What the supranuclear EoS from heavy-ion data can tell us about neutron star properties

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Work done in collaboration with:

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Outline

- Introduction: Neutron Star Masses
- Nuclear EoS from kaon production in heavy-ion collisions
- Implications for neutron stars:
  - Neutron star radii for light neutron stars
  - Maximum possible neutron star mass
- Summary
supernovae simulations: \( T = 1 \text{–} 50 \text{ MeV, } n = 10^{-10} \text{–} 2n_0 \)

proto-neutron star: \( T = 1 \text{–} 50 \text{ MeV, } n = 10^{-3} \text{–} 10n_0 \)

global properties of neutron stars: \( T = 0, \ n = 10^{-3} \text{–} 10n_0 \)

neutron star mergers: \( T = 0 \text{–} 100 \text{ MeV, } n = 10^{-10} \text{–} 10n_0 \)
Early universe at zero density and high temperature
neutron star matter at small temperature and high density
first order phase transition at high density (not deconfinement!)
probed by heavy-ion collisions at GSI, Darmstadt (FAIR)
Mass measurement of pulsar PSR J1903+0327 (Freire 2009)

- measure post-Keplerian parameters from pulsar timing
- Shapiro delay parameters $r$ and $s$ alone constrain $M = (1.67 \pm 0.11)M_\odot$
- combined with periastron advance $\dot{\omega}$: $M = (1.67 \pm 0.01)M_\odot$
- rotation of the companion star could influence $\dot{\omega}$ (follow-up observation with Hubble planned)
extremely strong signal for Shapiro delay

Shapiro delay parameters $r$ and $s$ alone give

$$M = (1.97 \pm 0.04) M_\odot$$ - new record!

by far the highest precisely measured pulsar mass!

considerable constraints on neutron star matter properties!
Constraints on the Mass–Radius Relation (Lattimer and Prakash 2004)

- Spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- Causality limit for EoS: $R > 3GM$
- Mass limit from PSR J1614-2230 (red band): $M = (1.97 \pm 0.04)M_\odot$
Kaon Subthreshold Production in Heavy-Ion Collisions
Input to transport models: the nucleon potential

- crucial input to control the amount of compression: the nucleon potential
- study two extreme cases using the Skyrme model
- hard EoS: stiffness parameter $K = 380$ MeV, soft EoS: $K = 200$ MeV
Heavy-ion collisions: density range probed with kaons

- Kaon production by associated production: $NN \rightarrow N\Lambda K$, $NN \rightarrow NNK\bar{K}$
- Produced in a baryon-rich medium at densities of $2n_0$ up to $3n_0$
- Long mean-free path of kaons: escape from the high-density region
Kaon production in heavy-ion collisions

- nuclear matter is compressed up to $2 - 3n_0$!
- long mean-free path of kaons: kaons can escape high density matter
- clear trend indicating high compression $\rightarrow$ a soft EoS

Sturm et al. (KaoS collaboration), PRL 2001
Fuchs, Faessler, Zabrodin, Zheng, PRL 2001
Confirmed KaoS data analysis: the nuclear EoS is soft!

- kaon production \((K^+)\) far below threshold
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV
- only calculations with a compression modulus of \(K_N \approx 200\) MeV and smaller can describe the data

Forster et al. (KaoS collaboration) 2007
Hartnack, Oeschler, Aichelin, 2006

\[ \frac{(M_{Au} A_{Au}^{-1})}{(M_{C} A_{C}^{-1})} \]

\[ E_{beam} = 0.8\ AGeV \]
\[ E_{beam} = 1.0\ AGeV \]

\[ K_N [\text{MeV}] \]

\[ 200 \quad 300 \quad 400 \]

\[ (M_{Au} A_{Au}^{-1})/(M_{C} A_{C}^{-1}) \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \]

\[ \text{data range} \]

\[ \text{IQMD with KN pot.} \]
\[ \text{IQMD w/o KN pot.} \]

\[ \Rightarrow \text{the nuclear equation of state is SOFT!} \]
Implication I: Neutron Star Radii and the Asymmetry Potential
Probing the EoS: Empirical Nucleon-Nucleon Interaction

Ansatz for the energy per particle with \( u = n / n_0 \) (Prakash et al. 1988):

\[
\frac{\epsilon}{n} = m_N + E_0^{kin} + \frac{A}{2} \cdot u + \frac{B}{\sigma + 1} u^\sigma + S_0 \cdot u^\gamma \cdot \left( \frac{n_n - n_p}{n} \right)^2
\]

corresponds to the nucleon Skyrme potential used in transport codes

- parameters \( A, B, \sigma \) fixed by nuclear matter properties \( n_0, E/A \), and compression modulus \( K_0 \)
- asymmetry energy \( S_0 \) fixed at \( n_0 \), density dependence \( \gamma \) can vary between 0.5 and 1.1
- pressure determined by the thermodynamic relation

\[
P = n^2 \frac{d}{dn} \left( \frac{\epsilon}{n} \right)
\]
Maximum neutron star mass and compression modulus

(Weissenborn, Chatterjee, JSB 2011)

- relativistic mean-field model: stiffness of EoS controlled by $\frac{m^*}{m}$ not the compression modulus $K_0$
- change in maximum mass for different compressibilities: at most $0.1M_\odot$
- adopt stiffness parameter $K$ from KaoS data analysis as a constraint on high density EoS only!
Low-Mass Neutron Star Radii and the Asymmetry Potential

- radii for different stiffness parameter (KaoS: $K < 200$ MeV)
- central density in a $1.25 M_{\odot}$ neutron star: around $3n_0$
- radius mostly sensitive to density dependence $\gamma$ of asymmetry energy

(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

(Lattimer and Prakash (2001), Carriere, Horowitz, Piekarewicz (2003), Bao-An Li et al. ...)

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Neutron Star Radii and the Asymmetry Potential

(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- radii for different masses and asymmetry potentials
- moderate change with mass, stronger dependence on density dependence $\gamma$ of asymmetry energy
- constraint from KaoS data analysis reduces uncertainty in isospin independent part of the nuclear EoS
A potential measure of the isospin potential

(Ferini, Gaitanos, Colonna, Di Toro, Wolter 2006)

- use different nucleon potentials with different asymmetry potentials
- particle ratios of kaons (pions) with different isospin: sensitive to different nuclear models
Implication II: Constraint on the Maximum Possible Neutron Star Mass
Maximum central density of a compact stars

maximally compact EoS: $p = s(\epsilon - \epsilon_c)$ with $s = 1$

stiffest possible EoS (Zeldovich 1961)

gives upper limit on compact star mass: $M_{\text{max}} = 4.1 M_\odot \left(\frac{\epsilon_{\text{sat.}}}{\epsilon_f}\right)^{1/2}$

Maximum Mass from Causality Argument

use EoS from Wiringa, Fiks, Fabrocini 1988 (Argonne $V_{14}$ potential)
probed only up to normal nuclear matter density (at most)
maximum possible mass due to causality: $M_{\text{max}} = 4.1 M_\odot$ at $\epsilon_f = \epsilon_{\text{saturation}}$
Constraint from heavy-ion data: nucleon potential at $2 - 3n_0$

- input to transport simulations: nucleon potential
- kaon production is sensitive to densities of $n = 2 - 3n_0$ ($n_0 = 0.17 \text{ fm}^{-3}$)
- constraint: nucleon potential must be below the curve for the Skyrme model with $K = 200 \text{ MeV}$ at a fiducial density of $n_f = 2 \ldots 3n_0$
Skyrme parameter set BSK8: fitted to masses of all known nuclei above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS

causality argument: \( p = \epsilon - \epsilon_c \) above the fiducial density \( \epsilon_f \)

Rhoades, Ruffini (1974), Kalogera, Baym (1996): \( M_{\text{max}} = 4.2M_\odot (\epsilon_0/\epsilon_f)^{1/2} \)
Skyrme parameter set Sly4: fitted to properties of spherical nuclei above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS

causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density $\epsilon_f$

Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\text{max}} = 4.2M_\odot(\epsilon_0/\epsilon_f)^{1/2}$
RMF parameter set TM1: fitted to properties of spherical nuclei above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS

causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density $\epsilon_f$

Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\text{max}} = 4.2M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
Constraint for neutron stars: causality plus heavy-ion data

- Maximum mass for neutron stars versus the fiducial density
- Same trend for various allowed nuclear models (NL3 is too stiff!)
- Main difference: the density dependence of the asymmetry energy
- Overall upper limit of a maximum mass of $M_{\text{max}} = 3M_{\odot}$ for $n_f = 2n_0$
Summary:

- analysis of kaon production provides a constraint on the nuclear EoS (nucleon potential) at $2 - 3n_0$

- implications for neutron stars:
  - radii of light neutron stars: only controlled by asymmetry potential
  - maximum mass of neutron stars: lower than $3M_\odot$ due to causality arguments

- strong interplay between heavy-ion physics and astrophysics
The Future: CBM@FAIR and NICA

left: equation of state and flow constraints,
right: compatible mass-radius relations and astrophysical constraints

higher baryon densities achieved at higher bombarding energy

probing densities beyond \( 2 - 3n_0 \)
X-Ray burster

- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- red shifted spectral lines measured!
  \[ z = 0.35 \rightarrow \frac{M}{M_\odot} = 1.5 \ (R/10 \text{ km}) \] (Cottam, Paerels, Mendez (2002))
- Cottam et al. (2008): not confirmed with burst data from 2003
x-ray burster with photospheric radius expansion

assume (color-corrected) black-body emission and Eddington flux at 'touch-down' (Özel 2006): simple model fit fails above a certain distance!

large correction from model atmosphere composition

(Suleimanov, Poutanen, Revnivtsev, Werner 2011)
Mass-Radius Constraints from X-Ray Burster and Binaries

(Steiner, Lattimer, Brown 2011)

- fit to three x-ray burster data with photospheric radius expansion and three quiescent x-ray binaries (from previous analysis)
- relax constraint at 'touch-down' to be on the surface \((r_{ph} \gg R)\)
- strong constraint on radius relation (left: combined fit, right: separate fits) - p.30
isolated neutron star, pulses in x-rays

phase space resolved x-ray spectroscopy

fit to geometry of hot spot etc. including redshift $z$

resulting compactness: $(M/M_\odot)/(R/\text{km}) = 0.087 \pm 0.004$

indication for a stiff equation of state

(Hambaryan, Suleimanov, Schwopa, Neuhäuser, Werner, Potekhin 2011)
two-component blackbody: small soft temperature, so as not to spoil the x-ray

this implies a rather LARGE radius so that the optical flux is right!

lower limit for radiation radius: \( R_{\infty} = \frac{R}{\sqrt{1 - \frac{2GM}{R}}} = 17 \text{ km (d/140 pc)} \)

from parallax measurement: distance \( d = 123(\pm11, -15) \text{ pc} \)

(Walter, Eisenbeiss, Lattimer, Kim, Hambaryan, Neuhäuser 2011)
neutron star merger simulation with 3D smoothed particle hydro code using conformal flatness approximation

strong correlation with peak frequency in gravitational waves and neutron star radius rather insensitive to masses of neutron stars

measurable with advanced LIGO in a few years
Effect of kaon potentials on double ratio

(Fuchs, Faessler, Zabrodin, Zheng 2001)

- study double ratio: compare kaon multiplicity in C+C with Au+Au collisions
- kaon potential is repulsive in dense matter
- effect is (nearly) linear in density $\rightarrow$ cancels in double ratio
study different transport models and cross sections

excitation function for kaon production ratio rather insensitive

main difference originates from the underlying EoS!