher energy gammas
Free Standing Target
1) ~2mm thickness (all μ stop)
2) ~40 MeV/c beam
3) ~10 rate increase
3) Ge, Neutron Det in (y,z) plane
4) LYSO below target
5) Target rotated ~45° around y and x axis
## Run Request

<table>
<thead>
<tr>
<th>Task</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Tuning</td>
<td>2.5</td>
</tr>
<tr>
<td>Commissioning</td>
<td>3.0</td>
</tr>
<tr>
<td>Proton Studies</td>
<td>10</td>
</tr>
<tr>
<td>Neutron/Gamma Studies</td>
<td>7.5</td>
</tr>
</tbody>
</table>

1) Proton paper needs confirmation before submission
2) Gamma and neutron work needs more studies
3) High energy gamma studies just beginning
Backup Slides
Titanium

### Prompt w/ Stop X-rays

<table>
<thead>
<tr>
<th>Transition</th>
<th>Energy (keV)</th>
<th>Relative Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2p-1s</td>
<td>942</td>
<td>100%</td>
</tr>
<tr>
<td>3p-1s</td>
<td>1122</td>
<td>10.2%</td>
</tr>
<tr>
<td>4p-1s</td>
<td>1189</td>
<td>3.1%</td>
</tr>
<tr>
<td>5p-1s</td>
<td>1220</td>
<td>3.6%</td>
</tr>
<tr>
<td>6p-1s</td>
<td>1236</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

*Absolute intensities not known*

### Prompt w/ Capture Gamma-rays

<table>
<thead>
<tr>
<th>Resultant Isotope</th>
<th>Energy (keV)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁴⁸Sc</td>
<td>121.4</td>
<td>10.5(9)%</td>
</tr>
<tr>
<td>⁴⁸Sc</td>
<td>130.9</td>
<td>10.4(9)%</td>
</tr>
<tr>
<td>⁴⁸Sc</td>
<td>370.3</td>
<td>12.2(8)%</td>
</tr>
<tr>
<td>⁴⁷Sc</td>
<td>807.8</td>
<td>13.0(15)%</td>
</tr>
</tbody>
</table>

- Initial step to learn absolute X-ray intensities
- With same setup improvement as required for Al data, simulations indicate the Prompt w/ Capture signal intensities can be measured better in < 2 days
- According to literature, all Delayed signals are too long lived to be measured by AlCap
- The literature is sparse, and other signals may be identified

2/10/2015 AlCap Experiment
Input spectra (ISO 8529-2 standard)

Unfolding using Gravel algorithm after convolution

Improving the unfolding using Maximum Entropy method

The results are preliminary, but do give us a good start. Data runs still need to be unfolded.

2/10/2015 AICap Experiment
Neutron Rates

An estimate of the SEU in various FPGA’s using information of the test in the iRoC report transmitted

1 Neutron Background at the standard NYC latitude 40.7° N (Sea-Level) → 14 n/hr/cm² → 3.9 x 10⁻³ n/s/cm²

2 1 FIT = 1 failure in 10⁹ hrs → 2.4 x 10⁻⁸ failure/day

3 Neutron Rate in the Tracker → 5 x 10⁴ n/s/cm²

4 Neutron Rate/Sea-Level Rate → 1.3 x 10⁻⁷

The above assumes no error correction, but this may take a number of clock cycles. Also note that the iRoC report does not include functional interrupts and transients due to ionizations or radiation damage.

<table>
<thead>
<tr>
<th>FPGA</th>
<th>Measured FIT Sea-Level</th>
<th>Scaled FIT Tracker</th>
<th>Failure/Day 300 FPGA</th>
<th>Failure//Day 300 FPGA</th>
<th>Failure/hr 300 FPGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actel</td>
<td>&lt;0.04</td>
<td>&lt;5.2x10⁵</td>
<td>&lt;0.01</td>
<td>&lt;3.6</td>
<td>--</td>
</tr>
<tr>
<td>Xilinx XC3S1000</td>
<td>320</td>
<td>4.2x10⁹</td>
<td>100</td>
<td>3.0x10⁴</td>
<td>1300</td>
</tr>
<tr>
<td>Altera</td>
<td>460</td>
<td>6.0x10⁹</td>
<td>144</td>
<td>4.3x10⁴</td>
<td>1800</td>
</tr>
</tbody>
</table>
• Estimating Neutron flux is important to the Tracker electronics radiation hardness.
  – Fast neutron is an important source of Single Electron Upset (and subsequent failure) in the real time operation of electronics system.

• Target Tolerance level
  = 1 [reset of all electronics] / day
  = 64 / 21600 reset/day/chip = 3x10^{-8} reset/sec/chip
  – This means we can endure DAQ recycling once a day. Channel/chip ratio not decided yet.

• Lifetime of exp (including duty rate) = 4x10^7 sec
• Life time neutron dose (all energy) = 2x10^{12} n/cm^2
  – Obtained from Mu2eG4. Muon capture neutron is dominant and considered only.

<table>
<thead>
<tr>
<th>(x10^{10} n/cm^2)</th>
<th>Thermal (KE &lt;1eV)</th>
<th>Epithermal (1eV&lt;KE&lt;1MeV)</th>
<th>Fast (KE&gt;1MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon capture</td>
<td>15.9</td>
<td>76.9</td>
<td>103</td>
</tr>
<tr>
<td>MBS</td>
<td>0.198</td>
<td>1.56</td>
<td>0.785</td>
</tr>
<tr>
<td>Beam Flash</td>
<td>0.240</td>
<td>1.28</td>
<td>1.56</td>
</tr>
<tr>
<td>Production Solenoid</td>
<td>0.561</td>
<td>0.087</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Experimental Upgrades

Mesytec MSI-8 16 Channel Preamp/shaper

Micron 65 μm 16 strip ΔE Silicon Detector
The calorimeter prototype was installed over a movable table in front to the photon’s beam.

- We have triggered using a coincidence between the OR of the discriminated signal from the sum of the central crystals (threshold on the sum ~ 5 MeV) and the reference tagging signal from the scintillating spectrometer.
Matrix assembly: cabling FEE

- The project and the development of the FEE have been done at LNF by the SEA electronic department.
- The Amp-HV is a multi-layer double-sided discrete component board that carries out the two tasks of amplifying the signal and providing a locally regulated bias voltage, thus significantly reducing the noise loop-area.

### Characteristics of the Amp-HV chip:

<table>
<thead>
<tr>
<th>Amp.</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>2.5V</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>70Mhz</td>
</tr>
<tr>
<td>Rise time</td>
<td>6ns</td>
</tr>
<tr>
<td>Polarity</td>
<td>Reversed</td>
</tr>
<tr>
<td>Output impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Stability with source capacity</td>
<td>300pf</td>
</tr>
<tr>
<td>Coupling output end source</td>
<td>AC</td>
</tr>
<tr>
<td>Noise, with source capacity</td>
<td>1000 enc</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>14mW</td>
</tr>
<tr>
<td>Power supply</td>
<td>6V</td>
</tr>
<tr>
<td>Input Protector over-Voltage</td>
<td>10mJ</td>
</tr>
<tr>
<td>Adjustment range Vout</td>
<td>250V to 500V</td>
</tr>
<tr>
<td>Accuracy, reading and writing, Vout</td>
<td>16 bit</td>
</tr>
<tr>
<td>Current limiter can be adjusted</td>
<td>tpc. 300μA</td>
</tr>
<tr>
<td>Noise tot.</td>
<td>2mVpp</td>
</tr>
<tr>
<td>Long-term stability</td>
<td>100ppm</td>
</tr>
<tr>
<td>Settling Time</td>
<td>&lt;500 us</td>
</tr>
</tbody>
</table>
| Typical power dissipation | < 
| Double filter high Voltage, attenuation | 135mW |
| 56db | |

2/10/2015
Folded/unfolded AmBe - Gravel

Input AmBe