Neutron lifetime anomaly and symmetries

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1. Neutron lifetime & Big-bang nucleosynthesis

Baryon density $\Omega_b h^2$

D/H

$^4\text{He}$

$^3\text{He}/H$

$\eta \times 10^{10}$

Baryon-to-photon ratio $\eta$

$^7\text{Be}$

$^7\text{Li}$

$^1\text{H}$

$^2\text{H}$

$^3\text{H}$

R.H. Cyburt et al., JCAP 0811, 012 (2008)
SBBN vs. Abundance data vs. WMAP

\[ \tau_n = 885.7 \pm 0.8 \text{ s (PDG2004)} \]
\[ \tau_n = 878.5 \pm 0.7 \pm 0.3 \text{ s (PNPI-ILL)} \]

\[ \tau_n \downarrow \rightarrow g_A \uparrow \rightarrow n/p \downarrow \rightarrow ^4\text{He}/^1\text{H} \downarrow \]

\[ \Delta[^4\text{He}/^1\text{H}](^3\text{He}(d,p)^4\text{He}:4\%)=0.0022 \]
\[ \Delta[^4\text{He}/^1\text{H}](\text{obs.})=0.003 \]
\[ \Delta[^4\text{He}/^1\text{H}](\tau_n:0.8\%)=0.0017 \]

G.J. Mathews, T. Kajino, T. S.
PRD71 (2005) 021302
Planck 2013

\[ t_n = 887.7 \pm 1.2 \text{(stat)} \pm 1.9 \text{(sys)} \, \text{s (NIST, 2013)} \]

Planck 2013

\[ t_n = 878.5 \pm 0.7 \text{(stat)} \pm 0.3 \text{(sys)} \, \text{s (PNPI, 2008)} \]

Precise data of \( t_n \) is indispensable for stringent test of BBN models!!
Current status of experimental data of neutron lifetime $\tau_n$

Decay rate in flight

Survival rate in storage
Unitarity test of CKM matrix

\[ |V_{us}| = 0.2255(19) \quad \text{(decays of K, Y, tau)} \]

\[ |V_{ub}| \sim 10^{-5} \]

\[ V_{ud} = 0.97418(27) \quad \text{(}0^+\rightarrow0^+\text{)} \]

\[ 0.9746(22) \quad \text{(} \tau_n \text{, PDG2008)} \]

\[ 0.9786(22) \quad \text{(} \tau_n \text{, Serebrov 2005)} \]

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(14) \quad \text{(}0^+\rightarrow0^+\text{)} \]

\[ 1.0007(44) \quad \text{(} \tau_n \text{, PDG2008)} \]

\[ 1.0085(44) \quad \text{(} \tau_n \text{, Serebrov 2005)} \]
Experimental method

(A) Decay-rate measurement (Sussex-ILL-NIST)

\[ R = \frac{dN}{dt} = \frac{N}{\tau_n} \]

(B) Survival-prob. measurement (PNPI-ILL-JINR)

\[ N(t) = N_0 \exp \left( -\frac{t}{\tau_n} \right) \]
**NIST experiment**  J.S.Nico et al., PRC71, 055502 (2005)

\[
N_n = L \int_A \frac{\Phi_n(v)}{v} \, da
\]

\[
R_p = \frac{\dot{N}_p}{\tau_n} = \frac{\varepsilon_p L}{\tau_n} \int_A \frac{\Phi_n(v)}{v} \, da
\]

\[
R_\alpha = \frac{\dot{N}_\alpha}{\tau_n} = \varepsilon_{th} v_{th} \left[ \sigma_{th}(n, \alpha) \right] N_{6Li} \int_A \frac{\Phi_n(v)}{v} \, da
\]

\[
\Rightarrow \frac{R_p}{R_\alpha} = \tau_n^{-1} \left( \frac{\varepsilon_p \sigma_{th} N_{6Li}}{\varepsilon_{th} v_{th}} \right) L
\]
PNPI-ILL experiment
A.P. Serebrov et al., PRC78, 035505 (2008)

- Fomblin (no-H oil) coating
  $\rightarrow$ UCN loss; $2 \times 10^{-6}$ /collision

- rotatable bottle
  $\rightarrow$ gravitational spectrometer
Result

\[ \tau_n = 878.5 \pm 0.7 \text{ [stat]} \pm 0.3 \text{ [sys]} \text{ (sec)} \]
Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort
- - - Is it an evidence of a new physics?

Neutron decay to dark sector with branching ratio of 1%

\[ n \rightarrow \text{Dark Matter} + \gamma \]
\[ n \rightarrow \text{Dark Matter} + \text{Dark Matter}' \]
\[ n \rightarrow \text{Dark Matter} + e^+e^- \]

B. Fornal and B. Grinstein, PRL120, 191801 (2018)
n $\rightarrow$ Dark Matter + $\gamma$

Constraints from Q-values of n and $^9$Be
$\rightarrow$ $0.782$ MeV < $E_\gamma$ < $1.664$ MeV

Z. Tang et al., PRL121, 022505 (2018)
Neutron disappearance inside the nucleus

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Constraint from $^{11}$Be decay width
Neutron-Mirror Neutron Oscillation

Anti-neutron \( \bar{n} \) \( \psi_{\bar{n}} = CP\psi_n \)

Mirror-neutron \( n' \) \( \psi_{n'} = P\psi_n \)

\[
\left( SU(3) \times SU(2) \times U(1) \right) \times \left( SU(3)' \times SU(2)' \times U(1)' \right)
\]
$$H_{nn'} = \begin{pmatrix} \Delta m - \mu_n B & 0 & 2\varepsilon & 0 \\ 0 & \Delta m + \mu_n B & 0 & 2\varepsilon \\ 2\varepsilon & 0 & -\Delta m & 0 \\ 0 & 2\varepsilon & 0 & -\Delta m \end{pmatrix}$$

* Mirror B is omitted.

$$P_{n\rightarrow n'}(t) = \frac{1}{2} \sin^2 2\theta_B^\pm$$, where

$$\tan 2\theta_B^\pm = \frac{2\varepsilon}{\Delta m \mp \mu_n B}$$

$$\rightarrow P_{n\rightarrow n'} \rightarrow 1$$, if $$\mu_n B \approx \pm \Delta m$$

Cf. MSW effect

In case of NIST experiment,

$$B = 4.6 \ [T] \rightarrow \mu_n B = 2.77 \times 10^{-7} \ [eV]$$

$$P_{nn'} = \frac{\Delta \tau_n}{\tau_n} \simeq 0.01 \rightarrow \sin^2 2\theta_B^\pm \simeq 0.02 \rightarrow \tan 2\theta_B^\pm \simeq 0.144$$

$$\rightarrow \Delta m \sim \varepsilon \sim 3.6 \times 10^{-6} \ [eV] = 3.6 \ [\mu eV]$$
\[ N_n = L \int_A \frac{\Phi_n(v)}{v} \, da \]

\[ R_p = \dot{N}_p = \frac{\varepsilon_p L}{\tau_n} \int_A \frac{\Phi_n(v)}{v} \, da \]

\[ R_\alpha = \dot{N}_\alpha = \varepsilon_{th} v_{th} \left[ \sigma_{th} (n, \alpha) \right] N_{6Li} \int_A \frac{\Phi_n(v)}{v} \, da \]

\[ \Rightarrow \frac{R_p}{R_\alpha} = \tau_n^{-1} \left( \frac{\varepsilon_p \sigma_{th} N_{6Li}}{\varepsilon_{th} v_{th}} \right) L \]
Our method

--- simultaneous measurement of neutron beta-decay and $^3\text{He}(n,p)^3\text{H}$ with the same detector (Time-Projection Chamber)

Cold Neutron

$E_n \sim 4\text{meV}$

$\beta$-decay

$^3\text{He}(n,p)^3\text{H}$ (Flux monitor)

$\tau_n = \frac{1}{\sigma_{^3\text{He}}(v)v\rho} \left( \frac{N_{^3\text{He}}}{\varepsilon_{^3\text{He}}} \right) \left( \frac{N_\beta}{\varepsilon_\beta} \right)$

No mag. field!
BL05 - the NOP beamline at J-PARC/MLF

Performance of BL05 Beam line

Beam flux at 1MW
- $3.9 \times 10^7$ n/cm$^2$/s (23mrad x 9mrad)
- $9.4 \times 10^7$ n/cm$^2$/s (11mrad x 9mrad)
- $4.3 \times 10^5$ n/µstr/cm$^2$/s

$E_n \sim 4$meV
J-PARC/MLF/BL05

Y. Arimoto et al.,
Prog. Theor. Exp. Phys. 02B007 (2012)

γ-ray shield (Fe)

Spin-Flip Chopper

DAQ

TPC

Gas line
Detector; Time Projection Chamber

- Anode wire: 29 of W–Au wires (+1750V)
- Field wire: 28 of Be–Cu (0V)
- Cathode wire: 120 of Be–Cu (0V)
- Drift length: 30 cm (~9000V)
- Gas mixture: He:CO2=85kPa:15kPa
- TPC size (mm): 300,300,970

High efficiency detection for both of β-decay and ³He reaction
PEEK frame & inner ⁶Li wall suppress BG. S/N ~ 1:1
Spin-Flip Chopper

K. Taketani et al.,
NIM A634, S134-S137

Polarized Neutrons → Spin flipper → Magnetic super mirror → Detector

Beam ON : Beam OFF ~400 : 1

TOF [msec]
Result

Our result

\[ \tau_n = 894.6 \pm 8.8 \text{ sec} \]

- 1.6\( \sigma \) with Storage method
- Upgrade projects are ongoing to achieve our goal precision of 1 sec
Systematic uncertainties
Result

Our result

$$\tau_n = 894.6 \pm 8.8 \pm 9.7 \text{ sec}$$

- Beam method: 888.0 ± 2.0 s
- Storage method: 879.4 ± 0.6 s

- 1.6σ with Storage method
- upgrade projects are ongoing to achieve our goal precision of 1 sec
Result

\[ \tau_n = 894.6 \pm 8.8 \text{ sec} \]

- 1.6\( \sigma \) with Storage method
- upgrade projects are ongoing to achieve our goal precision of 1 sec

Lattice QCD!!

Magnetic trap!!
\[ \tau_n = \frac{4908.6(1.9)}{\left| V_{ud} \right|^2 (1 + 3g_A^2)} = 884(15) \text{ [s]} \]
Summary

Slow neutrons provide unique opportunities for studies of fundamental physics which is related to the evolution of the universe as well as the origin of elements.

Example;

- $\tau_n$ should be determined with $\sim 0.1\%$ accuracy for BBN.
- Study of T-violation and n-nbar oscillation are important for understanding the origin of baryon number in the universe.

and more...