Stellar Signals of a Baryon-Number-Violating Long-Range Scalar Force

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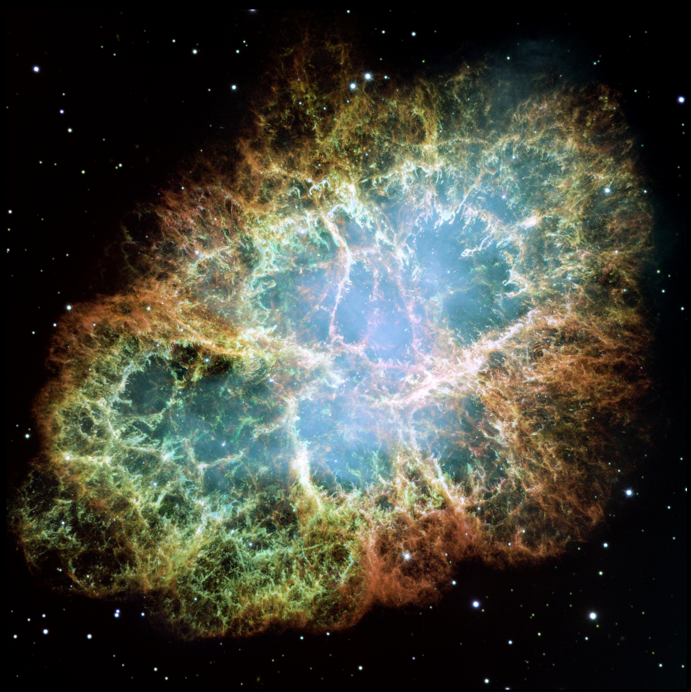
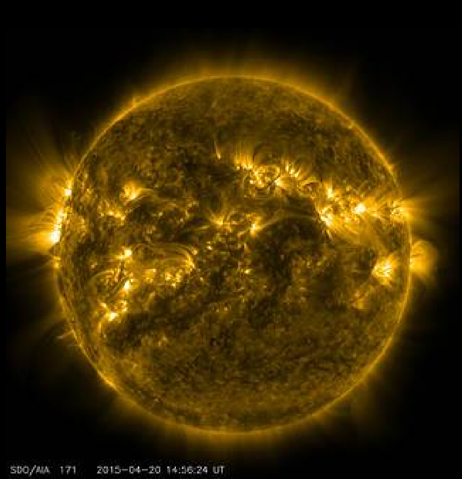
Credit:NASA





Based on: H.D., Phys.Rev.D 108 (2023) 1, 015023; 2304.06071 [hep-ph]

Scalars 2023, University of Warsaw, September 13-16, 2023

Baryon Number Violation (BNV)

- Experimental evidence: BNV extremely suppressed

- For example: $\tau(p \to \pi^0 e^+) > 2.4 \times 10^{34}$ yr, at 90% CL

Super-Kamiokande Collaboration., PDG

- Standard Model (SM): B protected by an accidental symmetry

- Not possible at renormalizable level, result of gauge invariance

- Effective Field Theory Description

- Mediated by higher dimensional operators, suppressed by large scales M

- Example dim-6 operator: $O_6 = \frac{(uud\,\ell)_R}{M^2}$

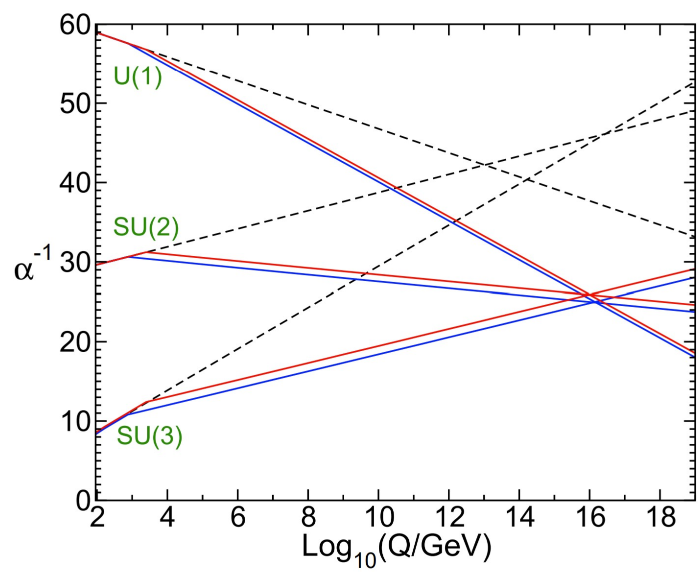
- Quark fields (u, d) lepton ℓ all right-handed

- Current bounds: $M \gtrsim 10^{16}$ GeV

- Consistent with a GUT at $\sim 10^{16}$ GeV

- Approximate in the SM (dashed)

- Improved by supersymmetry (MSSM; solid)



From S. Martin, hep-ph/9709356

Dark Sector Modification

- Possibility: suppressed dark sector interactions with the SM

- May mediate BNV, affect nucleon stability

- New light states as decay products; different kinematics ($p \to \pi^+ X, \ldots$)

- Example: new scalar $\phi \to$ BNV dim-7 operator $O_7 = \frac{\phi\,(uud\,\ell)_R}{\Lambda^3}$

- This talk: what if ϕ is *ultralight*?

- May arise in UV constructions (string moduli) E.g. Nusser, Gubser, Peebles, 2005

- Could be "fuzzy" dark matter (DM) Hu, Barkana, Gruzinov, 2000

- Interesting implications if ϕ couples to ordinary matter

- Nucleons or electrons

The Setup

- We will consider $\boxed{O_7 = \dfrac{\phi\,(uud\,\ell)_R}{\Lambda^3}}$ as dominant

- Illustrates the main physics; other choices (flavor, chirality) possible

- QCD confinement: O_7 can mediate $p \to \phi\,\ell^+$; will focus on $\ell = e$

- If $\langle\phi\rangle \neq 0$ (sourced by matter), p and e^+ can mix

- Can lead to ϕ-dependent rate for $p \to \pi^0\,e^+$, for example

- Assume that ϕ couples to nucleons $N = p, n$ through $\boxed{g_N \phi \bar{N}\,N}$

- Current 2σ bound by Microscope collaboration data $g_N \lesssim 8.0 \times 10^{-25}$

Microscope collaboration 2022; Fayet 2017

- Adopt $\boxed{g_N = 10^{-25}}$ and $\boxed{m_\phi = 10^{-16}\text{ eV}}$, as reference values

- Sun radius $R_\odot \approx 7.0 \times 10^5$ km $\sim (10^{-16}\text{ eV})^{-1}$

Formalism

- Chiral Lagrangian approach   Claudson, Wise, Hall, 1982

- Baryon number preserving interactions:

$$\mathcal{L}_{\mathsf{P}} = \left[\frac{(3F-D)}{2\sqrt{3}f_\pi}\,\partial_\mu\eta + \frac{(D+F)}{2f_\pi}\,\partial_\mu\pi^0\right]\bar{p}\gamma^\mu\gamma_5 p + \frac{(D+F)}{\sqrt{2}f_\pi}\,\partial_\mu\pi^+\,\bar{p}\gamma^\mu\gamma_5 n + \ldots$$

$f_\pi \approx 92$ MeV

- BNV, corresponding to O_7:

$$\mathcal{L}_{\mathsf{V}} = \frac{\beta}{\Lambda^3}\,\phi\,\left[\overline{e^c_R}\,p_R - \frac{i}{2f_\pi}(\sqrt{3}\eta + \pi^0)\overline{e^c_R}\,p_R\right] - \frac{\beta}{\Lambda^3}\,\phi\,\left[\frac{i}{\sqrt{2}f_\pi}\pi^+\overline{e^c_R}\,n_R\right] + \mathrm{H.C.}$$

$D = 0.80$, $F = 0.47$, $\beta = 0.01269(107)$ GeV^3 Aoki et al., RBC-UKQCD, 2008

Nucleon decay: (i) $p \to \phi\, e^+$ mediated by the first term in $\mathcal{L}_{\mathsf{V}}$, (ii) 3-body decays into ϕ, a meson, and e^+ from $\mathcal{L}_{\mathsf{V}}$, (iii) via emission of a meson by nucleons in $\mathcal{L}_{\mathsf{P}}$ and p-e^+ mixing from $\mathcal{L}_{\mathsf{V}}$, or (iv) via the point interactions in $\mathcal{L}_{\mathsf{V}}$ involving a nucleon, a meson, and e^+. Need $\langle\phi\rangle \neq 0$ for (iii), (iv).

Nucleon Decay Rates

- We will focus on 2-body decays; ignore m_e

- 3-body decays generally more suppressed by $\gtrsim O(10)$

- Proton decay

$$\boxed{\Gamma(p \to \phi\, e^+) = \frac{\kappa^2}{32\pi}}$$

$$\kappa \equiv \beta/\Lambda^3 \ ; \ \mu = \kappa\langle\phi\rangle$$

$$\boxed{\Gamma(p \to \mathcal{M} e^+) = \frac{\lambda_{\mathcal{M}}^2}{32\pi}\, m_p \left(1 - \frac{m_{\mathcal{M}}^2}{m_p^2}\right)^2}$$

$$\lambda_\pi \equiv \frac{(D+F+1)\mu}{2f_\pi} \ ; \ \lambda_\eta \equiv \frac{(3F-D+3)\mu}{2\sqrt{3}\, f_\pi}$$

- Neutron decay

$$\boxed{\Gamma(n \to \pi^- e^+) = \frac{\lambda_\pi^2}{16\pi}\, m_n \left(1 - \frac{m_{\pi^-}^2}{m_n^2}\right)^2}$$

Matter Effect on Nucleon Decay

- Our setup implies

$$\frac{\Gamma(p \to \phi\, e^+)}{\Gamma(p \to \mathcal{M} e^+)} \sim \left(\frac{f_\pi}{\langle\phi\rangle}\right)^2$$

- Implies $p \to \phi\, e^+$ dominates when $f_\pi \gg \langle\phi\rangle$: in "empty space" or if $g_N \to 0$

- For Earth, with $M_\oplus \approx 6.0 \times 10^{27}$ g: $\langle\phi\rangle_\oplus \sim 10^4 f_\pi$

- Negligible contribution from $p \to \phi\, e^+$ near Earth, astronomical bodies

- Galactic nucleon density ~ 1 per cm^3: $\langle\phi\rangle_{\mathrm{G}} \sim 10^{-7}$ eV$\ll f_\pi$

- Rescaling GeV scale DM decay bounds (factor of ~ 5): $\tau_N \gtrsim 10^{23}$ s

Bell, Galea, Petraki, 2010

- Much weaker than nucleon lifetime bounds from experiments

Constraints from Laboratory Experiments

- For $g_N = 0$ (or empty space), $p \to e^+ \phi$ dominates

- At 90% CL, $\tau[p \to e^+ X \text{ (massless)}] > 7.9 \times 10^{32}$ yr   PDG 2022

$$\boxed{O_7 = \frac{\phi\,(uud\,\ell)_R}{\Lambda^3}}$$

$$\Rightarrow \boxed{\Lambda \gtrsim 6 \times 10^9 \text{ GeV}} \quad ; \quad \text{Earth, } g_N = 0$$

- For $g_N \neq 0$, we find $\langle\phi\rangle_\oplus \approx 8.7 \times 10^2 \left(\frac{g_N}{10^{-25}}\right)$ GeV

- The most stringent bound from $p \to e^+ \pi^0$

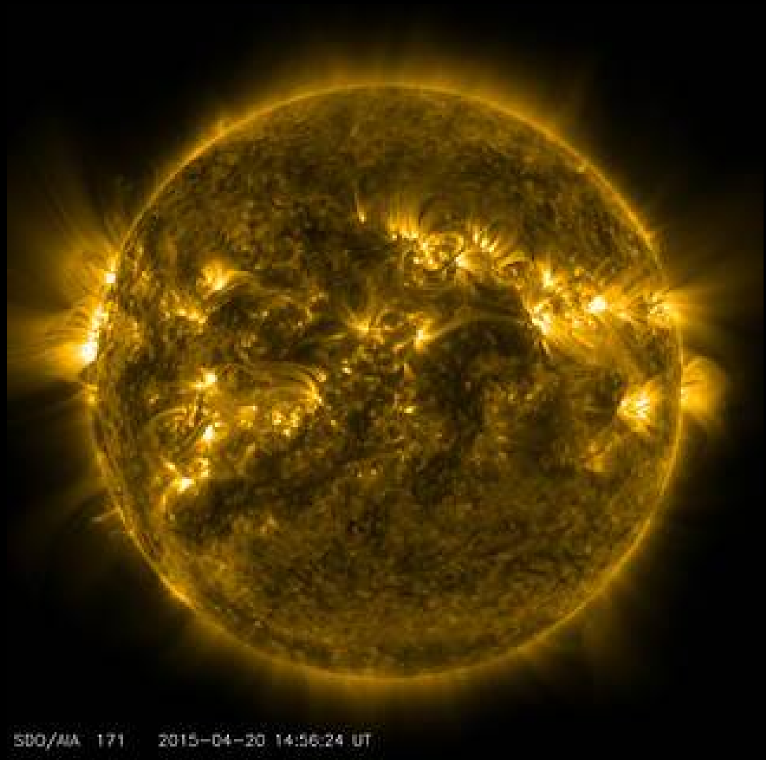
- $\tau(p \to e^+ \pi^0) > 1.6 \times 10^{34}$ yr, at 90% CL*   PDG 2022

* Used in the paper. PDG 2022 also cites a stronger updated bound, by 3/2, which would yield the same constraint on Λ at the presented level of accuracy.

$$\Rightarrow \boxed{\Lambda \gtrsim 2 \times 10^{11} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}} \quad ; \quad \text{Earth, } g_N \neq 0$$

- Next, we will inquire whether better bounds can be obtained if we look to the stars.

- Let us start with the closest one.



Solar Constraints

- Rapid N decay $\rightarrow$ anomalous flux of $\mathcal{O}$(10 MeV) νs from the Sun

- Super-Kamiokande (SK) has constrained such a flux from BNV

Ueno et al., (SK collaboration), 2012

\- For BNV mediated by monopoles predicted in GUTs   Rubakov, 1981; Callan, 1982

- SK analysis based on 176 kton-yr of data, focused on π^+ emission in p decay, leading to $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_\mu \nu_e$

\- In our minimal model, no prompt 2-body N decay into π^+

- We focus on $p \rightarrow e^+ \eta$ with $\eta \rightarrow \pi^+ \pi^- \pi^0$; $\pi^+ \pi^- \gamma$

\- Br($\eta \rightarrow \pi^+$) $\approx$ 27%   PDG, 2022

- We take $\mathcal{N}_p^\odot \approx 10^{57}$ and use BP2004 Solar model for the mass density $\rho(r)$ of the Sun   Bahcall and Pinsonneault, 2004

- Solar profile of ϕ $\quad r_0 = |\vec{r}_0|$: radial distance

$$\phi(r_0) = -\frac{g_N}{2m_N}\int_0^{R_\odot} dr\, r^2\, \rho(r) \int_{-1}^{+1} dx\, \frac{e^{-m_\phi|\vec{r}-\vec{r}_0|}}{|\vec{r}-\vec{r}_0|}$$

- Rate for $p \to \eta\, e^+$ in the Sun can be calculated using $\phi(r)$ via

$$\mathcal{R}_{\eta e} = \frac{4\pi}{m_N}\int_0^{R_\odot} dr\, r^2 \rho(r)\, \Gamma(r)_{(p\to\eta\, e^+)}$$

- SK 90% CL limit on the Solar ν flux $I_{90} = 166.6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

\- From the monopole catalyzed $p \to \pi^+ +$ ‘anything’ SK Collaboration, 2012

- Adapting SK analysis

$d_{\mathrm{AU}} \approx 1.5 \times 10^8$ km

$$\mathcal{R}_{\eta e} = \frac{4\pi\, d_{\mathrm{AU}}^2 I_{90}}{3\mathrm{Br}(\eta \to \pi^+)\,(1 - a_{\pi^+})}$$

\- $a_{\pi^+} = 0.2$ is π^+ absorption probability (solar center, used for entire volume)

$$\Rightarrow \boxed{\Lambda \gtrsim 2 \times 10^{10} \left(\frac{g_N}{10^{-25}}\right)^{1/3}\ \mathrm{GeV}} \quad ; \quad \text{Solar } \nu \text{ flux}$$

Neutron Star Heating through Nucleon Decay

- Estimate only using neutron decays; focus on $n \to \pi^- e^+$

- We take $M_{\text{NS}} \approx 1.5 M_\odot$ ($N_n \approx 2 \times 10^{57}$), $R_{\text{NS}} \approx 10$ km

- Assume $E \approx m_n$ gets deposited in the NS after n decay

- $n_N \sim 4 \times 10^{38}$ cm^{-3}, $\sigma_{\nu N} \sim 10^{-42}$ cm^2 for $E_\nu \sim 10$ MeV $\Rightarrow \lambda_\nu \sim \mathcal{O}(10 \text{ m}) \ll R_{\text{NS}}$

- One can assume all decay products scatter many times in the NS

- Constant density approximation

$$\rho_{\text{NS}} = \frac{M_{\text{NS}}}{(4\pi/3) R_{\text{NS}}^3} \approx 7 \times 10^{14} \text{ gcm}^{-3}$$

- For $r < R_{\text{SN}}$

$$\phi_{\text{NS}}(r) \approx -\frac{g_N \, \rho_{\text{NS}}}{6 \, m_n} R_{\text{NS}}^2 \left(3 - \frac{r^2}{R_{\text{NS}}^2}\right)$$

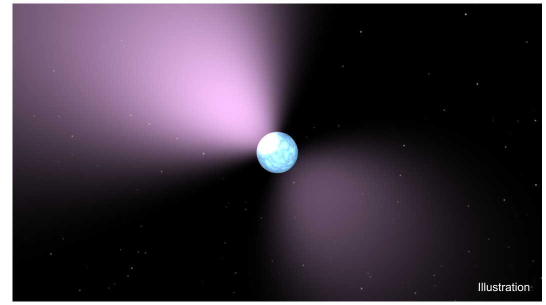
- Neutron decay rate

$$\Gamma_n^{\text{NS}} = 4\pi \frac{\rho_{\text{NS}}}{m_n} \int_0^{R_{\text{NS}}} dr \, r^2 \, \Gamma(r)_{(n \to \pi^- e^+)}$$

- In steady state: $\boxed{m_n \Gamma_n^{\text{NS}} \approx 4\pi R_{\text{NS}}^2 \, \sigma_{\text{SB}} T_{\text{NS}}^4}$

- Stefan-Boltzmann constant: $\sigma_{\text{SB}} = \pi^2/60$

- Surface temperature: T_{NS}



Credit:NASA

- Coldest known NS: pulsar PSR J2144-3933

- Hubble Space Telescope (HST) data: $T_{NS} < 42000$ K   Guillot *et al.*, 2019

- Distance from Earth ≈ 180 pc

- Estimated to be $\sim 3 \times 10^8$ yr old; $T_{\text{NS}} \sim \mathcal{O}(100 \text{ K})$ expected, without heating

Yakovlev, Pethick, 2004

- We get the bound

$$\boxed{\Lambda \gtrsim 7 \times 10^{11} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}} \quad ; \quad \text{NS (HST)}$$

- Potential improvements by James Webb Space Telescope

E.g., Chatterjee *et al.*, 2022

Aside:

- HST bound: $\lesssim \mathcal{O}(10^{47})$ νs from n decay over a few billion years
- Negligible compared to $\mathcal{O}(10^{58})$ νs from core collapse SN
  - One for each NS
- Do not expect a detectable anomalous diffuse neutrino background

Possible UV Realization

- Only an outline here, not a complete setup
- Postulate $\mathbb{Z}_2(e) = \mathbb{Z}_2(\phi) = -1$
- Dim-6 $(uude)_R$ forbidden; allows dim-7 $\phi(uude)_R$
- Vector-like $\mathcal{E}$ ($\mathbb{Z}_2$-even), with e_R SM charge, $m_{\mathcal{E}} \gtrsim 1$ TeV: $\boxed{y\,\phi\,\bar{\mathcal{E}}_L e_R + \text{H.C.}}$
- $\dfrac{(uud\,\mathcal{E})_R}{\Lambda'^2}$ allowed (*e.g.*, charge -1/3 leptoquark exchange)
- Integrate out $\mathcal{E} \Rightarrow \boxed{\dfrac{\phi(uude)_R}{\Lambda^3}}$ with $\Lambda^3 = \Lambda'^2 m_{\mathcal{E}}/y$
- Coupling $\phi\bar{q}q$ forbidden by $\mathbb{Z}_2$
- Need $\mathbb{Z}_2$-odd Φ with $\langle\Phi\rangle \neq 0 \Rightarrow \Phi\phi\bar{q}q$ (via vector-like heavy quarks) $\Rightarrow \phi\bar{q}q$
- Note: $\sim \dfrac{\Phi(uude)_R}{\Lambda^3}$ possible; suppressed effect if $\langle\Phi\rangle \ll \langle\phi\rangle$, $m_\Phi > m_p$ ($\langle\phi\rangle_\oplus \sim$ TeV)

Ultralight DM

- Thermal effects can yield "misaligned" ϕ Batell, Ghalsasi, 2020

- Assume coupling $g_e \phi \bar{e}e$, with $g_e \sim 10^{-25}$

$$\phi_i \sim g_e n_e / m_\phi^2$$

- 2σ bound $g_e \lesssim 1.4 \times 10^{-25}$ Microscope collaboration 2022; Fayet 2017

- Phenomenology roughly the same for $g_e \sim g_N$

- ϕ starts to oscillate when $H \sim m_\phi \Rightarrow T_i \sim$ MeV and $n_e \sim$ MeV^3

$$\phi_i \sim 10^{25} \text{ eV} \Rightarrow \rho(\phi_i) \sim m_\phi^2 \phi_i^2 \sim 10^{18} \text{ eV}^4$$

- By $T_f \sim$ eV (matter-radiation equality)

$$\rho(\phi) \sim (T_f/T_i)^3 \rho(\phi_i) \sim \text{ eV}^4$$

- Right size for DM

Summary and Conclusions

- We considered BNV via operators including an ultralight scalar

- If the ultralight scalar couples to ordinary matter, it can cause medium-dependent variations in nucleon lifetimes

- Terrestrial nucleon decay limits, as well as signals from stellar sources, were examined to constrain the model

- A novel handle on potential long-range forces

$$\boxed{O_7 = \frac{\phi\,(uud\,\ell)_R}{\Lambda^3}}$$

  - $\boxed{\Lambda \gtrsim 6 \times 10^9 \text{ GeV}}$ Earth, $g_N = 0$
  - $\boxed{\Lambda \gtrsim 2 \times 10^{11} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}}$ Earth
  - $\boxed{\Lambda \gtrsim 2 \times 10^{10} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}}$ Solar ν flux
  - $\boxed{\Lambda \gtrsim 7 \times 10^{11} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}}$ NS (HST)