Baryon Number Violation in Neutron Stars

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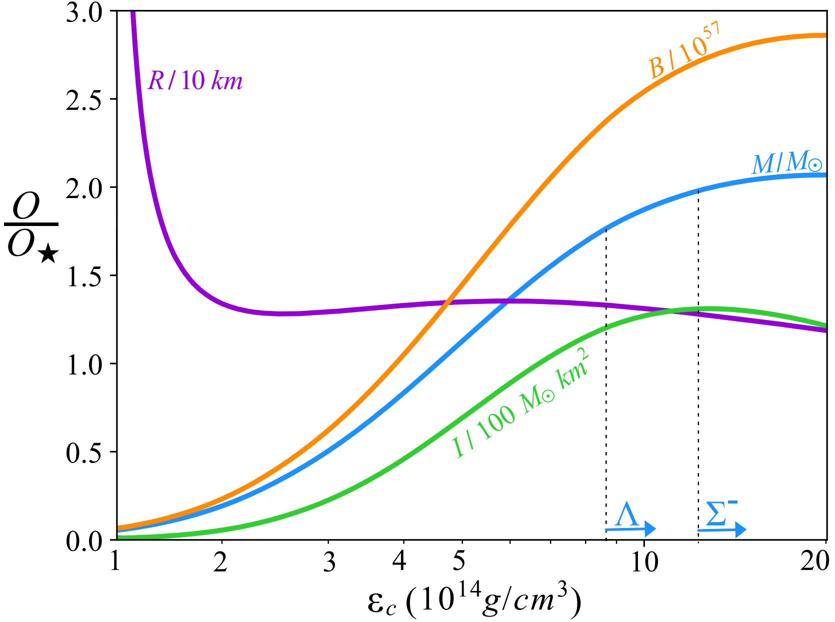
Baryon Number Violation

- Baryon number conservation is assumed to explain the apparent stability of matter
- Baryon number violation (BNV) motivated in some theoretical frameworks: Baryogenesis, GUT
- Best limits coming from neutrino experiments:
  - $\tau\,(n \to \nu\gamma) > 5.5 \times 10^{32}$ yr (SuperK $\sim 10^{34}$ nucleons)
  - $\tau\,(n \to \text{inv}) > 5.8 \times 10^{29}$ yr (KamLAND)
  - $\tau\,(nn \to \text{inv}) > 1.4 \times 10^{30}$ yr (KamLAND)
  - $\tau\,(\Lambda \to M^{\pm} l^{\mp}) \gtrsim 10^{-11}$ yr (CLAS @ Jefferson Lab)
- Can neutron stars yield limits on BNV too?

Neutron Stars

- Masses of about $1 - 2\ M_{\odot}$
- Radius: $R \sim 12$ km
- Density
  - Core densities many times larger than $n_{\text{sat}} \approx 0.16\,\text{fm}^{-3}$
- Contain 10^{57} baryons (may include hyperons)
  - Sensitive environment for new sources of BNV
- For a given equation of state (EoS), there is a unique family of stars (static & spherically symmetric) parameterized by the central energy density (ε_c) also known as the *single parameter sequence* of stars.



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

BNV Analysis Outline

BNV Microphysics

Details of the reaction such as Γ_{BNV}.

$\Updownarrow$

Star's Macroscopic Parameters

$\dot{B}, \dot{M}, \dot{R}, \dot{I}, \ldots$

$\Updownarrow$

Direct Observables

Spin-down rate, pulsar-binary orbital decay rate, ...

Model Independent Analysis

Under what condition(s) does the BNV microphysics decouple from the direct observables?

BNV Microphysics

$\Updownarrow$

Rate of change in baryon number $\dot{B}$

$\Updownarrow$

Change in other macroscopic parameters: $\dot{M}, \dot{R}, \dot{I}, \ldots$

$\Updownarrow$

Direct Observables: Spin-down rate, pulsar-binary orbital decay rate, ...

Model Independent Analysis

Need to check the model dependent effects of BNV!

BNV Effects in Neutron Stars

- The system is no longer subject to the B-conservation constraint and may reach lower energies (subject to electric charge conservation only).

  $\longrightarrow$ Baryon number conserving EoS is not valid anymore.

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Assumption I: If the BNV processes are much slower than other BNC processes, then on short time-scales the star would be in a quasi-chemical equilibrium enforced by BNC.

1. Local density (and pressure) changes, and fluid elements would go out of hydrostatic equilibrium ($\tau_{\text{hyd}} \sim$ ms).
2. Since baryon number is being violated, the $\beta-$equilibrium is disturbed $\mu_n \neq \mu_e + \mu_p$ ($\tau_{\text{Urca}} \sim 10^{-5} - 10^{5}\, s, \tau_{\text{modUrca}} \sim 10^{-4} - 10^{10}\, s$).

Another effect of BNV on neutron stars:

- There might be new species of particles produced which would modify EoS by contributing new terms to the pressure and energy.

  $\longrightarrow$ Highly model dependent!

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Assumption II: If the final states are already part of the matter, or disappear on a time-scale shorter than $\tau_{\rm BNV}$, EoS remains unchanged.

In the case of new particles in the final states:

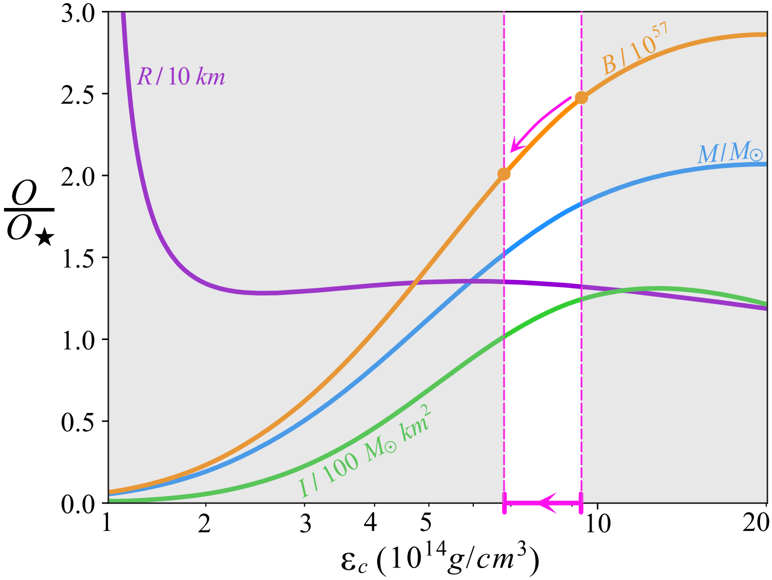
- The new final state particles participate in annihilation or decays into particles already present plus neutrinos and photons.
- Their production rate ($\Gamma_{\rm BNV}$) is much less than their elimination rate ($\Gamma_{\rm ann}$ or $\Gamma_{\rm dec}$)

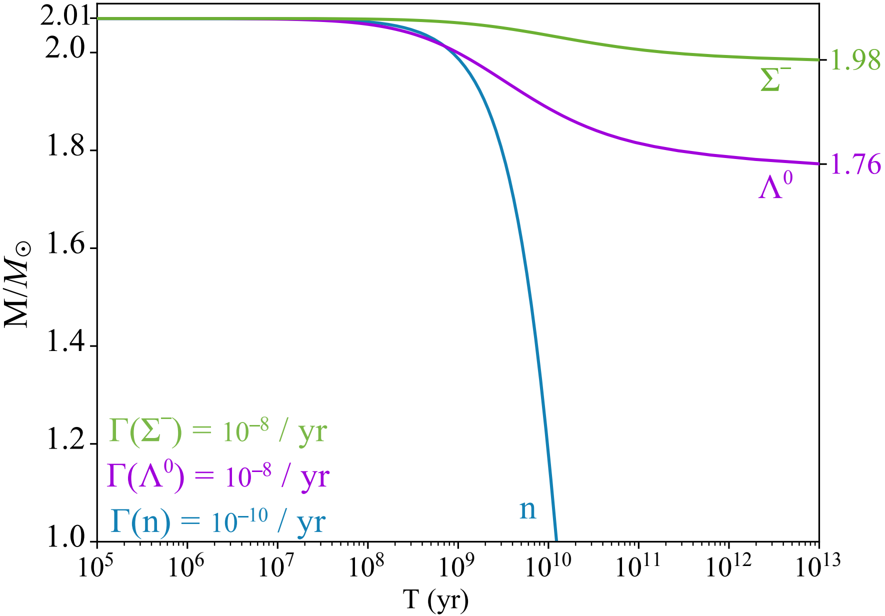
Examples: $n \to 3\nu$, $nn \to e^+e^-$, $n \to \chi\gamma$.

Neutron Star Evolution

Assumptions I & II : Slow BNV and negligible production of new particles

- The instantaneous state of a neutron star is given by the same BNC EoS (i.e., in the absence of BNV).
- The effect of slow BNV is considered as a perturbation to the BNC structure.
- The total baryon number would be slowly decreasing.


3.0
2.5
2.0
1.5
1.0
0.5
0.0
O / O★
R / 10 km
B / 10^57
M / M⊙
I / 100 M⊙ km^2
1
2
3
4
5
10
20
ε_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

Observational Signatures

Pulsar Spin-Down Rate

- Pulsar's spin period (P_s) and its derivative ($\dot{P}_s$) are accurately measured

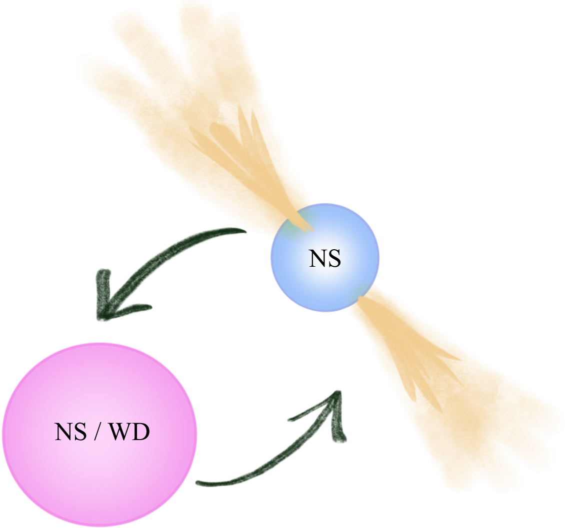
$$\left(\frac{\dot{P}_s}{P_s}\right)_{\rm BNV} = \left(\frac{\dot{I}}{I}\right)_{\rm BNV} = \left(\frac{d\ln I/d\varepsilon_c}{d\ln B/d\varepsilon_c}\right)\left(\frac{\dot{B}}{B}\right) \leq \left(\frac{\dot{P}_s}{P_s}\right)_{\rm Obs} \qquad (1)$$

Pulsar Spin-Down Rate

- Pulsar–white dwarf binary PSR J0348+0432
- $M_p = 2.01 \pm 0.04\, M_\odot$
- $P_s = 39\,\mathrm{ms}$, $\dot{P}_s = 2.4 \times 10^{-19}$
- $I = 193.4\,\mathrm{km}^3$
- Assuming BNV is from a decay:

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

Pulsar Binary Period Decay Rate



- Pulsar binary orbital period is sensitive to changes in masses of its components
- [Jeans, 1924]:

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}} = -2\left(\frac{\dot{M}_1^{\rm eff}+\dot{M}_2^{\rm eff}}{M_1+M_2}\right), \tag{2}$$

$M_{1,2}$: the masses for each of the components in the binary system.

- We consider three binary systems:
  - Double pulsar (PSR J0737-3039A/B)
  - Hulse-Taylor (PSR B1913+16)
  - White Dwarf - Neutron Star (PSR J1713+0747) $\longrightarrow$ BNV active in NS only!

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

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

- Neutron star observations are complementary to terrestrial studies of BNV:
  - Huge reservoir of baryons
  - Heavy NS may contain hyperons
- BNV will relocate the neutron stars along their one-parameter sequence away from the maximum mass configuration.
- Observation of neutron star masses below $M < 1\,M_{\odot}$ would point to a mass-loss mechanism which could be caused by BNV, or else a modification of neutron star genesis theories would be required.
- 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.

Thank You!

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