Precise Neutron Lifetime Measurement Using Pulsed Neutron Beams at J-PARC


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J-PARC Symposium 2019 @ Tsukuba
26/Sep./2019  PN/MLF-SY: Symmetry in particle and nuclear physics
Neutron lifetime

- The neutron decay with a mean lifetime of $879.4 \pm 0.6$ sec.

$$n \rightarrow p + e^- + \bar{\nu}_e$$

- The lifetime has been measured by two types of method.
  - **Beam method** count dead neutrons.
  - **Storage method** count living neutrons.

- The discrepancy (8.6 sec or 4.0σ) of these two methods is a long time problem.
Beam method

- Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam. J. Nico et al. Physical Review C 71.5 (2005): 055502. \( \tau_n = 886.6 \pm 1.2 \text{ (stat)} \pm 3.2 \text{ (syst)} \text{ sec} \)

- Improved determination of the neutron lifetime. A. T. Yue et al., Physical review letters 111.22 (2013): 222501. \( \tau_n = 887.7 \pm 1.2 \text{ (stat)} \pm 1.9 \text{ (syst)} \text{ sec} \)

- Monochromatic neutron beam was transported to the magnetic trap.
  - Neutron flux was monitored by a \( ^6 \text{Li} \) and detectors.
  - Protons from the neutron decays trapped in the magnetic and electric field.
  - Stored protons are released and detected by a proton detector.
Storage method

- **PNPI/ILL Large storage bottle**
  \[ \tau_n = 881.5 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ sec} \]

- **LANL Magnetic Trap**
  \[ \tau_n = 877.7 \pm 0.7 \text{ (stat)} \pm 0.4/-0.2 \text{ (syst)} \text{ sec} \]

- **PNPI/ILL Magnetic bottle**
  \[ \tau_n = 878.3 \pm 1.6 \text{ (stat)} \pm 1.0 \text{ (syst)} \text{ sec} \]
Physics motivation
Big bang nucleosynthesis

- Light elements ($A \leq 7$) were created in $10^3$ seconds after the big bang.
- Abundance of them is calculated by
  - baryon-to-photon ratio
  - nuclear cross sections
  - neutron lifetime.

- A recent observation\(^1\) has a small inconsistency with the standard cosmology. Effective neutrino generation $N_{\text{eff}} = 3.51 \pm 0.35$ is 1.5σ deviation from 3.

- CMB+BAO observation\(^2\) independently result $N_{\text{eff}} = 3.26 \pm 0.28$ which has 1.0σ deviation from 3.

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Unitarity of CKM matrix

- Neutron decay is one way to verify the unitarity of the CKM matrix (Cabibbo-Kobayashi-Maskawa).
- Calculation of $V_{ud}$ from neutron decay is simpler than nuclear ones but parameters have larger uncertainty.
  - Neutron lifetime $\tau_n (0.07\%)$
  - Axis/vector coupling constants $\lambda \equiv G_A/G_V (0.18\%)$
    \[
    |V_{ud}|^2 = \frac{(4908.7 \pm 1.9) \text{ sec}}{\tau_n (1 + 3 \lambda^2)}
    \]
- The parameters summarized by PDG2019 is consistent with unitarity.

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005
\]

\[
V_{CKM} = \\
\begin{pmatrix}
0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\
0.22438 \pm 0.00044 & 0.97359 & 0.04214 \pm 0.00076 \\
0.00896 & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \\
\end{pmatrix}
\]

PDG 2019
Unitarity of CKM matrix: $V_{ud}$ and $\lambda$

$V_{ud}$ : Unitary
$V_{ud}$ : Nuclear decay ($0^+ \rightarrow 0^+$)

$\lambda$ : Post 2002
$\lambda$ : Pre 2002

$\tau_n$ : Bottle method
$\tau_n$ : Beam method
Unitarity of CKM matrix: $V_{ud}$ and $\lambda$

- $V_{ud}$: Unitary
- $V_{ud}$: Nuclear decay ($0^+ \rightarrow 0^+$)
- $\tau_n$: Beam method
- $\tau_n$: Bottle method
- $\lambda$: Pre 2002
- $\lambda$: Post 2002
- $\lambda$: Post 2002

Graph showing the range of $V_{ud}$ and $\lambda$ with new radiative correction.
Unitarity of CKM matrix: $V_{ud}$ and $\lambda$

- $V_{ud}$: Unitary
- $\lambda$: New measurement
  - PERKEO-III, PRL122, 242501 (2019)
- $V_{ud}$: Nuclear decay ($0^+ \rightarrow 0^+$)
  - with new radiative correction
  - PRL121, 241804 (2018)
- $\tau_n$: Bottle method
- $\tau_n$: Beam method

$\lambda$: Pre 2002

$\lambda$: Post 2002

$\lambda$: Post 2002→
Unitarity of CKM matrix: $V_{ud}$ and $\lambda$

- Another new measurement
  - $V_{ud}$: Nuclear decay ($0^+ \rightarrow 0^+$)
  - $\tau_n$: Bottle method
  - $\tau_n$: Beam method

- New measurement
  - $\lambda$: PERKEO-III, PRL122, 242501 (2019)
  - $V_{ud}$: Unitary with new radiative correction

- $\lambda$: Another new measurement

aSPECT, arXiv:1908.04785v1
Neutron dark decay
Neutron dark decay

This paper suggested that the discrepancy can be explained by previously unobserved dark matter decay modes with 1% of usual beta decay.

Three decay mode candidates, where $\chi$ and $\phi$ are dark matters:

- $n \rightarrow \chi\gamma$  \quad (937.900 \text{ MeV} < m_\chi < 938.783 \text{ MeV})
- $n \rightarrow \chi e^+e^-$  \quad (937.900 \text{ MeV} < m_\chi < 938.543 \text{ MeV})
- $n \rightarrow \chi\phi$  \quad (937.900 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV})

The arrowed mass ranges are very short.
- These boundaries come from the stability of proton and $^9\text{Be}$. 

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

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(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)
Decay mode: \( n \rightarrow \chi \gamma \)

- The predicted energy range of gamma ray is \( 0.782 \text{ MeV} < E_\gamma < 1.664 \text{ MeV} \).
- The dark decay emits monochromatic gamma ray.
  - No gamma ray peak was observed with a germanium detector.
Decay mode: $n \to \chi e^+ e^-$

- They searched dark decay branch, $n \to \chi e^+ e^-$, in the electron spectrum data taken for $\lambda$ measurement (PERKEO-II).
- Constraints on the Dark Matter Interpretation $n \to \chi e^+ e^-$ of the Neutron Decay Anomaly with the PERKEO II experiment
- This work constraints electrons energy for $37.5 \text{ keV} < E_{e^+e^-} < 664 \text{ keV}$ with 5$\sigma$.
- $E_{e^+e^-} < 30 \text{ keV}$ is still alive.

Phys. Rev. Lett. 122, 222503
Decay mode: $n \rightarrow \chi \phi$

- Neutron star gives a constraint on characteristics of $\chi$.
  - Suppose $m_\chi \sim m_n$, neutron star whose mass is over $0.7M_\odot$ cannot be exist.
  - Actually $2M_\odot$ neutron stars are observed and they require $m_\chi = 1.2$ GeV.
  - $\chi$ must have repulsive self-interactions.

APR: calculated by Akmal, Pandharipande, and Ravenhal
Stiff & Soft: uncertainties associated with the nuclear interactions

**Figure 1. Hybrid EOS and underlying nuclear EOS.**

The standard maximally stiff EOS, the speed of sound in the high-density region $\Sigma = \chi^5 - \chi^3$, has been widely used to describe neutron matter.

The curves labelled APR, calculated by Akmal, Pandharipande, and Ravenhal, are consistent with our current understanding of Ravenhal labeled APR, calculated by Akmal, Pandharipande, and Ravenhal.

The curves labelled soft use a nuclear EOS with $\chi = 5$, has been widely used to describe neutron matter. The stiff EOS is obtained by using the largest pressure up to the maximum mass of neutron stars compatible with nuclear constraints from nuclear physics and is extrapolated to a high density to ensure that it produces a low pressure compatible with neutron matter calculations.

The standard nuclear EOS at small densities is shown as dash-dotted curves. The stiff EOS curves terminate at the maximum mass. For the stars predicted by the standard nuclear EOS as dash-dotted curves. The stiff EOS curves terminate at the maximum mass. For the stars predicted by the standard nuclear EOS as dash-dotted curves. The stiff EOS curves terminate at the maximum mass. For the stars predicted by the standard nuclear EOS as dash-dotted curves.

In what follows, we shall use these EOSs to demonstrate interesting values of the speed of sound in the high-density region $\Sigma = \chi^5 - \chi^3$, has been widely used to describe neutron matter.

Adding a dark baryon with baryon number and mass in the range $0.01 < m_\chi < 0.1$. The rate of production of dark baryons is small compared to the neutron decay lifetime.

Neutron decay channel $n \rightarrow \chi \phi$ must have repulsive self-interactions. Any exotic neutron decay channel must have repulsive self-interactions.

### Decays into Hadrons

- $n \rightarrow \chi \phi$

### Production of Dark Baryons

- Proton decay into a dark baryon and a lepton:
  - $p \rightarrow \chi \nu_e$

The mixing angle is suppressed at a finite momentum, i.e., $\chi < \chi^2$.

The existence of a weakly interacting dark matter candidate which carries baryon number and has a mass in the range $0.01 < m_\chi < 0.1$ can be robustly excluded.

### Constraints from Observations

- $m_\chi = 1.2$ GeV is consistent with observations of neutron stars.

### Summary

- Neutron star gives a constraint on characteristics of $\chi$.
- $m_\chi \sim m_n$, neutron star whose mass is over $0.7M_\odot$ cannot be exist.
- $2M_\odot$ neutron stars are observed and they require $m_\chi = 1.2$ GeV.
- $\chi$ must have repulsive self-interactions.

**Figure 1. Hybrid EOS and underlying nuclear EOS.**

The EOS labeled soft uses a nuclear EOS with $\chi = 5$.

The curve labelled soft uses a nuclear EOS with $\chi = 5$. The curve labelled APR, calculated by Akmal, Pandharipande, and Ravenhal, is consistent with our current understanding of Ravenhal labeled APR, calculated by Akmal, Pandharipande, and Ravenhal.

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Lifetime measurement at J-PARC
Measurement principle

- Neutron lifetime is calculated from the number of beta decay and $^3$He absorption.
- This is an in situ detection system of the neutron decay and flux.

\[
\tau_n = \frac{1}{\rho \sigma \nu} \frac{S_{\text{He}}/\epsilon_{\text{He}}}{S_\beta/\epsilon_\beta}
\]

<table>
<thead>
<tr>
<th>(\tau_n)</th>
<th>Neutron Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho)</td>
<td>$^3$He density</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>$^3$He neutron absorption cross section</td>
</tr>
<tr>
<td>(\nu)</td>
<td>Neutron velocity</td>
</tr>
<tr>
<td>(S_\beta)</td>
<td>Number of beta decay signal</td>
</tr>
<tr>
<td>(S_{\text{He}})</td>
<td>Number of $^3$He absorption signal</td>
</tr>
<tr>
<td>(\epsilon)</td>
<td>Cut efficiency</td>
</tr>
</tbody>
</table>

**Time Projection Chamber (TPC)**

\[n + ^3\text{He} \rightarrow p + ^3\text{H}\]

- $^3$He absorption
  - $= 572$ keV
  - $= 191$ keV

- beta decay
  - $< 0.754$ keV
  - $< 782$ keV

**TPC Gas**

$^4\text{He}:CO_2:^3\text{He} = 85\text{ kPa}:15\text{ kPa}:100\text{ mPa}$
Neutron is produced by injecting proton beam to mercury target.

**Beam line property**
- Neutron energy: \(~10\) meV
- Neutron velocity: \(~1000\) m/s
- Beta decay rate: 0.1 cps
- $^3$He absorption rate: 2.5 cps

**Spin Flip Chopper** makes short neutron bunches to reduce background.

$^6$LiF shutter is a 5 mm thick $^6$LiF plate to control neutron beam.

Cosmic veto counters is plastic scintillators to identify cosmic ray.
Acquired data

- We acquired 6 measurement series.
  - One measurement is corresponding to one gas set (~ one week).
  - In this talk, the datasets (until 2016) were used for analysis.
  - Total beam time was 282 hours.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Date</th>
<th>MLF power [kW]</th>
<th>Beam time [hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>May 2014</td>
<td>300</td>
<td>35.3</td>
</tr>
<tr>
<td>II</td>
<td>April 2015</td>
<td>500</td>
<td>15.8</td>
</tr>
<tr>
<td>III</td>
<td>April 2016</td>
<td>200</td>
<td>17.5</td>
</tr>
<tr>
<td>IV</td>
<td>April 2016</td>
<td>200</td>
<td>72.7</td>
</tr>
<tr>
<td>V</td>
<td>May 2016</td>
<td>200</td>
<td>69.4</td>
</tr>
<tr>
<td>VI</td>
<td>June 2016</td>
<td>200</td>
<td>71.1</td>
</tr>
</tbody>
</table>
Analysis

- We counted the number of $S_\beta$, $S_{\text{He}}$ using
  - time of flight
  - energy deposit
  - track geometry.

- Cut efficiencies $\varepsilon_\beta$, $\varepsilon_{\text{He}}$ were calculated by simulation.

- Background contamination for $S_\beta$ was estimated by simulation.
  - The scattering neutrons produce this irremovable background.

\[
\tau_n = \frac{1}{\rho \sigma v} \left( \frac{S_{\text{He}}}{\varepsilon_{\text{He}}} - \frac{S_\beta}{\varepsilon_\beta} \right)
\]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Maximum deposit energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25 keV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Entry</th>
<th>Distance from beam axis [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>48 mm</td>
</tr>
</tbody>
</table>

\[5333 \pm 7 \text{ barn} \]

\[2200 \text{ m/s}\]
Results

- The neutron lifetime was calculated for each measurement.

- The combined results from 2014 to 2016 is

\[ \tau_n = 896 \pm 10 \text{ (stat)} \pm 14 \text{ (syst)} \text{ sec} \]
Results

• Our result is plotted on the neutron lifetime history.
  • It is consistent with the other beam method and $1.0\sigma$ away from the storage method.
  • Upgrade projects are ongoing to achieve our goal precision of 0.1% (1 sec).

\[
\tau_n = 896 \pm 10 \text{ (stat)} ^{+14/-10} \text{ (syst)} \text{ sec}
\]
Upgrade plans

- Neutron beam upgrade
  - Neutron bunching machine (SFC) coil and mirror will be enlarged to transport more neutron beam.
  - Five times beam will be available. And **100 days** measurement achieves 0.1% (1 sec) accuracy.

- Low gas pressure operation
  - Lower scattering neutron in the TPC gas leads lower backgrounds (×1/2-1/10).
  - New ASIC amplifier was developed for lower power consumption (×1/50) and higher gain (×1-10) compared to current amp.

- Solenoidal magnet background suppression
  - Background electron coming from detector walls will be suppressed by magnetic field (×1/20).
  - The detector commissioning was completed. We will have a beam test on the next month.
Summary

• Neutron lifetime is an important parameter for BBN and CKM matrix, however there is $8.6 \text{ s (4.0σ)}$ deviation between two methods of measurement.

• The discrepancy may be explained by unobserved neutron dark decay modes.
  • Some of them were already eliminated.

• We are measuring the neutron lifetime at J-PARC MLF BL05.
  • The acquired data (2014-2016) were analysed.

• Our result is

$$\tau_n = 896 \pm 10 \text{ (stat)} ^{+14}_{-10} \text{ (syst) sec}$$

• Upgrade plans are ongoing
  • Beam optics upgrade makes beam intensity by 5 times
  • Low gas pressure operation suppress the background
  • Magnetic field suppress the background