Hypernuclei and Neutron Stars

"Measurement of the B(E2) of ${}^{7}_{\Lambda}$Li and Shrinkage of the Hypernuclear Size"

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Phys. Rev. Lett. 86, 1982 (2001)

http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.86.1982

We report on the first measurement of a hypernuclear γ-transition probability. γ rays emitted in the $E2(5/2^+ \to 1/2^+)$ transition of ${}^{7}_{\Lambda}$Li were detected by a large-acceptance germanium detector array (Hyperball), and the lifetime of the parent state $(5/2^+)$ was determined by the Doppler shift attenuation method. The obtained result, $5.8^{+0.9}_{-0.7} \pm 0.7$ ps, was then converted into the reduced transition probability $[B(E2)]$ to be $B(E2; 5/2^+ \to 1/2^+) = 3.6 \pm 0.5^{+0.5}_{-0.4}\ e^2\,\mathrm{fm}^4$. Compared with the $B(E2)$ of the corresponding $E2(3^+ \to 1^+)$ transition in the ^{6}Li nucleus, our result gives evidence that the size of the ^{6}Li core in ${}^{7}_{\Lambda}$Li is smaller than the ^{6}Li nucleus in the free space.

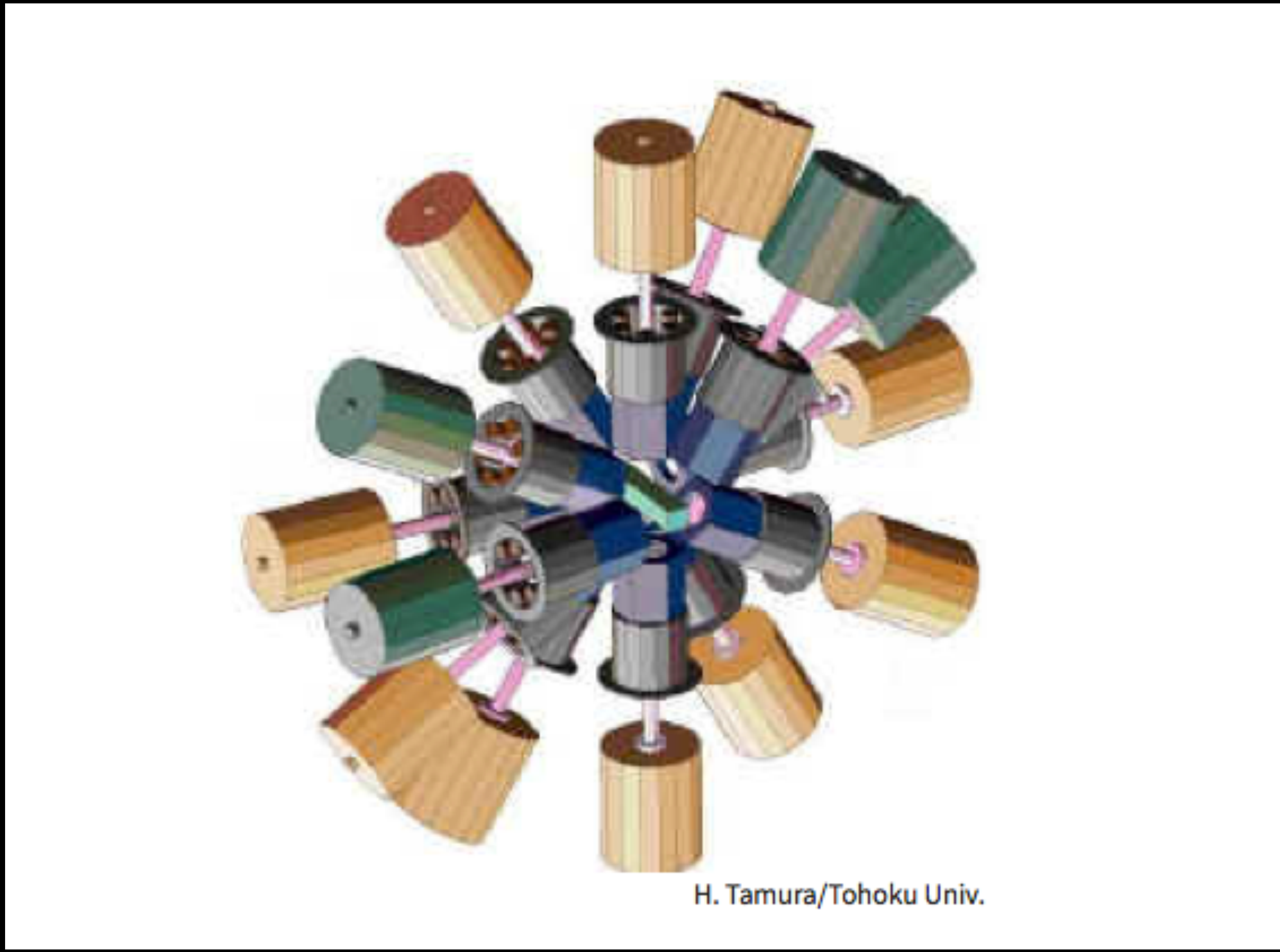
Could the presence of Λ's reduce the energy and therefore radii of neutron stars?

Λ = (uds)   *distinguishable* from n=(udd)

quark charges are u=+2/3 d=-1/3 s=-1/3

Λ is a "heavy neutron"
m_s(95MeV) > m_u (2MeV), m_d (5Mev)

Hyperball detector



Hyperball consists of 14 high-resolution germanium detectors giving precision energy measurements of γ-rays

Change of matter properties under the presence of impurities is an important subject in condensed matter physics. Similarly, bulk properties of nuclei, such as size, shape, collective motion, and so on might be changed by the presence of hyperons as impurities, although no experimental evidence has been found yet. In particular, significant reduction of nuclear size could be expected when a Λ hyperon is added to loosely bound light nuclei such as ^{6}Li [1–3]. Since a Λ particle does not suffer from Pauli blocking, it can locate at the center of a nucleus; then the Λ attracts surrounding nucleons and makes the nucleus shrink.

In order to obtain information on such a possible size contraction experimentally, we used the $E2(5/2^+ \to 1/2^+)$ transition in $^7_\Lambda$Li (see Fig. 1). The reduced transition probability [$B(E2)$] is very sensitive to size contraction as it is approximately proportional to fourth power of the nuclear size. In the weak coupling limit, since the $E2(5/2^+ \to 1/2^+)$ transition in $^7_\Lambda$Li is due to the $E2(3^+ \to 1^+)$ transition in ^{6}Li core, we introduce a factor S which naively represents degree of size change of ^{6}Li core [3] by

$$S = \left[\frac{9}{7} \frac{B(E2; ^7_\Lambda \mathrm{Li} 5/2^+ \to 1/2^+)}{B(E2; ^6\mathrm{Li} 3^+ \to 1^+)} \right]^{1/4}, \qquad (1)$$

where the factor 9/7 comes from the fact that the $B(E2)$ of the core transition ($3^+ \to 1^+$) is distributed to the two $E2$ transitions in $^7_\Lambda$Li as $B(E2; ^7_\Lambda\mathrm{Li}5/2^+ \to 1/2^+) : B(E2; ^7_\Lambda\mathrm{Li}5/2^+ \to 3/2^+) = 7 : 2$ in this limit [4]. If the ^{6}Li core in $^7_\Lambda$Li is the same as the ^{6}Li nucleus in the free space, this size factor equals unity. As we know the $B(E2; ^6\mathrm{Li}3^+ \to$

reaction is

$$\pi(1\mathrm{GeV}) + {}^7\mathrm{Li} \to {}^7\mathrm{Li}^* + k$$

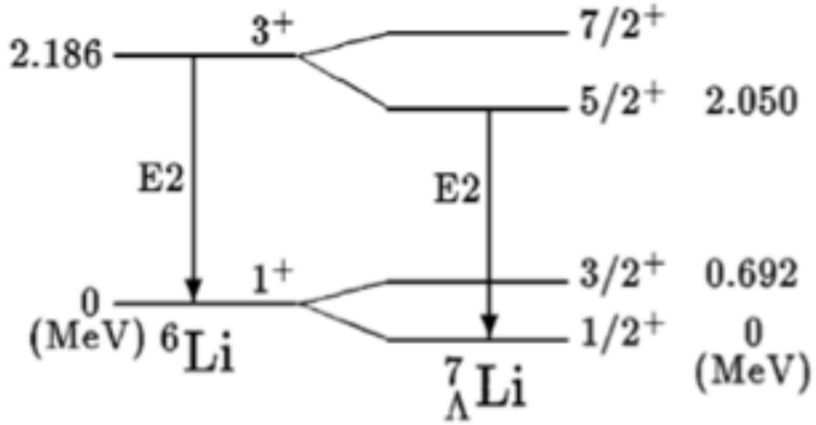


FIG. 1. Low-lying states of $^{7}_{\Lambda}$Li. Excitation energies are taken from Ref. [7]. Corresponding levels of ^{6}Li are also shown.

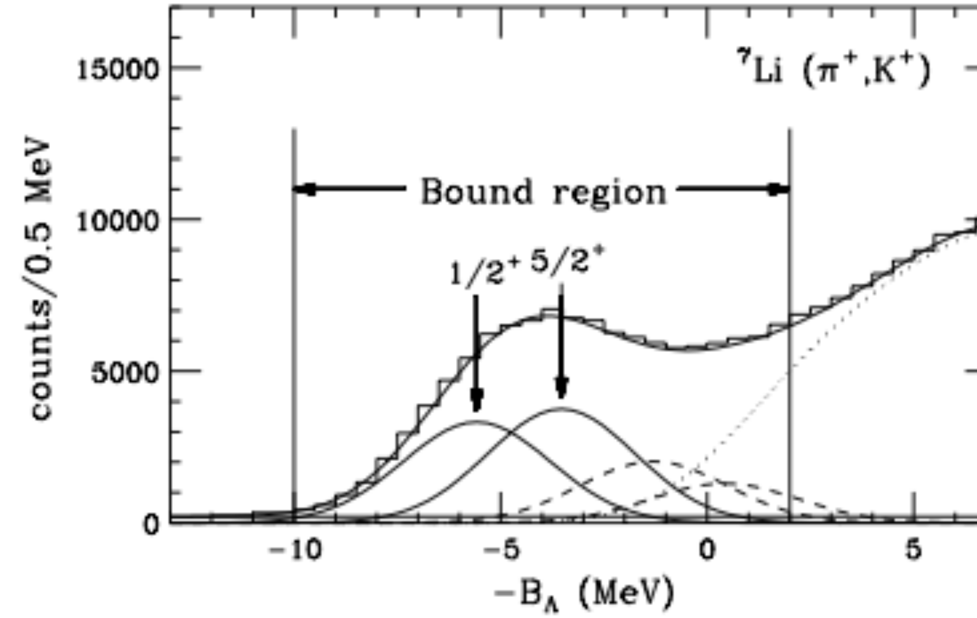


FIG. 2. Hypernuclear mass spectrum of $^{7}_{\Lambda}$Li (plotted versus the Λ binding energy, B_{Λ}) taken in the (π^+, K^+) reaction with a 25 cm thick ^{7}Li target. See Ref. [7] for the decomposition and assignments of states. The "bound region" is defined as shown.

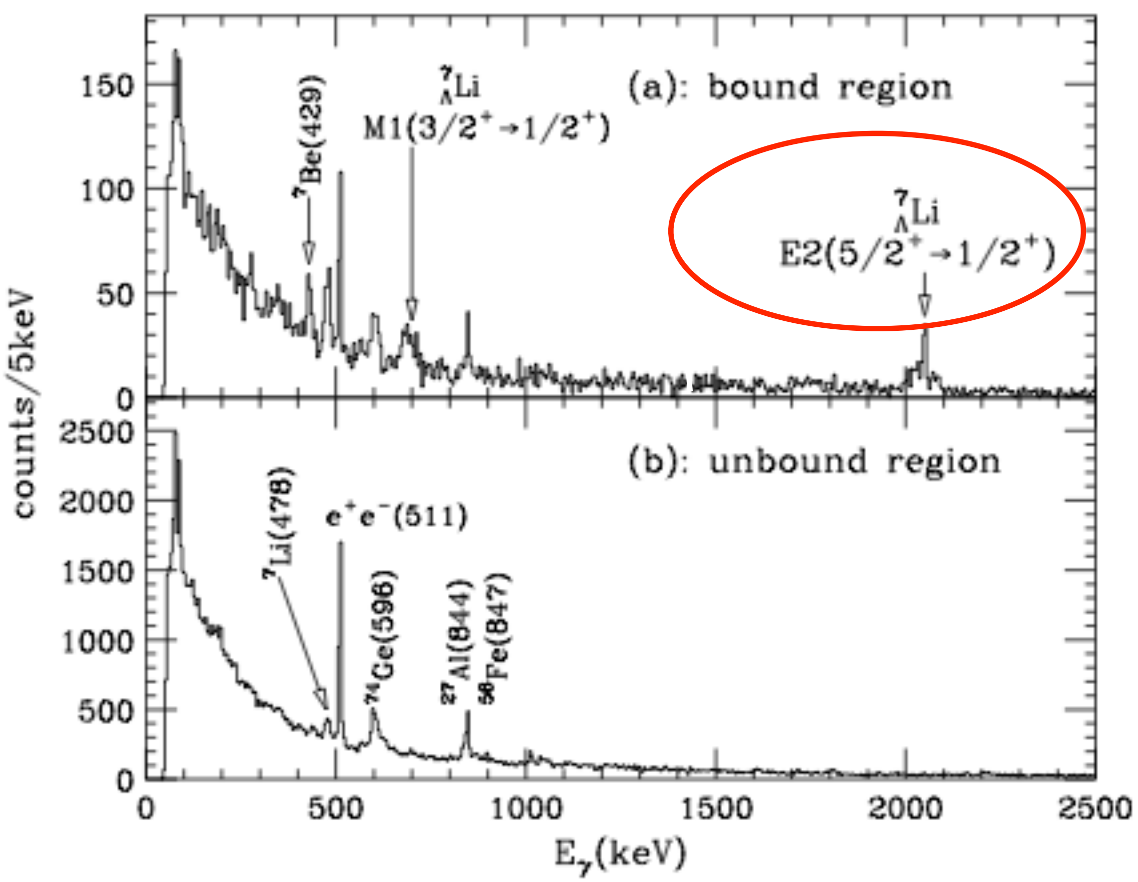


FIG. 3. γ-ray energy spectra measured in coincidence with the ^{7}Li(π^+, K^+) reaction. (a) For the bound region, and (b) for the unbound region ($-B_{\Lambda} > 2$ MeV). See Ref. [7] for the assignment of the peaks.

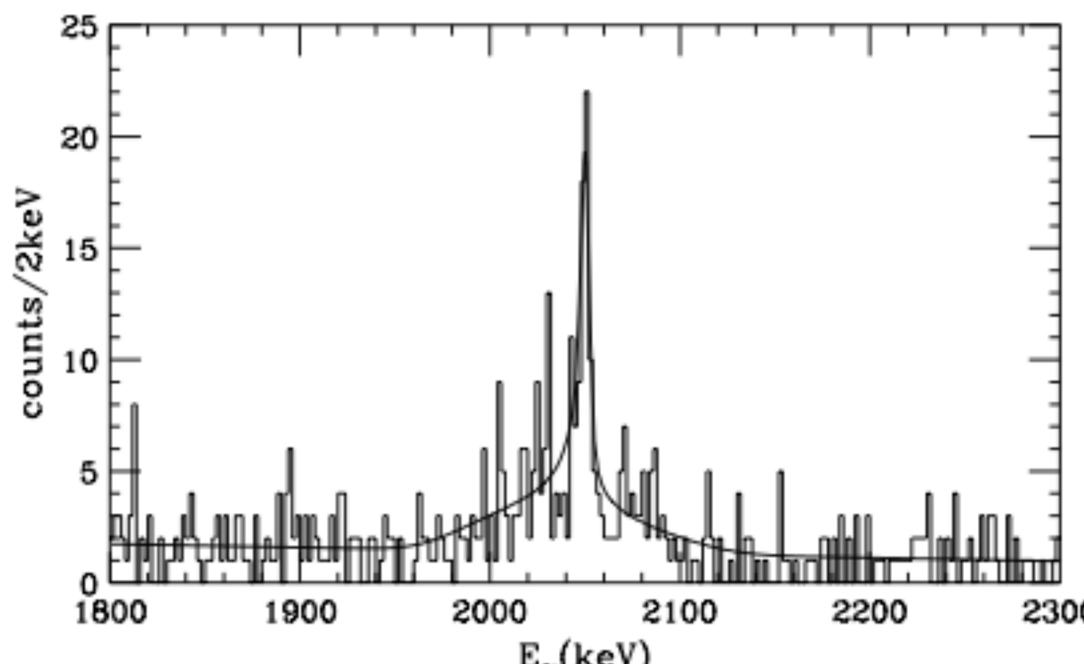


FIG. 4. γ-ray energy spectrum around the $E2$ peak. The result of the fitting to simulated spectra (see text) is shown with the solid line.

Size factor from measured branding ratios is
$S=0.81 \pm 0.04$

https://arxiv.org/pdf/1304.6875v1.pdf

Neutron stars with masses above 1.8 M manifested as radio pulsars.

We report the measurement of a 2.01±0.04 solar mass (M) pulsar in a 2.46-hr orbit with a 0.172 ± 0.003 M white dwarf.

https://arxiv.org/pdf/1512.06832.pdf

The EOS of neutron matter and the effect of Λ hyperons to neutron star structure

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(Received December 22, 2015)

The structure of neutron stars is determined by the equation of state of the matter inside the star, which relies on the knowledge of nuclear interactions. While radii of neutron stars mostly depend on the equation of state of neutron matter at nuclear densities, their maximum mass can be drastically affected by the appearance of hyperons at higher densities in the inner core of the star. We summarize recent quantum Monte Carlo results on the calculation of the equation of state of neutron matter at nuclear and higher densities. We report about the development of realistic hyperon-nucleon interactions based on the available experimental data for light- and medium-heavy hypernuclei and on the effect of Λ hyperons to the neutron star structure.

KEYWORDS: neutron stars, neutron matter, hyperons, hypernuclei, hyperon puzzle

Equation of state: Energy/nucleon(density, Λ fraction)

Calculate Neutron Star Mass(density)

ΛN Potential model

The two-body ΛN force is modeled with a Urbana-type potential [23], consistent with the available Λp scattering data

$$v_{\lambda i} = v_0(r_{\lambda i}) + \frac{1}{4} v_\sigma T_\pi^2(r_{\lambda i})\, \boldsymbol{\sigma}_\lambda \cdot \boldsymbol{\sigma}_i \,, \tag{3}$$

$$T_\pi(r) = \left[1 + \frac{3}{\mu_\pi r} + \frac{3}{(\mu_\pi r)^2}\right] \frac{e^{-\mu_\pi r}}{\mu_\pi r}\left(1 - e^{-cr^2}\right)^2 , \tag{8}$$

where μ_π is the pion reduced mass

$$\mu_\pi = \frac{1}{\hbar}\frac{m_{\pi^0} + 2\, m_{\pi^\pm}}{3} \qquad \frac{1}{\mu_\pi} \simeq 1.4 \text{ fm} . \tag{9}$$

σ spin

τ isospin

Λ has isospin 0

while the three-body potential $v_{\lambda ij}$ is written as the sum of 2π-exchange contributions $v_{\lambda ij}^{2\pi} = v_{\lambda ij}^{2\pi,P} + v_{\lambda ij}^{2\pi,S}$ and a spin-dependent dispersive term $v_{\lambda ij}^{D}$:

$$v_{\lambda ij}^{2\pi,P} = -\frac{C_P}{6}\left\{X_{i\lambda}, X_{\lambda j}\right\} \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \,,$$

The main outcome of the study is that the saturation property of the Λ binding energy is reproduced only with the inclusion of the ΛNN interaction. However, with the

$$v_{\lambda ij}^{2\pi,S} = C_S\, Z(r_{\lambda i}) Z\left(r_{\lambda j}\right) \boldsymbol{\sigma}_i \cdot \hat{\boldsymbol{r}}_{i\lambda} \boldsymbol{\sigma}_j \cdot \hat{\boldsymbol{r}}_{j\lambda} \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \,, \tag{4}$$

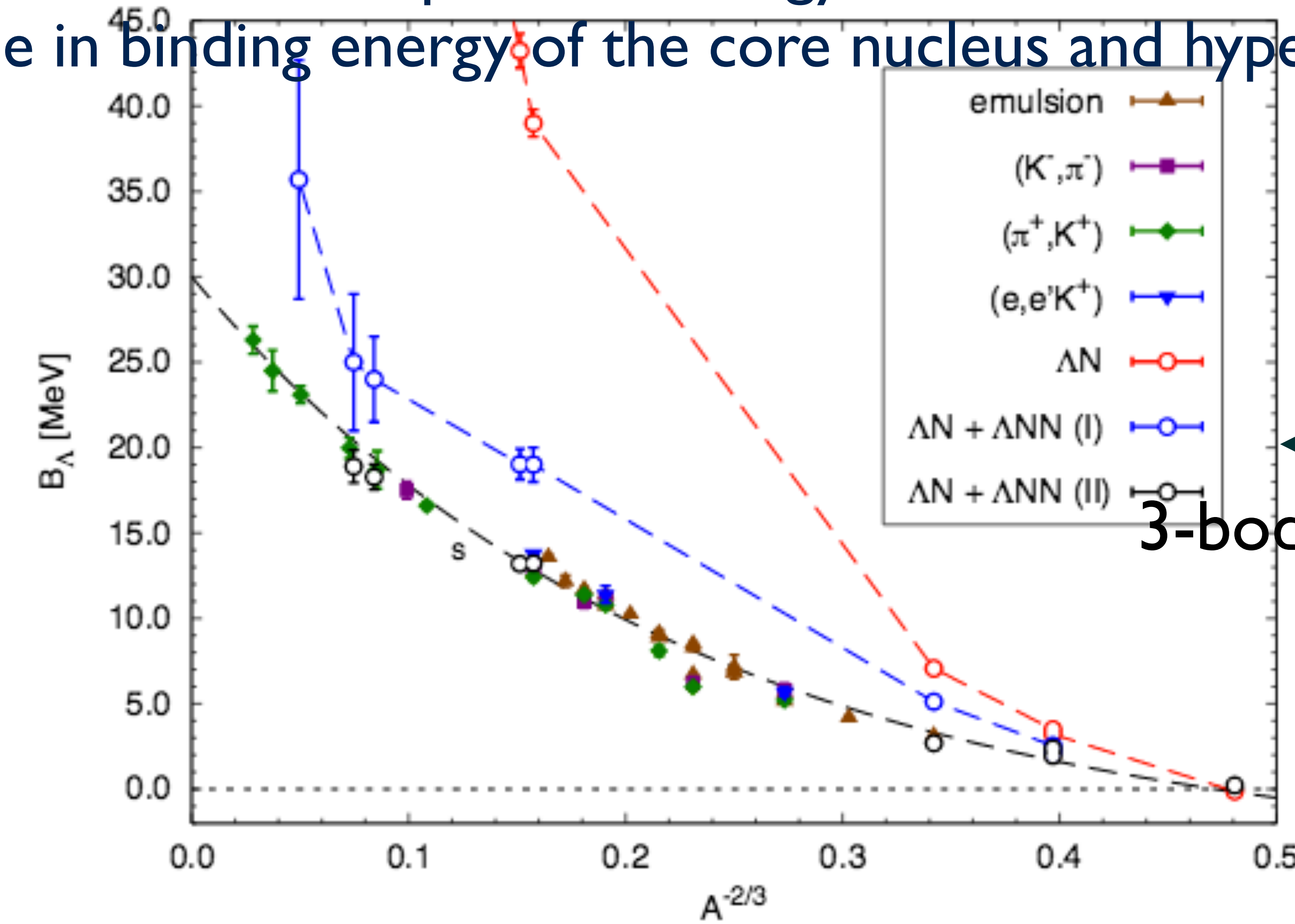
$$v_{\lambda ij}^{D} = W_D\, T_\pi^2(r_{\lambda i})\, T_\pi^2\left(r_{\lambda j}\right)\left[1 + \frac{1}{6}\boldsymbol{\sigma}_\lambda \cdot \left(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j\right)\right] .$$

All the details of the hypernuclear interaction, together with the complete list of parameters, can be found in Refs. [19, 20, 24].

Figure in Gandolfi and Lonardoni

Fit of model to hyper-nuclei production data

Λ separation energy B_Λ =
difference in binding energy of the core nucleus and hypernucleus



3-body interaction

Figure 4. Solid symbols are the available B_Λ experimental values in s wave for different hypernuclear production mechanisms (see Ref. [22] for the complete list of experimental references). Empty symbols refer to quantum Monte Carlo results. Red dots (upper curve) is the case of two-body ΛN interaction alone. Blue (middle curve) and black (lower curve) dots are the results obtained including two different parametrizations of the three-body hyperon-nucleon force [22, 24].

Energy(ρ)

Pure Neutron Matter (PNM) stiffest EOS

http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.114.092301

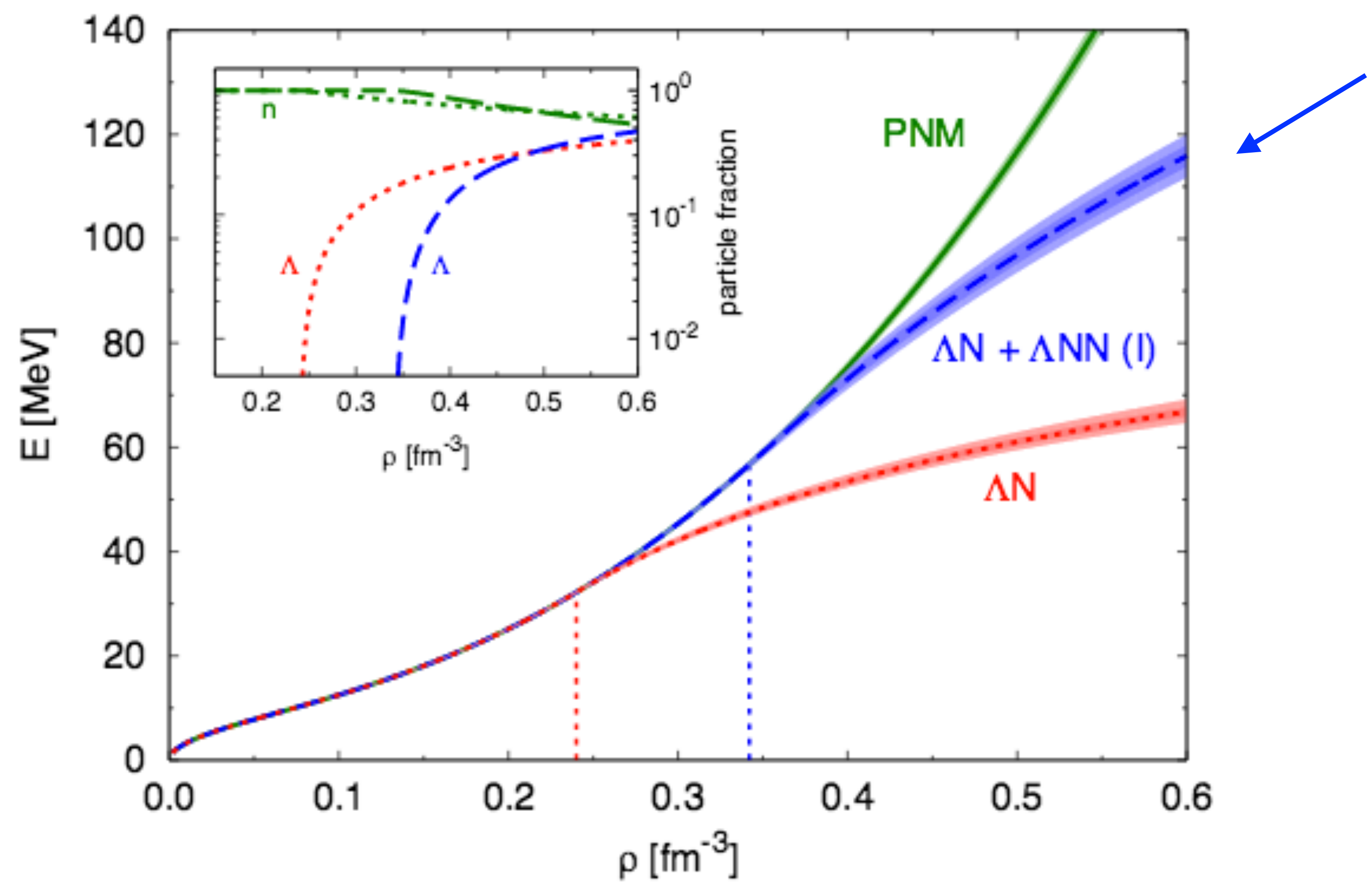


Figure 6. Equations of state. Green solid curves refer to pure neutron matter calculated with realistic two- plus three-nucleon potentials. The red dotted curve represents hyper matter with hyperons interacting via the two-body ΛN force alone. The blue dashed and black dotted-dashed curves are obtained including two different parametrizations of the three-body hyperon-nucleon potential. Shaded regions represent the uncertainties on the results. In the inset, neutron and lambda fractions corresponding to the two hyper-neutron matter EOSs. The figure is taken from Ref. [52].

only PNM explains very heavy neutron stars in this model

http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.114.092301

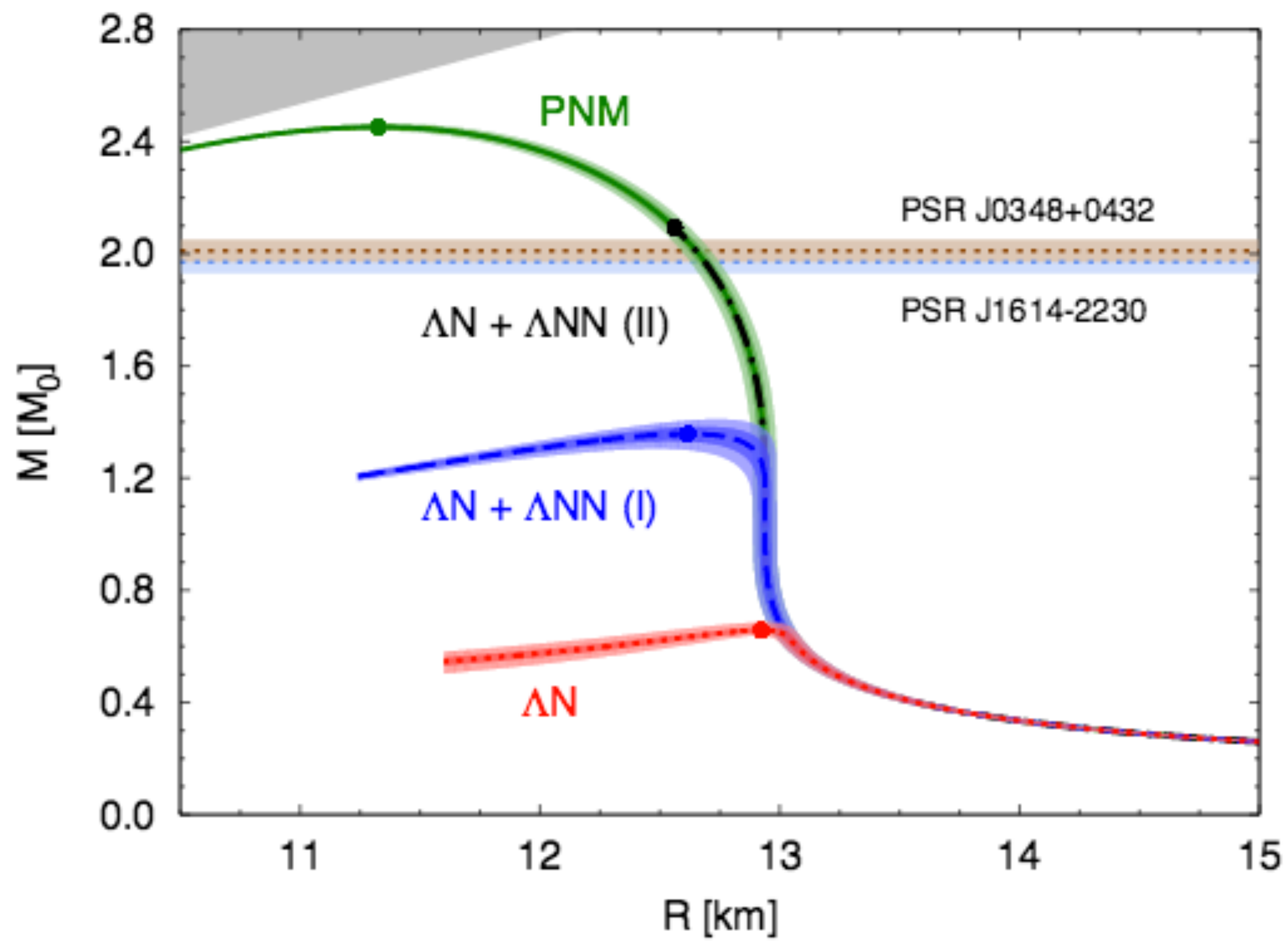


Figure 7. Mass-radius relations. The color scheme is the same as Fig. 6. Full dots represent the predicted maximum masses. Horizontal bands at $\sim 2M_\odot$ are the observed masses of the heavy pulsars PSR J1614-2230 [29] and PSR J0348+0432 [34]. The grey shaded region is the excluded part of the plot due to causality. The figure is taken from Ref. [52].

Tolman-Oppenheimer-Volkoff equations

Hyperon Puzzle

https://arxiv.org/pdf/1612.03758.pdf

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Dec. 2016

Introduction. The interactions of hyperons (Λ, Σ, Ξ) with nucleons (N) have been in the focus of studies for a variety of reasons [1]. A prominent one that has attracted wide attention recently is connected with the role that hyperons might play for the mass and size of neutron stars [2, 3, 4]. The observation of $2M_\odot$ neutron stars [5, 6] sets strongly restrictive constraints for the possible appearance of hyperons in neutron star matter and, accordingly, for the in-medium properties of hyperons and the hyperon-nucleon (YN) interaction itself [7, 8, 9, 10]. In order to stabilize such massive objects against gravitational collapse a sufficiently stiff equation-of-state (EoS) is required which does not leave much room for the presence of hyperons in the dense neutron star cores. A naive introduction of Λ-hyperons as an additional baryonic degree of freedom softens the EoS such that it fails to support $2M_\odot$ neutron stars [11]. This is what is commonly referred to as *the hyperon puzzle*.

$\Lambda n \leftrightarrow \Sigma n$

Λ(I=0) spin 1/2 baryon

Σ(I=1) spin 1/2 baryon