First Order Phase Transition From Hyper Nuclear Matter to Deconfined Quark Matter

Mahboubeh Shahrbaf Motlagh
Collaborators: David Blaschke, Ana Gabriela Grunfeld, Hamid Reza Moshfegh

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The number of nucleons is supposed to be infinite.

Coulomb interaction is disregarded because of the strong interaction between nucleons.

The density of nuclear matter is supposed to be finite:

\[ \rho = \lim_{N,V \to \infty} \frac{N}{V} \]

<table>
<thead>
<tr>
<th>$\rho_0 (fm^{-3})$</th>
<th>0.1748</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0/A (MeV)$</td>
<td>-15.58</td>
</tr>
<tr>
<td>$E_{sym} (MeV)$</td>
<td>39.9</td>
</tr>
<tr>
<td>$K_0$</td>
<td>295.77</td>
</tr>
</tbody>
</table>
For PSRJ0740+6620

\[ M_{\text{max}} = 2.17^{+0.11}_{-0.10} M_\odot \]

for the binary neutron star merger GW170817

\[ R(1.6 M_\odot) > 10.7 \text{ km} \]

&

\[ R(1.4 M_\odot) < 13.6 \text{ km} \]
Hyperon Puzzle
Phase Transition From Hyper Nuclear Matter to Deconfined Quark Matter as a Solution to the Hyperon Puzzle

Initiation of a new collaboration that joins different domains of state-of-the-art expertise

LOCV
For hadronic phase

nl-NJL
For quark phase
Hamiltonian of nuclear matter: 

\[ H = \sum_i \frac{p_i^2}{2m_i} + \sum_{i \neq j} V(ij) \]

Trial wave function: 

\[ \Psi(1 \ldots A) = F(1 \ldots A)\Phi(1 \ldots A) \]

\[ E = \langle H \rangle = \frac{1}{N} \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = E_1 + E_{MB} \cong E_1 + E_2 \]

**LOCV method**  
Lowest Order Constrained Variational method

**Characteristics**

- A pure variational method in configuration space
- Generalized to finite temperature
- Calculation of correlation functions
- Using both central and tensor correlation functions
- Energy per baryon and correlation functions are state-dependent
- Using normalization condition as the only constraint
Nonlocal Nambu–Jona-Lasinio model (nl-NJL model)

- Nonlocal covariant extension of the NJL model
- Quark fields interact via nonlocal (momentum dependent) vertices
- Nonlocal interactions regularize the model in such a way there is not need to introduce sharp cutoffs

Characteristics:
- Constant coefficients (model A)
- Density-dependent coefficients (model B)

First Order Phase Transition (PT) by a Maxwell construction

\[ \mu_H = \mu_Q = \mu_c \]
\[ T_H = T_Q = T_c \]
\[ P_H(\mu_B, \mu_e) = P_H(\mu_B, \mu_e) = p_c \]
Model A
Model B
Main results:

1. Model A: PT in Symmetric matter for $\eta<0.09$ while for this cases there is no PT in CS matter.
2. Model B: PT in both CS matter and symmetric matter for set 1.
3. We have a large difference in critical density for the onset of deconfinement in CS matter and symmetric matter. Onset density for CS matter lies at $n=0.38 \text{ fm}^{-3}$ while for symmetric matter it is at $n=0.95 \text{ fm}^{-3}$. 

![Graphs showing pressure versus chemical potential for different models and densities.](image_url)
Thank you
LOCV Method: Lowest Order Constrained Variational Method

\[ f(ij) = \sum_{\alpha p=1}^{3} f_{\alpha}^{p}(ij) O_{\alpha}^{p}(ij) \]

\[ \alpha = \{J, L, S, T, T_z\} \]

\[ O_{\alpha}^{p}(ij) = 1, \quad \frac{1}{6} (S_{12} + 4P_t), \quad \frac{1}{6} (2P_t - S_{12}) \]

\[ S_{12} = 3(\mathbf{\sigma}_1 \cdot \mathbf{\hat{r}})(\mathbf{\sigma}_2 \cdot \mathbf{\hat{r}}) - \mathbf{\sigma}_1 \cdot \mathbf{\sigma}_2 \]

\[ p=1 \text{ for } s=0 \]

\[ p=2,3 \text{ for } s=1 \text{ with } L=J \]

\[ p=2,3 \text{ for } s=1 \text{ with } J=L\pm1 \]
\[ |ij\rangle = |k_1, 1/2, m_{\sigma_1}, 1/2, m_{\tau_1}, k_2, 1/2, m_{\sigma_2}, 1/2, m_{\tau_2}\rangle \]

\[ \langle \Psi | \Psi \rangle = 1 - \sum_{ij} \langle ij | F_p^2 - F^2 | ij - ji \rangle \quad : \quad \chi = \frac{1}{N} \sum_{ij} \langle ij | F_p^2 - F^2 | ij - ji \rangle = 0 \]

\[ F_p = \begin{cases} \left(1 - \frac{9}{2} \left( \frac{I_I(Kf)}{Kfr} \right)^2 \right)^{-1/2} & T_z = \pm 1 \\ 1 & T_z = 0 \end{cases} \]

\[ E_2 = \int dr \left[ G \left( f'^2 (r) \right) + S(f(r)) - \lambda(f(r)) \right] = \int dr L(f'(r), f(r)), \delta E_2 = 0 \]

\[ \frac{\partial L}{\partial f} - \frac{\partial}{\partial r} \frac{\partial L}{\partial f'} = 0 \]

The only constraint in LOCV method is renormalization condition of wave functions