Implications for compact stars of a soft nuclear equation-of-state from heavy-ion data

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Outline

To use data from heavy-ion collisions to help to constrain the EoS for neutron stars

- Motivation
- Subthreshold $K^+$ production in A+A collisions
- Low mass neutron stars:
  - radii and moments of inertia
- Maximum neutron star masses
- Summary

Sagert, LT, Chatterjee, Schaffner-Bielich and Sturm, Phys. Rev. D 86 (2012) 045802
Motivation

Explain the high mass of some pulsars such as
PSR J1614-2230\(^1\): (1.97 ± 0.04) \(M_\odot\)
PSR J0348+0432\(^2\): (2.01 ± 0.04) \(M_\odot\)
PSR J1748-2021\(^3\): (2.74 ± 0.2) \(M_\odot\)
in connection to the properties of dense matter

Today, (firm) information exists about the properties of nuclear matter around its saturation density \(n_0 = 0.16 \text{ fm}^{-3} \Rightarrow \rho_0 = 2.7 \times 10^{14} \text{ g/cm}^3\) (i.e., \(K_0, S_0\))

What about matter \(n \gg n_0\)?
Example in HI collisions: Flow of matter in nuclear collisions

- Flow and EoS are linked:
  \[ t_e \approx \frac{R}{c_s} \]
  \[ c_s = c \sqrt{\frac{\partial P}{\partial \epsilon}} \]

- Data and flow calculations constrain EoS for symmetric matter: EoS soften due to a phase transition (quark matter) at \( \rho > 3\rho_0 \)

However, the relation of flow and EoS depends strongly on transport model Andronic '05

- For neutron matter, need of constraints on symmetry energy

Danielewicz, Lacey and Lynch, Science '02
**Subthreshold K⁺ production in A+A collisions**

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**Kaons in nuclear collisions as a probe for EoS**

- K⁺ are a good probe to study dense and hot matter because they are created in a high density phase and not reabsorbed in the medium.


- KaoS data favours soft EoS (K≈ 200 MeV) that tests matter at 2-3n₀, which corresponds to Uₐ with small repulsion.

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*Fuchs, Faessler, Zabrodin and Zheng ‘01; Sturm et al ‘01; Hartnack, Oeschler and Aichelin ‘06; Hartnack, Oeschler, Leifels, Bratkovskaya, Aichelin ‘12*
Low mass neutron stars: radii and moments of inertia

Given Skyrme-type EoS* used for KaoS data

\[
\frac{E}{A} = m_n (1 - Y_p) + m_p Y_p + E_0 u^3 + \frac{B u}{2} + D \frac{u^\sigma}{(\sigma + 1)} + (1 - 2Y_p)^2 \left[ \left( \frac{2}{3} - 1 \right) E_0 \left( u^\frac{2}{3} - F(u) \right) + S_0 u^\gamma \right],
\]

with \( u = n/n_0 \), we analyze radii \( R \) and moments of inertia \( I \) of non-rotating neutron star configurations with \( 1.25 \, M_\odot \) in dependence of \( K \) for different setups of \( S_0 \) and \( \gamma \), i.e., different slopes of symmetry energy:

\[
L = 3n_0 \frac{dS(n_b)}{dn_b} \big|_{n_0}
\]

At \( K \approx 200 \, \text{MeV} \), stiff and soft symmetry energy configurations lead to

\[
\Delta R \sim 1.5 \, \text{km} \quad \Delta I \sim 2.5 \times 10^{43} \, \text{g cm}^2
\]

Central densities are \( \leq 3.4 \, n_0 \) (KaoS data)

*Prakash, Ainsworth, Lattimer '88
Radii and moments of inertia of light neutron stars with masses of \((1.1-1.6) \, M_\odot\) for \(K \approx 200 \, \text{MeV}\) for different configuration of symmetry energy.

We find that neutron stars with \(M \leq 1.3 \, M_\odot\) have central densities that can be probed by the KaoS experiment.

**Conclusion:**
given that KaoS experiment tests the stiffness of matter within light neutron stars, radius and moment of inertia measurements of light neutron stars could distinguish between a soft and a stiff behaviour of the symmetry energy.

Radius measurements and moments of inertia? Future LOFT mission?
Maximum neutron star masses

Calculate the highest possible mass using the restriction that the hadronic EoS should fulfill the analysis of KaoS data ($U_N$ with small repulsion) for $n_{\text{crit}} \approx (2-3)n_0$

To calculate the highest allowed maximum mass, KaoS results are applied for $2n_0 \leq n_{\text{crit}} \leq 3n_0$ and the stiffest possible EoS is used for $n > n_{\text{crit}}$

Conclusion: $M_{\text{high}} \leq 3 M_\odot$

To explain pulsar of $2.7 M_\odot$, need a prompt transition at $2.5n_0$

1 Kalogera and Baym’s idea
2 Freire et al ’08
**Summary**

$K^+$ multiplicities from heavy-ion collisions at GSI (KaoS) indicate that the nuclear EoS is soft ($U_N$ with small repulsion) for $(2-3)n_0$. We apply these results to study the implications on neutron star properties:

- **Light neutron stars** ($M \leq 1.3 \, M_\odot$): radii and moments of inertia are sensitive to the density dependence of symmetry energy.

- KaoS results confirms the highest possible neutron star mass of $3 \, M_\odot$.

**FUTURE:**
Large Observatory For X-ray Timing (LOFT)?