Study of Muon Capture for Muon to Electron Conversion Experiments

Yoshitaka Kuno,
Department of Physics, Osaka University
on behalf of the AlCap Collaboration

PSI BVR Meeting, January 15, 2013
Outline

- Importance and Urgency
  - overview of $\mu$-e conversion searches:
    - Mu2e (FNAL) and COMET (J-PARC)
  - The AlCap Collaboration (jointly formed by Mu2e and COMET)
- Overview of the Work Packages (WP1, WP2 and WP3) of This Proposal
  - WP1 (proton emission after muon capture)
  - WP2 (gamma and X-ray emission after muon capture)
  - WP3 (neutron emission after muon capture)
- Beam Requirements and Beam Time Request
- Summary
μ-e Conversion Search
μ-e Conversion Search

- Two experiments are going to start to search for the μ-e conversion process: COMET@J-PARC and Mu2e@FNAL.
- These are stopped muon experiments. When a μ⁻ in stopped in a material, ...

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- These are stopped muon experiments. When a μ- in stopped in a material, ...

1s state in a muonic atom

Fates of the μ- within the SM
- Muon decay in orbit
  \[ \mu^- \rightarrow e^- \nu \bar{\nu} \]
- Nuclear muon capture
  \[ \mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1) \]
μ-e Conversion Search

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Beyond the SM

\[ \mu^- + (A, Z) \rightarrow e^- + (A, Z) \]

Forbidden by the SM, because the lepton flavor is changed to μ-flavor to e-flavor.

Event signature:
- a single mono-energetic electron of 100MeV

in the SM + ν masses

μ-e conversion can be occur via ν-mixing, but expected rate is well below the experimentally accessible range. Rate \( \sim O(10^{-54}) \)

Discovery of the μ-e conversion is a clear evidence of new physics beyond the SM.

in the SM + new physics

A wide variety of proposed extensions to the SM predict observable μ-e conversion rate.
Both experiments have received strong endorsements from Japan and US communities.

- **COMET** : "is a high priority component for the J-PARC program." (KEK/J-PARC-PAC March/2012)
- The IPNS proposed, as the first priority item in the next 5-year plan, to construct a proton beam line and the 1st half of solenoid magnets for COMET Phase-I. The PAC endorsed the laboratory plan.
- **Mu2e** : "should be strongly encouraged in all budget scenarios considered by the panel." (P5 report)
  - got the CD-1 approval in July 2012!
- These experiments are now optimizing their parameter to get the final design.

COMET Phase-I :
**physics run 2017**
- BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL
  - 8GeV-3.2kW proton beam, 6x10^{9} μ/s, 18 days
  - 90deg. bend solenoid, cylindrical detector
  - Background study for the phase2

COMET Phase-II :
**physics run 2021**
- BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL
  - 8GeV-56kW proton beam, 10^{11} μ/s, 2x10^{7}s
  - 180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter

**Mu2e** :
**physics run 2021**
- BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL
  - 8GeV-8kW proton beam, 3 years
  - 2x90deg. S-shape bend solenoid, straw tracker+calorimeter

A factor of 10,000 better sensitivity than the current upper limit (SINDRUM II)
Both experiments have received strong endorsements from Japan and US communities.

COMET: “is a high priority component for the J-PARC program.” (KEK/J-PARC-PAC March/2012)

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got the CD-1 approval two days ago!

These experiments are now optimizing their parameter to get the final design.

---

**COMET Phase-I**

**physics run 2017-**

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**Mu2e**

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- 8GeV-8kW proton beam, 3 years
- 2x90deg. S-shape bend solenoid, straw tracker+calorimeter
Schedule of COMET and Mu2e

**COMET**
- **COMET Phase-I**
  - S.E.S < $3 \times 10^{-15}$

**Mu2e**
- **S.E.S = $2.4 \times 10^{-17}$**

Timeline:
- **2010**
  - Design, R&D
  - Construction
- **2012**
  - Design, R&D
  - Construction
- **2014**
  - Construction
- **2016**
  - Physics Run
  - Construction
- **2018**
  - Physics Run
  - Construction
- **2020**
  - Engineering Run
- **2022**
  - Physics Run

**Approved**
- CD-0
- CD-1
- CD-2&3a
- CD-3b
- CD-4

**Final Design**
-(

**Satisfied**
- K.P.P.

**CD-0 Approved**
- CD-1 Approved
- CD-2&3a Approved
- CD-3b Approved
- CD-4 Approved
For both experiments critical design decisions need to be finalized in the next 12-18 months.
This Proposal
Three Work Packages

- **WP1: Charged Particle Emission after Muon Capture**
  - Kammel (Washington) and Kuno (Osaka)
  - Rate and spectrum with precision 5% down to 2.5 MeV

- **WP2: Gamma and X-ray Emission after Muon Capture**
  - Lynn (PNNL) and Miller (Boston)
  - X-ray and gamma-ray for normalization (by Ge detector), and radiative muon decay (by a NaI detector)

- **WP3: Neutron Emission after Muon Capture**
  - Hungerford (Houston) and Winter (ANL)
  - Rate and spectrum from 1 MeV up to 10 MeV
  - BG for calorimeters and cosmic-ray veto, damage to electronics
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Ready to start in spring 2013
Three Work Packages

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The AlCap Collaboration

- Osaka University
  - Y. Kuno, H. Sakamoto, T. Itahashi, Y. Hino, A. Sato, T. Yai, T.H. Nam
- Univ. College London
  - M. Wing, M. Lancaster, A. Edmonds
- Imperial College London
  - B. Krikler, A. Kurup, Y. Uchida

COMET

- Univ. Washington
  - P. Kammel, D. Hertzog, F. Wauters, M. Murray
- Boston University
  - J. Miller, E. Barnes, A. Kolarkar
- Univ. Massachusetts Amherst
  - D. Kawall, K. Kumar
- FermiLab
  - R. Bernstein, V. Rusu
- Pacific North National Laboratory
  - D. M. Asner, R. Bonicalzi, M. Schram, G. Warren, L. Wood

Mu2e

Joint force
WP1: Charged Particle Emission after Muon Capture
WP1: Design issue with protons

- A crucial component in optimizing the designs is the background from the products of the nuclear capture process. In particular, protons are a significant source of hits in the tracking detectors. Probability of proton emission would be 0.05~0.15 per muon.

Optimization of the target thickness and the absorber

- Both COMET Phase-I and Mu2e need the rate and energy spectra of proton emission as a function of the target thickness.
**WP1 Current Exp. Data : Rate**


Table 4.14

Probabilities in units of $10^{-3}$ per muon capture for the reaction $\frac{4}{3}X(\mu, vp)\frac{4}{3}Y$ and for inclusive proton emission calculated by Lifshitz and Singer [343,348]. The experimental data are from Wyttenbach et al. [333], except when otherwise referenced. For $\Sigma(\mu, vp(xn))$ the experimental figures are lower limits, determined from the actually measured channels. The figures in crescent parentheses are estimates for the total inclusive rate derived from the measured exclusive channels by the use of the approximate regularity noted in Ref. [333], viz: $(\mu, vp) : (\mu, vpn) : (\mu, vp2n) : (\mu, vp3n) = 1 : 6 : 4 : 4$

<table>
<thead>
<tr>
<th>Capturing nucleus</th>
<th>((\mu, vp)) calculation</th>
<th>Experiment</th>
<th>$\Sigma(\mu, vp(xn))$ calculation</th>
<th>Experiment</th>
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</tr>
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<tbody>
<tr>
<td>$^{27}_{13}$Al</td>
<td>9.7</td>
<td>(4.7)</td>
<td>40</td>
<td>$&gt; 28 \pm 4$</td>
<td>(70)</td>
</tr>
<tr>
<td>$^{31}_{14}$Si</td>
<td>32</td>
<td>53 ± 10$^a$</td>
<td>144$^b$</td>
<td>150 ± 30$^b$</td>
<td>(91)</td>
</tr>
<tr>
<td>$^{31}_{15}$P</td>
<td>6.7</td>
<td>(6.3)</td>
<td>35</td>
<td>$&gt; 61 \pm 6$</td>
<td>(91)</td>
</tr>
<tr>
<td>$^{39}_{19}$K</td>
<td>19</td>
<td>32 ± 6$^a$</td>
<td>67</td>
<td>$&gt; 28 \pm 4$</td>
<td>(70)</td>
</tr>
<tr>
<td>$^{41}_{19}$K</td>
<td>5.1</td>
<td>(4.7)</td>
<td>30</td>
<td>$&gt; 20 \pm 1.8$</td>
<td>(32)</td>
</tr>
<tr>
<td>$^{47}_{23}$V</td>
<td>3.7</td>
<td>2.9 ± 0.4</td>
<td>25</td>
<td>$&gt; 26 \pm 2.5$</td>
<td>(35)</td>
</tr>
<tr>
<td>$^{54}_{25}$Mn</td>
<td>2.4</td>
<td>2.8 ± 0.4</td>
<td>16</td>
<td>$&gt; 37 \pm 3.4$</td>
<td>(50)</td>
</tr>
<tr>
<td>$^{59}_{27}$Co</td>
<td>8.9</td>
<td>21.4 ± 2.3$^c$</td>
<td>49</td>
<td>40 ± 5$^c$</td>
<td>(36)</td>
</tr>
<tr>
<td>$^{60}_{26}$Ni</td>
<td>5.7</td>
<td>2.9 ± 0.6</td>
<td>25</td>
<td>$&gt; 17 \pm 3$</td>
<td>(36)</td>
</tr>
<tr>
<td>$^{63}_{28}$Cu</td>
<td>1.2</td>
<td>(2.3)</td>
<td>11</td>
<td>$&gt; 35 \pm 4.5$</td>
<td>(36)</td>
</tr>
<tr>
<td>$^{65}_{28}$Cu</td>
<td>1.5</td>
<td>1.4 ± 0.2</td>
<td>14</td>
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<td>(19)</td>
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<tr>
<td>$^{75}_{33}$As</td>
<td>2.7</td>
<td>22</td>
<td>[22]$^d$</td>
<td>[11]$^d$</td>
<td></td>
</tr>
<tr>
<td>$^{79}_{35}$Br</td>
<td>2.3</td>
<td>18</td>
<td>$&gt; 11 \pm 1$</td>
<td>(12)</td>
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</tr>
<tr>
<td>$^{107}_{47}$Ag</td>
<td>0.63</td>
<td>(0.77)</td>
<td>7.2</td>
<td>$&gt; 4.9 \pm 0.5$</td>
<td>(6.7)</td>
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<tr>
<td>$^{115}_{49}$In</td>
<td>0.75</td>
<td>0.48 ± 0.07</td>
<td>8.7</td>
<td>$&gt; 3.4 \pm 0.3$</td>
<td>(4.6)</td>
</tr>
<tr>
<td>$^{123}_{53}$Cs</td>
<td>0.26</td>
<td>0.30 ± 0.04</td>
<td>4.1</td>
<td>$&gt; 0.7 \pm 0.1$</td>
<td>(3.0)</td>
</tr>
<tr>
<td>$^{165}_{76}$Ho</td>
<td>0.15</td>
<td>0.26 ± 0.04</td>
<td>2.8</td>
<td>$&gt; 2.0 \pm 0.8$</td>
<td>(4.1)</td>
</tr>
</tbody>
</table>

*no Ti data*
**WP1 Current Exp. Data : Rate**

**Table 4.14**

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<td></td>
<td></td>
</tr>
<tr>
<td>$^{67}$Fe</td>
<td>6.7</td>
<td>35</td>
<td>&gt; 61 ± 6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Activation experiment**


Reaction probabilities per captured muon $^a)$

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}$Na</td>
<td>$^{27}$Al</td>
<td>$^{21}$P</td>
<td>Target</td>
<td>Reaction Factor</td>
<td>$(\mu^-, p\overline{p})$</td>
<td>$(\mu^-, pn\overline{n})$</td>
</tr>
<tr>
<td></td>
<td>&gt; .995</td>
<td>&gt; .999</td>
<td>&gt; .995</td>
<td>&gt; .999</td>
<td>&gt; .995</td>
<td>&gt; .999</td>
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<td>&gt; .999</td>
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<td>&gt; .999</td>
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</tr>
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</table>

*no data* | *no data* | *no data* | *no data* | *no data* | *no data* | *no data* | *no data* | *no data* | *no data* |
FIG. 2. Yield of charged particles following $\mu^+$ capture in aluminum target. The filled circles represent results of the present work, with representative error bars shown. The straight line is an exponential fit to the data with $E > 40$ MeV. The open squares represent results of Budyashov et al. (Ref. 12) for silicon. The open triangles represent results of Balandin et al. (Ref. 13) for magnesium.

Yield range is too high for our purpose.

- Beam quality was not enough to stop muons in a thin target.
- thick target: 1.27mm
- no low energy data
- large background rate
WP1 Current Exp. Data: \( E_{\text{dist.}} \)

Si (active target)

Charged particle spectrum from muons stopped in Si.

Both COMET and Mu2e are using this spectrum with a parameterization for their design optimization.

Good energy range, but Si


Table 1:

<table>
<thead>
<tr>
<th>Author</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hungerford</td>
<td>[2]</td>
<td>MECO note 34</td>
</tr>
<tr>
<td>Morse</td>
<td>[5]</td>
<td>MECO note 82</td>
</tr>
<tr>
<td>Sobottka et al.</td>
<td>[6]</td>
<td>Si measurement</td>
</tr>
<tr>
<td>Wyttenbach et al.</td>
<td>[7]</td>
<td>Activation technique</td>
</tr>
</tbody>
</table>
WP1 Current Exp. Data: Summary

- **There are no data**, in the relevant energy range, on the products of muon nuclear capture from an Al target (and Ti).
  - ratio of p:d:α
  - the absolute proton rate
  - energy distribution

- Mu2e and COMET are presently using parameterization of the muon-capture data taken from Si in 1968.

- Uncertainties in the proton spectra have significant ramifications for the design of COMET Phase-I and Mu2e.

- **We must measure them. This WP1 proposal.**
WP1: Experiment

- **Goal of the experiment**
  - to measure the rate and energy spectra of the charged particles (p, d, α) emitted after muon captured on some targets:
    - **Al**: the default stopping target for COMET and Mu2e
    - **Ti**: possible target for future μ-e conv. experiments.
    - **Si (active)**: for cross-check against the previous data and systematics studies
  - A precision of 5% down to an energy of 2.5 MeV is required for both the rate and the energy spectra. (2.5 MeV~71 MeV/c for proton).

- **Essential points**
  - Thin targets and a low energy muon beam with a small Δp/p
    - to achieve a high and well determined rate of stopped muons
    - Due to ΔE of the charged particles in the target, we need to correct the energy spectra by a response function. To reduce the systematic uncertainty from the response function, the ΔE in the target must be small enough.
Experimental Setup

Negative muon

Mylar window

Target
Al, Si, Ti

Vacuum chamber
φ305.31mm
Experimental Setup

- Negative muon
- Trigger plastic counter-1
- Trigger with muon stopped
- Target: Al, Si, Ti
- Vacuum chamber φ 305.31 mm
- Mylar window
Experimental Setup

negative muon

Trigger plastic counter-1

Target Al, Si, Ti

muonic X-ray

Ge detector

Count number of stopped muons for normalization

Vacuum chamber φ305.31mm

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Experimental Setup

**Target**
- Al, Si, Ti

**Charged particle detectors**
- Si (t65µm)
- Si (t1500µm)
- Plastic scintillation

**Trigger with muon stopped**

**Trigger plastic counter-1**

**Trigger plastic counter-2**

**Vacuum chamber**
- φ305.31mm

- Count number of stopped muons for normalization

- Ge detector

- Mylar window

- Count number of stopped muons for normalization

**Experimental Setup**

- Negative muon

- Charged particle

- Muonic X-ray
This setup is an improved version of a test experiment performed by part of this collaboration at PSI in 2009.

The most of the equipments are already available.
Particle Identification by dE/dx

Assumed energy resolution: 140 keV for Si1 and 40 keV for Si2
WP1 Rates estimation

<table>
<thead>
<tr>
<th>Target thickness (μm)</th>
<th>Muon momentum (MeV/c)</th>
<th>% Stopping in target</th>
<th>Event rate (Hz) All particles</th>
<th>Event rate (Hz) Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>26</td>
<td>22.2</td>
<td>34.8</td>
<td>4.6</td>
</tr>
<tr>
<td>100</td>
<td>27</td>
<td>32.9</td>
<td>48.5</td>
<td>5.4</td>
</tr>
<tr>
<td>150</td>
<td>28</td>
<td>38.5</td>
<td>54.5</td>
<td>4.8</td>
</tr>
<tr>
<td>200</td>
<td>28</td>
<td>51.2</td>
<td>47.7</td>
<td>4.5</td>
</tr>
</tbody>
</table>

- Event rates were estimated using Geant4 simulations. The total event rate is below 100 Hz for all the considered targets.
- the rates of protons are rather low (5 Hz) and as such approximately 1.5 days of data taking will be required to accumulate the necessary statistics (~0.5 M events) for a given target.
WP1 Systematic Uncertainties

- **Response Function**
  - Uncertainties can be minimized using
    - an optimal cloud muon beam at $\pi E_1$ and
    - the use of the active Si target
  - where both the initial and final proton energies can be determined.

- **Absolute Rate**
  - The proton detection efficiency will be determined from detailed GEANT4 simulations of the Si detectors.
  - The number of stopped muons will be determined independently from both
    - the Ge detector and
    - the electron telescope and
  - a cross-checked using data from the active silicon target.
WP1 Systematic Uncertainties

- **Particle Identification Efficiency**
  - Particle identification will be made using $dE/dx$ vs. $E$ in the Si detectors, with the efficiency determined from the GEANT4 simulation.

- **Backgrounds**
  - Electron background will be determined using $dE/dX$ vs. $E$ and the veto counter.
  -Muon scattering background will be eliminated by putting lead shields.
  - A GEANT4-based evaluation of backgrounds from muons that stop in the lead shields.
WP1 Estimation of Running time

- **A precision of 5% for energy spectra (2.5 - 10MeV) is required for both the rate and the energy spectra.**
  - 500 k proton events needed for each sample.
  - Energy bin size = 0.1 MeV → 75 bins
  - Average 6k events for each bin
  - Proton rate ~5 Hz → 100k sec ~ 30 hours for each
  - About 1.5 days for each sample.
  - Including a time for changing targets, pumping chamber, beam tuning
  - 3 sample each for Al and Ti (6 in total), plus 2 Si active targets (8 samples in total)
  - Total: about 12 days for proton measurement.
WP1: Readiness

- Most of equipments are already available:
  - chamber, pump, targets, lead shields, detector mounts
  - Si and plastic scintillator detectors
  - preamps, PMT, ...

- A vacuum chamber has been tested at UW

- Si and plastic scintillators have been tested at UW and OU

- A custom DAQ based on “Midas” is being developed, and tested with the detectors (OU)

- A study of Monte Carlo simulation is being done to the optimize geometry (OU)
WP2: Gamma and X-ray Emission after Muon Capture
WP2 Present Knowledge

- When a negative muon is captured in an atomic orbit, it cascades down to the 1s level with $10^{-13}$ s by emitting X-rays and Auger electrons. The muonic X-ray from 2p to 1s transition occurs $\sim$80% of the time.
- Muonic X-rays can be used to count a number of muons stopped in the target.
- Radiative muon decays (RMD) have been measured.

![a typical muonic X-ray spectrum](image1)

![radiative muon decay (simulation)](image2)
WP2 Relevance for μ-e conversion

- A method of proper normalization of a number of stopping muons has to be established.
- (1) Measurement of muonic X-rays in a pulsed beam will be used as the primary method.
- (2) As an alternative, delayed gamma-rays after muon capture can be measured in a spill-off time. For Al, 1.01 MeV and 843.76 MeV delayed gamma from excited state of Al, where $^{27}$Mg lifetime is 9.5 min.
- (3) As an another alternative, bound radiative muon decays can be used, in particular energy range of 55 MeV to 75-85 MeV ($\text{BR} \sim 10^{-5}$)

- Ge detectors are used for (1) and (2), whereas a NaI detector is used for (3).
- PNNL develops a high-rate segmented Ge detector with fast amp.

Table 6: Energies of muonic X-rays in selected target elements.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Si (keV)</th>
<th>Al (keV)</th>
<th>Ti (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2p \rightarrow 1s$</td>
<td>400</td>
<td>347</td>
<td>1021</td>
</tr>
<tr>
<td>$3p \rightarrow 1s$</td>
<td>477</td>
<td>413</td>
<td>1210</td>
</tr>
<tr>
<td>$4p \rightarrow 1s$</td>
<td>504</td>
<td>436</td>
<td>1277</td>
</tr>
<tr>
<td>$3d \rightarrow 2p$</td>
<td>77</td>
<td>66</td>
<td>189</td>
</tr>
</tbody>
</table>
WP2 Experiment

- The AlCap collaboration propose to test several schemes to monitor the number of stopped muons in the muon-stopping target.

- High purity Germanium detector
  - We will install a high-purity germanium (HPG) detector at the port of the vacuum chamber for WP1 to measure muonic X-rays. A typical resolution of 2 keV for 1 MeV photon. The normalization method can be cross-checked with an active Si target run in WP1.
  - A high-speed 14-16 bit data acquisition system will be used to record high-resolution raw waveform data, in addition to online monitoring.
  - The measurements would include muonic X-rays and delayed gamma-rays.
  - The study of both immediate and long-term effects of neutrons on the HPG detector.

- NaI Detector
  - A NaI detector will be used to measure high energy photons from the muon stopping target, with the primary goal of evaluating alternative means of monitoring the stopped muon rate.
  - The NaI detector has 9 PMTs and their signals are digitized by waveform digitizers. The rate of photons, up to about 80-90 MeV, will be measured.
WP3: Neutron Emission after Muon Capture
Neutron emission after muon capture is not well understood, and can be described by direct and evaporation processes (via giant dipole resonances).

High energy neutrons (above 10 MeV) come from direct emission with an exponential decrease as a function of increasing energy.

Low energy neutrons that may come from evaporation processes depend on nuclear structure and is less well defined.

\[
\mu^- + A(N, p) \rightarrow \nu \mu + A(N + 1, p - 1)^
A(N + 1, p - 1)^
\rightarrow xN + x'p + x''\gamma
\]

two steps via evaporation

Average neutron multiplicity from measurements are shown in right

neutron energy spectra of low (left) and high (right).

<table>
<thead>
<tr>
<th>Target</th>
<th>Avg. Mult.</th>
<th>Multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Al</td>
<td>1.262 ± 0.059</td>
<td>0.449 ± 0.027</td>
</tr>
<tr>
<td>Si</td>
<td>0.864 ± 0.072</td>
<td>0.611 ± 0.042</td>
</tr>
<tr>
<td>Ca</td>
<td>0.746 ± 0.032</td>
<td>0.633 ± 0.021</td>
</tr>
<tr>
<td>Fe</td>
<td>1.125 ± 0.041</td>
<td>0.495 ± 0.018</td>
</tr>
</tbody>
</table>

Yoshitaka Kuno, Study of Muon Capture for Muon to Electron Conversion Experiments
WP3 Relevance for μ-e conversion

- Neutrons emitted from muon capture at the muon-stopping target (beam stop) at Mu2e and COMET would become a problem for single rates of the electron calorimeters and the cosmic-ray veto, although tracking chambers are not sensitive to neutrons.

- Estimated calorimeter rates of neutrons and gammas are about 300 kHz and 85 kHz respectively.

- Simulation shows those introduces pileup probability of 40% and 20% (with energy deposition of 0.5 MeV and 0.7 MeV) respectively.

- Fast neutrons will cause damages on the front-end electronics.

- From the MARS simulation, a dose of $5 \times 10^4$ n/s/cm$^2$ is obtained. For a IC ship of 1 cm$^2$ area, $4 \times 10^7$ second running time is allowed to get the tolerant level of about $10^{12}$ neutrons.

- Therefore, it would be important to understand the rate and spectrum of neutrons emitted after muon capture.

<table>
<thead>
<tr>
<th>Source</th>
<th>Thermal ($T &lt; 1$ eV)</th>
<th>Epithermal ($1$ eV &lt; $T &lt; 1$ MeV)</th>
<th>Fast ($T &gt; 1$ eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping Target</td>
<td>16</td>
<td>77</td>
<td>100</td>
</tr>
<tr>
<td>Muon Beam Stop</td>
<td>0.2</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>Beam Flash</td>
<td>0.2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Production Solenoid</td>
<td>0.6</td>
<td>0.09</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4: Neutron Background Sources on the Tracker as a function of Neutron Kinetic Energy, $T$

Aluminum Neutron Energy Spectrum

neutron energy spectrum from Al from the MARS simulation
WP3 Experiment

- Rate and spectrum of neutrons emitted from muon capture on Al target will be measured.
- Neutron counters from the MuSun experiment will be used. They are six cylindrical cells of 13cm diameter and 13cm depth, containing 1.2 liters of BC501A organic liquid scintillator. They are coupled to PMT.
- Instead of TOF, the neutron spectrum unfolding technique is considered with a detector response function.
- The 12-bit, 170 MHz waveform digitizers (from MuSun) will be used for readout. The digitization allows separation of neutrons from gammas by pulse shape discrimination (PSD).

Figure 15: The FLUKA simulated spectrum for proton(red), neutron(blue), and gamma(black) emission per $\mu$ stop after $\mu$ capture on Al

Figure 16: A FLUKA simulation of the energy correlation between neutron (vertical) and prompt gamma (horizontal) emission after $\mu$ capture on Al

Figure 17: a) Digitized signal from a BC501A neutron detector (x-axis in ns). b) Neutron-gamma separation via pulse shape discrimination. The slow integral corresponds to the sum of the bins 5 to 20 to the right of the peak of the digitized signal. The lower band contains $\gamma$s and the upper band the neutrons.
Beam Requirements and Beam Request
Beam Requirement

- Experiment area:
  - πE1 beam line

- Required beam properties:
  - particle: μ-
  - momentum: 25-35 MeV/c
  - momentum bite: < 2% FWHM
  - beam spot: <2 cm in diameter
  - intensity: 2x10⁴ s⁻¹
  - beam purity: < 10% electrons
Beam Time Request

- **We request** two 4 week PSI beam blocks. One is scheduled in 2013, and the next one is in 2014.

- **In spring 2013,** we like to carry out **WP1 (proton emission)** with **WP2 (muonic X-ray emission).**
  - week 1: setup. commission beam counters and detectors, a vacuum chamber.
  - week 2: beam optimization,
  - week 3: high statistics measurements with 3 targets of Al and Ti, 25-200µm.
  - week 4: high statistics measurements (continued). Last days dedicated neutron measurements.

- **In early 2014,** we like to carry out **WP3 (neutron emission)** with **WP2 (muonic gamma-ray emission and RMD).**
Currently, $M = 1$ is achieved at an electron-equivalent energy of 200 keV corresponding to a neutron energy of about 0.7 MeV (MuSun analysis, see also [21]).

5 Organization

5.1 Organization and Responsibilities

The organization and responsibilities for the three work packages is given below.

<table>
<thead>
<tr>
<th>Work Package</th>
<th>Set-up</th>
<th>Detectors</th>
<th>Electronics</th>
<th>DAQ</th>
<th>Simulation/Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP1</td>
<td>UW, OU</td>
<td>UW, OU, FNAL</td>
<td>UW, OU</td>
<td>OU, UCL</td>
<td>OU, UCL, UW</td>
</tr>
<tr>
<td>WP2</td>
<td>PNNL</td>
<td>PNNL, BU</td>
<td>PNNL, UW</td>
<td>PNNL, OU</td>
<td>PNNL, BU</td>
</tr>
<tr>
<td>WP3</td>
<td>UH, ANL</td>
<td>UH, UW</td>
<td>ANL</td>
<td>ANL, OU</td>
<td>UH, ANL</td>
</tr>
</tbody>
</table>

5.1.1 WP1

We have a vacuum chamber and Si detectors, which were used for a similar measurement at PSI in 2009. The vacuum chamber is being tested now at University of Washington (UW). The two existing Si detectors are also being tested at UW. A possibility to prepare another set of Si detectors is being considered. Amplifiers for the existing Si detectors are available. The Osaka University (OU) group is preparing DAQ system based on a PSI standard data acquisition system (MIDAS). Monte Carlo simulations necessary to optimize detector configuration is undergoing at OU and University College London (UCL).

Data will be analyzed independently at Osaka University, University of Washington, and University College London, using standard analysis libraries and our own analysis routines. There is no special requirement on data analysis support to PSI.

5.1.2 WP2

PNNL has a number of HPGe detectors available; one appropriate for the experiment will be chosen and tested in advance. A mechanical cooling system is currently under test at PNNL as well and is expected to be used at PSI. Due to the desired high rate and resolution requirements for the raw HPGe pulse data, PNNL will provide its own DAQ system for data collection. The raw data will be provided to the other DAQ system if desired, and the coordination and timestamps between the two systems will be handled carefully.

HPGe data will be analyzed at Pacific Northwest National Laboratory using standard analysis libraries and our own analysis routines. There is no special requirement on data analysis support to PSI.

5.1.3 WP3

As mentioned above, we plan to use existing neutron detectors and readout electronics provided by the MuSun collaboration. We are also considering to build a small neutron detectors, with optimal resolution. We plan to calibrate the detectors before the final experiment and have started to study and test unfolding methods.

5.2 Requests to PSI

We request limited hardware support from PSI. This includes...
Summary

- Search for $\mu$-$e$ conversion would have a great potential to find an evidence of physics beyond the Standard Model.

- The two experiments in preparation, Mu2e at FNAL and COMET (Phase-I in particular) at J-PARC, need to finalize their detector design in one year. For design optimization, we need accurate data sets of particle emission from muon capture.

- The AlCap collaboration, formed jointly by Mu2e and COMET, proposes an experiment to measure the rate and energy of particle emissions after muon capture at the $\pi E1$ beam channel, in two 4-week blocks of the beam time in spring 2013 and early 2014.
Silicon Detectors

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Design</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>MSQ25-65 (65 microns)</td>
<td>4,000 pF total 1,000 pF per quadrant</td>
</tr>
<tr>
<td>2</td>
<td>MSX25-140 (140 microns)</td>
<td>2,000 pF</td>
</tr>
<tr>
<td>2</td>
<td>MSX25-150 (150 microns)</td>
<td>300 pF</td>
</tr>
</tbody>
</table>

All detectors will be in PCB frames and are totally depleted.