The influence of the symmetry energy on the structure of hyperon stars.

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Matter To The Deepest
Recent Developments In Physics Of Fundamental Interactions
XXXIX International Conference of Theoretical Physics

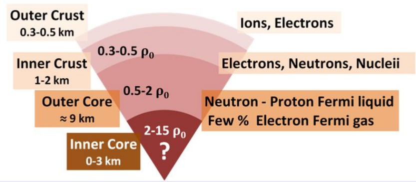
Ustron 2015

Study of nuclear matter at densities above saturation density

Motivation:

- better understanding of the physics of neutron stars
- examining the possibility of the existence of strange baryons in the very inner part of a neutron star

Modelling neutron star structure and composition



P. Haensel et al. 2007

Outer core - n, p, e, μ matter under β equilibrium

$$\varepsilon = \varepsilon_N(n_n, n_p) + \varepsilon_l(e, \mu)$$

Equilibrium conditions:

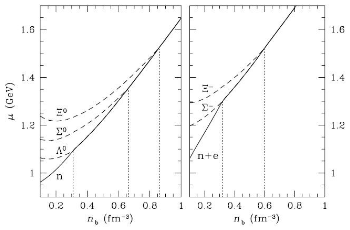
1. $\mu_n = \mu_p + \mu_e$
2. $\mu_\mu = \mu_e$

Schematic structure of a neutron star

- atmosphere
- outer crust - lattice of neutron-rich heavy nuclei, degenerate, relativistic electrons - correction to radius $\sim$ 10 percent
- inner crust - as above plus degenerate non-relativistic neutrons
- outer core - homogeneous nucleonic matter
- inner core - may contain exotic forms of matter

Modelling neutron star structure and composition

Threshold chemical potentials of hyperons



P. Haensel et al. 2007
Apppearance of hyperons - at $2 - 3\mathrm{n}_0$

Equilibrium conditions - contribution of hyperons to β equilibrium.

1. $\mu_{\Xi^-} = \mu_{\Sigma^-} = \mu_\mathrm{n} + \mu_\mathrm{e}$
2. $\mu_{\Xi^0} = \mu_{\Sigma^0} = \mu_\Lambda = \mu_\mathrm{n}$
3. $\mu_{\Sigma^+} = \mu_\mathrm{p} = \mu_\mathrm{n} - \mu_\mathrm{e}$

hyperon onset points - hyperon threshold densities $\mathrm{n_Y}$

$$\lim_{\mathrm{n_Y}\to 0} = \frac{\partial\varepsilon}{\partial \mathrm{n_b}}\,|_\mathrm{eq} = \mu^0_\mathrm{Y}$$

For $\mathrm{n_b} > \mathrm{n_Y^{th}}$ hyperon Y become stable in dense matter.

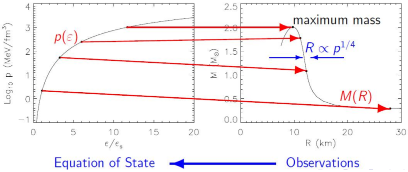
Modelling neutron star structure and composition - Tolman-Oppenheimer-Volkoff equation

$$\frac{d\mathcal{P}}{dr} = -\frac{G}{c^4}\frac{(\mathcal{E}+\mathcal{P})\left(mc^2+4\pi r^3\mathcal{P}\right)}{r\left(r-2Gm/c^2\right)}$$

$$\frac{dm}{dr} = 4\pi r^2\frac{\mathcal{E}}{c^2}$$

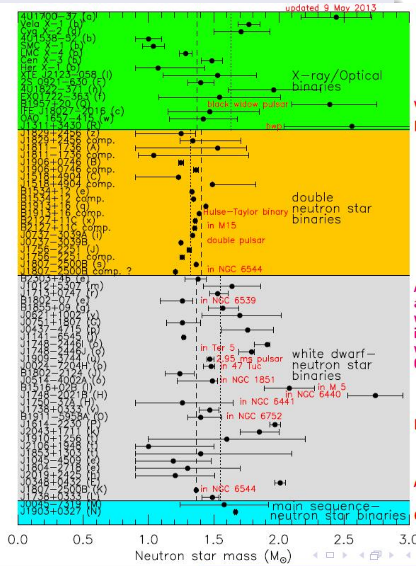
- M – R relations
- details about the internal structure of a neutron star
- provides data on the impact of a given model on the internal structure of a neutron star

Solution of the TOV equations needs supplementation by the equation of state (EoS) of the matter of a neutron star $\mathcal{P}(\mathcal{E}(n_B))$



Lattimer et al. 2013

Measured neutron star masses.



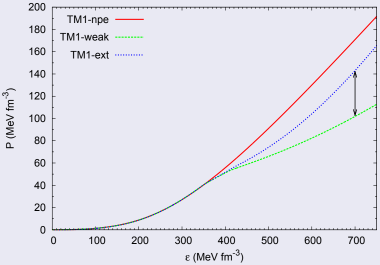
Lattimer et al. 2013

There are no precise simultaneous measurements of neutron star mass and radius.
Constraints on the mass-radius relation

- radius - not strong enough
- mass
  1. PSR J1614-2230, NS-WD binary system, $M_{NS} = 1.97 \pm 0.4 M_\odot$, $M_{WD} = 0.5 M_\odot$ P.Demorest et al. 2010
  2. PSR J0348+0432, NS-WD binary system, $M_{NS} = 2.01 \pm 0.4 M_\odot$, $M_{WD} = 0.172 M_\odot$ Antoniadis et al. 2013

Hyperon puzzle.

$M_{max} \geq M_{measured} \Rightarrow M_{max} \geq 2M_\odot$
Massive neutron stars - strong constraint on the equation of state - requires stiff equation of state
Hyperons soften the equation of state significantly.



Equation of state of isospin asymmetric nuclear matter - two component system of N nucleons

The energy differences of the states with different composition of protons and neutrons are encoded in the symmetry energy.

$$\mathrm{E_{sym}(N_p, N_n) \equiv E(N_p, N_n) - E(N_p = N/2, N_n = N/2)}$$

$$\delta_\mathrm{a} = \frac{\mathrm{N_n - N_p}}{\mathrm{N_B}} = 1 - 2\mathrm{Y_p}$$

$$\mathrm{E_{sym}(N, \delta_a) \equiv E(N, \delta_a) - E(N, \delta_a = 0)}$$

1. symmetric nuclear matter (SNM) $\delta_\mathrm{a} = 0 \Rightarrow \mathrm{N_n = N_p}$
2. pure neutron matter (PNM) $\delta_\mathrm{a} = 1 \Rightarrow \mathrm{N_p} = 0$

$$\mathrm{E_{sym}(n_B) = E(n_B, \delta_a = 1) - E(n_B, \delta_a = 0)}$$

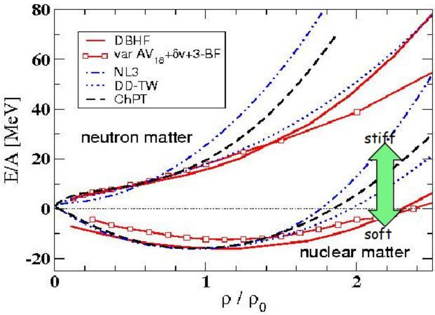
$$\mathrm{E(n_0, \delta_a = 1) = E_{sym}(n_0) + E(n_B, \delta_a = 0)}$$

Using the expansion

$$E(n_B, y_p) = E(n_B, y_p = 1/2) + (1 - 2y_p)^2 S_2(n_B) + \ldots$$

$$S_2(n_B) = S_v + \frac{L}{3}\frac{n_B - n_0}{n_0} + \ldots$$

$S_v \simeq 31$ MeV, $L \simeq 50$ MeV



Symmetry energy- connections to neutron star parameters

- Proton fraction

$$\mu_{\mathrm{p}} - \mu_{\mathrm{n}} = \frac{\partial \mathrm{E}_{\mathrm{Tot}}}{\partial \mathrm{Y}_{\mathrm{p}}} = 4\mathrm{E}_{\mathrm{sym}}(\mathrm{n}_{\mathrm{B}})(1 - 2\mathrm{Y}_{\mathrm{p}})$$

$\mathrm{E}_{\mathrm{Tot}} = \mathrm{E} + \mathrm{E}_{\mathrm{e}}$ at saturation $\mathrm{n}_{\mathrm{B}} = \mathrm{n}_0$

$$\mathrm{Y}_{\mathrm{p}} \approx \frac{1}{3\pi^2 \mathrm{n}_0} \left(\frac{4\mathrm{S}_{\mathrm{v}}}{\hbar \mathrm{c}} \right)^3 \approx 0.04$$

- Pressure at saturation density

$$\mathrm{p}_{\beta}(\mathrm{n}_0) = \simeq \frac{\mathrm{L}}{3} \mathrm{n}_0 \left(1 - \left(\frac{4\mathrm{S}_{\mathrm{v}}}{\hbar \mathrm{c}} \right)^3 \frac{4 - 3\mathrm{S}_{\mathrm{v}}/\mathrm{L}}{3\pi^2 \mathrm{n}_0} + \dots \right)$$

Symmetry energy- connections to neutron star parameters

Pressure- radius correlations

$$R = C(n_B, M)(p_\beta/\mathrm{MeVfm}^{-3})^{1/4}$$

Coefficients $C(n_B, 1.4M_\odot)$

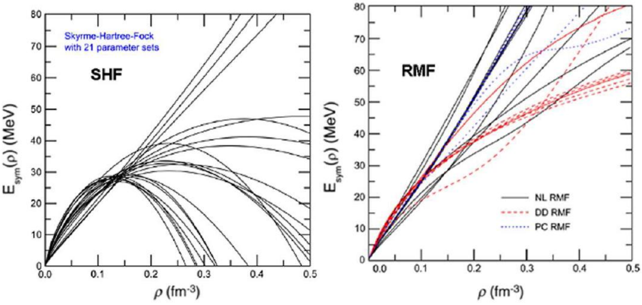
$M_*/M_\odot$	n_0	$1.5n_0$	$2n_0$
1.3	9.30±0.58	6.99±0.30	5.72±0.25
2.0	9.52±0.49	7.06±0.24	5.68±0.14

Coefficients appropriate for $n_B = n_0$ - $C(n_0, 1.4M_\odot)$

- Crust-core transition density and pressure
- Crust thickness

Theoretical predictions for symmetry energy

Theoretical considerations predict wide range of symmetry energies for densities below and above saturation density $n_0 = 0.16\text{fm}^{-3}$.



Density dependence of the symmetry energy predicted by various theoretical calculations. (Shetty, 2010)

Nuclear matter with strangeness degrees of freedom - system of nucleons and hyperons

Modification of the symmetry energy by the presence of hyperons.

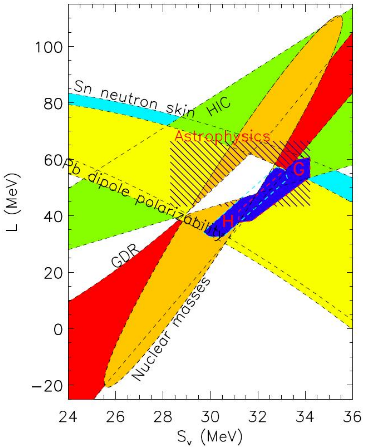
$$\mathrm{E}^{\mathrm{H}}_{\mathrm{sym}}(\mathrm{n_B}, \delta_{\mathrm{a}}, \mathrm{y_i}) = \mathrm{E}(\mathrm{n_B}, \delta_{\mathrm{a}}, \mathrm{y_i}) - \mathrm{E}(\mathrm{n_B}, \delta_{\mathrm{a}} = 0, \mathrm{y_i})$$

In this case: $\mathrm{n_B} = \mathrm{n_N} + \mathrm{y}$ and $\mathrm{y} = \sum_{\mathrm{i}} \mathrm{y_i}$ - total hperon number density

Pure neutron matter $\longrightarrow \mathrm{y} = 0$

Experimental constraints for symmetry energy parameters.

- Constraint for the centroid energy of the giant dipole resonance for ^{208}Pb - $S_2(0.1) \simeq (24.1 \pm 0.9)$ MeV
- Consensus agreement of the six experimental constraints 44 MeV $< L < 66$ MeV
- Results of neutron matter studies - direct estimates of S_v and L consistent with the results determined from nuclear experiments



Astrophysical considerations

Measurements of neutron star radii

Estimation of neutron star radii - distant measurement and atmospheric modelling required.

Photospheric Radius Expansion Bursts

- Accreation from the companion (MS star) - overflowing the Roche lobe
- Unstable burning of the accreated material
- Spread of the nuclear burning accros stellar surface - sudden increase in X-ray luminosity and temperature
- X-ray bursts

The average neutron star mass and radius implied by these results: $\bar{\mathrm{M}} = 1.65 \pm 0.12\mathrm{M}_{\odot}$, $\bar{\mathrm{R}} = 10.77 \pm 0.65$.

QLMXBs

- Neutron stars in binary system with intermittently accreated matter from evolving companion star.
- Episodes of accretion separated by long periods of quiescence.
- Low magnetic field
- Compression of matter in the crust induces nuclear reactions
- Sufficient amount of heat is released to warm the star
- Neutron stars cool via neutrino radiation from their interiors and X-ray from their surfaces

The emitted X-ray spectra (for a given composition) depend on: R, T_{eff}, $g = GM(1+z)/R^2$ (observed spectra - D and N_H)
J.Lattimer, 2014

The model

$$\mathcal{L} = \sum_{\mathrm{B}} \mathcal{L}_{\mathcal{B}} + \mathcal{L}_{\mathcal{M}} + \mathcal{L}_{\mathrm{NL}} + \mathcal{L}_{\mathrm{L}}$$

$$\mathcal{L}_{\mathcal{B}} = \bar{\psi}_{\mathrm{B}}(\gamma_\mu \mathrm{i}\mathrm{D}^\mu - \mathrm{M}^\star_{\mathrm{B}})\psi_{\mathrm{B}}$$

$$\mathrm{M}^\star_{\mathrm{B}} = \mathrm{M} - \mathrm{g}_{\mathrm{B}\sigma}\sigma - \mathrm{g}_{\mathrm{B}\sigma^\star}\sigma^\star$$

$$\mathrm{D}_\mu = \partial_\mu + \mathrm{i}\mathrm{g}_{\mathrm{B}\omega}\omega_\mu + \mathrm{i}\mathrm{g}_{\mathrm{B}\phi}\phi_\mu + \mathrm{i}\mathrm{g}_{\mathrm{B}\rho}\mathrm{I}_{\mathrm{B}}\boldsymbol{\rho}_\mu$$

$$\mathcal{L}_{\mathrm{NL}} = -\frac{1}{3}\mathrm{g}_3\sigma^3 - \frac{1}{4}\mathrm{g}_4\sigma^4 + \sum_{\mathrm{i,j,k}} \mathrm{C}_{\mathrm{ijk}}\omega^{\mathrm{i}}_\mu \rho^{\mathrm{j}}_\mu \phi^{\mathrm{k}}_\mu$$

Constituents of the model

- baryons: $\mathcal{B} \in \{\mathrm{n}, \mathrm{p}, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-\}$
- leptons: $\mathrm{L} \in \{\mathrm{e}^-, \mu^-\}$
- mezons: $\mathcal{M} \in \{\sigma, \omega_\mu, \rho^{\mathrm{a}}_\mu\} \cup \{\sigma^*, \varphi_\mu\}$

Coupling constants

- vector meson-hyperon - SU(6) symmetry
- scalar meson-hyperon - hypernuclear potential in nuclear matter

The Walecka-type models

Very "stiff" form of the symmetry energy. To provide additional freedom in varying the density dependence of the symmetry energy the model is supplemented by the term:

$$\Lambda_{\rm V}(g_\omega \omega)^2 (g_\rho \rho)^2$$

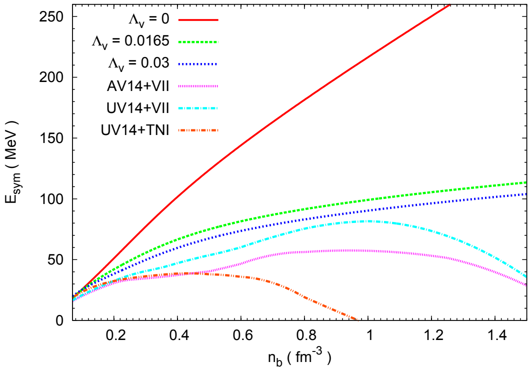
The density dependence of the symmetry energy

$$E_{\rm sym}(n_B) = \frac{k_F^2}{6\sqrt{(k_F^2 + M_{\rm eff}^2)}} + \frac{k_F^3}{12(m_\rho^2/g_\rho^2 + 2\Lambda_{\rm V}(g_\omega\omega)^2)}$$

for $\Lambda_{\rm V} = 0$ the symmetry energy varies linearly with the density.

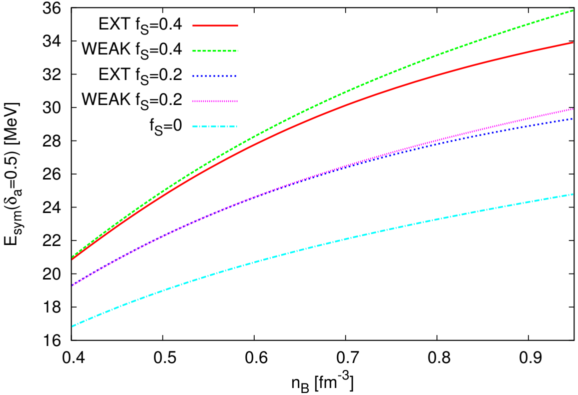
TM1 nonlinear (isovector sector)					
$\Lambda_{\rm V}$	0	0.014	0.015	0.016	0.0165
g_ρ	9.264	9.872	9.937	10.003	10.037
L (MeV)	108.58	77.52	75.81	74.16	73.36

Density dependence of symmetry energy



Calculations performed for different values of parameter Λ_V and compared with the results obtained for the AV14+VII, UV14+VII and UV14+TNI models.(R.B.Wiringa,1988) The inclusion of $\omega - \rho$ coupling softens the symmetry energy.

Modification of the symmetry energy for nuclear matter with hyperons.



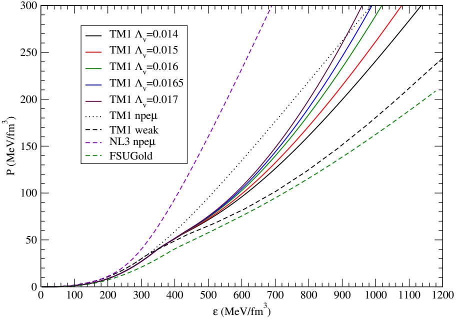
Modification of neutron star parameters

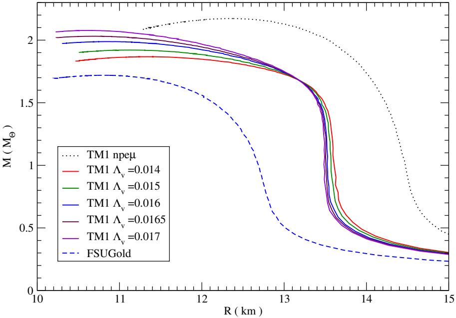
Equations of state

Results obtained for non-strange and and strangeness-rich matter for different parameterizations.

Mass-radius relations

Neutron star matter with hyperons - the maximum mass range:
$1.86 - 2.03 M_{\odot}$





Modification of neutron star parameters

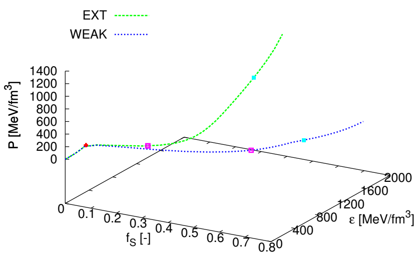
Neutron star matter with hyperons - equations of state

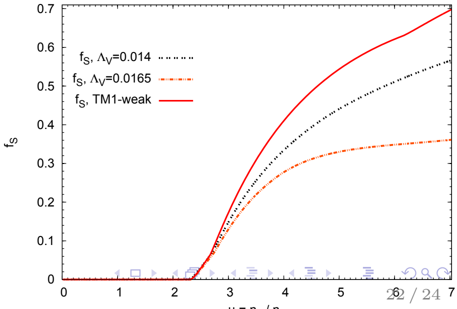
Pressure and energy density dependence on strangeness fraction.

Density dependence of strangeness fraction

$$f_S = \frac{\sum_i n_i |s_i|}{n_B}$$

Hyperon supression at high density

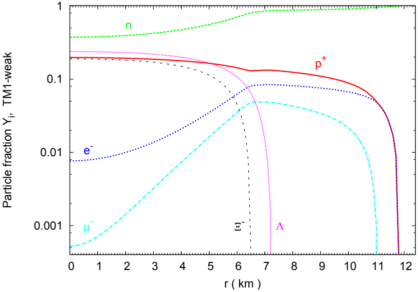


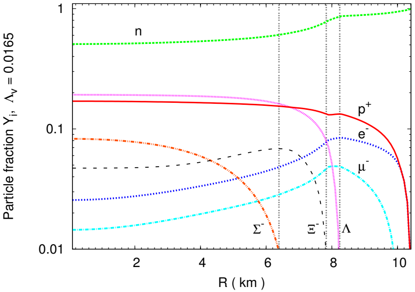


Modification of the internal structure of a neutron star

Neutron star matter with hyperons

Composition of the maximum mass configurations





Conclusions

- Different neutron star observables are sensitive to the density dependence of the symmetry energy - some of them depend on symmetry energy at relatively low density
- Hyperons affects the nuclear symmetry energy
- Modifies properties and structure of a neutron star