(Entirely) Dark Decay of the Neutron

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Based on Jim Cline, J.Cornell, arXiv:1803.04961
A Solution for the Neutron Lifetime Puzzle

Bottle: $\tau_n = 879.6 \pm 0.6 \text{ s}$  \quad Beam: $\tau_n = 888.0 \pm 2.0 \text{ s}$

A neutron dark decay scenario which has not been directly experimentally tested:

Neutron decays to fermion DM candidate and a dark boson.
Low Energy Effective Model

Two new fields:
• $\chi$, Dirac fermion charged under $U(1)'$, carries baryon number
• $A'$, Dark photon

$$\mathcal{L}_{\text{eff}} = \bar{\chi}(i\partial_\mu - ig' A'_\mu - m_\chi)\chi + \bar{n}(i\partial_\mu - m_n + \mu_n \sigma^{\mu\nu} F_{\mu\nu}) n$$

$$- \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'\mu A'_\mu - \delta m \bar{n}_R \chi_L + \text{h.c.} - \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Two diagrams are shown:

1. $n \rightarrow \chi \gamma$
   $$\Gamma_{n \rightarrow \chi \gamma} \propto \frac{\mu_n^2 (\delta m)^2}{m_A'^2}$$

2. $n \rightarrow \chi A'$
   $$\Gamma_{n \rightarrow \chi A'} \propto \frac{g'^2 (\delta m)^2}{m_A'^2}$$
Mass Limits

• For the neutron to decay to $\chi + A'$: $m_\chi + m_{A'} < 939.6$ MeV

• For $^9$Be to NOT decay to $\chi + \gamma$: $m_\chi > 937.8$ MeV (this also stabilizes the proton)

• For $\chi$ to NOT decay to a proton, electron and anti-neutrino: $m_\chi < 938.8$ MeV (viable DM component)

Our benchmark values:

$$m_\chi = 937.9 \text{ MeV}$$  \hspace{1cm} (A) $m_{A'} = 1.35$ MeV

$$A' \rightarrow e^+ e^-$$

(B) $m_{A'} = 0.5$ MeV

$$A' \rightarrow 3\gamma$$
Tolman–Oppenheimer–Volkoff Limit

\[ \frac{dp}{dr} = -G\left(\rho(1 + \epsilon/c^2) + p/c^2\right) \frac{m + 4\pi r^3 p/c^2}{r(r - 2Gm/c^2)} \]

Solve numerically to find where \( p = 0 \). This gives the maximal size of a neutron star.

Observed neutron star masses.

No n-DM conversion

\( m_x \approx m_n \)

\( m_x = 1.2 \text{ GeV} \)

McKeen, et al., 2018
Baym, et al., 2018

Motta, Guichon, Thomas, 2018

n-DM conversion allowed. The conversion reduces the neutron degeneracy pressure.
Self-interactions Lead to Large Neutron Stars

The pressure from $\chi$ self-interactions ultimately causes their number density to decrease.

For 2 solar mass neutron star to exist:

$$\frac{m_{A'}}{g'} \lesssim (45 - 60) \text{ MeV}$$

Depending on nuclear equation of state.
UV Model

We need to generate neutron-χ mixing ($\delta m$) and $A'$ mass.

3 new complex scalars:
- $\Phi_1$ – SU(3)c triplet, carries U(1)' charge
- $\Phi_2$ – SU(3)c triplet
- $\phi$ – carries U(1)' charge, obtains v.e.v. ($v'$), giving mass to $A'$

Let

$$\mathcal{L} \supset \lambda_1 \bar{d}^a P_L \chi \Phi_{1,a} + \lambda_2 \epsilon^{abc} \bar{u}_a P_R d_b \Phi_{2,c} + \mu \Phi_{1,a} \Phi_{2,a}^* \phi$$

Leads to mixing term:

$$\frac{\beta \mu \lambda_1 \lambda_2 v'}{m_{\Phi_1}^2 m_{\Phi_2}^2} \bar{n} P_L \chi$$

Masses:
- $m_\phi > 1.5$ TeV to avoid LHC limits on colored scalars ATLAS, 2107
- $m_\phi = 70$ MeV (benchmark value) to avoid $n \rightarrow \phi \chi$ decays
Relic Density of Dark Matter and Dark Radiation

We assume standard thermal freeze out production.

χ Relic Abundance:

\[ \Omega_D = \frac{1 \times 10^{-25} \text{cm}^3/\text{s}}{\langle \sigma_{\text{ann}} v \rangle} \Omega_{\text{DM}} \]

A’ Relic Abundance:

- The A’ are relativistic at freeze out with large number density.
- We require they decay before they make up half of the universe’s energy density, to avoid disturbing Big Bang Nucleosynthesis/Cosmic Microwave Background.

(A) \( m_{A'} = 1.35 \text{ MeV} \)
\( \tau_{A'} < 540 \text{ s} \)

(B) \( m_{A'} = 0.5 \text{ MeV} \)
\( \tau_{A'} < 3920 \text{ s} \)

Steigman, Dasgupta, Beacom, 2012

Cirelli, et al., 2016
Limits on DM Annihilation

\[ \Phi_{\gamma,e^\pm} \propto \rho^2 \langle \sigma v \rangle \propto \frac{1}{\langle \sigma v \rangle} \]

With thermal production, larger g’ ultimately leads to reduced annihilation rate.

We consider limits on the annihilation rate from:
• Observations of dwarf spheroidal galaxies with Fermi-LAT
• Distortions of the CMB anisotropy spectrum as observed by Planck.

In both cases, Sommerfeld enhancement is important.
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\[ \chi \rightarrow A' \rightarrow 3\gamma \]

\[ m_\chi = 937.9 \text{ MeV} \]
\[ m_{A'} = 0.5 \text{ MeV} \]
\[ m_\phi = 70.0 \text{ MeV} \]

\[ \frac{\Omega_\chi}{\Omega_{DM}} = 0.08\% \]
Limits on Kinetic Mixing

Limits on $\epsilon$ come from:

- Beam dump experiments, particularly E137
- Supernova cooling limits from observations of SN 1987A
- BBN/CMB

Andreas, Niebuhr, Ringwald, 2012

Chang, Essig, McDermott, 2016
Direct Detection

An observable which depends on both $\varepsilon$ and $g$.
We use the recent limits from CRESST-III on light DM.

$\chi q A' q \chi \gamma m_\chi = 937.9 \text{ MeV}$

$\phi m_\phi = 70.0 \text{ MeV}$

$A' \rightarrow e^+ e^-$

$A' \rightarrow 3\gamma$

BBN/CMB

Stars

Supernova

Neutron

Direct Detection

CMB

BBN

Neutron

Direct Detection

Gamma

Direct Detection
Direct Detection

\[ m_{\chi} = 937.9 \text{ MeV} \]
\[ m_{A'} = 1.35 \text{ MeV} \]
\[ m_{\phi} = 70.0 \text{ MeV} \]

937.8 MeV < \( m_{\chi} \) < 938.8 MeV
1.0 MeV < \( m_{A'} \) < 1.8 MeV
Summary

• Neutron decays to SM particles + DM have been largely experimentally ruled out as viable explanations for the neutron lifetime puzzle.

• Neutron decays to multiple dark sector particles are still viable!

• The dark particle that carries baryon number in these decays must have strong repulsive self-interactions to avoid neutron star bounds.

• A dark matter + dark photon model is one way to realize this.

• The dark matter candidate in such a model is strongly constrained by astrophysical observations and cosmological considerations. It can make up no more than roughly 1% of the total DM density.
Backups
DM Self-Scattering Limits

• Neutron stars limit the $\chi$ self-scattering cross section to be:

$$\sigma_{\chi\chi} = \frac{g' A^4 m_\chi^2}{\pi m_A^4} \gtrsim 3 \times 10^{-20} \text{ cm}^2$$

Clowes, et al., 2006

• Observations of the Bullet Cluster limit

$$\frac{\sigma_{\text{DM DM}}}{m_{\text{DM}}} < 2 \times 10^{-24} \text{ cm}^2 / \text{GeV}$$

Markevitch, et al., 2004

• These limits do not apply if less than roughly 10% of the DM is strongly self-interacting. Therefore $\chi$ can be no more than 10% of the DM.

Pollack, Spergel, Steinhard, 2014