Nucleon - Light Dark Matter Annihilation through Baryon Number Violation

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base on arXiv:1808.10644 (PRD98. 075026)

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Outline

Background on neutron lifetime anomaly

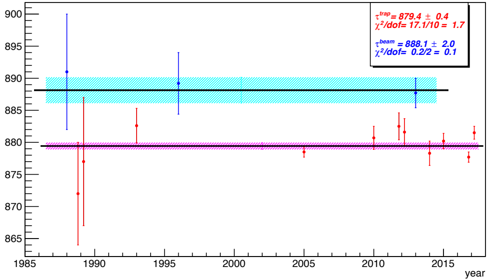


Figure: The trap (red) and beam (blue). (Z. Berezhiani 1812.11089)

Counting: remaining neutrons protons

$$\tau_{bottle} = 879.6 \pm 0.6 \text{ s} \qquad \tau_{beam} = 888.0 \pm 2.0 \text{ s} \qquad (4\sigma)$$

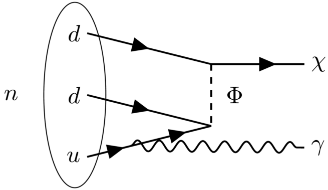
decaying neutron $>$ proton number

$$\Delta\Gamma = 7 \times 10^{-30}\text{GeV} \quad \text{or} \quad \Delta\tau \approx 8s \quad (\sim 1\%)$$

Background: Neutron dark decay

Neutron dark decay(B. Fornal et al. 1801.01124):

Color-triplet iso-singlet scalar (Φ) & Dark matter (χ)



Process:

$$n \to \chi + \gamma \quad (\sim 1\%)$$

Signal:

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

Besides, mirror model: dark neutron + photon/dark photon (1812.11089).

Note that ...

Dark matter model

A color triplet, iso-singlet scalar Φ with $Y = -\frac{1}{3}$ or $+\frac{2}{3}$ and a singlet fermionic dark matter (DM) χ

$$\begin{aligned}\mathcal{L}_1 &= \lambda_1 \Phi^* \chi d_R + \lambda_1' \Phi u_R d_R + m_\Phi^2 |\Phi|^2 + \frac{1}{2} m_\chi \bar{\chi}^c \chi + \text{c.c.} \quad \textbf{(I)} \\ \mathcal{L}_2 &= \lambda_2 \Phi^* \chi u_R + \lambda_{2ij}' \Phi d_{Ri} d_{Rj} + m_\Phi^2 |\Phi|^2 + \frac{1}{2} m_\chi \bar{\chi}^c \chi + \text{c.c.} \quad \textbf{(II)}\end{aligned}$$

where R denote right-handed fermion fields and the color indices is omitted. In model II, two down-type quarks in the second term must be different flavor due to antisymmetric color indices. Here DM is Majorana or Dirac fermion. The second terms is baryon number violation. Such as, *baryogenesis*(B. Dutta et al., 1304.0711), *small-scale problem*(G. Karananas et al., 1805.03656), *n-$\bar{n}$ oscillation*(D. McKeen et al., 1512.05359; B. Dutta et al., 1712.02713) etc. The Min$(\lambda, \lambda') \leq 0.07$ at $m_\Phi \sim \mathcal{O}$(TeV) from collider constraint. (Y. Gao et al., 1401.1825)

$\chi - n$ mixing

If the scalar $m_\Phi \gg \mathcal{O}(\text{TeV})$ and $m_\chi \sim \mathcal{O}(\text{GeV})$,

$$\mathcal{L} \supset \frac{\beta\lambda'\lambda}{m_\Phi^2}(\chi u_R d_R d_R),$$

where $\beta_{udd} \approx 0.0144$ GeV^3 ($\sim \Lambda_{QCD}^3$) from LQCD (only 1st gen.).(Aoki et al. 1705.01338).

Therefore, the (anti-) dark matter (χ) mixes with neutron (udd).

- If $m_\chi > m_p + m_e$, DM decay

$$\begin{aligned} \chi &\rightarrow p + e^- + \bar{\nu}_e \\ &\rightarrow \bar{p} + e^+ + \nu_e \end{aligned}$$

- If $m_\chi < m_p - m_e$, Proton decay

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

Thus,

$$m_p - m_e < m_\chi < m_p + m_e \quad \text{or} \quad |m_\chi - m_p| < m_e$$

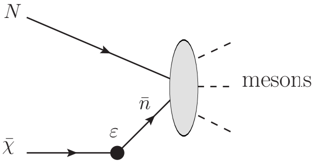
Nucleon - Dark matter Annihilation

In $\mathcal{L} \supset \frac{\beta\lambda'\lambda}{m_\Phi^2}(\chi u_R d_R d_R)$, we define the mixing parameter: $\varepsilon = \frac{\beta\lambda'\lambda}{m_\Phi^2}$

The mixing angle: $\theta = \frac{\varepsilon}{m_n - m_\chi} = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)} \quad (\varepsilon \ll m_n - m_\chi)$

where $\beta_{udd} \approx 0.0144$ GeV^3, $m_n \approx 0.94$ GeV and assume $\lambda, \lambda' \sim \mathcal{O}(1)$.

The nucleon - DM annihilation cross section $\sigma_{N\chi}$,



$$\sigma_{N\chi} = \theta^2 \sigma_{N\bar{n}}$$

$$\theta = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)}$$

The annihilation process for nucleon-antinucleon is $2 \to n$ $(n \geq 2)$, thus $\sigma_{N\bar{n}}$ is fixed by experimental data.

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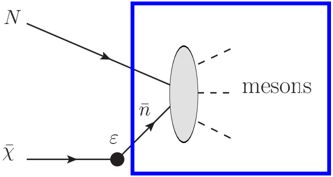

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$\bar{n} - N(A)$ Annihilation

At low incident momentum($p_{\bar{n}} < 1\text{GeV}$),

- $\sigma v(P_{\bar{n}} = 0) = 44 \pm 3.5$ mb when $v \to 0$ (Mutchler et al.PRD38, 742)
- $\sigma(P_{\bar{n}}, A) = \sigma_0(P_{\bar{n}})A^{2/3}$, (Astrua et al. Nucl. Phys. A697, 209)

The cross section σ_0 is insensitive to $\alpha = Z/A$, $Z(A)$ is proton (atomic) number [six different nuclei: C, Al, Cu, Ag, Sn and Pb targets], thus

$$\sigma_0(P_{\bar{n}}) \simeq \sigma_{p\bar{n}}(P_{\bar{n}}) \approx \sigma_{n\bar{n}}(P_{\bar{n}})$$

Then the annihilation cross section for dark matter and nucleon (nucleus)

$$\begin{aligned} \sigma_{\chi N} v_\chi &\approx 44 \times \frac{(\beta\lambda'\lambda)^2}{m_\Phi^4(m_n - m_\chi)^2} \\ \sigma_{\chi A} v_\chi &\approx 44 \times \frac{(\beta\lambda'\lambda)^2 A^{2/3}}{m_\Phi^4(m_n - m_\chi)^2} \end{aligned}$$

Experimental search

DM annihilation to nucleons, producing several mesons(decay to muon), can be probed to stringent limits at large-volume water Cherenkov detectors experiment. Due to same final state with $N-\bar{n}$ annihilation, the constraint is given by n-$\bar{n}$ oscillation search at Super Kamiokande (SK), SNO or JUNO.

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

Table: The branching ratios for the $\bar{n}$+nucleon annihilations. These factors were derived from $\bar{p}p$ and $\bar{p}d$ bubble chamber data.(SK,1109.4227)

Constraint

In SK, the dark matter can annihilate with proton and oxygen nucleus.

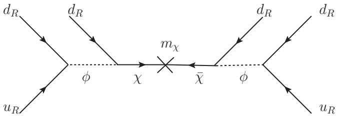
The corresponding event rate,

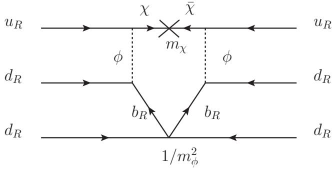
$$R = \frac{\mathrm{d}N_{\mathrm{t}}}{\mathrm{d}t} = A_{eff}\phi_\chi = \eta N_{\mathrm{t}} n_\chi \sigma_{\chi\mathrm{t}} v_\chi$$

where the effective area of target $A_{eff} = \eta\sigma_{\chi\mathrm{t}} N_{\mathrm{t}}$ and the flux density $\phi_\chi = n_\chi v_\chi$. $\eta = 12.1\%$, $n_\chi \simeq 0.43\,\mathrm{cm}^{-3}$, $N_p \simeq 6.13 \times 10^{33}$, $N_{\mathrm{o}} \simeq 3.06 \times 10^{33}$ (SK, 1109.4227). Here 22.5 kton water during 1489 live-day.

Comparison: n-$\bar{n}$ oscillation

If the dark matter is the Majorana fermion, $\mathcal{L} \supset \frac{\beta\lambda'\lambda}{m_\Phi^2}(\chi u_R d_R d'_R)$ is $\Delta B = 1$ operater, it generates n-$\bar{n}$ oscillation.





1st gen. (1512.05359) 3rd gen. (1712.0271)

$\beta_{udd} = 0.0144\text{GeV}^3$(1st gen.). $\tau_{n\bar{n}} > 2.7 \times 10^8$ s (SK)

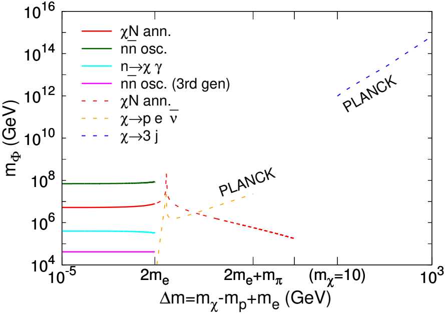
Besides, neutron dark decay($n \to \chi + \gamma$).

$m_\Phi - \Delta m$ limits

$\chi - N$ annihilation: $m_\Phi \sim \mathcal{O}(10^7)$GeV, Majorana & Dirac fermion.
If $m_\chi > m_p + m_e$, DM decay:

- $\chi \to p + e^- + \bar{\nu}$ $\quad (m_p + m_e < m_\chi < m_p + m_e + m_\pi)$
- $\chi \to 3$ jets $\quad (m_\chi > 10$ GeV$) \quad (b -$ quark$)$

where $\tau_\chi = 10^{24}$ s from PLANCK with $\mathrm{e^+e^-}$ and $\mathrm{b\bar{b}}$.(1610.06933)
In addition, mixing angle $\theta = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)}$, exits a pole when $m_\chi = m_n$.



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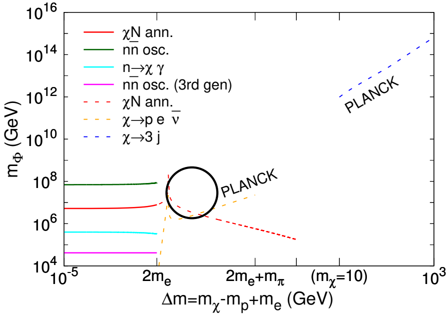


Alternative searches-Indirect detection

- The DM annihilates with hydrogen and helium of ISM (Interstellar medium).
- The differential γ-flux,

$$\frac{\mathrm{d}\phi_\gamma(\chi N)}{\mathrm{d}E\mathrm{d}\Omega} = \theta^2 \frac{\langle v\sigma_{\chi N}\rangle}{8\pi m_\chi m_N}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\int_{\mathrm{los}} \rho_\chi \rho_B \mathrm{d}s$$

$$\frac{\mathrm{d}\phi_\gamma(\chi\chi)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{\langle v\sigma_{\chi\chi}\rangle}{8\pi m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\int_{\mathrm{los}} \rho_\chi^2 \mathrm{d}s$$

where ρ_B smaller than ρ_χ two orders of magnitude.

- The $\theta^2\langle\sigma v\rangle(\pi^0)_{\gamma\gamma} \sim \mathcal{O}(10^{-41})\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_\Phi \sim \mathcal{O}(10^7)$ GeV , while $\langle\sigma v\rangle(\chi\bar{\chi})_{\gamma\gamma} \geq 10^{-30}\,\mathrm{cm}^3\mathrm{s}^{-1}$ from Fermi-LAT, thus it is impossible to detect the signal from $\chi - N$ annihilation at present.

Alternative searches-Neutron star (NS) heating

The DM is accelerated as it approaches a neutron star.

- DM elastically scatter off neutron in NS.
- DM annihilation in NS.

The total Energy is $E_t \approx 1.35 m_\chi$, where $1\text{GeV} \leq m_\chi \leq 10^6\text{GeV}$.
For an typical old NS, $M = 1.5 M_\odot$, $R = 10\,\text{km}$.
The heating rate: $\dot{E} = E_t \dot{N} f$, where $\dot{N} = \pi b^2 v_\chi n_\chi$ is the number rate of dark matter flux, f is the capture efficiency, $f = \min\left[\sigma_{\chi n}/\sigma_{th}, 1\right]$.
The NS luminosity is $L = \dot{E} = 4\pi\sigma_B R^2 (T/\sqrt{1-2GM/R})^4$.

At saturation(100%), heating ↔ radiation, the observed temperature:

T=1750 K

T=2480 K

Alternative searches-Neutron star (NS) heating

- The DM annihilates with neutron in NS, E_t ∼2.2 GeV.
- For relativistic DM, $\sigma_{\chi n}^{ann} \approx \theta^2(38.0 + 35.0/P_{\bar{n}}(\mathrm{GeV}))$, $P_{\bar{n}} \approx 0.85$GeV.
- DM heating $\leftrightarrow$ black-body radiation, at $m_\Phi \sim \mathcal{O}(10^7)$ GeV, surface temperature $T_s \simeq 134$ K.
- For a distant observer, $T_o \simeq$ 100 K due to gravitational redshift, it is below the current experimental sensitivities.

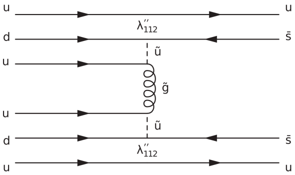
$\Lambda - \bar{\Lambda}$ oscillation @ BES-III

- The $\Lambda - \bar{\Lambda}$ oscillation time at BES-III($10 \times 10^9 J/\Psi$ and $3 \times 10^9 \Psi(2S)$) (X. W. Kang et al. 0906.0230)

$$\tau_{\Lambda-\bar{\Lambda}} > 10^{-6} \text{ s} \qquad (\Lambda = uds)$$

In the future, at the τ-charm factory with luminosity of 10^{35} cm^{-2}s^{-1}, the expected lifetime $\tau_{\Lambda-\bar{\Lambda}} > 10^{-4}$ s at 90% confidence level.

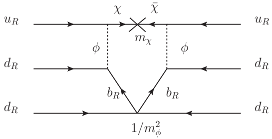
- The $\Lambda - \bar{\Lambda}$ oscillation is $\Delta s = 2$ process. $pp \to K^+K^+$ search in $^{16}\text{O} \to ^{14}\text{C}K^+K^+$ at SK, $\Lambda - \bar{\Lambda}$ oscillation times (at tree level)(K. Aitken et al. 1708.01259)



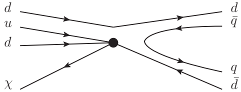
$$\tau_{\Lambda-\bar{\Lambda}} > \mathcal{O}(10^6) \text{ s}$$

where $\beta_{uds} \sim 10^{-2}$.

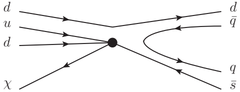
s/b quark contribution



$\Delta b = 2$ at loop-level



(a) $n + \chi \to \pi + \pi$



(b) $n+\chi \to \pi+K \, (\Delta s = 1)$

$$\sigma_{\pi K} \sim \sigma_{\pi\pi}$$

Except K, π mass difference in the final state.
At same rate, $m_\Phi \sim \mathcal{O}(10^{6-7})$ GeV for $\Delta s = 1$ operator.

Summary

- DM can directly annihilate with baryons through BNV. Assuming color-triplet, iso-singlet scalar(s) and a fermionic dark matter (Majorama or Dirac).
- From the $n - \bar{n}$ oscillation at the SuperK experiment, we constrain the stringent limit m_Φ up to 10^7 GeV.
- For Majorana-DM, the constraint is one order in magnitude lower than $n - \bar{n}$ oscillation.
- In the Dirac case, DM - nucleon annihilation gives much stronger bounds than neutron decay ($n \to \chi + \gamma$).
- In DM decay($m_\chi > m_p + m_e$), the SuperK bounds exceed that from DM stability (from PLANCK) at a small mass range.
- We also consider indirect detection, neutron star heating, which are significantly below the reach of current experiments at $m_\Phi \sim 10^7$ GeV.

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