Symmetry energy effects on the Equation of State of dense matter

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Introduction

Nuclear symmetry energy and its density dependence plays an important role in finite nuclei as well as neutron stars. The development of radioactive beam facilities has enabled us to explore the neutron-rich matter where, symmetry energy effects seems to be well pronounced. Further, the composition, dynamics and stability of neutron star are strongly influenced by the density dependence of the symmetry energy. On the experimental side, the Heavy-ion collisions can reveal the density dependence of symmetry energy of dense matter. In this work we investigate the effects of density dependant symmetry energy on the EOS of neutron star in a field theoretical model within the framework of the Relativistic mean-field theory.

Formalism

The Lagrangian density that we use in the present context is given in [1]. The symmetry energy for this Lagrangian is given by

\[ E_{\text{sym}}(\rho) = \frac{k_F^2}{6E_F} + \frac{g^2}{12\pi^2} \left( m_F^* \right)^3, \]

where \( E_F = \sqrt{k_F^2 + m^2} \) and the nucleon Fermi momentum and effective mass are \( k_F \) and \( m^* = m - g_s\phi_0 \). The effective rho-meson mass is \( m_{\rho}^* = m_{\rho}^2 + 2g_\rho^2(A_\rho g_\rho^2V_0^2) \).

We use the recently proposed NL3* parameter set [2] with addition of isoscalar-isovector coupling \( \Lambda_v \). All the combinations of \( \Lambda_v \) and \( g_\rho \) is adjusted to \( E_{\text{sym}}(\bar{\rho}) = 26.35 \text{ MeV} \) at an average density \( \bar{\rho} \) corresponding to \( k_F = 1.15 \text{ fm}^{-1} \) where the binding energy of \( ^{208}\text{Pb} \) is reproduced. Since it has been noted that the skin thickness of neutron-rich heavy nucleus, for example, \( ^{208}\text{Pb} \), are linearly correlated with symmetry pressure at a density slightly below the \( \rho_0 \). Since the same pressure supports a neutron star at supranormal densities against gravitational collapse, suggests an underlying correlation between neutron skin of heavy nuclei and neutron star radii.

Results

Figure 1 shows the density dependence of the nuclear symmetry energy \( E_{\text{sym}}(\rho) \) at various isoscalar-isovector coupling \( \Lambda_v \) for the NL3* parameter set. The sets show the systematic trend that a flatter symmetry energy at supranormal densities \( \rho \gtrsim \rho_0 \) leads to a softer energy dependence at sub-saturation densities. The \( \Lambda_v = 0 \) set exhibits almost linear density-dependent symmetry energy behavior which can be realized from Eq. (1) as
FIG. 1: Density dependence of symmetry energy for different couplings of $\Lambda_v$.

$E_{\text{sym}}(\rho) \propto k_F^3 \propto \rho$ at high densities.

TABLE I: Results for the NL3* parameter set. The slope parameter $L$ and $K_{\text{asy}} \approx K_{\text{sym}} - 6L$ are given.

<table>
<thead>
<tr>
<th>$\Lambda_v$</th>
<th>$g_v^2$</th>
<th>$L$ (MeV)</th>
<th>$K_{\text{asy}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>83.72</td>
<td>122.634</td>
<td>-630.244</td>
</tr>
<tr>
<td>0.010</td>
<td>96.06</td>
<td>88.838</td>
<td>-586.450</td>
</tr>
<tr>
<td>0.020</td>
<td>112.69</td>
<td>67.819</td>
<td>-461.039</td>
</tr>
<tr>
<td>0.030</td>
<td>136.26</td>
<td>54.290</td>
<td>-325.945</td>
</tr>
</tbody>
</table>

The slope and curvature parameters that determine the density dependence of $E_{\text{sym}}$ at $\rho_0$ are $L = 3\rho_0 E_{\text{sym}}(\rho)/\partial \rho|_{\rho_0}$ and $K_{\text{sym}} = 9\rho_0^2 \partial^2 E_{\text{sym}}(\rho)/\partial^2 \rho|_{\rho_0}$, respectively. The incompressibility of asymmetric nuclear matter with an asymmetry $\delta = (\rho_n - \rho_p)/\rho$ can be expressed as $K_\delta = K_0 + K_{\text{asy}} \delta^2$, where the density dependence of the symmetry energy is embedded in $K_{\text{asy}} \approx K_{\text{sym}} - 6L$. Estimates of $L = 88 \pm 25$ MeV and $K_{\text{asy}} = -500 \pm 50$ MeV have been obtained from isospin diffusion data [3]. Whereas the isoscaling data [4] predict $L \approx 65$ MeV and $K_{\text{asy}} \approx -453$ MeV, and from nucleon emission ratios $L \approx 55$ MeV has been extracted. From the $L$ and $K_{\text{asy}}$ values obtained for the NL3* in Table I it appears that all sets with $\Lambda_v \lesssim 0.03$ gives symmetry energy that are consistent with the constraint of $L = 88 \pm 25$ MeV and $K_{\text{asy}} = -500 \pm 50$ MeV or $-550 \pm 100$ MeV around the saturation density.

References