Neutron lifetime anomaly

Bartosz Fornal

University of Utah

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In collaboration with: Benjamin Grinstein
How does our Universe work?
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How does our Universe work?
We know quite a lot, but there is much more that we don’t understand!
We know quite a lot, but there is much more that we don’t understand!
What exactly is dark matter?
What exactly is dark matter?
Neutron decay in the Standard Model

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
Neutron lifetime in the Standard Model

Theoretical prediction

\[ \tau_n = \frac{4908.6(1.9) \text{ s}}{|V_{ud}|^2 (1 + 3g_A^2)} \]


\[ \mathcal{M} = \frac{1}{\sqrt{2}} G_F V_{ud} g_V \left[ \bar{p} \gamma_\mu n - g_A \bar{p} \gamma_5 \gamma_\mu n \right] \left[ \bar{e} \gamma^\mu (1 - \gamma_5) \nu \right] \]

Using the PDG average for \( g_A \)

\[ 880.5 \text{ s} < \tau_n < 886.0 \text{ s} \]

Chang et al., Nature 558, 91 (2018)

Lattice QCD result

\[ 870 \text{ s} < \tau_n < 900 \text{ s} \]
Bottle experiments

Decaying exponential fit to data points

\[
\frac{dN_n(t)}{dt} = -\frac{N_n(t)}{\tau_n}
\]

\[
N_n(t) = N_n(0) e^{-t/\tau_n}
\]

\[
\tau_{\text{bottle}} = \tau_n
\]

Source: https://www.scientificamerican.com
Beam experiments

Only the decay rate to **protons** is measured

\[
\frac{dN_p(t)}{dt} = - \frac{N_n(t)}{\tau_n^{\text{beam}}}
\]

Source: https://www.scientificamerican.com
Beam experiments

Only the decay rate to protons is measured

\[
\frac{dN_p(t)}{dt} = - \frac{N_n(t)}{\tau_n^{\text{beam}}}
\]

\[
\tau_n^{\text{beam}} = - \frac{N_n}{dN_p/dt}
\]
Beam experiments

Only the decay rate to protons is measured

\[ \frac{dN_p(t)}{dt} = - \frac{N_n(t)}{\tau_n^{\text{beam}}} \]

\[ \tau_n^{\text{beam}} = - \frac{N_n}{dN_p/dt} = - \frac{N_n}{\text{Br}(n \rightarrow p + \text{anything}) \cdot dN_n/dt} \]
Beam experiments

Only the decay rate to protons is measured.

\[
\frac{dN_p(t)}{dt} = - \frac{N_n(t)}{\tau_n^{\text{beam}}} \]

\[
\tau_n^{\text{beam}} = - \frac{N_n}{dN_p/dt} = - \frac{N_n}{\text{Br}(n \rightarrow p + \text{anything}) dN_n/dt} \]
Beam experiments

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\]

\[
\tau_n^{\text{beam}} = -\frac{N_n}{dN_p/dt} = \frac{N_n}{\text{Br}(n \rightarrow p + \text{anything}) dN_n/dt}
\]

\[
\tau_n \geq \tau_n^{\text{bottle}}
\]

Source: https://www.scientificamerican.com
Neutron lifetime measurements

Beam method average\(^*\) (blue zone): 888.0 ± 2.1 seconds

Bottle method average (green zone): 879.6 ± 0.6 seconds

Disagreement

\[ \tau_{n}^{\text{beam}} = 888.0 \pm 2.1 \text{ s} \]

\[ \tau_{n}^{\text{bottle}} = 879.3 \pm 0.8 \text{ s} \]

Discrepancy

\[ \frac{\Delta \tau_{n}}{\tau_{n}} \approx 1\% \]

4 σ
**Neutron dark decay**

**Dark Matter Interpretation of the Neutron Decay Anomaly**

Bartosz Fornal and Benjamín Grinstein

*Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA*

(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

\[
\text{Br}(n \rightarrow p + \text{anything}) \approx 99\%
\]

\[
\text{Br}(n \rightarrow \text{anything} \neq p) \approx 1\%
\]

\[n \rightarrow \text{dark particle(s)} + \text{SM particle(s)}\]

\[n \rightarrow \text{dark particles}\]
# Nuclear physics bounds

## p MEAN LIFE

A test of baryon conservation. See the "p Partial Mean Lives" section below for limits for identified final states. The limits here are to "anything" or are for "disappearance" modes of a bound proton (p) or (n). See also the 3ν modes in the "Partial Mean Lives" section. Table 1 of BACK 03 is a nice summary.

<table>
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<tr>
<th>LIMIT (years)</th>
<th>PARTICLE</th>
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<th>COMMENT</th>
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- - - We do not use the following data for averages, fits, limits, etc. - - -
Nuclear physics bounds

$p$ MEAN LIFE

A test of baryon conservation. See the “$p$ Partial Mean Lives” section below for limits for identified final states. The limits here are to “anything” or are for “disappearance” modes of a bound proton ($p$) or ($n$). See also the $3\nu$ modes in the “Partial Mean Lives” section. Table 1 of BACK 03 is a nice summary.

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<td>SNO</td>
</tr>
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We do not use the following data for averages, fits, limits, etc.

$^{16}$O limits valid only if sum of masses of neutron decay products $M_f < m_n - 20.9$ MeV

$m_n - 20.9$ MeV < $M_f$ < $m_n$ is not ruled out this way!
Nuclear physics bounds – $^9$Be

$^9$Be would not be stable if $M_f < m_n - S_n$

$^9$Be is stable if $m_n - S_n < M_f < m_n$

$937.900 \text{ MeV} < M_f < 939.565 \text{ MeV}$
$^8$Be is not stable with respect to the decay into two alpha particles, thus one gets a more restrictive bound on $M_f$

\[ 937.993 \text{ MeV} < M_f < 939.565 \text{ MeV} \]

*Pfutzner & Riisager, PRC 97, 042501(R) (2018)*
New neutron decay channels

$937.993 \text{ MeV} < M_f < 939.565 \text{ MeV}$

- neutron $\rightarrow$ dark particle + photon
- neutron $\rightarrow$ dark particle + $e^+e^-$
- neutron $\rightarrow$ two dark particles
- neutron $\rightarrow$ ...
Neutron → dark particle + photon

Dark particle mass
\[ 937.993 \text{ MeV} < m_\chi < 939.565 \text{ MeV} \]

Photon energy
\[ 0 < E_\gamma < 1.572 \text{ MeV} \]

Dark matter case
\[ 0.782 \text{ MeV} < E_\gamma < 1.572 \text{ MeV} \]
Neutron $\rightarrow$ dark particle + photon

Effective Lagrangian

$$\mathcal{L}_{1}^{\text{eff}} = \bar{n} \left( i \slashed{\partial} - m_n + \frac{g_{n\epsilon}}{2m_n} \sigma^{\mu\nu} F_{\mu\nu} \right) n + \bar{\chi} \left( i \slashed{\partial} - m_\chi \right) \chi + \varepsilon (\bar{n} \chi + \bar{\chi} n)$$

$$\mathcal{L}_{n\rightarrow\chi\gamma}^{\text{eff}} = \frac{g_{n\epsilon}}{2m_n} \frac{\varepsilon}{(m_n - m_\chi)} \bar{\chi} \sigma^{\mu\nu} F_{\mu\nu} n$$

Neutron dark decay rate

$$\Delta \Gamma_{n\rightarrow\chi\gamma} = \frac{g_{n\epsilon}^2 \epsilon^2}{8\pi} \left( 1 - \frac{m_\chi^2}{m_n^2} \right)^3 \frac{m_n \varepsilon^2}{(m_n - m_\chi)^2}$$
Model 1
(minimal)

Lagrangian

\[ \mathcal{L}_1 = \left( \lambda_q \varepsilon^{ijk} u_{Li}^c d_{Rj} \Phi_k + \lambda_\chi \Phi^* i \bar{\chi} d_{Ri} + \text{h.c.} \right) - M_\Phi^2 |\Phi|^2 - m_\chi \bar{\chi} \chi \]

\[ \varepsilon = \frac{\beta \lambda_q \lambda_\chi}{M_\Phi^2} \]

where

\[ \langle 0 | \varepsilon^{ijk} (u_{Li}^c d_{Rj}) d_{Rk}^\rho |n \rangle = \beta \left( \frac{1+\gamma_5}{2} \right)^\rho \sigma u^{\sigma} \]

To explain the neutron lifetime discrepancy

\[ \Delta \Gamma_{n \to \chi \gamma} \approx \frac{\Gamma_n}{100} \]

\[ \frac{M_\Phi}{\sqrt{|\lambda_q \lambda_\chi|}} \approx 400 \text{ TeV} \]
Neutron → two dark particles

Constraints on masses

\[ 937.993 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV} \]

\[ 937.993 \text{ MeV} < m_\tilde{\chi} \]
Neutron dark decay rate

\[ \Delta \Gamma_{n \rightarrow \chi \phi} = \frac{|\lambda_\phi|^2}{16\pi} \sqrt{f(x,y)} \frac{m_n \varepsilon^2}{(m_n - m_\chi)^2} \]

\[ f(x,y) = [(1 - x)^2 - y^2][(1 + x)^2 - y^2]^3 \]

\[ x = m_\chi/m_n \quad y = m_\phi/m_n \]

\[ \varepsilon = \frac{\beta \lambda_q \lambda_\chi}{M_\Phi^2} \]

\[ \lambda_\phi \approx 0.04 \]

\[ \Delta \Gamma_{n \rightarrow \chi \phi} \approx \frac{\Gamma_n}{100} \]

\[ \frac{M_\Phi}{\sqrt{|\lambda_q \lambda_\chi|}} \approx 1600 \text{ TeV} \]
Theoretical and experimental developments

**Theory**
- Neutron star constraints
- Self-interacting dark sector
- Repulsive DM-baryon interactions
- Baryogenesis, meson dark decays, ...

**Experiment**
- Neutron dark decays
- Nuclear dark decays
- Beam and bottle measurements
Neutron star constraints

Tolman-Oppenheimer-Volkoff equation without self-interactions

→ neutron star masses < 0.8 $M_\odot$

McKeen, Nelson, Reddy & Zhou,
PRL 121, 061802 (2018), arXiv:1802.08244

Baym, Beck, Geltenbort & Shelton,
PRL 121, 061801 (2018), arXiv:1802.08282

Motta, Guichon & Thomas,
Neutron star constraints

Tolman-Oppenheimer-Volkoff equation without self-interactions

→ neutron star masses < 0.8 $M_\odot$

Observed neutron star masses allowed if there are:

→ strong repulsive self-interactions in the dark sector

~ SIDM (Spergel & Steinhardt, PRL 84, 3760 (2000))

→ repulsive DM-neutron interactions
Model with dark sector self-interactions (1)

**Effective Lagrangian**

\[
\mathcal{L}_{\text{eff}} = \bar{n} \left( i \slashed{D} - m_n + \frac{g_n e}{2m_n} \sigma^{\mu\nu} F_{\mu\nu} \right) n \\
+ \bar{\chi} \left( i \slashed{D} - m_{\chi} \right) \chi + \varepsilon (\bar{n} \chi + \bar{\chi} n) \\
- \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\delta}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^{\mu}
\]

\[D_\mu = \partial_\mu - ig' A'_\mu\]

**Neutron dark decay**

\[n \rightarrow \chi A'\]

-Cline & Cornell, JHEP 07, 081 (2018)-

**Low-scale baryogenesis**

-Bringmann, Cline & Cornell, PRD 99, 035024 (2019)-
Model with dark sector self-interactions (2)

Dark sector Lagrangian

\[ \mathcal{L}_D = g \bar{\chi} Z^D \chi + (\lambda \phi \bar{\chi} \chi \phi + \text{h.c.}) - i g Z^\mu_D (\phi^* \partial_\mu \phi - \phi \partial_\mu \phi^*) \]

Highlights of the model:

- \( \chi \) can constitute all of the dark matter in the universe; model consistent with astrophysical constraints
- solves small-scale structure problems of \( \Lambda \)CDM
Model with DM-neutron repulsive interactions

Lagrangian

\[ \mathcal{L} = \lambda_q \epsilon^{ijk} u^c_{Li} d_{Rj} \Phi_k + \lambda_X \Phi^* i \bar{\chi} d_{Ri} + \lambda_{\phi} \bar{\chi} \chi \phi \]
\[ + \mu H^\dagger H \phi + g_{\chi} \bar{\chi} \chi \phi + \text{h.c.} \]

Grinstein, Kouvaris & Nielsen,
PRL 123 (2019) 091601

Costs energy to convert neutrons to dark matter in a neutron environment:

\[ \Delta E_0 = m_\chi - \mu_{\text{nuc}}(n_F) + \frac{n_F |g_\chi g_n|}{2m_\phi^2} > 0 \]

Zero DM density energetically favored
Other theoretical follow-ups

Neutral hadron dark decays

*Barducci, Fabbrichesi & Gabrielli, PRD 98, 035049 (2018)*

Neutron-mirror neutron oscillations

*Berezhiani, EPJ C 79, 484 (2019); Berezhiani, LHEP 118, 1 (2019); BF & Grinstein, arXiv:1902.08975*

Special case of neutron dark decay with

$\chi = n'$
Other theoretical follow-ups

Neutral hadron dark decays
Barducci, Fabbrichesi & Gabrielli, PRD 98, 035049 (2018)

Neutron-mirror neutron oscillations
Berezhiani, EPJ C 79, 484 (2019); Berezhiani, LHEP 118, 1 (2019);
BF & Grinstein, arXiv:1902.08975

Special case of neutron dark decay with $\chi = n'$
Experiment: Neutron → dark matter + photon

Los Alamos UCN

Tang et al., PRL 121, 022505 (2018)

$0.782 \text{ MeV} < E_\gamma < 1.664 \text{ MeV}$

2.2 $\sigma$ exclusion
Experiment: Neutron $\rightarrow$ dark particle $+ e^+e^-$

Los Alamos UCN

ILL, Grenoble

Sun et al., PRC 97, 052501 (2018)

Klopf et al., PRL 122, 222503 (2019)

$E_{e^+e^-} \gtrsim 2m_e + 100$ keV

$E_{e^+e^-} \gtrsim 2m_e + 30$ keV
Nuclear dark decays

Possible in unstable nuclei with $S_n < 1.572 \text{ MeV}$

$937.993 \text{ MeV} < M_f < m_n - S_n$

$^{11}\text{Li} \rightarrow ^{10}\text{Li} + \chi \rightarrow ^{9}\text{Li} + n + \chi$

$S_n(^{11}\text{Li}) = 0.396 \text{ MeV}$

Best candidate:

$^{11}\text{Be} \rightarrow ^{10}\text{Be} + \tilde{\chi}^* \rightarrow ^{10}\text{Be} + \chi + \phi$

$S_n(^{11}\text{Be}) = 0.502 \text{ MeV}$

**Pfutzner & Riisager, Examining the possibility to observe neutron dark decay in nuclei, PRC 97, 042501(R) (2018)**
Unexplained result in $^{11}$Be decays

Unexpectedly high number of $^{10}$Be nuclei produced in $^{11}$Be decays was observed

$$\text{Br } (^{11}\text{Be} \to ^{10}\text{Be} + ?) \approx 8 \times 10^{-6}$$

Riisager et al., $^{11}$Be(βp), a quasi-free neutron decay?, PLB 732, 305 (2014)

[Image: Element decay diagram and predicted branching ratios]
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Riisager et al., $^{11}\text{Be}(\beta p)$, a quasi-free neutron decay?, PLB 732, 305 (2014)

$^{10}\text{Be}$ nuclei can be produced through $\beta$-delayed proton emission, but theoretical estimates give

$$\text{Br}({^{11}\text{Be} \xrightarrow{\beta} ^{11}\text{B} \rightarrow ^{10}\text{Be} + p}) \approx 2 \times 10^{-8}$$

https://www.nndc.bnl.gov/nudat2
Unexplained result in $^{11}$Be decays

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$^{10}$Be nuclei can be produced through $\beta$-delayed proton emission, but theoretical estimates give

$$\text{Br} \left( ^{11}\text{Be} \beta \rightarrow ^{11}\text{B} \rightarrow ^{10}\text{Be} + p \right) \approx 2 \times 10^{-8}$$

Narrow resonance or dark decay ?

Pfutzner & Riisager, PRC 97, 042501(R) (2018)

https://www.nndc.bnl.gov/nudat2
$^{11}\text{Be}$ decay experiments

Are there protons in the final state of $^{11}\text{Be}$ decays?

This would test ALL neutron dark decay channels with:

$937.993 \text{ MeV} < M_f < 939.064 \text{ MeV}$

$\rightarrow$ CERN – ISOLDE

$\rightarrow$ TRIUMF

$\rightarrow$ MSU
Ongoing beam and bottle experiments

NIST Center for Neutron Research

J–PARC, Japan
Ongoing beam and bottle experiments

Add a proton detection system in bottle experiments!
Final remarks

Working models solving the neutron lifetime puzzle

Neutron dark decays with a smaller rate possible

\[ \frac{\Delta \Gamma_{n \rightarrow \chi + \ldots}}{\Gamma_n} \ll 1\% \]

+ dark Z

or

+ repulsive \( n - \chi \) interaction
Very wishful thinking

https://en.wikipedia.org, modified
Thank you!