Role of hyperon–scalar-meson couplings on the EoS

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GC and A. Sedrakian, Phys. Rev. C 87, 055806 (2013)

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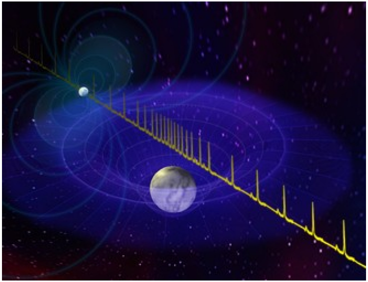
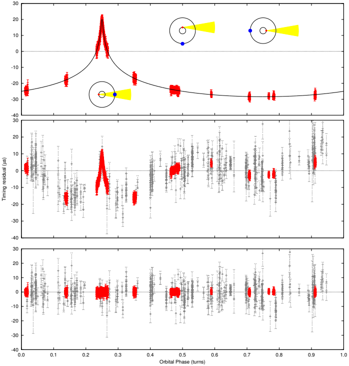
outline

hyperon puzzle

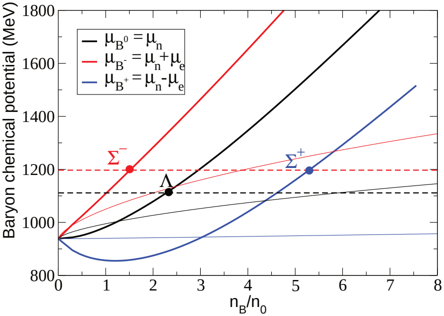
PSR J1614-2230: $M = 1.97 \pm 0.04\, M_\odot$ pulsar





Here we present radio timing observations of the binary millisecond pulsar J1614-2230 that show a strong Shapiro delay signature. We calculate the pulsars mass to be 1.97 ± 0.04 solar masses which rules out almost all currently proposed hyperon or boson condensate equations of state. (Demorest et al, 2010, Nature 467, 1081)

onset of hyperons in neutron star matter



Page and Reddy (2006)

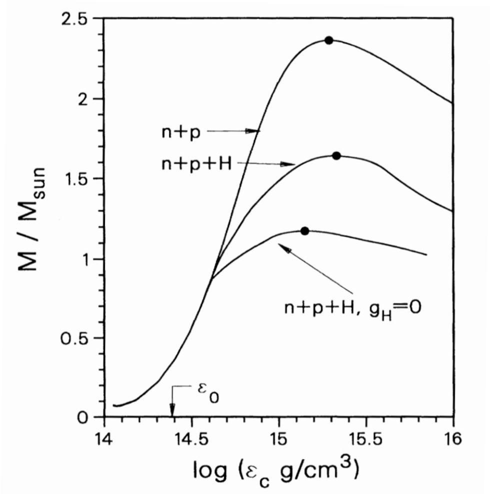
- thin lines: free gas
- thick lines: with mean-field NN potential
- horizontal lines are hyperon vacuum masses

- hyperons appear, when its in-medium energy equals its chemical potential:

$$\mu(Y) = \omega(Y) = m_Y + U_Y(n), \text{ with } \mu(Y) = B(Y) \cdot \mu_n - Q(Y) \cdot \mu_e$$

- onset in several models: RMF, DBHF, DDMF, ξ with SU(3) symmetry
- HIC?

consequences of hyperons on the maximum mass of neutron stars



Glendenning and Moszkowski (1991)

- neutron star with nucleons and leptons only: $M \approx 2.3 M_\odot$
- substantial decrease of the maximum mass due to hyperons
- maximum mass for "giant hypernuclei": $M \approx 1.7 M_\odot$
- noninteracting hyperons result in a too low mass: $M \approx 1.4 M_\odot$

hyperon coupling constants: $g_{\sigma YY} = g_{\rho YY} = 0.6 g_{\rho NN}$ and $g_{\omega YY} = 0.658 g_{\rho NN}$

At a given density, the presence of hyperons increases the number of Fermi spheres to be occupied leading to a lower pressure

how can we study this problem?

analytical, first-principle treatment of QCD is currently a cherished dream. . .

- extremely high energies/densities → perturbative QCD
- very low energies/densities → well defined nuclear physics based on NN potentials
- intermediate energies/densities → many effective models - astrophysical applications:
  - supernovae
  - compact objects (white dwarfs, neutron stars, black holes)

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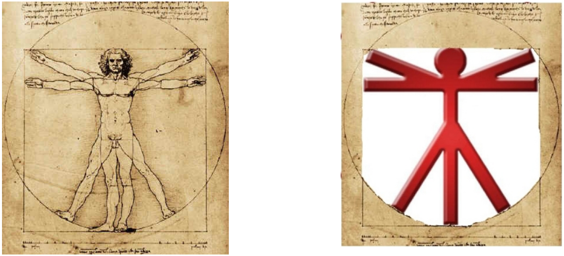
what is an effective model?

full model effective model

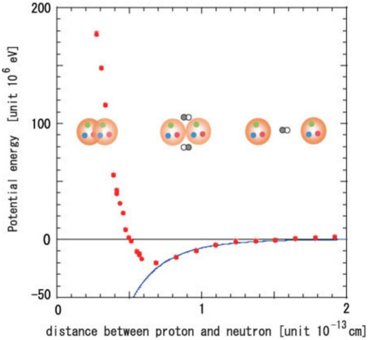


d.o.f.: observable particles (hadrons) instead of quarks and gluons

RMF

relativistic mean-field (RMF) model

basic assumptions and features for describing nuclear (and hypernuclear) properties:



- nucleons (and hyperons) interact through meson exchange
- assume that only low spin, isospin is needed (from OBEP)
- only Hartree diagrams
- σ–meson: mimics attractive potential
- nonlinearities of the σ–meson–field: needed for a correct compression modulus of nuclear matter (not always)
- ω–meson: repulsive part of the potential
- ρ–meson: isospin dependent part of the potential

RMF Lagrangian

full Lagrangian

$$\begin{aligned}\mathcal{L}_B &= \sum_B \bar{\psi}_B[\gamma^\mu(i\partial_\mu - g_{\omega BB}\omega_\mu - \frac{1}{2}g_{\rho BB}\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu) - (m_B - g_{\sigma BB}\sigma)]\psi_B \\ &+ \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\cdot\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^\mu\cdot\boldsymbol{\rho}_\mu \\ &+ \sum_{e^-,\mu^-} \bar{\psi}_\lambda(i\gamma^\mu\partial_\mu - m_\lambda)\psi_\lambda \\ &- \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\end{aligned}$$

baryon octet: p, n, Λ, Σ's and Ξ's
mesons: σ, ω and ρ
leptons: e^-, μ^- (and neutrinos at finite-temperature)
photons

nucleonic parametrization

meson-nucleon coupling constants - DD-ME2 parametrization

ansatz:

$$g_{iNN}(\rho) = g_{iNN}(\rho_{\text{sat}}) f_i(x) \qquad \text{for} \quad i = \sigma, \omega$$

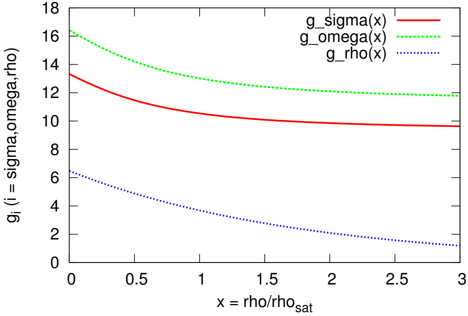
where

$$f_i(x) = a_i \frac{1 + b_i (x + d_i)^2}{1 + c_i (x + d_i)^2} \qquad x = \rho/\rho_{\text{sat}}$$

and

$$g_{\rho NN}(\rho) = g_{\rho NN}(\rho_{\text{sat}}) \exp[-a_\rho (x - 1)]$$

in total 8 parameters to be adjusted to reproduce the properties of symmetric and asymmetric nuclear matter, binding energies, charge radii, and neutron radii of spherical nuclei



(Niksic et al., 2008)

rearrangement self-energy contributions

$$
\begin{aligned}
P = & -\frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\
& + \frac{1}{3}\sum_B \frac{2J_B+1}{2\pi^2}\int_0^\infty \frac{k^4\,dk}{(k^2+m_B^{*2})^{1/2}}\left[f(E_k-\mu_B^*)+f(E_k+\mu_B^*)\right] \\
& + \frac{1}{3}\sum_{l=e^-,\mu^-}\frac{1}{\pi^2}\int_0^\infty \frac{k^4\,dk}{(k^2+m_l^2)^{1/2}}\left[f(E_k-\mu_l)+f(E_k+\mu_l)\right] \\
& + \rho_B\Sigma_r,
\end{aligned}
$$

where Σ_r is the rearrangement self-energy:

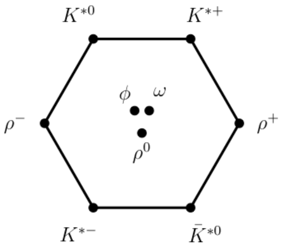
$$
\Sigma_r = \frac{\partial g_{NN\omega}}{\partial \rho_B}\omega_0\rho_B - \frac{\partial g_{NN\sigma}}{\partial \rho_B}\sigma\rho_S,
$$

thermodynamic consistency

$$
P = \rho_B^2\frac{\partial}{\partial\rho_B}\left(\frac{\epsilon}{\rho_B}\right)
$$

hyperonic parametrization

choice of hyperon couplings - vector mesons



VDM: universal coupling of $\boldsymbol{\rho}$ to the isospin current

$$g_{\Xi\Xi\rho} = g_{NN\rho} = \frac{1}{2} g_{\Sigma\Sigma\rho}, \quad g_{\Lambda\Lambda\rho} = 0$$

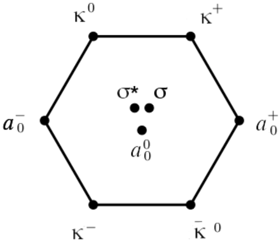
quark model and ideal mixing: mesons

$$\begin{aligned} \omega &\sim \frac{1}{\sqrt{2}} \left(\bar{u}u + \bar{d}d\right) \\ \phi &\sim \bar{s}s \end{aligned}$$

simple strangeness-content counting

$$g_{\Sigma\Sigma\omega} = g_{\Lambda\Lambda\omega} = 2 g_{\Xi\Xi\omega} = \frac{2}{3} g_{NN\omega}$$

choice of hyperon couplings - scalar mesons



for the scalar octet (de Swart, 1955):

$$\begin{aligned} g_{NNa_0} &= g_S, & g_{NN\sigma_8} &= \frac{1}{\sqrt{3}} g_S(4\alpha_S - 1) \\ g_{\Sigma\Sigma a_0} &= 2g_S\alpha_S, & g_{\Sigma\Sigma\sigma_8} &= \frac{2}{\sqrt{3}} g_S(1-\alpha_S) \\ g_{\Lambda\Lambda a_0} &= 0, & g_{\Lambda\Lambda\sigma_8} &= -\frac{2}{\sqrt{3}} g_S(1-\alpha_S) \\ g_{\Xi\Xi a_0} &= -g_S(1-2\alpha_S), & g_{\Xi\Xi\sigma_8} &= -\frac{1}{\sqrt{3}} g_S(1+2\alpha_S) \end{aligned}$$

nonet mixing:

$$g_{BB\sigma} = \cos\theta_S g_1 + \sin\theta_S g_{BB\sigma_8}$$

relation independent on θ_S, α_S, g_1 and g_S!

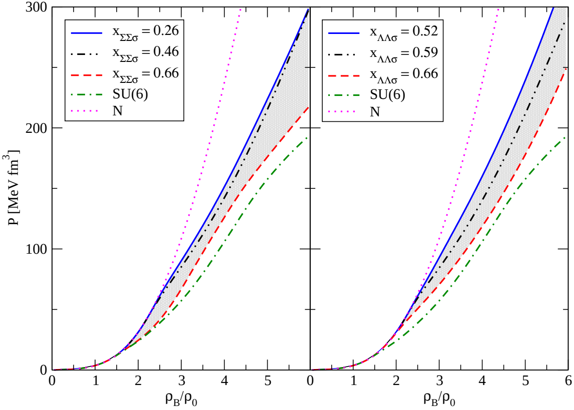
$$\boxed{2(g_{NN\sigma} + g_{\Xi\Xi\sigma}) = 3g_{\Lambda\Lambda\sigma} + g_{\Sigma\Sigma\sigma}}$$

parameter study by fixing one of the couplings to NSC89

results

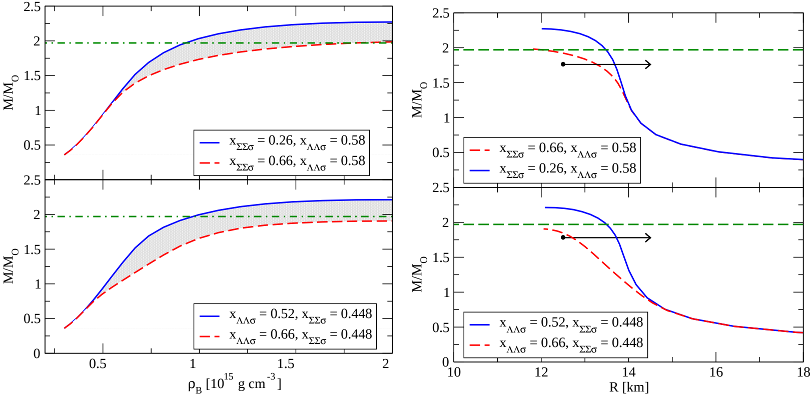
results for zero-temperature

hyperon coupling constants fixed by NSC89

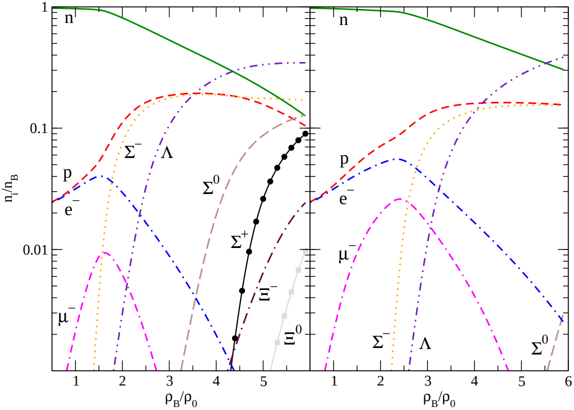


$x_{\Lambda\Lambda\sigma} = 0.58$ $x_{\Sigma\Sigma\sigma} = 0.448$

mass-radius relation



particle fractions: zero temperature

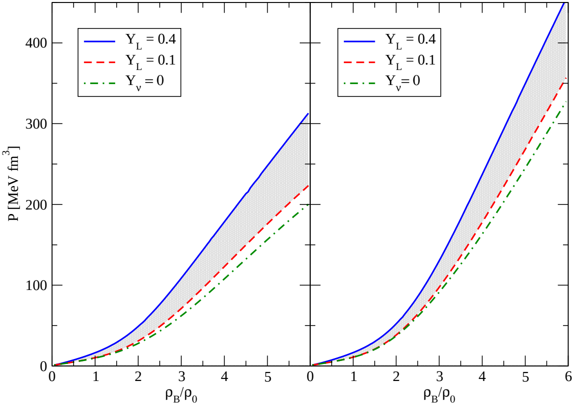


symmetric case stiffest (hyp) case

- deleptonization due to negative hyperon onset
- shift of hyperon onset in case of small *attractive* couplings ($g_{Y\sigma}$)

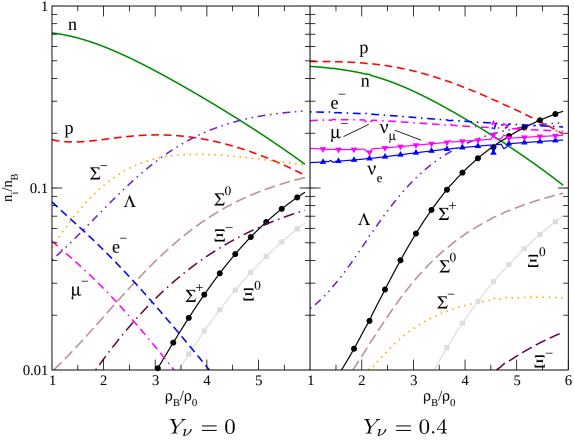
finite-temperature and neutrino trapping

new dof (neutrinos) → new constraint: fixed lepton fraction



($T = 30$ MeV)

particle fractions: finite temperature



$Y_\nu = 0$ $Y_\nu = 0.4$

- no deleptonization due to fixed lepton fraction
- positive charged hyperons favoured due to the presence of electrons
- inversion of charged hyperon onset

summary

summary

summary

- recent data ($2M_\odot$ NS) and hyperon puzzle
- realistic meson-nucleon interaction at finite density
- choice of hyperon couplings: parameter study for scalar-hyperon interaction
- finte temperature and neutrino trapping

outlook

- effect of pions from chiral lagrangians
- strong magnetic field contribution

thanks for your attention!