Baryon Number Violation in Neutron Stars

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Baryon Number Violation

- Baryon number conservation is assumed to explain the apparent stability of matter

- Baryon number violation (BNV) motivated in some theoretical frameworks: Baryogenesis, GUT ($p \to e^+\pi^0$)

- Best (nucleonic) limits coming from neutrino experiments:
  - $\tau\,(n \to \nu\gamma) > 5.5 \times 10^{32}$ yr (SuperK $\sim 10^{34}$ nucleons)[1]
  - $\tau\,(n \to \text{inv}) > 5.8 \times 10^{29}$ yr (KamLAND)[2]
  - $\tau\,(nn \to \text{inv}) > 1.4 \times 10^{30}$ yr (KamLAND)[2]

- Hyperonic limits
  - $\tau\left(\Lambda \to M^{\pm}l^{\mp}\right) \gtrsim 10^{-11}$ yr (CLAS @ Jefferson Lab)[3]
  - $\tau\,(\Lambda \to \text{invisible}) \gtrsim 10^{-13}$ yr (BESIII)[4]
  - $\tau\,(\Lambda \to \chi\gamma) \gtrsim 10^{-10}$ yr (SN1987a) [Alonso-Álvarez et al., 2021]

- NS is a sensitive environment for new sources of BNV
  - Contain 10^{57} baryons (may include hyperons)
  - Core densities can be many times larger than $n_{\text{sat}} \approx 0.16\,\text{fm}^{-3}$

1: [Takhistov et al., 2015], 2: [Araki et al., 2006] 3: [McCracken et al., 2015], 4: [Ablikim et al., 2021]

BNV Effects in Neutron Stars

Quasi-equilibrium conditions:

1. BNV time-scales are much longer than τ_{hyd} and τ_β.
2. The final states are already included in the EoS, or disappear on a time-scale shorter than τ_{BNV}.

Therefore:

- The instantaneous state of a neutron star is given by the same Baryon Number Conserving (BNC) EoS (i.e., in the absence of BNV).
- The effect of slow BNV is considered as a perturbation to the BNC structure.
- The heating effects due to BNV may change the cooling curve but we assume $T \ll E_F$ holds.
- The rate of change in the total baryon number ($\dot{B}$) uniquely determines the evolution of the NS along its one-parameter sequence.

Examples: $n \to 3\nu$, $nn \to e^+e^-$, $n \to \chi\gamma$.

Observation: Pulsar Spin-Down

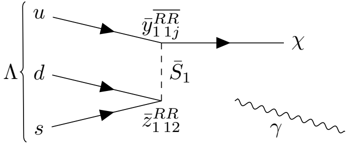
$$\left(\frac{\dot{P}_s}{P_s}\right)_{\rm BNV} = \left(\frac{\dot{I}}{I}\right)_{\rm BNV} = \left(\frac{d\ln I/d\varepsilon_c}{d\ln B/d\varepsilon_c}\right)\left(\frac{\dot{B}}{B}\right) \leq \left|\left(\frac{\dot{P}_s}{P_s}\right)_{\rm Obs}\right| \qquad (1)$$

- Pulsar–WD binary PSR J0348+0432
- $\tau_{\rm WD}^{\rm cool} \sim 2$ Gyr (Roche lobe detachment)
- $M_p = 2.01 \pm 0.04\, M_\odot$, $P_s = 39\,{\rm ms}$, $\dot{P}_s = 2.4 \times 10^{-19}$
- Sensitivity to in-medium BNV decay rate (per particle) defined as $\dot{B} = \text{fraction} \times B \times \Gamma$:

$$\begin{aligned} \Gamma_n &< 1.7 \times 10^{-9} \quad {\rm yr}^{-1} \\ \Gamma_\Lambda &< 2.8 \times 10^{-7} \quad {\rm yr}^{-1} \\ \Gamma_{\Sigma^-} &< 6.5 \times 10^{-5} \quad {\rm yr}^{-1} \end{aligned}$$

A Specific Model

- Generalize the model from Ref. [Fajfer and Susič, 2021] for RMF models in NS $\left(\overline{S}_1 = \left(\overline{3}, 1, -2/3\right)\right)$:



- Effective low-energy magnetic interaction induced by mixing

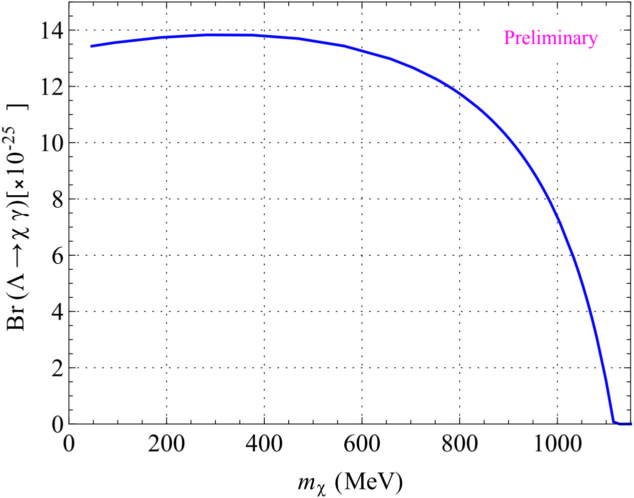
$$\mathcal{L}^{*\mathrm{eff}}_{\Lambda\to\chi\gamma} = \frac{g_\Lambda\, e}{8(m^*_\Lambda + V_\Lambda)}\,\frac{\varepsilon_\Lambda}{m^*_\Lambda + V_\Lambda - m_\chi}\overline{\chi}\sigma^{\alpha\beta}F_{\alpha\beta}\Lambda, \tag{2}$$

  $g_\Lambda \approx -1.22$.

- Assume χ will decay and violate B explicitly (faster than $\Lambda \to \chi\gamma$).

- Choice of EoS: CMF-1 [Dexheimer and Schramm, 2008]

Translate limits on the mixing parameter (ϵ_Λ) into vacuum rates:



This is 20 orders of magnitude better than BESIII limit on $\mathrm{Br}(\Lambda \to \mathrm{inv})$!

Observation: Pulsar Binary Orbital Decay

[Damour and Taylor, 1991]:

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\text{obs}} = \underbrace{\left(\frac{\dot{P}_b}{P_b}\right)^{\text{GR}} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}}}_{\text{intrinsic}} + \left(\frac{\dot{P}_b}{P_b}\right)^{\text{ext}}, \tag{3}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}} = \left(\frac{\dot{P}_b}{P_b}\right)^{\text{BNV}} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{\Omega}}, \tag{4}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\text{BNV}} = \frac{-2}{M_1 + M_2} \sum_{i=1,2} \left(\frac{\dot{B}_i}{B_i}\right) \left[\eta_i^{(M)} M_i + \eta_i^{(I)} \left(\frac{2\pi^2 I_i}{P_{s,i}^2}\right)\right], \tag{5}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\dot{\Omega}} = \frac{8\pi^2}{M_1 + M_2} \left(\frac{I_1 \dot{P}_{s,1}}{P_{s,1}^3} + \frac{I_2 \dot{P}_{s,2}}{P_{s,2}^3}\right), \tag{6}$$

$\eta^{(O)} \equiv (\dot{O}/O)/(\dot{B}/B) \approx \mathcal{O}(1)$.

We consider three binary systems:

- Double pulsar (PSR J0737-3039A/B)
- Hulse-Taylor (PSR B1913+16)
- White Dwarf - Neutron Star (PSR J1713+0747)
  ⟶ BNV active in NS only!

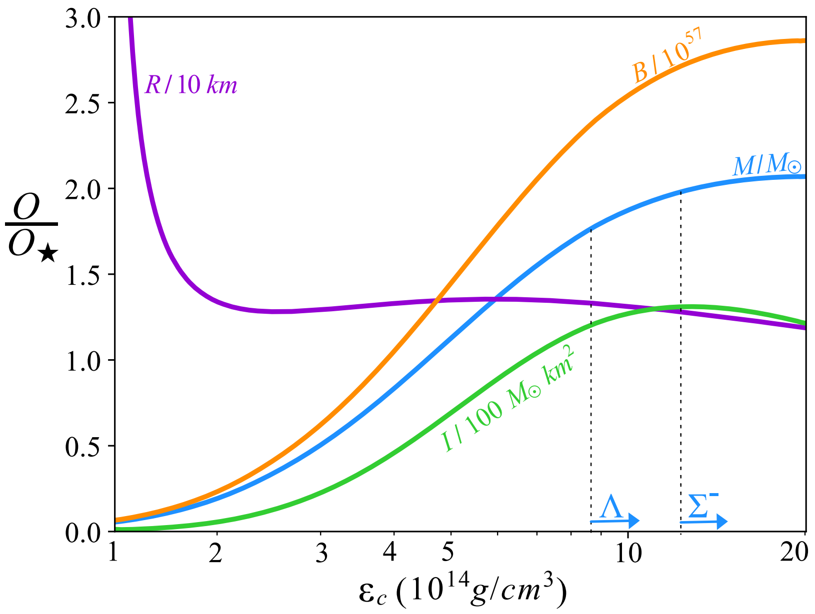
Name	J0737-3039A/B	B1913+16	J1713+0747
$(\frac{\dot{P}_b}{P_b})^{2\sigma}_{\rm BNV}$ (yr^{-1})	7.3×10^{-13}	1.4×10^{-11}	1.8×10^{-12}
$\Gamma_n^{2\sigma}$ (yr^{-1})	4×10^{-13}	7×10^{-12}	1×10^{-12}

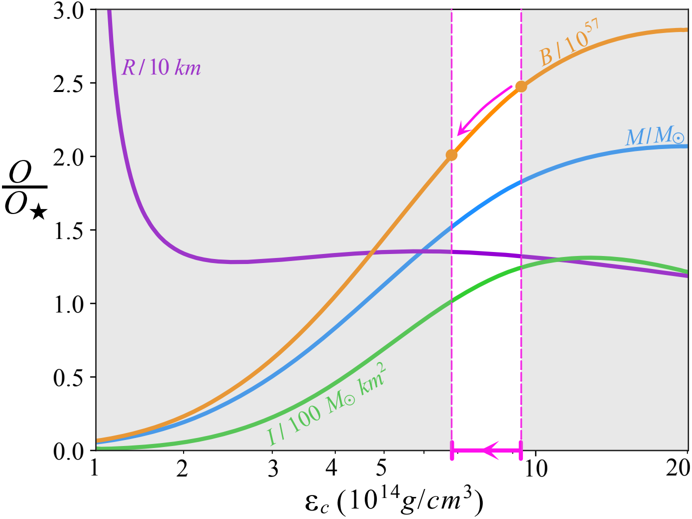
No hyperons in these systems.
⟶ BNV would involve nucleons: neutron decay, dinucleon decay etc.

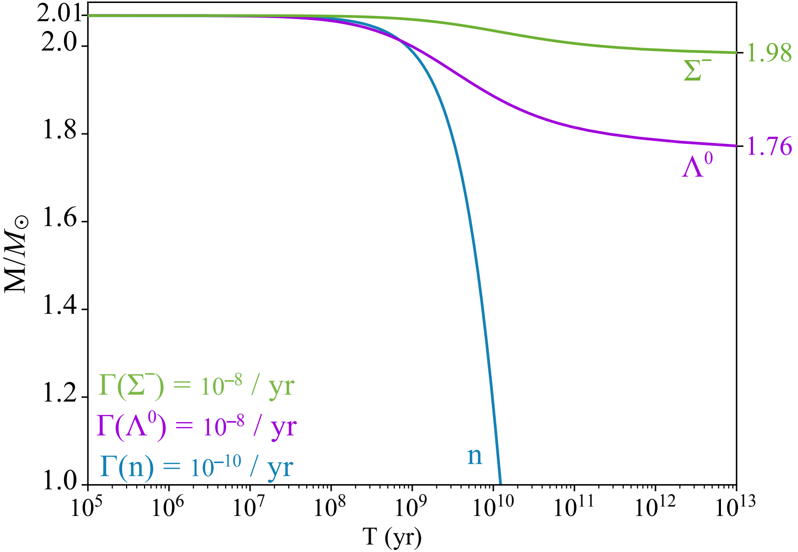
Conclusion

- Neutron star observations are complementary to terrestrial studies of BNV:
  - Huge reservoir of baryons
  - Heavy NS may contain hyperons
- BNV relocates the neutron star along its one-parameter sequence.
- NS hyperonic limits are potentially many orders of magnitude better than terrestrial bounds.
- Orbital periods of pulsar binaries can lead to stringent constraints on this generic class of BNV: $\Gamma_{\mathrm{BNV}} \lesssim 10^{-12}\,\mathrm{yr}^{-1}$.
- Heat will be produced as a result of BNV which would modify the standard cooling of neutron stars.

Back-up


3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\frac{O}{O_\star}$
1
2
3
4
5
10
20
$\varepsilon_c\,(10^{14} g/cm^3)$
$R\,/\,10\ km$
$B\,/\,10^{57}$
$M/M_\odot$
$I\,/\,100\ M_\odot\ km^2$
Λ
Σ^-


R / 10 km
B / 10^57
M / M⊙
I / 100 M⊙ km^2
$\frac{O}{O_\star}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
10
20
$\varepsilon_c\,(10^{14} g/cm^3)$


2.01
2.0
1.8
1.6
1.4
1.2
1.0
$M/M_\odot$
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
T (yr)
1.98
Σ^-
1.76
Λ^0
n
$\Gamma(\Sigma^-) = 10^{-8}$ / yr
$\Gamma(\Lambda^0) = 10^{-8}$ / yr
$\Gamma(n) = 10^{-10}$ / yr

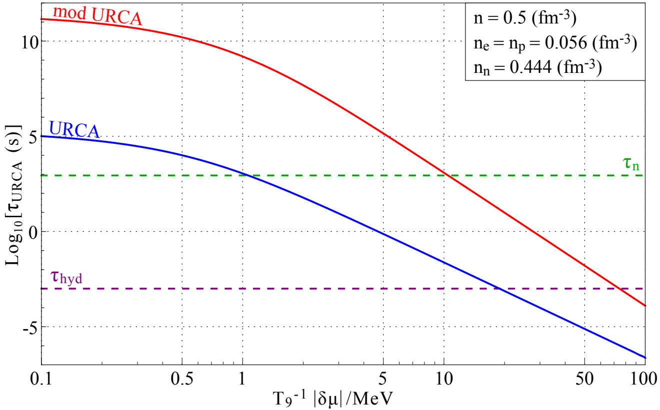


Figure: Timescales for the URCA (blue) and modified URCA (red) reactions in the *npe* model as a function of temperature (T_9), and β-disequilibrium ($\delta\mu$). The free neutron life-time (τ_n), and hydrodynamic response time (τ_{hyd}) are plotted in dashed green and purple for comparison.

Constraints from NS Heating

- The coldest known neutron star (PSR J2144–3933) has $T \approx 42,000$ K.
- This limits $P_{\text{Heat}}^{\text{BNV}} \lesssim 10^{33}\,\text{MeV}/s$.
- Assuming neutrons are completely turned into heat: $\Gamma \lesssim 10^{30}$ neutrons per second.
- Given that $B \approx 10^{57}$, we get $\Gamma_{\text{BNV}} \lesssim 10^{-27}$ per second ($10^{-20}\,\text{yr}^{-1}$).

Limits from NS heating has the potential to improve the bound on Γ_{BNV} (up to ~ 8 orders of magnitude).

Thank You!

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