Soft EoS from heavy-ion data and the implications for compact stars

Irina Sagert

Institute for Theoretical Physics, University of Frankfurt, Germany

Ladek Zdroj, The Complex Physics of Compact Stars
Subthreshold production of $K^+$ by multiple NN collisions or secondary collisions

Comparison of Kaon production in Au+Au and C+C collisions to reveal effects from the compressibility

Nuclear matter is compressed up to $3n_0$ for energies of 1 - 1.5 AGeV

Kaons are predominantly produced at $2n_0$

$\rightarrow K_0 \sim 200$ MeV can describe the trend of Kaon production data
Compressibility and Mass-Radius relation of Compact stars

To Do:
Using a soft equation of state ($K_0 \sim 200$ MeV) calculate the dependence on $K_0$ and on the symmetry term of:

1. Maximum masses of neutron stars (Prakash et al. 1988 → Result: $M_{\text{max}} \leq 2 \, M_{\odot}$)
2. Low mass stars ($M_{\text{star}} \sim 1.18 \, M_{\odot}$) (Horowitz and Piekarewicz)
3. Highest possible mass (Rhoades and Ruffini)
4. Onset of exotic matter/quark matter
Equation of State

\[
\frac{\epsilon(n)}{n} = m_n (1 - x_p) + m_p x_p + E_0 u^{2/3} + \frac{A}{2} u + \frac{B}{\sigma + 1} u^\sigma + (1 - x_p)^2 S(u)
\]

\[
S(u) = (2^{2/3} - 1) E_0 \left( u^{2/3} - F(u) \right) + S_0 F(u), \quad F(u) = u^\alpha
\]

where

- \( E_0 \) ... average kinetic energy of symmetric matter at \( n_0 \)
- \( u = n/n_0 \)
- \( \sigma, A, B \) ... parameters depending on \( K_0 \) and \( B_E \):
  - \( B_E = (E/A - m_n) |_{n_0} \sim 16\, \text{MeV} \)
  - \( K_0 = 9 \frac{dp}{dn} |_{n_0} \)
- \( S_0 \) ... asymmetry energy at \( n_0 \)
- \( x_p \) ... proton fraction
Parameters depend on saturation density, binding energy, compressibility and asymmetry energy.

Variation of values for:

- $K_0 = 150\text{MeV} - 200\text{MeV}$
- $S_0 = 28\text{MeV} - 32\text{MeV}$
- $\alpha = 0.7 - 1.1$
- $n_0 = 0.15\text{fm}^{-3} - 0.17\text{fm}^{-3}$
Ingredients for the EoS

- Center of the star: Phenomenological EoS
- Inner crust: Negele and Vauterain
- Outer crust: Hempel et al.
Mass-Radius relation

Maximum Mass

Figure: $n_0 = 0.16 \text{ fm}^3$
Mass-Radius relation

Maximum Mass

Figure: $n_0 = 0.15 \text{ fm}^3$
Measurement of a low mass pulsar with $M_{\text{star}} \sim 1.18 \pm 0.02 \, M_\odot$. 
$n_0 = 0.16 \text{ fm}^{-3}$, $M_{\text{star}} = 1.18M_{\odot}$
$n_0 = 0.16 \text{ fm}^{-3}$, $M_{\text{star}} = 1.18 M_{\odot}$

$\alpha = 1.1$
$\alpha = 0.7$
Hybrid stars

Figure:

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Soft EoS and Compact stars
Stiffest causal EoS: \( p = \epsilon \) gives the absolute highest mass of a compact star.

Construction of EoS:

- For low densities EoS should fulfill the softness constraints from KaoS
- For high densities the EoS goes into the stiffest EoS
Stiffest EoS

\[ n_0 = 0.16 \text{ fm}^{-3}, \quad K_0 = 200 \text{ MeV} - 160 \text{ MeV} \]

\[ S_0 = 30 \text{ MeV}, \quad \alpha = 1, \quad n_{\text{crit}} = 2.5 n_0 \]
Mass-Radius relation

Stiffest EoS

$n_0 = 0.16 \text{ fm}^{-3}$, $K_0 = 200 \text{ MeV}$

$S_0 = 30 \text{ MeV}$, $\alpha = 1$, $n_{\text{crit}} = 2.5 n_0$
Stiffest EoS

- $n_0 = 0.16$ fm$^{-3}$, $K_0 = 200$ MeV, $n_{\text{crit}} = 2.5 \ n_0$
- $S_0 = 30$ MeV, $\alpha = 1.0$
- $S_0 = 28$ MeV, $\alpha = 0.7$
- $S_0 = 32$ MeV, $\alpha = 1.1$

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Soft EoS and Compact stars
Stiffest EoS

\[ n_0 = 0.16 \text{ fm}^{-3}, K_0 = 200 \text{ MeV}, S_0 = 30 \text{ MeV}, \alpha = 1 \]

\[ n_{\text{crit}} = 2.5 n_0 \quad \text{red curve} \]

\[ n_{\text{crit}} = 2.0 n_0 \quad \text{green dotted curve} \]
The diagram illustrates the mass-radius relation for different equation of state (EoS) parameters. It shows the relationship between the mass of a compact star (in solar masses, $M_{\odot}$) and its radius (in kilometers, km) for different values of the parameters $K_0 = 200$ MeV, $S_0 = 30$ MeV, and $\alpha = 1$. The curves represent different values of $n_0$, the nuclear density, and $n_{\text{crit}}$, the critical density, with $n_0 = 0.16$ fm$^{-3}$ and $n_{\text{crit}} = 2.5 n_0$, and $n_0 = 0.15$ fm$^{-3}$ and $n_{\text{crit}} = 2.0 n_0$. These conditions are plotted to highlight the effects of different EoS on the compact star's properties.