Destabilizing Matter through a Long-Range Force

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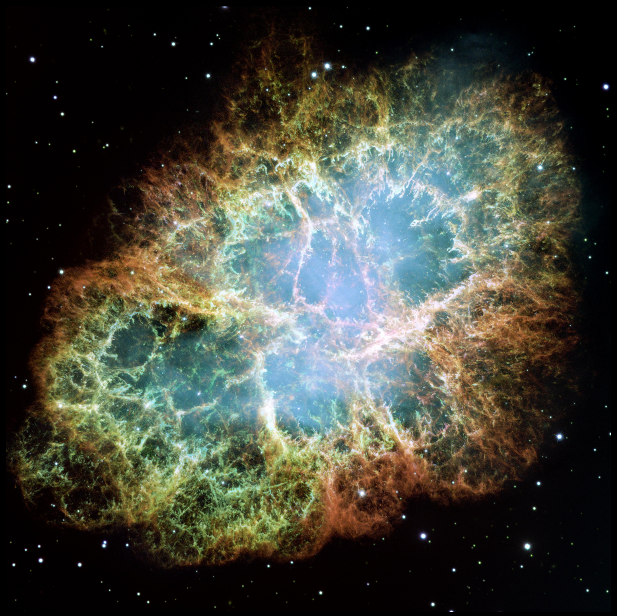


Based on: H.D., Phys.Rev.D 108 (2023) 1, 015023; 2304.06071 [hep-ph]

Talk at Rencontres de Moriond 2024

La Thuile, Italy, March 24-31, 2024

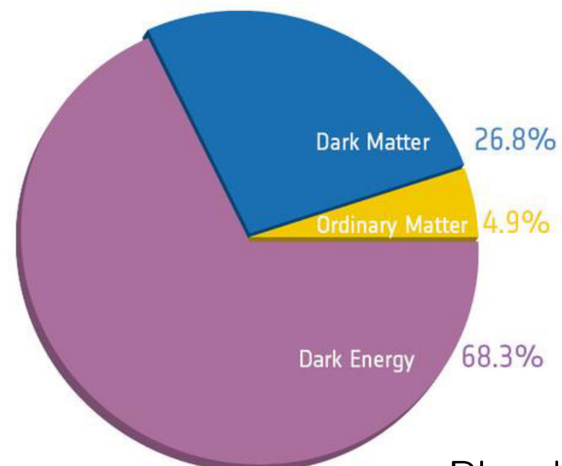
Introduction

- Ordinary matter ($\sim 5\%$) made of nucleons (p, n) is very stable:
  - Over far longer than cosmological time scales ($\sim 10^{10}$ years)
  - Searches have only yielded strong bounds, *e.g.*

$$\tau(p \to \pi^0 \ell^+) > 1.6\,(0.77) \times 10^{34} \text{ yr, for } \ell = e\ (\mu)\text{, at 90\% CL}$$

Super-Kamiokande Collaboration; PDG

- Dark matter ($\sim 27\%$): requires new physics
  - Perhaps a new sector with its own forces



Planck

- This talk: a new long-range force
  - Ultralight scalar ϕ
  - Can be sourced by astronomical objects
- Long range force: local background effects
  - Like an electric or gravitational field

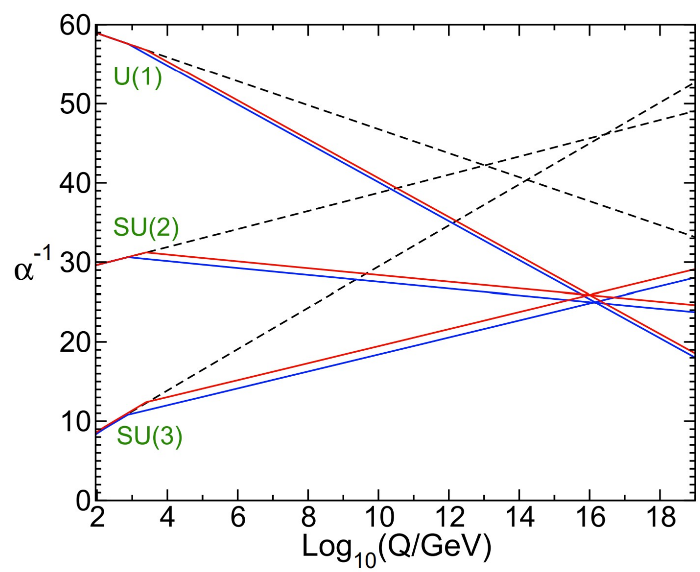
Baryon Number Violation (BNV)

- In the SM, proton decay naturally suppressed, *e.g.*:

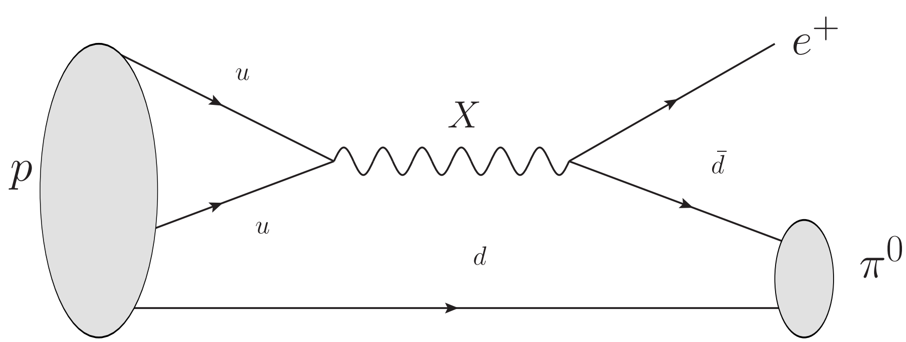
$$O_6 = \frac{(uud\ell)_R}{M^2}$$

  - M could be large, maybe near $M_{\mathrm{P}} \approx 1.2 \times 10^{19}$ GeV
  - A consequence of gauge invariance
  - Baryon number: *accidental symmetry*

- Current bounds $M \gtrsim 10^{16}$ GeV
  - Consistent with a GUT interpretation
  - SM (dashed) ; MSSM (solid)



From S. Martin, hep-ph/9709356



New Physics and Nucleon Decay

- New light physics can affect nucleon decay

E.g., HD 2013; Heeck 2020; Fajfer and Susic 2020

- Consider a light new scalar ϕ from a different sector

- One can write down, for example, a dim-7 operator

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

- For $m_\phi < m_p - m_e$ one can have $p \to \phi\, e^+$

- However, if $\langle\phi\rangle \neq 0$, dim-7 $\to$ dim-6: $\frac{\phi\,(uud\,\ell)_R}{\Lambda^3} \to \left(\frac{\langle\phi\rangle}{\Lambda}\right)\frac{(uud\,\ell)_R}{\Lambda^2}$
  - Effectively, the coefficient of a dim-6 operator becomes a *background field*

A New Scalar Force

- Assume an ultralight scalar ϕ of mass $\boxed{m_\phi = 10^{-16}\ \text{eV}}$
  - Can arise in a variety of contexts (CPV axions, string moduli,. . .)
  - Sun's radius $R_\odot \approx 7 \times 10^5$ km $\sim (10^{-16}\ \text{eV})^{-1}$
- Possible coupling to nucleons N: $g_N\, \phi\, \bar{N} N$
  - $g_N \lesssim 8.0 \times 10^{-25}$ (2σ) Microscope Collaboration 2022; Fayet 2017
- We will use reference value $\boxed{g_N = 10^{-25}}$
- Astronomical objects can *coherently* source significant $\langle \phi \rangle$ values

$$\langle \phi_* \rangle \approx -\frac{g_N (M_*/m_N)}{4\pi\, R_*}$$

(m_N: nucleon mass)

- We will focus on

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

  - As an example, other choices possible
  - Can lead to environment-dependent nucleon decay rates $\propto \langle \phi_* \rangle^2$

Formalism

- Using chiral perturbation theory   Claudson, Wise, Hall, 1982

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

$$\mathcal{L}_{(\Delta B=1)} = \frac{\beta}{\Lambda^3}\,\phi\,\left[\overline{e^c_R}\,p_R - \frac{i}{2f_\pi}(\sqrt{3}\eta + \pi^0)\overline{e^c_R}\,p_R\right] - \frac{\beta}{\Lambda^3}\,\phi\,\left[\frac{i}{\sqrt{2}f_\pi}\pi^+\overline{e^c_R}\,n_R\right] + \text{H.C.}$$

$D = 0.80$, $F = 0.47$, $\beta = 0.01269(107)$ GeV^3, Aoki et al., RBC-UKQCD, 2008 ; $f_\pi \approx 92$ MeV

- Focus on 2-body decays; ignore m_e $\mathcal{M} = \pi^0, \eta$

Proton decays: $\boxed{\Gamma(p \to \phi\, e^+) = \frac{\kappa^2}{32\pi}\, m_p}$ and $\boxed{\Gamma(p \to \mathcal{M} e^+) = \frac{\lambda^2_{\mathcal{M}}}{32\pi}\, m_p \left(1 - \frac{m^2_{\mathcal{M}}}{m^2_p}\right)^2}$

- Implies $p \to \phi\, e^+$ dominant when $f_\pi \gg \langle\phi\rangle$ (empty space or $g_N \to 0$)

Neutron decay: $\boxed{\Gamma(n \to \pi^- e^+) = \frac{\lambda^2_\pi}{16\pi}\, m_n \left(1 - \frac{m^2_{\pi^-}}{m^2_n}\right)^2}$

$\kappa \equiv \beta/\Lambda^3$; $\mu = \kappa\langle\phi\rangle$; $\lambda_\pi \equiv \frac{(D+F+1)\mu}{2f_\pi}$; $\lambda_\eta \equiv \frac{(3F-D+3)\mu}{2\sqrt{3}\, f_\pi}$

"Local" Constraints

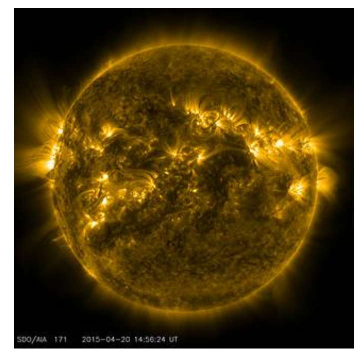
- Laboratory searches *
  - $\tau(p \to e^+\pi^0) > 1.6 \times 10^{34}$ yr (90% CL) PDG 2022

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

* PDG 2022 also cites an updated bound, stronger by 3/2, which constrains Λ at the same level.

- Search for anomalous flux of $\mathcal{O}(10$ MeV) solar neutrinos
  - Super-Kamiokande (SK) search for BNV Ueno et al., (SK Collab.), 2012

  \- Monopole (GUT) mediated Rubakov 1981; Callan 1982



  - SK: 176 kton-yr of data, focused on π^+ from p decays
  - We consider $p \to e^+\eta$ with Br$(\eta \to \pi^+ X) \approx 27\%$ PDG 2022

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

Bahcall and Pinsonneault, 2004

  - Rate of $p \to e^+\eta$ in the Sun:

$$\mathcal{R}_{\eta e} = \frac{4\pi}{m_N}\int_0^{R_\odot} dr\, r^2 \rho(r)\, \Gamma(r)_{(p\to\eta\, e^+)} \Rightarrow \boxed{\Lambda \gtrsim 2 \times 10^{10} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}}$$

Neutron Star Heating via Nucleon Decay

- Neutron star (NS) mass $M_{\mathrm{NS}} \approx 1.5 M_{\odot}$ and radius $R_{\mathrm{NS}} \approx 10$ km
  - $n_N \sim 4 \times 10^{38}$ cm^{-3}
- Focus on neutron decay $n \to \pi^- e^+$, depositing $E \approx m_n$ in the NS
  - $\sigma_{\nu N} \sim 10^{-42}$ cm^2 for $E_\nu \sim 10$ MeV $\Rightarrow \lambda_\nu \sim \mathcal{O}(10 \text{ m}) \ll R_{\mathrm{NS}}$
  - All decay products scatter many times in the NS
- Constant density approximation

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

- For $r < R_{\mathrm{NS}}$

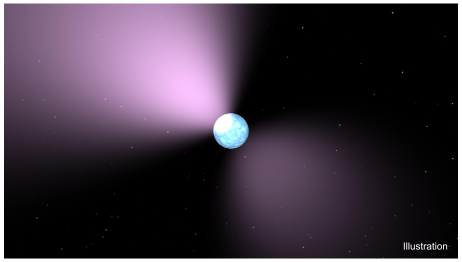
$$\phi_{\mathrm{NS}}(r) \approx -\frac{g_N \, \rho_{\mathrm{NS}}}{6 \, m_n} R_{\mathrm{NS}}^2 \left(3 - \frac{r^2}{R_{\mathrm{NS}}^2}\right)$$

- Neutron decay rate in NS

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

Observational Bound

- Steady state: $m_n \Gamma_n^{\text{NS}} = 4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T_{\text{NS}}^4$
  - 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: $T_{\text{NS}} < 42000$ K   Guillot *et al.*, 2019
  - Distance from Earth ≈ 180 pc, estimated to be 3×10^8 yr old
  - $T_{\text{NS}} \sim \mathcal{O}(100 \text{ K})$ expected without heating   Yakovlev, Pethick, 2004

- The NS heating bound yields

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

  - Potential improvements from James Webb Space Telescope

E.g., Chatterjee *et al.*, 2022; Raj, Shivanna, Rachh, 2024

Ultralight Dark Matter

- Alternative assumptions can make ϕ viable DM
- Example: allow for electron coupling $g_e \phi \, \bar{e} e$ with $g_e \sim 10^{-25}$
  - $g_e \lesssim 1.4 \times 10^{-25}$ at 2σ Microscope collaboration 2022; Fayet 2017
- $\phi \sim g_e n_e m_\phi^{-2}$ by "thermal misalignment" Batell, Ghalsasi, 2020
- ϕ starts oscillating once $H \sim m_\phi$ corresponding to $T \sim$ MeV, $n_e \sim T^3$
- For $m_\phi \sim 10^{-16}$ eV we find $\phi_i \sim 10^{25}$ eV
- Initial energy density $\rho_i \sim m_\phi^2 \phi_i^2 \sim 10^{18}$ eV^4 redshifts like T^{-3}
- At $T \sim$ eV (matter-radiation equality): $\rho_i \to \mathcal{O}(\text{eV}^4) \Rightarrow \phi$ could be DM
- For $\rho_{\text{DM}} \sim 0.3$ GeV cm^{-3} (Solar system): $\phi_{\text{DM}} \sim 10^{13}$ eV, $\mathcal{O}(10)$ large than $\phi_\oplus$
  - Would not lead to stronger constraint from nucleon decay data than from NS heating
  - Introduces time variation due to wavelike nature of ϕ DM
  - Further phenomenology beyond the scope of this talk

Concluding Remarks

- We considered the effect of an ultralight scalar ϕ on BNV
- Besides providing a final state, ϕ may be sourced by matter
- Our discussion focused on a particular operator, as an example
- This can enhance standard operators mediating BNV near astronomical bodies
  - $\langle\phi\rangle(x)$ as a Wilson coefficient in the EFT
- We examined laboratory bounds, as well as solar neutrino emission and neutron star heating via BNV
- Current HST observations of the coldest known pulsar seem to provide the strongest bounds on our setup
  - Data from JWST could provide improved bounds
- Depending on choice of parameters, ϕ could be an ultralight DM candidate