Mu2e-II/III: DIO Studies for Titanium Stopping Target

Kyle J. Knoepfel
Fermi National Accelerator Laboratory

July 31, 2013
Prerequisites

![Graph showing POT pulse and various decay times for muons and charged pions.]  

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>% muons that decay</td>
<td>39%</td>
<td>15%</td>
</tr>
<tr>
<td>% of decays in timing window</td>
<td>50%</td>
<td>30%</td>
</tr>
<tr>
<td>Time constant for muon decay</td>
<td>864 ns</td>
<td>329 ns</td>
</tr>
</tbody>
</table>

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Context

• In the Mu2e experiment, dominant irreducible background originates from SM muon decays:
  – Decays in orbit (DIOs)
    \[ \mu^- + N \rightarrow e^- \bar{\nu}_e \nu_\mu + N \]

• Energy distribution of electron from muon decay given by (modified) Michel spectrum:
  – Normal Michel spectrum endpoint: 52.8 MeV
  – Mu2e signal at \( E > 100 \) MeV, so how can this be a background?
Context

- In the Mu2e experiment, dominant irreducible background originates from SM muon decays:
  - Decays in orbit (DIOs)
    \[ \mu^- + N \rightarrow e^- \bar{\nu}_e \nu_\mu + N \]

- Presence of atomic nucleus \(\rightarrow\) momentum transfer

  Kinematic endpoint (Al): \(E_e = 104.973\) MeV
  Kinematic endpoint (Ti): \(E_e = 104.272\) MeV

- Mu2e signal at \(E > 100\) MeV, so how can this be a background?

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Previous DIO assumptions

• In the feasibility study (arXiv:1307.1168), we did not have the expected DIO spectrum implemented in the Mu2e computing framework.

• The DIO background was computed by scaling the background:

\[
\frac{1 - C_{Ti}}{1 - C_{Al}} \times \frac{\epsilon(t_0, Ti)}{\epsilon(t_0, Al)} \approx 0.24
\]

  Difference in capture fractions    Difference in decay-time distribution

• Naively, DIO background for Ti looks to be ¼ that of Al.

• Did not include differences in the electron energy spectrum (i.e. differential decay rate).

Those differences now taken into account – today’s topic.
Implementing the *Czarnecki, et al* DIO spectrum

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**Muon decay in orbit: Spectrum of high-energy electrons**

Andrzej Czarnecki and Xavier Garcia i Tormo  
*Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2G7*

William J. Marciano  
*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*  
(Received 11 May 2011; published 14 July 2011)
Implementing the *Czarnecki, et al* DIO spectrum

- Very readable approach to calculating the $E_e$ spectrum.
- No closed form solution for the full spectrum.
- But there are some simple approximations.
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Implementing the Czarnecki, et al DIO spectrum

• Very readable, simple approach to calculating the E spectrum.
• No closed form solution for the full spectrum.
• But there are some simple approximations.

Implementing the Czarnecki, et al DIO spectrum

\[
P^{(\text{Ti})}(E_e) = a_{5}^{(\text{Ti})} \delta_{(\text{Ti})}^5 + a_{6}^{(\text{Ti})} \delta_{(\text{Ti})}^6 + a_{7}^{(\text{Ti})} \delta_{(\text{Ti})}^7 + a_{8}^{(\text{Ti})} \delta_{(\text{Ti})}^8, \tag{29}
\]

with

\[
a_{5}^{(\text{Ti})} = 4.44278 \times 10^{-16}, \quad a_{6}^{(\text{Ti})} = 9.06648 \times 10^{-17}, \tag{30}
\]
\[
a_{7}^{(\text{Ti})} = -4.26245 \times 10^{-18}, \quad a_{8}^{(\text{Ti})} = 8.193 \times 10^{-19},
\]

the energies expressed in MeV,

\[
\delta_{(\text{Ti})} = E_\mu - E_e - \frac{E_e^2}{2m_{\text{Ti}}}, \tag{31}
\]
Comparing Al-Ti DIO spectra (1)

Normalized per DIO

Kinematic endpoints

Normalized per DIO

Al shape

Ti shape

Kinematic endpoints

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Comparing Al-Ti DIO spectra (1)

Intersection at ~102.5 MeV

Normalized per DIO
- Al shape
- Ti shape
Comparing Al-Ti DIO spectra (2)

Al weighted by 0.39 decay fraction
Ti weighted by 0.15 decay fraction

Normalized per muon stop
Al weighted by 0.39 decay fraction
Ti weighted by 0.15 decay fraction

Kinematic endpoints
Comparing Al-Ti DIO spectra (2)

Normalized per muon stop

Al weighted by 0.39 decay fraction
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Simulated DIO studies

• Offline Mu2e geometry (G4) is being finalized.
• Geometry used includes:
  – Half-length inner proton absorber
  – Outer proton absorber
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• Geometry used includes:
  – Half-length inner proton absorber
  – Outer proton absorber

• Four situations considered:
  [0] Al w/baseline mu2e (validation)
  [1] Ti w/baseline mu2e
  [2] Ti w/narrower stopping target foils
     • Same stopping target mass as in Al case
  [3] Ti case (2) with smaller tracker straw walls
     • 8 µm thick vs. 15 µm thick (baseline)
Simulated DIO studies – Assumptions

• The number of stopped muons is assumed to be $7.56 \times 10^{17}$.

• The assumed value of $R_{\mu e}$ is $10^{-16}$.

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

Coherent $\mu \rightarrow e$ conversion

Muon capture
Case 0: Al baseline validation

Stopping Target: Al

Signal: 5.653 ± 0.016
DIO : 0.189 ± 0.003
Case 1: Ti baseline detector design

Stopping Target: Ti

Signal: 3.514 ± 0.015
DIO: 0.196 ± 0.021
Case 2: Ti with thinner target foils

Stopping Target: Ti

Signal: 4.768 ± 0.018
DIO : 0.190 ± 0.010
Case 3: Ti case 2 + thinner straw walls

Stopping Target: Ti

Signal: 4.991 ± 0.018
DIO : 0.190 ± 0.005

Reconstructed e⁻ momentum (MeV/c)

Events / 0.01 MeV/c
Conclusions

• Ti DIO spectrum (*a la* Czarnecki *et al*) now fully implemented in Mu2e Offline computing framework

• For the same number of stopped muons (7.56 \times 10^{17}) and the same $R_{\mu e}$ (10^{-16}), and modest changes to the geometry:
  – Reasonable separation between DIO and signal distributions for Titanium,
  – Roughly 5 signal events for 0.2 DIO events
  – Comparable to Al case

• Can further optimize the window for < 1 DIO event for 10 \times the number of stopped muons.
Back-up Slides
Generated distributions

<table>
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Aluminum
Titanium
Generated distributions

- Aluminum
- Titanium

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Generated distributions with weighting & reco cuts

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<tr>
<td>Entries    1.000001e+07</td>
</tr>
<tr>
<td>Mean       100.6</td>
</tr>
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<td>RMS        0.5062</td>
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Testing Momentum Resolution between Ti and Al

Generate electrons with $p_{\text{true}} = 100$ MeV/c

Al: Mean = -0.047  RMS = 0.277
Ti: Mean = -0.047  RMS = 0.275
Testing Momentum Resolution between Ti and Al

Generate electrons with $p_{\text{true}} = 100$ MeV/c

Al: Mean = -0.047  RMS = 0.277
Ti: Mean = -0.047  RMS = 0.275