MuSun: Muon Capture on the Deuteron

ICNFP 2014 Crete
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On behalf of the MuSun collaboration
MuSun Goal

Measure the rate $\Lambda_d$ for muon capture on the deuteron to better than 1.5% precision.

Note: $\Lambda_d$ denotes the capture rate from the doublet hyperfine state of the muonic deuterium atom in its 1S ground state.
Physics Motivation

$\mu^- + d \rightarrow \nu_\mu + n + n$

- Simplest process on a compound nucleus that can both be calculated and measured to a high degree of precision.

- The discrepancy between theoretical and experimental results requires better precision measurement. (2.9σ)

- Clean and accurate channel to determine the Low Energy Constant (LEC) in Effective field theory.

- Astrophysical & neutrino interests: processes such as pp fusion and neutrino deuterium scattering are closely related to mud capture.
ChPT Lagrangian

\[ \mathcal{L}_{eff} = \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \ldots \]

\[ \mathcal{L}^{(1)}_{\pi N} = \bar{\Psi} \left(i D_\mu \gamma^\mu - M_N + \frac{g_A}{2} u_\mu \gamma^\mu \gamma_5\right) \Psi \]

\[ \mathcal{L}^{(2)}_{\pi N} = \sum_{i=1}^{7} \bar{\Psi} O_{i}^{(2)} \Psi \]

\[ \mathcal{L}^{(3)}_{\pi N} = \sum_{i=1}^{23} \bar{\Psi} O_{i}^{(3)} \Psi \]
From ChPT to $\mu$-d capture

Triton $\beta$ decay

$^3H \rightarrow ^3He + e^- + \bar{\nu}_e$

Solar pp fusion

$p + p \rightarrow d + e^+ + \nu_e$

SNO vd scattering

$\nu_e + d \rightarrow p + p + e^-$

$M \propto \langle \Psi_{nn} | j^\alpha | \Psi_d \rangle \bar{\nu}_\mu \gamma^\alpha (1 - \gamma_5) \mu$

Latest result: $\Lambda_d = 399 \pm 3$ s$^{-1}$

Musan experiment (1.5%)
Experimental method: lifetime technique

Focus on sources of the muon disappearance:

- **Muon decay:**
  \[ \mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e \]
- **Muon capture:**
  \[ \mu^- + d \rightarrow \nu_\mu + n + n \]

\[ \Lambda_{\mu^-} = \Lambda_{\text{cap}} + \Lambda_{\text{dec}} \]
\[ \Lambda_{\mu^+} = \Lambda_{\text{dec}} \sim 455\text{kHz} \]
\[ \Lambda_{\text{cap}} = \Lambda_{\mu^-} - \Lambda_{\mu^+} \sim 400\text{Hz} \pm 6\text{Hz} \]

- Determine \( \Lambda_{\text{cap}} \) to 1.5% level.
- Measure \( \Lambda_{\mu^-} \) to 10ppm.
- Require \( 10^{10} \) events.
Experimental design

- Intense low energy muon beam.
Experimental setup
Experimental setup

 Beamline

 Magnets

 Kicker
 Muon on request

 Separator

 Magnets

 MuSC

 MuSC

 MuPC

 MuPC

 Entrance counter

 Detector

 e- detector

 TPC
Entrance counter

Goal: Identify good muon entrances and avoid pile-up. $t=0$ for the experiment!

- $\mu$SC
- $\mu$PC
- !$\mu$SCA
- Kicker

$\mu$ entrance time $t = 0$ for MuSun

Position

VETO

Pile-up

Good $\mu$ Entrance

Raw $\mu$PC

$\mu$PC && $\mu$SC
• ePC1 & ePC2: Wire chambers to get \((r, \Phi, Z)\), extrapolate decay e- track.
• eSC: 16 Scintillators segments, to determine the electron time.
• Lifetime technique: get \(t_e - t_\mu\), select “good” data to fill in lifetime histogram.
Electron detector

Goal: Identify electron tracks from muon decay
Cryo TPC- target & cut box

- Ultrapure Deuterium target to stop the muons
- Ionization chamber: drift electrons 0.4cm/μs.
- Reconstruct 3D muon track, make cuts of data to define good muon stops.

Cathode

9 * 12 cm²
48 pads->X/Z
Muon track reconstruction

TPC

Cathode

μ-

e-

e-

e-

e-

Anode pads

XZ plane

$\frac{dE}{dZ}$

Bragg Peak

μ-

Muon entrance time

Time (us)
MuSun event

-30us

“good” muon entrance

+30us

“good” e-track

“good” muon stop in TPC

MuSun Event

• 3 parameters expo fit to extract the slope as the muon disappearance rate.

• Tricky to define “good” in each level

\[ f(t) = Ne^{-\frac{t}{\tau}} + B \]

DANGEROUS
Time dependent cuts introduce systematic error.

8/1/14
Systematics: Non-Deuterium capture

- D2 gas is surrounded by the High Z material
  - Apply Fiducial Volume Cut
  - Delay the fit window
- Impurities in the gas, Medium Z N2, and O2
  - 1ppb N2->2Hz correction
  - Low temperature to freeze out the impurities
  - Gas chromatography and Xray tagging

<table>
<thead>
<tr>
<th>element</th>
<th>$\mu$ capture rate (Hz)</th>
<th>life (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>$\sim 400$</td>
<td>2194</td>
</tr>
<tr>
<td>N</td>
<td>$65 \times 10^3$</td>
<td>1930</td>
</tr>
<tr>
<td>O</td>
<td>$98 \times 10^3$</td>
<td>1810</td>
</tr>
<tr>
<td>Si</td>
<td>$850 \times 10^3$</td>
<td>760</td>
</tr>
<tr>
<td>Fe</td>
<td>$4400 \times 10^3$</td>
<td>207</td>
</tr>
<tr>
<td>Au</td>
<td>$12 000 \times 10^3$</td>
<td>74</td>
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</tbody>
</table>
Systematics-muon catalyzed fusion

Muon catalyzed fusion
Prompt ~ ns

$\mu d$ quartet

$\mu d$ doublet

$\mu$, $+t+p$

$\mu$, $+^{3}\text{He}+n$

$\mu^{3}\text{He}+n$

$\Phi\lambda_{qd}$

$\Phi\lambda_{dd}$

$\Phi\lambda_{qd}$

MuSun TPC

proton

triton

hWaveformDisplayBase

$\mu^{-}$

He3
Proton + triton fusion happens ~5% of all muon stops (3% inside FidVol)

Net migration caused by fusion is 1.5% of fusion events ->450ppm of all stops.

Proton travels about 16mm, confuses the tracking algorithm as to whether or not the muon stopped within Fiducial Volume.
According to the Monte Carlo simulation, fusion interference causes a ~50Hz systematic error. (Ongoing work)
Other Systematics

- Electron interference
- Muon scattering -> High Z Capture
- Electron track definition
- Mu+ spin rotation.
- Isotope contamination

<table>
<thead>
<tr>
<th>Statistics</th>
<th>3.4</th>
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</thead>
<tbody>
<tr>
<td>Chemical Impurities</td>
<td>2</td>
</tr>
<tr>
<td>Estimated Error in Analysis</td>
<td>2</td>
</tr>
<tr>
<td>$\mu + p$ hard scattering</td>
<td>1</td>
</tr>
<tr>
<td>$\mu$ pileup veto inefficiency</td>
<td>1</td>
</tr>
<tr>
<td>$\mu d$ diffusion</td>
<td>.5</td>
</tr>
<tr>
<td>$^1$H contamination</td>
<td>$\sim$ 0</td>
</tr>
<tr>
<td>Fusion Processes</td>
<td>1</td>
</tr>
<tr>
<td>Muon Kinetics (quartet, $^3$He, etc.)</td>
<td>.5</td>
</tr>
</tbody>
</table>

$Total Systematic Error$ 3.3

$Total Error$ 4.7
status

- Data collected 2011: 5e9
- Data collection in 2013: 2e9
- Taking data 2014 for 3 weeks
- Ongoing various systematics on the impurity, fusion interference, pile-up, etc. expect preliminary result in 2015.

Collaboration:
Thanks!
Pile up protection: Kicker is active for 25μs, to make sure there is only one muon in the TPC.
TPC conditions

Goal: Maximize the population of $\mu d$ doublet.

Temperature $T = 33K$
Density of deuterium gas $\phi = 6\%$ of liquid $H_2$.

$\lambda_{dq}$ is near 0 at low $T$ => quick depopulation of quartet

At low $T$, doublet doesn’t
Problem: energy deposition by the electron track, if interfere with the muon track, could lead to a time-dependent muon stop acceptance.
Impurity – vapor pressure

\[ \text{\phi} = 0.064 \quad \text{p} = 5.6 \text{ bar} \]
Impurity-software

muon capture on gas impurities

noise

fusion background

Delayed events with decay electron
Delayed events with no decay electron

Energy (keV)