Effect of the symmetry energy on the EOS of compact stars

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Motivation

- How do compact star properties depend on the $\epsilon_{sym}$?
  - strangeness content?
  - onset of the of DU?
  - the mass-radius curve?
  - the pasta phase?
L: experimental overview

- Colo et al 2010, pigmy dipole resonances
- Tsang et al 2009, isoscaling
- Chen et al 2005, isospin diffusion
- Danielewicz 2003, mass formula
- Danielewicz, Lee 2009, isospin analogue states
- Centelles et al 2009, neutron skin thickness
- Klimliewicz et al 2007, pigmy DR
- BHF, Vidana et al 2008
Transition density versus $L$

From thermodynamic spinodal

$L$ and $\rho_t$ are well correlated.

$K_{sym}$ and $\rho_t$ are also correlated due to an existing correlation between $L$ and $K_{sym}$.

From ID constraints on $L$ (Chen et al 2005).

BHF: $L=66.5$ MeV.
Hyperon content and $L$

Hyperon content depends on:

- hyperon-meson interaction
- properties of nucleonic EOS

example: effect of $\epsilon_{\text{sym}}(\rho)$

$L(\text{IUFSU}) = 47.2 \text{ MeV}, \ L(\text{set 7}) = 99.2 \text{ MeV}$
Outline

EOS

Hyperon interaction

Strangeness content, mass and radius

Crust
EOS
RMF Lagrangian for stellar matter

- Lagrangian density

\[ \mathcal{L}_{NLWM} = \sum_{B=baryons} \mathcal{L}_B + \mathcal{L}_{mesons} + \mathcal{L}_l + \mathcal{L}_\gamma, \]

- Nucleon contribution: \( \mathcal{L}_B = \bar{\psi}_B \left[ \gamma_\mu D^\mu_B - M^*_B \right] \psi_B \),
  \( D^\mu_B = i\partial^\mu - g_{\omega B} \omega^\mu - \frac{g_{\rho B}}{2} \tau \cdot \mathbf{b}^\mu - g_{\phi B} \phi^\mu - eA^\mu \frac{1+\tau_3}{2} \)
  \( M^*_B = M_B - g_{\sigma B} \sigma - g_{\sigma^* B} \sigma^* \)

- Meson contribution

\[ \mathcal{L}_{mesons} = \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\sigma^*} + \mathcal{L}_\phi + \mathcal{L}_{non-linear} \]

- Lepton contribution: \( \mathcal{L}_l = \sum_l \bar{\psi}_l \left[ \gamma_\mu (i\partial^\mu + eA^\mu) - m_l \right] \psi_l \)
RMF: Non Linear Terms

- **$\omega$ meson**
  - $L_{n\omega} = \frac{1}{4!} \xi g^4_V (V_\mu V^\mu)^2$ (Sugara & Toki NPA579)
  - introduced to reproduce Dirac-Brueckner results (TM1)
  - describes the observed flattening of vector self-energy at high densities
  - $m_{\omega,\text{eff}}^2 = m_\omega^2 + \frac{\xi}{6} g^4_\omega \omega_0^2 + 2 \Lambda_\omega g^2_\omega g^2_\rho b_0^2$, $\omega_0 = \frac{g_\omega}{m_{\omega,\text{eff}}^2} \rho_B$

- **$\omega - \rho$ term**
  - $L_{\rho\omega} = \Lambda_\omega g^2_\rho \bar{\rho}_\mu \cdot \bar{\rho}_\mu g^2_\omega \omega_\mu \omega^\mu$
  - modulates $\epsilon_{\text{sym}}(\rho)$ (Horowitz& Piekerawicz PRL86)
  - collective modes fix coupling (Piekerawicz (2004))
  - FSU parametrization (Todd-Rutel & Piekerawicz) : too soft
  - IU-FSU parametrization (Fattoyev 2010)
    - similar $\epsilon_{\text{sym}}$ as FSU, harder EOS at high densities
    - satisfies pressure constraints of Steiner et al 2010
  - $m_{\rho,\text{eff}}^2 = m_\rho^2 + 2 \Lambda_\omega g^2_\omega g^2_\rho \omega_0^2$, $b_0 = \frac{g_\rho}{m_{\rho,\text{eff}}^2} \rho_3$
Effect of $L$ on fields strength

thin: $L=110$ MeV
thick: $L=55$ MeV
RMF: modeling the EOS

- yellow: constraints from flow of matter in nuclear collisions (Danielewicz 2002)
RMF: symmetry energy

\[ \varepsilon_{\text{sym}} \text{ (MeV)} \]

\[ \rho \text{ (fm}^{-3}\text{)} \]

- NL3
- TM1
- \( \Lambda_v = 0.03 \)
- GM1
- GM3
- FSU
- IUFSU
Hyperon-meson interaction

- Hypernuclei binding energy (SET A)
  - $\omega$ and $\rho$-hyperon couplings: SU(6) symmetry
    \[
    \frac{1}{2} g_{\omega\Lambda} = \frac{1}{2} g_{\omega\Sigma} = g_{\omega\Xi} = \frac{1}{3} g_{\omega N}
    \]
  - $\sigma$-hyperon couplings: hypernuclei binding energies in SNM
    \[
    V_j = x_{\omega j} V_\omega - x_{\sigma j} V_\sigma
    \]
    \[
    V_\Lambda = -28 \text{ MeV} \ , \ V_\Sigma = 30 \text{ MeV} \ , \ V_\Xi = -18 \text{ MeV} .
    \]
- AGS E885 collaboration (2000): $K^- +^{12}\text{C} \rightarrow K^+ +^{12}\text{Be}$
  - “results are consistent with the theoretical predictions when a potential depth $V_\Xi$ of 14 MeV or less is assumed”
- We will test the effect of changing $V_\Sigma$ and $V_\Xi$
Hyperon-meson interaction

- **SET B**: \( x_{\sigma j} = 0.8 \) (Glendenning & Mozskowski 1991)
  - Accurately extrapolated value of the \( \Lambda \) hyperon binding in saturated nuclear matter
    \[
    V_\Lambda = -28 = x_{\omega \Lambda} V_\omega - x_{\sigma \Lambda} V_\sigma
    \]
  - neutron stars masses \( \rightarrow x_{\Lambda \sigma} \leq 0.9 \)
  - \( x_i \Sigma = x_i \Lambda = x_i \Xi \), \( i = \sigma, \omega, \rho \)
Hyperon-strange meson interaction

- Couplings $\phi, \sigma^*$-nucleons
  - $g_{\phi N} = g_{\sigma^* N} = 0$

- Couplings $\phi$-hyperons
  - $2g_{\phi \Lambda} = 2g_{\phi \Sigma} = g_{\phi \Xi} = -\frac{2\sqrt{2}}{3} g_{\omega N}$
  - brings extra repulsion in the hyperon sector

- Couplings $\sigma^*$-baryons: two options
  - weak attractive YY interaction ($U_{\Lambda}^{(\Lambda)} \sim -5$ MeV)
  - $\Lambda\Lambda$ only slightly attractive (Gal and Millener (PLB2011))
    $\rightarrow g_{\sigma^* B} = 0$
Hyperon onset density

dependence on $L$

- Fix hyperon interaction ($V_\Lambda = -28\text{MeV}$, $V_\Xi = 0$)

- hyperon onset: $\mu_B = M_B^* + g_\omega V_0 + g_{\rho_B} t_B b_0 = \mu_n - q_B \mu_e$

- Small $L$ (large $\Lambda_v$) favors the onset of $\Sigma^-$
Maximum mass: depends on nucleonic EOS and hyperon-interaction
Radius: effect of $\epsilon_{\text{sym}}$

Stars with $1 \, M_\odot$, $1.4 \, M_\odot$, $M_{\max}$

- $1 \, M_\odot$, $1.4 \, M_\odot \rightarrow$ central baryonic density $1.5 - 3 \rho_0$
- $R$ is sensitive to $L$
- $L$ also affects the maximum mass
- the smaller $L$ the smaller $R$
Direct URCA: effect of \( \epsilon_{sym} \)

**IUFSU & modified IUFSU**

**NL3, GM1, GM3, NL\( \rho \), FSU, IUFSU**

- **No hyperons**: larger \( L \rightarrow \) smaller \( (Y_p - Y_n) \rightarrow \) smaller \( \rho_{DU} \)
- **With hyperons**: for low \( L \), hyperons decrease \( \rho_{DU} \)
  - if \( \Sigma^- \), \( \Xi^- \) first hyperon \( (Y_p \text{ increases}) \)
  - if \( \Lambda \) first hyperon: \( Y_n \), \( Y_p \) decrease, net effect defines behavior
Testing hyperon-meson couplings

- **nucleonic EOS**: TM1 parametrization and modified versions
  - TM1 with $L = 110$ MeV,
  - TM1 $\omega \rho$ term with $L = 55$ MeV
  - TM1-(2) with a reduction of 33% of the strength of the vector quartic term
  - all versions satisfy constraints from nuclear matter flow in HI collisions

- **hyperonic interactions**
  - fix $V_\Lambda = -28$ MeV, $V_\Sigma = 30$ MeV
  - vary $V_\Xi$
  - include $\sigma^*$ and $\phi$, weak coupling
  - include only $\phi$
Hyperon fraction

- Smaller $L \rightarrow$ smaller hyperon fraction for a given density
- the strange meson reduces the strangeness fraction
- an harder EOS (TM1-2): larger strangeness fraction
Smaller $L \rightarrow$ smaller electron fraction for a given density

cooling is affected: smaller electron fraction $\rightarrow$ larger $\nu$ fraction in $\nu$ trapped matter.
Nucleonic EoS for Dense Stellar Matter

strange mesons: harder EOS and larger central densities.
Total Hyperon content

Strange mesons → larger hyperon fractions and masses
Effect of L on mass/radius

\[ M[M_\odot] \]

\[ R[km] \]

- np
- npH, \( U_\Xi^N = 18\text{MeV} \)
- npH, \( U_\Xi^N = -18\text{MeV} \)
- npH with \( \phi \), \( U_\Xi^N = 18\text{MeV} \)

\( \Lambda_v = 0.03 \) (thick line)

\( \Lambda_v = 0.0 \) (thin line)
Mass radius curve

- strangeness only for $M > 1.5M_\odot$
- hyperon interaction: $0.2M_\odot$ uncertainty
- TM1 versus TM1 - 2: $0.1M_\odot$ dispersion
- $L = 55$ MeV: smaller radius [1 km (np), 0.3-0.6 km (hyp)]
Hyperons in compact stars

- **Strangeness in compact stars**
  - smaller content for a smaller $L \rightarrow$ smaller effect of the hyperon interaction uncertainty

- **Mass/radius properties of compact stars**
  - sensitive to the high density dependence of the EOS and the hyperon interaction
  - $R$ is clearly correlated with $L$
  - smaller radius for a smaller $L$, larger differences for $np$ stars
  - uncertainty in hyperon interaction ($V_\Xi$ and $\sigma^*, \phi$)):
    \[ \sim 0.2 \, M_\odot \]
  - $L$ defines $y_\rho$: properties dependent on $y_\rho$ are correlated with $L$ ($\rho_{URCA}$)
  - J1614-2230 mass: does not exclude hyperons from the EOS taking into account our lack of knowledge on the EOS at high densities and hyperon interaction
The crust
Spinodal versus Binodal

Thermodynamic spinodal versus binodal

Thermodynamic versus dynamic spinodal
Pasta phase

- proposed by Ravenhall, Pethick, Wilson PRL1983
- “pasta” phase is a frustated system that results from the competition between electromagnetic and strong forces.
- appears at $\rho \sim 0.0001 - 0.1 \text{ fm}^{-3}$ at the inner crust of NS
- Horowitz et al PRC69 2004 (QMD); Maruyama et al PRC82, 015802 (2005) (within TF, T=0); Watanabe et al, PRL94 2005, PRC77 2007; PRC81 2010 (within QMD); Avancini et al, PRC78,015802 (2008), PRC79 035804 (2009) (within TF T=0 and T finite)
- Pasta phase affects neutrino opacity and transport properties (Sonoda 2007)
- low energy collective modes of the lasagna type structures seem to have an important effect on the specific heat (Di Gallo et al PRC84, 045801)
Symmetry energy and surface energy

(a) Symmetry energy $E_{\text{sym}}$ [MeV] as a function of density $\rho/\rho_0$ for different models.

(b) Symmetry energy $L$ [MeV] as a function of density $\rho/\rho_0$ for different models.

(c) Surface energy $\sigma$ [MeV fm$^{-2}$] as a function of strangeness $x$ for different models.

(d) Surface energy $\sigma$ [MeV fm$^{-2}$] as a function of $Y_{pg}$ (particle to particle ratio) for different models at $T = 5$ MeV.

Models include NL3, DD-ME2, DD-ME8, NL3 $\omega\rho$, FSU, IU-FSU, and SLy4.
Pasta TF calculation

- minimization of the energy per particle under $\beta$-equilibrium, (Z and N treated as integers)
- a fixed Z and N number at a given density determines the WS volume
- $\beta$-equilibrium condition determines N
- droplet, rods and slabs were considered
- Wigner-Seitz approximation was considered, the WS cell having the shape of the clusters
droplets, rods, slabs: TF and RMF (Grill PRC85 055808, 2012)
Wigner-Seitz radius and proton fraction

- results are consistent, differences occur for pasta densities
Mass number and $Z/A$ in clusters

- Differences at large $\rho$ when $Z/A < 0.5$
Pasta phase
Effect of $L$ on $A$ and $Z$

- larger surface energy $\rightarrow$ larger $A$
- larger $L$, larger $e_{sym}$ for $\rho > 0.1$ fm$^{-3}$ $\rightarrow$ larger $Z$
Pasta clusters
Z and Wigner Seitz radius

(a)

(b)

(c)
Effect of $T$ in $\beta$-equilibrium pasta phase

- **NL3**: only spherical structures
- **Onset of rods and slabs**: $\sim T$ independent
$\epsilon_{\text{sym}}$ and the pasta phase

- main properties of the Wigner-Seitz cells obtained within the HFB and HF formalisms are reproduced:
  - the average proton number and the neutron number and the Wigner-Seitz cell radius
  - BUT proton shell effects are missing
- Cluster structure reflect model properties
  - small $L \rightarrow$ larger cells and proton and neutron numbers
  - NL3 with large $L$ ($L=118$ MeV): no non-spherical clusters
  - IUFSU with small $L$ ($L=45$ MeV) low density pasta onset, high crust-core density transition, smaller background gas densities
- Models with similar $\epsilon_{\text{sym}}$ show similar pasta properties
Collaborators

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Thank you!