MuSun

Precision muon capture on the deuteron

Daniel J. Salvat
Center for Experimental Nuclear Physics and Astrophysics
University of Washington
Muon capture

\[ q^2 \sim m^2_\mu \]

\[ \mu^- \quad W \quad U \]

<table>
<thead>
<tr>
<th>Z (Z_{\text{eff}})</th>
<th>Element</th>
<th>Mean-life (ns)</th>
<th>Capture rate ( \times 10^3 \text{(s}^{-1}) )</th>
<th>Huff factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (1.00)</td>
<td>( ^1\mu^- )</td>
<td>2197.03 (4)</td>
<td>455.16</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>( ^1\text{H} )</td>
<td>2194.90 (7)</td>
<td>0.450 (20)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>( ^2\text{H} )</td>
<td>2194.53 (11)</td>
<td>0.470 (29)</td>
<td>1.00</td>
</tr>
<tr>
<td>2 (1.98)</td>
<td>( ^3\text{He} )</td>
<td>2186.70 (10)</td>
<td>2.15 (2)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>( ^4\text{He} )</td>
<td>2195.31 (5)</td>
<td>0.356 (26)</td>
<td>1.00</td>
</tr>
<tr>
<td>3 (2.94)</td>
<td>( ^6\text{Li} )</td>
<td>2175.3 (4)</td>
<td>4.68 (12)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>( ^7\text{Li} )</td>
<td>2186.8 (4)</td>
<td>2.26 (12)</td>
<td>1.00</td>
</tr>
<tr>
<td>4 (3.89)</td>
<td>( ^9\text{Be} )</td>
<td>2168 (3)</td>
<td>6.1 (6)</td>
<td>1.00</td>
</tr>
<tr>
<td>5 (4.81)</td>
<td>( ^{10}\text{B} )</td>
<td>2072 (3)</td>
<td>27.5 (7)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>( ^{11}\text{B (lhfs)} )</td>
<td>2089 (3)</td>
<td>23.5 (7)</td>
<td>1.00</td>
</tr>
<tr>
<td>6 (5.72)</td>
<td>( ^{12}\text{C} )</td>
<td>2028 (2)</td>
<td>37.9 (5)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>( ^{13}\text{C} )</td>
<td>2037 (8)</td>
<td>35.0 (20)</td>
<td>1.00</td>
</tr>
<tr>
<td>7 (6.61)</td>
<td>( ^{14}\text{N} )</td>
<td>1919 (15)</td>
<td>66 (4)</td>
<td>1.00</td>
</tr>
<tr>
<td>8 (7.49)</td>
<td>( ^{16}\text{O} )</td>
<td>1796 (3)</td>
<td>102.5 (10)</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>( ^{18}\text{O} )</td>
<td>1844 (5)</td>
<td>88.0 (14)</td>
<td>0.998</td>
</tr>
<tr>
<td>9 (8.32)</td>
<td>( ^{19}\text{F (lhfs)} )</td>
<td>1463 (5)</td>
<td>229 (1)</td>
<td>0.998</td>
</tr>
<tr>
<td>13 (11.48)</td>
<td>( ^{27}\text{Al (lhfs)} )</td>
<td>864 (2)</td>
<td>705 (3)</td>
<td>0.993</td>
</tr>
<tr>
<td>14 (12.22)</td>
<td>( ^{28}\text{Si} )</td>
<td>758 (2)</td>
<td>868 (3)</td>
<td>0.992</td>
</tr>
<tr>
<td>20 (16.15)</td>
<td>Ca</td>
<td>334 (2)</td>
<td>2546 (20)</td>
<td>0.985</td>
</tr>
<tr>
<td>40 (25.61)</td>
<td>Zr</td>
<td>110.4 (10)</td>
<td>8630 (80)</td>
<td>0.940</td>
</tr>
<tr>
<td>82 (34.18)</td>
<td>Pb</td>
<td>74.8 (4)</td>
<td>12985 (70)</td>
<td>0.844</td>
</tr>
<tr>
<td>83 (34.00)</td>
<td>Bi</td>
<td>73.4 (4)</td>
<td>13240 (70)</td>
<td>0.840</td>
</tr>
<tr>
<td>90 (34.73)</td>
<td>Th</td>
<td>77.3 (3)</td>
<td>12560 (50)</td>
<td>0.824</td>
</tr>
<tr>
<td>92 (34.94)</td>
<td>U</td>
<td>77.0 (4)</td>
<td>12610 (70)</td>
<td>0.820</td>
</tr>
</tbody>
</table>
Single-nucleon capture in MuCap

With axial-vector charge as input, muon capture offers insight into the induced pseudoscalar coupling
Single-nucleon capture in MuCap

- Excellent agreement with chiral perturbation theory prediction
- Leverages an ultra-high purity hydrogen time projection chamber

What else can we learn from precision muon capture?

\[ \Lambda_{\text{MuCap}}^S = 714.9 \pm 5.4_{\text{stat}} \pm 5.1_{\text{syst}} \, \text{s}^{-1} \]
\( \mu-d \) capture and chiral effective field theory

probe of two-body axial current, relating other weak two-body reactions
The MuSun measurement

$\delta \Lambda_{d} = 1.5\%$

single contact term $L_{1A}$
## By the numbers

<table>
<thead>
<tr>
<th>method</th>
<th>$L_{1A}$ (fm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>two-body</strong></td>
<td></td>
</tr>
<tr>
<td>reactor $\bar{\nu} + d$</td>
<td>$3.6 \pm 5.5$ [11]</td>
</tr>
<tr>
<td>ES, CC, NC in SNO</td>
<td>$4.0 \pm 6.3$ [41]</td>
</tr>
<tr>
<td>MuSun proposal</td>
<td>$\pm 1.25$</td>
</tr>
<tr>
<td><strong>three-body</strong></td>
<td></td>
</tr>
<tr>
<td>tritium beta decay</td>
<td>$4.2 \pm 3.7$ [11], $4.2 \pm 0.1$ [41]</td>
</tr>
<tr>
<td><strong>other</strong></td>
<td></td>
</tr>
<tr>
<td>helioseismology</td>
<td>$4.8 \pm 6.7$ [42]</td>
</tr>
</tbody>
</table>


The lifetime method

\[ e^{-(\lambda_\mu + + \Lambda_D)t} \]

- measure \( \mu^- \) lifetime in \( D_2 \) gas
- compare to known free \( \mu^- \) lifetime
- free decay 1000 times faster!
- 1.5% measurement of \( \Lambda_D \) requires \( \sim 10^{-5} \) precision in disappearance rate!

\[ \mu^- + d \rightarrow (\nu_\mu + n + n) \]

It's either this, or count fast neutrons with known efficiency

no charged particles in the final state
$\mu$ production at the Paul Scherrer Institute

590 MeV protons on carbon target

\[ \downarrow \]

stopped pions

\[ \downarrow \]

decay into muons
πE1 at the Paul Scherrer Institute

- ~few MeV muons ($p \sim 40$ MeV/c)
- Electrostatic beam kicker for one muon at a time
- $E \times B$ separator to remove electron contamination
Greetings from Villigen
Muons enter the apparatus at $t_{\text{start}}$

- fast scintillator to set $t=0$
  - send signal to beam kicker -- one $\mu$ at a time
- MWPC for beam profile
- annular scintillator for veto
- thin beryllium window to enter $D_2$ volume
Muons stop in $D_2$ gas

- 48 anode ion chamber
- reconstruct x-y-z position
- make fiducial cuts
Muons decay at $t_{\text{stop}}$

- 32 scint. paddles for timing
- track reconstruction using two cylindrical MWPCs
Muon kinetics in deuterium

- statistical population of $\mu d$ states
- hyperfine transition to doublet state
- $d\mu d$ forms ~5% of the time (mostly from quartet), m.c.f
- most are recycled to $\mu d$ to start cycle again

We want to maximize population of doublet state
Muon kinetics in deuterium

- doublet to quartet rate suppressed at low $T$
- resonant molecular formation ($T$ dependence)
- density dependence

- $P=5$ bar
- $T=31$ K $\leftrightarrow \varphi=6\%$
Ultrapure cryo-TPC

- High Z materials
  - Ag cathode
  - Ag plated Cu anode
  - Ag/Au-plated W wires
- Low-noise cryo-preamps

\[ v_d = 4 \frac{mm}{\mu s} \]

\[ E = 322 \text{ keV} \]
\[ \sigma_E = 16.9 \text{ keV} \]
Tracking muons

hWaveformDisplayBase
Events in the TPC

Energy of fiducial muon tracks

$\mu + 2p - t$

$\mu + p - t$

$\mu + n - He$

Energy one pad upstream [keV]

Energy on stop pad [keV]

S-energy of fiducial muon tracks

S-energy [keV]
Target purity

\[ \text{1 ppb N}_2 \Rightarrow \Delta \Lambda_{d} \sim 3 \text{ s}^{-1} \]
CHUPS and gas chromatography

Chromatography

Cryo-distillation for <100 ppb H₂

5 l/min continuous flow

Impurity injection for calib.

Zeolite filtration

~1 ppb purity and measurement sensitivity!

Isotope separation
Production runs and statistics

- Production runs in 2014 & 2015
- ~3 kHz fid. vol $\mu^-$ $\Rightarrow$ ~$10^9$ evt/week
- Have $10^{10}$ candidate events in hand!
- $\mu^+$ useful for systematic checks
Outlook

- MuSun offers a unique glimpse into the nucleus
  - first determination of $d^R$ in the two-nucleon system, leading to robust understanding of solar fusion and CC $\nu$-$d$ cross section
- with a unique experiment comes unique challenges
  - developed techniques to understand muon kinetic/fusion effects
  - path forward on constraining backgrounds, wall stops, impurities
- $\sim 12 \cdot 10^9$ events in the bag
  - potential prelim. result from 2014 soon, 2015 analysis underway