Key Nuclear Physics Issues

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INT Program 14-2a:
Neutron Star Coalescence as a Fundamental Physics Laboratory

July 14-18, 2014, Seattle, University of Wasington

Topics/Questions to be addressed

Consistency with Neutron Matter and Heavy-Ion Collisions

- Can the EOS used in heavy-ion collisions support a 2 $\mathrm{M}_\odot$ neutron star?

Thermal Properties of Dense matter: The Bulk Phase

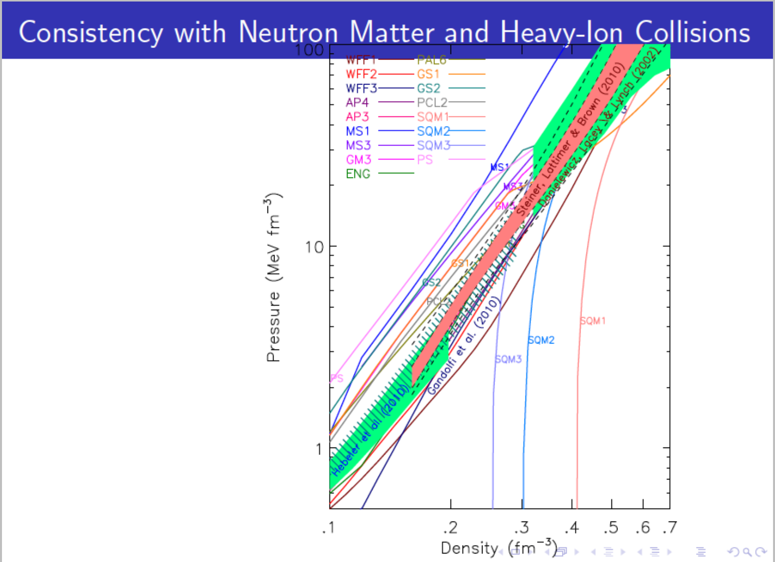
- Can we identify physical quantities (possibly accessible to experiments) that control thermal effects?
- The curious behavior of nucleon effective masses.

Thermal Properties of Dense Matter: The Inhomogeneous Phase

- How do nuclei respond to heat?
- Are theoretical tools in place to pin down the thermal properties of highly neutron-rich nuclei?

Some questions requiring answers.

Current situation



J. M. Lattimer, Ann. Rev. Nucl. Part. Sci. **62**, 488 (2012)

Theoretical Analysis of Heavy-Ion Collisions

$$\begin{aligned}\frac{\partial f}{\partial t} &+ \vec{\nabla}_p U \cdot \vec{\nabla}_r f - \vec{\nabla}_r U \cdot \vec{\nabla}_p f = \\ &- \frac{1}{(2\pi)^6} \int d^3 p_2 \, d^3 p_{2'} \, d\Omega \frac{d\sigma_{NN}}{d\Omega} \, v_{12} (2\pi)^3 \, \delta^3(\vec{p} + \vec{p}_2 - \vec{p}_{1'} - \vec{p}_{2'}) \\ &\times \left[f f_2 (1 - f_{1'})(1 - f_{2'}) - f_{1'} f_{2'} (1 - f)(1 - f_2) \right] .\end{aligned}$$

$f(\vec{r}, \vec{p}, t)$: Phase space distribution function of a nucleon

$d\sigma_{NN}/d\Omega$: Differential nucleon–nucleon cross section

v_{12}: Relative velocity

$U \equiv U(n, \vec{p})$ = Mean field or the single particle potential

From a Hamiltonian density (EOS) of many-body physics,

$$\epsilon_{k\,i} = k_i^2 \frac{\partial \mathcal{H}}{\partial \tau_i} + \frac{\partial \mathcal{H}}{\partial n} = \frac{\hbar^2 k^2}{2m} + U_i(n, k)$$

Observables confronted include:

(i) the mean transverse momentum per nucleon $\langle p_x \rangle / A$ versus rapidity y/y_{proj},
(ii) flow angle from a sphericity analysis,
(iii) azimuthal distributions, and (iv) radial flow.

Theory vs. Heavy-Ion Data

Beam energies: $E_{lab}/A = 0.5 - 2$ GeV

Highest densities reached: $n/n_0 = 2 - 3$

1. G. F. Bertsch & S. Das Gupta, Phys. Rep. **160**, 189 (1988)
2. C. Gale, G.M. Welke, M. Prakash, S.J. Lee, & S. Das Gupta, Phys. Rev. C **41**, 1545 (1989)
3. P. Danielewicz, R. Lacey & W.G. Lynch, Science, **298**, 1592 (2002)
4. C.B. Das, S. Das Gupta, C. Gale & Bao-An Li, Phys. Rev. C **67**, 034611 (2003)

Confrontation with Data

Beam energies: $\frac{E_{lab}}{A} = 0.5 - 2$ GeV

Highest densities reached: $\frac{n}{n_0} = 2 - 3$

Particle detection inefficiencies cause the experimental transverse momenta in the backward direction to be artificially biased towards large negative values and are therefore unreliable.

C. Gale, G.M. Welke, M. Prakash, S.J. Lee, & S. Das Gupta, Phys. Rev. C **41**, 1545 (1989)

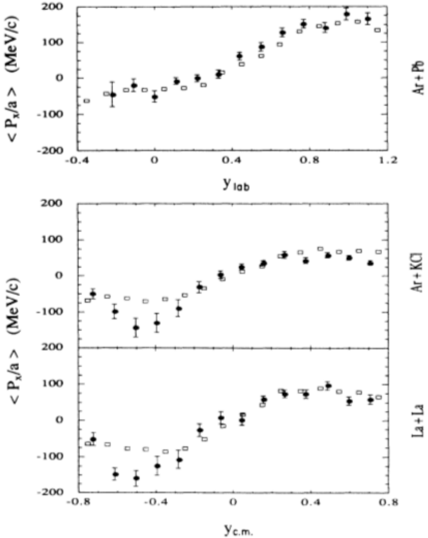


FIG. 10. Transverse momentum per nucleon as a function of rapidity in reactions of 800 MeV per projectile nucleon. Results of BUU simulations with the MDYI interaction (open squares) are compared with the data of Ref. 12 (solid circles). Results for Ar+Pb are in the lab, for La+La and Ar+KCl in the center of mass.

Confrontation with Neutron Star Data (Masses)

Property	MDYI(0)	Skyrme	Experiment	Reference
n_0 (fm^{-3})	0.163	0.160	0.17 ± 0.02	[?, ?, ?, ?]
E_0 (MeV)	-16.10	-15.99	-16 ± 1	[?, ?]
K_0 (MeV)	212.4	239.6	230 ± 30	[?, ?]
			240 ± 20	[?]
S_v (MeV)	30.54	30.0	30-35	[?, ?]
L_v (MeV)	60.24	50.0	40-70	[?, ?]
K_v (MeV)	-81.67	-90.0	-100 ± 200	TW
m_0^*/m	0.67	0.67	0.8 ± 0.1	[?, ?]
$M_{max}(M_\odot)$	1.90	2.13	2.01 ± 0.04	[?]
R_{max}(km)	10.06	10.41	11.0 ± 1.0	[?]
$R_{1.4}$(km)	12.14	12.24	11.5 ± 0.7	[?]

Table: With the exception of the last three, entries in this table are at the equilibrium density n_0 of symmetric nuclear matter for the MDYI and Skyrme models. E_0 is the energy per particle, K_0 is the compression modulus, m_0^*/m is the ratio of the Landau effective mass to mass in vacuum, S_v is the nuclear symmetry energy parameter, L_v and K_v, are related to the first and second derivatives of the symmetry energy, respectively. M_{max} is the maximum neutron star mass predicted by the given EOS and R_{max} the radius associated with it. The prediction for the radius of a 1.4 $M_\odot$ neutron star is given by $R_{1.4}$.

Confrontation with Neutron Star Data (Masses)

Property	MDYIc	Skyrme	Experiment	Reference
n_0 (fm^{-3})	0.160	0.160	0.17 ± 0.02	[?, ?, ?, ?]
E_0 (MeV)	-16.00	-15.99	-16 ± 1	[?, ?]
K_0 (MeV)	240.0	239.6	230 ± 30	[?, ?]
			240+20	[?]
S_v (MeV)	30.0	30.0	30-35	[?, ?]
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Summary of the EOS from heavy-ion collisions

The equation of state implied by the momentum-dependent potential required to fit heavy-ion flow data (and consistent with the analyses of giant resonances of nuclei) is able to support a 2 $\mathrm{M}_\odot$ neutron star.

Thermal properties of EOS's with momentum-dependent forces under investigation.

C. Constantinos, B. Muccioli, M. Prakash & J.M. Lattimer, Ongoing work.

Thermal properties & the nucleon effective mass

Landau Fermi Liquid Theory (Degenerate Limit)

- Interaction switched-on adiabatically
- Entropy density and number density maintain their free Fermi-gas forms:

$$
\begin{aligned}
s_i &= \frac{1}{V}\sum_{k_i}\left[f_{k_i}\ln f_{k_i} + (1-f_{k_i})\ln(1-f_{k_i})\right] \\
n_i &= \frac{1}{V}\sum_{k} f_{k_i}(T)
\end{aligned}
$$

- $\int d\varepsilon \frac{\delta s}{\delta T} \quad \Rightarrow \quad s_i = 2a_i n_i T$

$$a_i = \frac{\pi^2}{2}\frac{m_i^*}{k_{Fi}^2}$$ level density parameter

Degenerate Limit Thermodynamics

Maxwell's relations:

- Energy density
$$\frac{d\varepsilon}{ds} = T$$
$$\varepsilon(n,T) = \varepsilon(n,0) + \frac{T^2}{n}\sum_i a_i n_i$$

- Pressure
$$\frac{dp}{dT} = -n^2\frac{d(s/n)}{dn}$$
$$p(n,T) = p(n,0) + \sum_i \left[a_i n_i - n\frac{d(a_i n_i)}{dn}\right] T^2$$

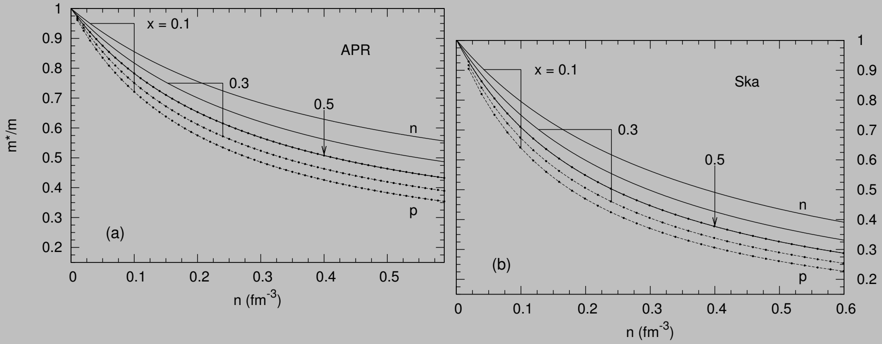
- Chemical potentials
$$\frac{d\mu}{dT} = -\frac{ds}{dn}$$
$$\mu(n,T) = \mu(n,0) - T^2\left[\frac{a_i}{3} + \sum_j \frac{n_j a_j}{m_j^*}\frac{dm_j^*}{dn_i}\right]$$

- Free energy density
$$\frac{d\mathcal{F}}{dT} = -s$$
$$\mathcal{F}(n,T) = \mathcal{F}(n,0) - \frac{T^2}{n}\sum_i a_i n_i$$

Nucleon effective masses in models - I

Landau effective masses:

$$m_i^* \equiv \hbar^2 k_{F\,i} \left(\left. \frac{\partial \epsilon_{k\,i}}{\partial k} \right|_{k_{F\,i}} \right)^{-1}, \qquad i = n, p$$

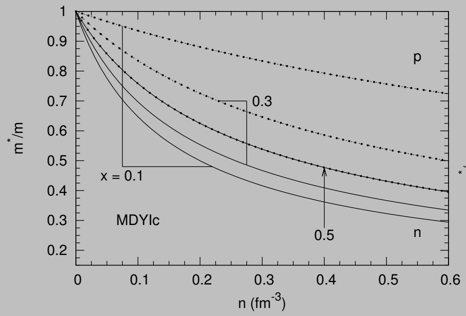


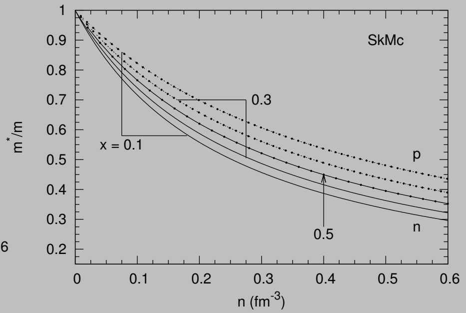
Note the isospin dependence of m^*'s ($x = n_p/n_b$ is the proton fraction).

Nucleon effective masses in models - II

Landau effective masses:

$$m_i^* \equiv \hbar^2 k_{F\,i} \left(\left. \frac{\partial \epsilon_{k\,i}}{\partial k} \right|_{k_{F\,i}} \right)^{-1} , \qquad i = n, p$$





Note the reversal in the isospin dependence of m^*'s ($x = n_p/n_b$ is the proton fraction). Several energy density functionals (that fit properties of nuclei well) in current use display this reversed behavior.

Isospin dependence of nucleon effective masses

- Can microscopic calculations shed light on the correct behavior of m_n^* and m_p^* as a function of proton fraction $x = n_p/n_b$ in dense matter? Some indications exist, but a firm answer is desirable.

- Can experimental results involving nuclei establish the isospin dependence of neutron and proton effective masses in low-density bulk matter? Extracting bulk matter properties of nucleon effective masses from nuclear data will involve reliable accounting of effects due to the surface, shell plus pairing, and collective motion.

Nuclei & their Level Density Parameter

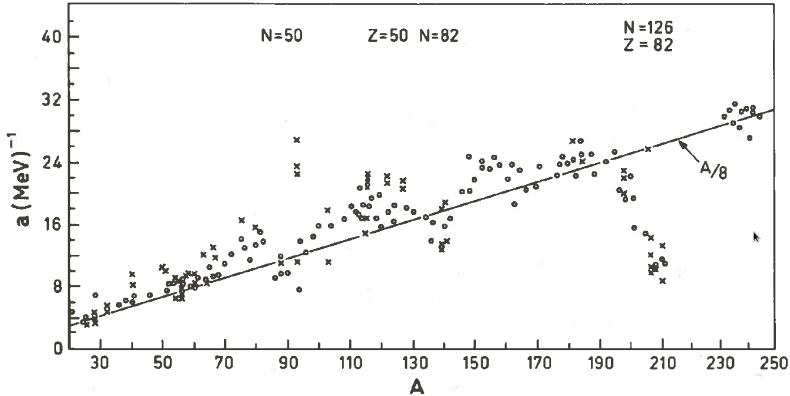


Figure 2-12 The parameter *a* appearing in the Fermi gas level density formula has been determined by comparison with the average spacings observed in slow neutron resonances (values indicated by o), and from evaporation spectra (values indicated by x). The figure is based on the analysis of E. Erba, U. Facchini, and E. Saetta-Menichella, *Nuovo cimento* **22**, 1237 (1961). This analysis also confirms the consistency with direct level counts.

- A. Bohr & B. Mottelson, Nuclear Structure, Vol. I, p. 187

Role of Collective Effects

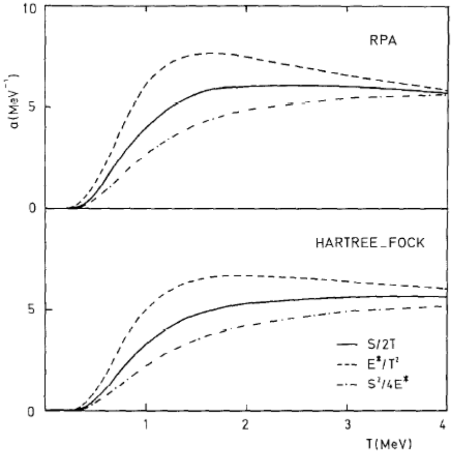


Fig. 4. Variation of the quantities $S/2T$, E^*/T^2 and $S^2/4E^*$ calculated in ^{56}Ni using the Hartree–Fock method and the random-phase approximation, as functions of the temperature T (MeV).

N. Vinh Mau & D. Vautherin, Nucl. Phys. **A445** 245 (1985)

Thermal Effects - Numerical Results

- For the EOS's of APR and Ska, cf. Constantinos, Muccioli, Prakash and Lattimer, Phys. Rev. C **89**, 065802 (2014). Here, results (for the bulk phase) relevant for proto-neutron star, supernova and binary merger simulations are available.

- Thermal properties of EOS's with momentum-dependent interactions under investigation.

Longstanding questions & new ones requiring answers - I

- What are the maximum and minimum masses of neutron stars? The former has implications for the minimum mass of a black hole (and the total number of stellar-mass black holes in our Universe), the progenitor mass, and the EOS of hadronic matter. The minimum mass raises questions about stellar evolution and its formation.

- What is the radius of a neutron star whose mass is accurately measured? *Precise measurements of masses, radii, and moment of inertia for several individual stars would pin down the EOS without recourse to models.* Can measurements of chirp masses, quadrupole polarizabilities (related to Love numbers), etc., from gravity-wave detections be used to advantage?

- What are neutron star cooling curves telling us? Superfluidity attenuates cooling under most conditions, while exotica (e.g., hyperons, quarks) hasten it.

Longstanding questions & new ones requiring answers - II

- Flares associated with intense surface magnetic fields found in many neutron stars (termed "magnetars") continue to baffle us. What is the microscopic origin of such fields and what are their magnitudes in the interiors of neutron stars? What can be learned from the modeling of Quasi Periodic Observables (QPO's) in magnetar flares?
- What phases are there in the phase diagram of dense matter at low temperatures? How do we use neutron star observations to learn about those phases?
- What is the nature of absorption features detected from isolated neutron stars?

Longstanding questions & new ones requiring answers - III

- Is there a limit to the spin frequency of milli-second pulsars? If so, why? Can gravitational radiation from rapidly rotating pulsars undergoing accretion limit their spin up?

- What is the emission process for X-ray bursts? What precisely controls the durations of these bursts and of inter-bursts?

- Is unstable burning of Carbon (C) the real cause of super bursts? Can the condition for igniting such burning be met with our understanding of the C-C fusion?

Longstanding questions & new ones requiring answers - IV

- Is there real evidence for enhanced neutrino cooling in high mass neutron stars?
- Why do glitches occur? What is the trigger that couples the superfluid to the crust for less than a minute? What are the relevant dissipative processes?
- How does one link the microphysics of transport, heat flow, superfluidity, viscosity, vortices/flux tubes to average macro-modes in neutron star phenomenology?

Above questions taken from M. Prakash, Pramana (2014), in press, arXiv: 1404.1966