High-Density Matter: Current Status and Future Challenges

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QCD phase diagram

- Early universe
- RHIC, LHC
- Critical point?
- Deconfinement and chiral transition
- Supernovae
- Color Superconductor?
- Net Baryon Density

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Outline:

1. The Equation of State

2. Nuclear physics input

3. Observational constraints: neutron stars
   proto-neutron stars
   core-collapse supernovae

4. Terrestrial experiments: heavy ion collisions

5. Quark-meson coupling model

6. Summary and outlook
The Equation of State (EoS)

Relation between pressure $P$, energy density $\varepsilon$, particle number density $\rho$ at temperature $T$

$$\begin{align*}
P &= \frac{2}{\rho} \left( \frac{\partial (\rho \mathcal{I}/\lambda)}{\partial \rho} \right)_{s/}, \\
(\varepsilon, T) &= \sum_f f(\varepsilon, T)
\end{align*}$$

summation over $f$ includes all hadronic (baryons, mesons), leptonic and quark (if applicable) components present in the system at density $\rho$ and temperature $T$

Two key points:

The EoS is dependent on composition
CONSTITUENTS + INTERACTIONS

$\varepsilon_f$ and ITS DENSITY AND TEMPERATURE DEPENDENCE must be determined by nuclear and/or particle models.
$P, \varepsilon, \rho, T +$

**Hadrons**

- $n, p$
- $Y, \Delta$
- $\Pi, K$

**Quarks**

- $u, d, s$

**EoS**

**Symmetric**
- Asymmetric
- Pure neutron
- Beta-equilibrium
- Superfluidity
- Superconductivity

**Strangeness**

**Boson Condensates**

**Color superconductivity**
- CFL phase, Quarkonium

**Hybrids, phase transitions, threshold conditions**
The “Universal” EoS of high density matter with all the physically allowed components is not observed in nature in its entirety.

We are sensitive only to projections to particular sectors (sets of degrees of freedom) which can be constrained by observation and/or measurements.

**Long term aim:**

All sectors are described consistently within a unified model.
At present – a large variety of models are in use:

**HADRONIC MATTER:**

Many variants of microscopic and phenomenological models at a different level of complexity:
Mean-field (non)relativistic models, Chiral effective field theory, “Ab initio” models with 2- and 3-body forces

**QUARK MATTER:**

MIT bag, Nambu-Jona-Lasinio (NJL)
Polyakov – NJL (PNJL), Polyakov - Quark Meson (PQM)
Chromo-dielectric (CDM), Dyson-Schwinger (DS)

Forces (interactions) between the constituents are not known. Each model HAS FREE PARAMETERS which has to fitted to data.
NUCLEAR MATTER PROPERTIES FROM MEAN FIELD MODELS WITH DENSITY DEPENDENT EFFECTIVE INTERACTION:

1. 240 non-relativistic models based on the Skyrme interaction - density dependent effective nucleon-nucleon force dependent on up to 15 adjustable parameters were recently tested against the most up-to-date constraints on properties of nuclear matter:

SET 1: 5 satisfied all the constraints  Dutra et al., PRC 85, 035201

2. 263 relativistic mean field models were tested against 3 slightly different sets of constraints and the number of models that satisfied the constraints

SET 1: 2 models
SET 2a: 4 models (30)  Dutra et al., arXiv:1405.3633 [nucl-th]
SET 2b: 3 models (35)
Pressure in pure neutron matter at sub-saturation density

Whittenbury et al., 2013

Binding energy per particle in symmetric nuclear matter

Li et al., PRC74, 047304 (2006)
Examples of EoS of ud(s) matter in different models

- Logoteta et al. D-S
- Logoteta et al. CDM
- Logoteta et al. NJL
- Kurkela et al. Perturbative QCD
- Weissenborn et al., MIT bag

Logoteta et al., PRD85, 023003 (2012)
Kurkela et al., PRD81, 105021(2010)
Chen et al., PRD86, 045006 (2012)
Weissenborn et sl., 2011
Empirical approach:

**Assumptions:** The “universal EoS” can be approximated by a combination of models and observation data

Questions:

Physical content?

Predictive power?

How sensitive is observation to microphysics?
Do we have enough data to fix our theories?

Astronomical Observation:

NEUTRON STARS
Proto-neutron stars
Supernovae

Terrestrial experiments:

HEAVY ION COLLISIONS
Hypernuclei

Lattice QCD Thermodynamics:

Calculation currently available only for zero baryo-chemical potential. Extrapolation to finite potential is provided by models - convergence problem. The \((T,\mu)\) coordinates of the critical point is particularly interesting.

W. Weise / Progress in Particle and Nuclear Physics 67, 299–311 (2012)
Neutron Stars
Extreme conditions in neutron stars allow wide speculations about their internal structure: WHICH ARE REALLY THERE?
Basic model of (non-rotating) neutron star properties:

Tolman-Oppenheimer-Volkoff (TOV) equations for hydrostatic equilibrium of a spherical object with isotropic mass distribution in general relativity:

- **Input:** The Equation of State $P(\varepsilon)$ – pressure as a function of energy density
- **Output:** Mass as a function of Radius $M(R)$

\[
\frac{dP}{dr} = -\frac{GM(r)\varepsilon}{r^2} \left(1 + \frac{P}{\varepsilon c^2}\right) \left(1 + 4\pi r^3 \frac{P}{M(r)c^2}\right) \frac{1}{1 - 2GM(r)/rc^2}
\]

\[
M(r) = \int_0^r 4\pi r'^2 \varepsilon(r') \, dr'
\]

I. Precise determination of a neutron star mass alone is not sufficient to compare models with observation.

II. Strong dependence on the equation of state
A selection of five most accurately measured neutron star masses:

**PSR J0737-3039** the first double pulsar (A,B)
M = 1.249+/-.001 M⊙ (Lyne et al., Science 303, 1153 (2004))
P = 2.77s (B)

**PSR B1913+16** NS binary (Hulse-Taylor)
P = 59 ms

**PSR J1903+0327** NS on an eccentric orbit around MS star
M=1.667±0.021 M⊙: (Freire, P. C. C. et al., MNRAS, 412, 2763 (2011))
P = 2.5 ms

**PSR J1614-2230** NS+WD
M_g = 1.97+/-.04 M⊙ (Demorest at al., Nature 467, 1081 (2010))
P = 3.15 ms

**PSR J0348+0432** NS+WD
M_g = 2.03+/-.03 M⊙ (Antoniades et al., Science 340, 448 (2013))
P = 39 ms
NS mass can be measured only in binary systems. 

**BUT**

Only 5-10% of known pulsars are in binaries

Artist's impression of a binary system containing a pulsar (smaller object with jets of light) and a white dwarf. The result of their mutual orbit generates gravitational waves, shown as the ripples in space-time.
Examples of TOV solutions for different EoS $P = f(\varepsilon)$

Each point on the “goose neck–like” curve represents a maximum mass of a neutron star model with a particular central energy density $\varepsilon$.


MAIN INTEREST: MAXIMUM (M,R) PROVIDES CONSTRAINT ON THE EOS
Simultaneous determination of mass and radius
Low-mass X-ray binaries inside globular clusters
(bursting and transiently accreting)

Problems:
Distance, atmosphere, redshift, EoS.....

Latest:

1.4 $M_{\text{sol}}$ \hspace{1cm} 11.15 < R < 12.66 km


All masses \hspace{1cm} 7.6 < R < 10.4 km

Main difference: H or He atmosphere

Ignition T of H and He in the accreting material from the companion is reached at the surface of the star
Cassiopeia A (Cas A)

Remnant of the historical 1680 SN explosion discovered in 1999 with Chandra X-ray Observatory

Isolated young neutron star with a carbon atmosphere and low magnetic field provided precise data on unexpected rapid cooling

\[ T_s \text{(K)} \]

Neutron Star in Cas A

Observation 2000 - 2009


(Added 2012 point)
Rapid cooling is triggered by neutron superfluidity in dense matter enhanced by neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel in the star’s core. Large proton superconductivity need to be present in the core.

Page et al., PRL 106,081101 (2011)

The cooling rates account for medium-modified one-pion exchange in dense matter and polarization effects in the pair-breaking formations of superfluid neutrons and protons.

Blaschke et al., PRC 85, 022802(R) 2012

Relativistic model of a 2D rotating neutron star combined with relativistic thermal energy transport: Frequency dependent composition and temperature distribution

Weber, Compstar Tahiti 2012
Negreiros et al., PRD 85, 014019 (2012)
Re-analysis and a new 2012 point

Light blue triangles: Typical 1 σ errors in T for two different normalisations

Different \( N_H \) (blue)
Same \( N_H \) (red)
Core collapse supernovae
Proto-neutron stars and their evolution

Data on sensitivity of CCS simulation to EoS limited (Lattimer-Swesty or Shen) or non-existent
From progenitor stars via CCSNe to neutron stars

- what is the state of matter during all these stages?

Slide from M.Hempel, Russbach, 2014
What energy density is available during the formation of the PNS? (essential time up to 60 sec after bounce)

T. Fischer, talk at CSQCD II, May 2009
Physical conditions for appearance: hyperons, π and K meson condensates u d s matter +

THRESHOLD DENSITIES UNKNOWN – STRONGLY MODEL DEPENDENT
Can quark matter be created in NS cores?
Heavy Ion Collisions
Heavy Ion collisions:

GSI, MSU, Texas A&M, RHIC, LHC existing
FAIR (GSI), NICA (Dubna, Russia) planned

Measurement: Beam energy 35 A MeV – 5.5 A TeV
Collisions (Au,Au), (Sn,Sn), (Cu,Cu)
but also (p,p) for a comparison
Transverse and Elliptical particle flow

Calculation: Transport models -- empirical mean field potentials
Fit to data $\rightarrow$ energy density $\rightarrow$ $P(\varepsilon)$ $\rightarrow$ the EoS

Quantum Molecular Dynamics
(e.g. Yingxun Zhang, Zhuxia Li, Akira Ono)
Matter in HIC and compact objects have different EoS:

**Central A-A collision:**
- Strongly beam energy dependent
- Beam energy $< 1$GeV/ A:
  - Temperature: $< 50$ MeV
  - Energy density: $\sim 1 - 2$ GeV/fm$^3$
  - Baryon density $< \rho_0$
  - Time scale to cool-down: $10^{-22-24}$ s
  - No neutrinos

**Strong Interaction:** (S, B and L conserved)
- Time scale $10^{-24}$ s

**NEARLY SYMMETRIC MATTER**

- Inelastic NN scatterings,
  - N,N*, $\Delta$’s
  - LOTS of PIONS
  - strangeness
- less important (kaons)
  - ? (Local)EQUILIBRIUM?

**Proto-neutron star:**
- (progenitor mass dependent)
- $\sim 8 – 20$ solar mass
  - Temperature: $< 50$ MeV
  - Energy density: $\sim 1$ GeV/fm$^3$
  - Baryon density $\sim 2-3 \rho_s$
  - Time scale to cool-down: $1 -10$ s
  - Neutrino rich matter

**Strong +Weak Interaction:** (B and L con)
- Time scale $10^{-10}$ s

**HIGHLY ASYMMETRIC MATTER**

- Higher T: strangeness produced in weak processes
- Lower T: freeze-out
- N, strange baryons and mesons,
  - NO PIONS, leptons
  - EQUILIBRIUM
SUMMARY SO FAR

I. Current models have limited predictive power – they have too many parameters and it is impossible to constrain them unambiguously.

II. Models are often adjusted to fit only a selected class of data well, but their failure elsewhere is neglected. Such models cannot be right. Even “minimal” models are of a limited use in a broader context.

POSSIBLE SOLUTION?

I. Understand behaviour of hadrons in medium

II. Evaluate basic assumptions of each models and regions of applicability. Focus on models with INDIVIDUAL parameters constrained by physics. Microphysics is important!

DATA LIMITED BY AVAILABLE TECHNIQUE – PHYSICS SHOULD BE ADOPTED AS A CONSTRAINT
Coulomb force:

2 electrical charges:

\[ |F_{Q-q}| = |F_{q-Q}| = k \frac{|q \times Q|}{r^2} \]
Many electrical charges:

principle of superposition

Force acting on a charge $q$ at position $r$ due to $N$ discrete charges:

$$F(r) = \sum_{i=1}^{N} \frac{q_i (r - r_i)}{4 \pi \varepsilon_0 |r - r_i|^3}$$
Nuclear force

2 nucleons:
nucleon-nucleon scattering
tractable with many parameters
no unique model
Many nucleons: force depends on medium (density) and momentum – strong, weak and elmg interactions play role – intractable?
Quark-Meson-Coupling Model

History:
Original: Pierre Guichon (Saclay), Tony Thomas (Adelaide) 1980’
Several variants developed in Japan, Europe, Brazil, Korea, China

Main idea:
Effective model of the MEDIUM EFFECT on baryon structure and interactions
Quark level – coupling between u and d quarks of non-overlapping baryons by meson exchange - significantly simplifies as compared to nucleonic level.

http://www.physics.adelaide.edu.au/cssm/lattice/ Schematic (Guichon)
WHAT WE DO:

For technical details see Whittenbury et al. PRC 89, 065801 (2014)

1. Take a baryon in medium as an MIT bag (with one quon exchange) immersed in a mean scalar field (NJL in progress)

2. Solve the bag equations in the scalar field to obtain a dynamical effective mass

\[ M_N^* = M_N - g_N d + \frac{d}{2} (g_N)^2 \]

the last term represents the response of the nucleon to the scalar field \( d = 0.22 R_B \) and the coupling constants for a free nucleon are calculated.

3. Construct QMC Lagrangian on a hadronic level in the same way as in RMF but using the effective baryon mass \( M_N^* \) and proceed to calculate standard observables.

4. Technically: Full Fock term is included (vector and tensor), and \( \sigma \omega \rho \pi \) mesons
Parameters (very little maneuvering space):

3 meson-quark coupling constants:

\[ g_{\sigma}^q, \ g_{\omega}^q, \ \text{and} \ g_{\rho}^q \ \text{for} \ q = u, d \ (g_{\alpha}^s = 0 \ \text{for all mesons} \ \alpha). \]

Fixed to saturation density 0.16 fm\(^{-3}\), binding energy of SNM -16 MeV and the symmetry energy 32.5 MeV

Meson masses: \( \omega, \rho, \pi \) keep their physical values
\[ \sigma = 700 \ \text{MeV} \]

Cut-off parameter \( \Lambda \) (in form-factors in the exchange terms)
constrained between 0.9 and 1.3 GeV

Free nucleon radius: 1 fm (limited sensitivity within change +/- 20%)

All other parameters either calculated or fixed by symmetry.
### Results: Nuclear Matter and Cold Neutron Stars
*(Full Baryon Octet included)*

<table>
<thead>
<tr>
<th>Model</th>
<th>$g_{\sigma N}$</th>
<th>$g_{\omega N}$</th>
<th>$g_{\rho}$</th>
<th>$K_0$ (MeV)</th>
<th>$L$ (MeV)</th>
<th>$R$ (km)</th>
<th>$M_{\text{max}}$ ($M_\odot$)</th>
<th>$\rho_c^{\text{max}}$ ($\rho_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>10.42</td>
<td>11.02</td>
<td>4.55</td>
<td>298</td>
<td>101</td>
<td>12.27</td>
<td>1.93</td>
<td>5.52</td>
</tr>
<tr>
<td>$\Lambda = 1.0$</td>
<td>10.74</td>
<td>11.66</td>
<td>4.68</td>
<td>305</td>
<td>106</td>
<td>12.45</td>
<td>2.00</td>
<td>5.32</td>
</tr>
<tr>
<td>$\Lambda = 1.1$</td>
<td>11.10</td>
<td>12.33</td>
<td>4.84</td>
<td>312</td>
<td>111</td>
<td>12.64</td>
<td>2.07</td>
<td>5.12</td>
</tr>
<tr>
<td>$\Lambda = 1.2$</td>
<td>11.49</td>
<td>13.06</td>
<td>5.03</td>
<td>319</td>
<td>117</td>
<td>12.83</td>
<td>2.14</td>
<td>4.92</td>
</tr>
<tr>
<td>$\Lambda = 1.3$</td>
<td>11.93</td>
<td>13.85</td>
<td>5.24</td>
<td>329</td>
<td>124</td>
<td>13.02</td>
<td>2.23</td>
<td>4.74</td>
</tr>
<tr>
<td>$R = 0.8$</td>
<td>11.20</td>
<td>12.01</td>
<td>4.52</td>
<td>300</td>
<td>110</td>
<td>12.41</td>
<td>1.98</td>
<td>5.38</td>
</tr>
</tbody>
</table>
NEW DEVELOPMENT:

FINITE NUCLEI:
QMC implemented into a 2D Hartree-Fock + BCS model

Preliminary results: Ground state binding energy and charge radii within 1% or less for:
  C\textsubscript{12}, O\textsubscript{16}, Ca\textsubscript{20} - 50, Ni 56 – 78, Sn100 – 134,
  Gd146, Pb 198 – 208, Fm\textsubscript{248-256}, No\textsubscript{254-256},
  Rf\textsubscript{256,258}, Hs\textsubscript{264,266}, Sg\textsubscript{260,262}, Ds\textsubscript{270}

Deformation of superheavy nuclei
Satisfactory spin-orbit splitting and charge density distribution

Near future projects:
Extention to 3D – β-γ potential energy surfaces.
Matrix elements in harmonic oscillator basis – shell model
Table 2
Single-particle energies (in MeV) for $^{17}_Y$O, $^{41}_Y$Ca and $^{49}_Y$Ca hypernuclei. The experimental data are taken from Ref. [5, Table 11] for $^{16}_O$ and from Ref. [33] for $^{40}_Ca$.

<table>
<thead>
<tr>
<th></th>
<th>$^{16}_O$ (Expt.)</th>
<th>$^{17}_O$</th>
<th>$^{17}_{\Xi^0}O$</th>
<th>$^{40}_Ca$ (Expt.)</th>
<th>$^{41}_Ca$</th>
<th>$^{41}_{\Xi^0}Ca$</th>
<th>$^{49}_Ca$</th>
<th>$^{49}_{\Xi^0}Ca$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1s_{1/2}$</td>
<td>$-12.42 \pm 0.05 \pm 0.36$</td>
<td>$-16.2$</td>
<td>$-5.3$</td>
<td>$-18.7 \pm 1.1$</td>
<td>$-20.6$</td>
<td>$-5.5$</td>
<td>$-21.9$</td>
<td>$-9.4$</td>
</tr>
</tbody>
</table>

Same as Table 2 but for $^{91}_Y$Zr and $^{208}_Y$Pb hypernuclei. The experimental data are taken from Ref. [5, Table 13].

<table>
<thead>
<tr>
<th></th>
<th>$^{89}_\Lambda Yb$ (Expt.)</th>
<th>$^{91}_\Lambda Zr$</th>
<th>$^{91}_{\Xi^0}Zr$</th>
<th>$^{208}_\Lambda Pb$ (Expt.)</th>
<th>$^{209}_\Lambda Pb$</th>
<th>$^{209}_{\Xi^0}Pb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1s_{1/2}$</td>
<td>$-23.1 \pm 0.5$</td>
<td>$-24.0$</td>
<td>$-9.9$</td>
<td>$-26.3 \pm 0.8$</td>
<td>$-26.9$</td>
<td>$-15.0$</td>
</tr>
</tbody>
</table>


Good agreement with experiment

Predicts bound cascade hypernuclei – experiment at JPARC - pending
N, Λ, Ξ, ω, D, J/ψ in nuclear matter

QCD & hadron structure

Density dependent effective NN (and N Λ, N Ξ) forces

Structure of finite nuclei & hypernuclei

Courtesy Anthony Thomas University of Adelaide
Low energy nuclear physics is essential for understanding of many phenomena in the Universe

We should seek NEW PHYSICS beyond the “nuclear standard model” approaches

The field is open and there is always light at the end of the tunnel.......