High Density EOS
– Heavy-Ion Collisions,
Compact Stars and Strangeness –

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Quarks and Compact Stars 2017
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- Introduction
- EOS softening probed in heavy-ion collisions
- Compact star matter EOS and Strangeness
- Summary
Contents

Request from organizers (Muto)
Review of dense matter & strangeness nuclear physics
with emphasis on heavy-ion physics and QGP formation

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Introduction,
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Summary
Neutron star – Is it made of neutrons?

- Possibilities of various constituents in neutron star core
  - Strange Hadrons
  - Meson condensate (K, π)
  - Quark matter
  - Quark pair condensate (Color superconductor)

NS core = Densest stable matter existing in our universe.

R ~ 10 km

M ~ 1.4 M⊙, ρ_c ~ (3-10) ρ₀
\[ \delta = \frac{(N-Z)}{A} \] 
(or \( Y_Q \) (hadron) = \( \frac{Q_h}{B} \sim (1-\delta)/2 \))
(ρ, T) during SN & BH formation

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, JPG 35 ('08) 085201; AO et al., NPA 835 ('10) 374.

Shen EOS + hyperons
(\(\rho, T, Y_e\)) during SN, BH formation, BNSM

**SN**

C. Ott

**BH form.**

C. Ott

See also

Oertel+16

**BNSM**

K. Kuchi

AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11), 284
QCD phase transition is not only an academic problem, but also a subject which would be measured in HIC or Compact Stars.
Highest Density Matter at J-PARC?

Central 1 fm$^3$ cube.

AO, JHF workshop ('02); J. Phys. Conf. Ser. 668 ('16)012004

Nara, Otuka, AO, Maruyama ('97)
How do heavy-ion collisions look like?

Au+Au, 10.6 A GeV

Pb+Pb, 158 A GeV

JAMming on the Web  http://www.jcprg.org/jow/
Contents & Conclusions

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Conclusions

- We may find a (first-order) QCD phase transition at $\sqrt{s_{NN}}=(5-20)$GeV (J-PARC energy) via collective flow analysis.
- Massive NSs imply stiff EOS at isospin asymmetric dense matter, and suggest (at least) one of 3B repulsive force, transition to stiff quark matter, or modified gravity is necessary.
EOS softening probed in heavy-ion collisions
QCD phase transition

QCD phase transition at top RHIC & LHC energies

- Jet quenching, Nuclear Modification Factor (Energy loss), Statistical Hadron Production, Parton Collectivity ($v_2$), ...
  → QGP formation

- Crossover (lattice QCD)

One of Next Grand Challenges
= Detecting 1st or 2nd order phase transition in QCD
Nuclear Liquid-Gas Phase Transition

Caloric curve → LG phase transition (Smoking gun)


T. Furuta, A. Ono ('09)

AO, Randrup ('98)
Non-monotonic behavior in $K^+/\pi^+$ ratio (Horn), $m_T$ slope par. (Step or re-hardening), rapidity dist. width of $\pi$

E.g. A. Rustamov (2012)

N. Otuka, P.K.Sahu, M. Isse, Y. Nara, AO, nucl-th/010205
QCD phase transition at top RHIC & LHC energies

- Jet quenching, Nuclear Modification Factor (Energy loss), Statistical Hadron Production, Parton Collectivity ($v_2$), ...
  → QGP formation
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One of Next Grand Challenges
= Detecting 1st or 2nd order phase transition in QCD

- (Partial) Chiral restoration → Modification of hadron properties
- Critical Point → Large fluctuation of conserved charges
- First-order phase transition → Softening of EOS
  → Non-monotonic behavior of proton number moment ($\kappa\sigma^2$) and collective flow ($dv_1/dy$)
Non-monotonic behavior of $\kappa \sigma^2$ and $dv_1/dy$. CP & FOPT signal?

STAR Collab. (PRL 112('14)032302

STAR Collab., PRL 112('14)162301.
Two ways to probe QCD phase transition

QGP $\rightarrow$ Hadrons
Final State Observables
Cumulants, ...

Hadrons $\rightarrow$ QGP
Early Stage Observables
Caution: (Partial) Equilibration is necessary!

Randrup, Cleymans ('06,'09)
What is directed flow?

- \( v_1 \) or \( \langle p_x \rangle \) as a function of \( y \)
  - is called directed flow.
  - Created in the overlapping stage of two nuclei
  - \( \rightarrow \) Sensitive to the EOS in the early stage.
  - Becomes smaller at higher energies.

How can we explain non-monotonic dependence of \( dv_1/dy \)?

- \( \rightarrow \) Softening or Geometry

\[ v_1 = \langle p_x/p_T \rangle = \langle \cos \varphi \rangle \]
Does the “Wiggle” signal the QGP?

- Hydro predicts wiggle with QGP EOS.

- Baryon stopping + Positive space-momentum correlation leads wiggle (w/o QGP)

L. P. Csernai, D. Röhrich, PLB 45 (1999), 454.


Bowling Pin Mechanism
Negative $dv_1/dy$ around $\sqrt{s_{NN}} \sim 10$ GeV

Yes in Hydrodynamics

- Protons
- Antiprotons
- Pions

27 GeV

19.6 GeV

11.5 GeV

7.7 GeV

Black: Crossover, Red: 1st

Y. B. Ivanov and A. A. Soldatov, PRC91 (2015)024915

No at around $\sqrt{s_{NN}} \sim 10$ GeV in transport models.

V. P. Konchakovski, W. Cassing, Y. B. Ivanov, V. D. Toneev, PRC90('14)014903
Does Directed Flow Collapse Signal Phase Tr.? 

- Negative $dv_1/dy$ at high-energy ($\sqrt{s_{NN}} > 20$ GeV)
  - Geometric origin (bowling pin mechanism), not related to FOPT
    
    R. Snellings, H. Sorge, S. Voloshin, F. Wang, N. Xu, PRL84,2803('00)

- Negative $dv_1/dy$ at $\sqrt{s_{NN}} \sim 10$ GeV
  - Yes, in three-fluid simulations. → Thermalization?
    
    Y. B. Ivanov and A. A. Soldatov, PRC91('15)024915

  - No, in transport models incl. hybrid.
    

  Exception: B.A.Li, C.M.Ko ('98) with FOPT EOS

We investigate the directed flow at BES energies in hadronic transport model with / without mean field effects with / without softening effects via attractive orbit.
Hadron Transport Model

Microscopic Transport Models

= Boltzmann Eq. with potential effects

\[ \frac{\partial f}{\partial t} + v \cdot \nabla f - \nabla U \cdot \nabla p f = I_{\text{coll}} \]

\[ I_{\text{coll}}(r, p) = -\frac{1}{2} \int \frac{dp^2}{(2\pi)^3} d\Omega \, v_{12} \frac{d\sigma}{d\Omega} \left[ f f_2(1 - f_3)(1 - f_4) \right] - (12 \leftrightarrow 34) \]

- UrQMD 3.4 (Frankfurt), PHSD Giessen (Cassing), GiBUU 1.6 Giessen (Mosel), AMPT (Texas A&M), JAM (Y. Nara)

- Hadron-string transport model JAM

  Hadronic cascade with resonance and string excitation
  \[ \text{Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.} \]

  Potential term \( \rightarrow \) Mean field effects in the framework of RQMD/S
  \[ \text{Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.} \]
  \[ \text{Tomoyuki Maruyama et al., Prog. Theor. Phys. 96(1996), 263.} \]
  \[ \text{Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908.} \]
Pot. Eff. on the $v_1$ is significant, but $dv_1/dy$ becomes negative only at $\sqrt{s_{NN}} > 20$ GeV.

Hadronic approach does not explain directed flow collapse at 10-20 GeV even with potential effects.

JAM/M: only formed baryons feel potential forces
JAM/Mq: pre-formed hadron feel potential with factor 2/3 for diquark, and 1/3 for quark
JAM/Mf: both formed and pre-formed hadrons feel potential forces.

Y. Nara, AO, NPA 956 ('16), 284 (QM2015 proc.)
Softening Effects via Attractive Orbit Scattering

- Attractive orbit scattering simulates softening of EOS
  
  P. Danielewicz, S. Pratt, PRC 53, 249 (1996)
  H. Sorge, PRL 82, 2048 (1999).

\[ P = P_f + \frac{1}{3V\Delta t} \sum_{i,j} q_{ij} \cdot (r_i - r_j) \]

(Virial theorem)

- With attractive orbit, particle trajectories are bended toward denser region.

  → Attractive orbit scattering simulates time evolution with softer EOS!

Let us examine the EOS softening effects, which cannot be explained in hadronic mean field potential, by using attractive orbit scatterings!

Y. Nara, H. Niemi, AO, H. Stöcker, PRC 94 ('16), 034906
Directed Flow with Attractive Orbits

Nara, Niemi, AO, Stöcker ('16)

27 GeV

protons

10-40%

π^-

JAM

JAM Attractive

Softening!

mid-central (10-40 %)

central (0-10 %)
Mean Field + Attractive Orbit

Nara, Niemi, AO, Stöcker ('16)

MF+Attractive Orbit make $dv_1/dy$ negative at $\sqrt{s_{NN}} \sim 10$ GeV

Softening!
Softening of EOS by Attractive Orbits

\[ \Delta P = -\frac{\rho}{3(\delta \tau_i + \delta \tau_j)} \left( (p_i' - p_i)^\mu (x_i - x_j)_\mu \right) \]

\[ \delta \tau_i + \delta \tau_j \]

Pressure in simulated EOS \(\sim\) EOS-Q (e.g. Song, Heinz ('08))

H. Sorge, PRL82('99)2048.

Pressure in simulated EOS \(\sim\) EOS-Q (e.g. Song, Heinz ('08))

A. Ohnishi @ QCS2017, Feb. 22, 2017, Kyoto
**Softening: Where and How much?**

*P. Danielewicz, P.B. Gossiaux, R.A. Lacey, nucl-th/9808013 (Les Houches 1998)*

*Previous analyses: $\rho_B = (3-10)\, \rho_0$, $P = (80-700)\, \text{MeV/fm}^3$*

*B. A. Li, C. M. Ko, PRC58 ('98) 1382*

*H. Song, U. W. Heinz, PRC77('08)064901*

*J. Steinheimer, J. Randrup, V. Koch, PRC89('14)034901.*
Compact star matter EOS and Strangeness
Neutron star – Is it made of neutrons?

Possibilities of various constituents in neutron star core

- Strange Hadrons
  - Proton
  - $\Lambda$ hyperon
- Meson condensate ($K$, $\pi$)
  - $K^+$, $K^-$, $\pi^+$, $\pi^-$
- Quark matter
- Quark pair condensate (Color superconductor)
  - $u$, $d$, $s$, $\bar{u}$, $\bar{d}$, $\bar{s}$

NS core = Densest stable matter existing in our universe.

$R \sim 10\ km$

$M \sim 1.4\ M_\odot$, $\rho_c \sim (3-10)\ \rho_0$
Hyperons in Dense Matter

What appears at high density?

- Nucleon superfluid ($^3S_1$, $^3P_2$), Pion condensation, Kaon condensation, Baryon Rich QGP, Color SuperConductor (CSC), Quarkyonic Matter, ....

- Hyperons

  Tsuruta, Cameron (66); Langer, Rosen (70); Pandharipande (71); Itoh(75); Glendenning; Weber, Weigel; Sugahara, Toki; Schaffner, Mishustin; Balberg, Gal; Baldo et al.; Vidana et al.; Nishizaki, Yamamoto, Takatsuka; Kohno, Fujiwara et al.; Sahu, Ohnishi; Ishizuka, Ohnishi, Sumiyoshi, Yamada; ...

Chemical potential overtakes $\Lambda$ mass → appearance of $\Lambda$
Neutron Star Masses

NS masses in NS binaries can be measured precisely by using some of GR effects via doppler shifts.

- Perihelion shift + Einstein delay
  \[ M = 1.442 \pm 0.003 \, M_{\odot} \]
  (Hulse-Taylor pulsar)
  *Taylor, Weisenberg ('89)*

- Many NSs have \( M \sim 1.4 \, M_{\odot} \).

Lattimer (2013)
Massive Neutron Star Puzzle

- Observation of massive neutron stars ($M \sim 2 M_\odot$)
  - PSR J1614-2230 (NS-WD binary), $1.97 \pm 0.04 M_\odot$
    - Demorest et al., Nature 467('10)1081 (Oct. 28, 2010).
    - "Kinematical" measurement (Shapiro delay, GR) + large inclination angle
  - PSR J0348+0432 (NS-WS binary), $2.01 \pm 0.04 M_\odot$
    - Antoniadis et al., Science 340('13)1233232.

No Exotics in NS?
Bruckner-Hartree-Fock theory with Hyperons

- Microscopic G-matrix calculation with realistic NN, YN potential and microscopic (or phen.) 3N force (or 3B force).
  - Interaction dep. (V18, N93, ...) is large → Need finite nuclear info.  
    E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / M.Tamura et al.

- NS collapses with hyperons w/o 3BF.

Z.H.Li, H.-J.Schulze, PRC78('08),028801.

S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.
What did we miss?

- Hyperon potential in nuclear matter?
  - \( U_\Lambda(\rho_0) \sim -30\,\text{MeV}, U_\Sigma(\rho_0) > +20\,\text{MeV}, U_\Xi(\rho_0) \sim -14\,\text{MeV} \)

- Hyperon-Hyperon potential?
  - If vacuum \( \Lambda\Lambda \) potential is much more attractive than Nagara event implies, \( \Lambda\Lambda N \) potential must be very repulsive.

- Kaon potential in nuclear matter?

- Three-baryon (3B) interaction?

- Quark matter core?

- Modified gravity?
New analysis of $\Sigma$ production reaction: $^6\text{Li} (\pi^-, K^+) \Sigma^- {^5}\text{He}$ (Honda, Harada) 
\[ \rightarrow U_\Sigma \sim +30 \text{ MeV} \text{ (consistent)} \]

New $\Xi$ hypernuclei $\rightarrow$ B.E. $= 9 \text{ MeV} \& 1 \text{ MeV}$ (Takahashi (A01), Nakazawa, Kanatsuki, Yamamoto) 
\[ \rightarrow \text{Deeper than previous estimate!} \]
ΛΛ potential?

Nagara fit → $a_0(ΛΛ) = -0.575$ fm or $-0.77$ fm

Hiyama, Kamimura, Motoba, Yamada, Yamamoto ('02), Filikhin, Gal ('02)

New approach: ΛΛ correlation from HIC (Morita)
→ $-1.25$ fm $< a_0(ΛΛ) < 0$ (Consistent with Nagara)

Exp: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
Theor.: Morita et al., T. Furumoto, AO, PRC91('15)024916.
Remaining possibilities

Three-baryon (3B) interaction ?

“Universal” 3B repulsion
Nishizaki, Takatsuka, Yamamoto ('02), Tamagaki ('08),
Yamamoto, Furumoto, Yasutake, Rijken ('13)

Repulsive ΛNN potential (or density dep. ΛN pot.)
Lonardoni, Lovato, Gandolfi, Pederiva ('15), Togashi, Hiyama, Yamamoto, Takano ('16),
Tsubakihara, Harada, AO ('16)

Medium modification of baryons (Quark Meson Coupling model)
J.Rikovska-Stone, P.A.M.Guichon, H.H.Matevosyan, A.W.Thomas ('07),
Miyatsu, Yamamuro, Nakazato ('13)

Quark matter NS core ?

First order phase transition

Crossover transition to quark matter Masuda, Hatsuda, Takatsuka ('12)

Modified Gravity Astashenok et al. ('14), M.-K. Cheoun's talk
Hyperon Puzzle

Lonardoni, Lovato, Gandolfi, Pederiva ('15),

Yamamoto, Furumoto, Yasutake, Rijken ('13)

Togashi, Hiyama, Takano, Yamamoto ('16).

Crossover: Masuda, Hatsuda, Takatsuka ('12).

QMC, Miyatsu, Yamamuro, Nakazato ('13)

Rikovska-Stone, Guichon, Matevosyan, Thomas ('07).
How can we discriminate 3B force?

- Precise measurement and calc. of Λ separation energy (J-PARC, JLab) and Few-body hypernuclei
  E.g. E. Hiyama, Y. Kino, M. Kamimura, PPNP51('03)223.
  → Λ potential depth, shape and A-dep.

- Collective flow of Hyperons

- “microscopic” 3-body force
  - Chiral EFT Haidenbauer et al. ('13) → we need more data to fix LECs
  - Lattice 3B Doi et al. (HAL QCD)('12) → much CPU at Phys. point, but doable
  - Quark model 3BF Nakamoto, Suzuki ('16) → 3B Pauli blocking effects are small
  - Quark model 3B force with KMT AO, Kashiwa, Morita

![Graph showing Λ potential depth, shape, and A-dependence](image-url)
What is the origin of repulsive 3B force

- Short range ($r < 0.6$ fm) core of 2B force
  - vector boson exch., Pomeron exch.,
  - quark exclusion + one gluon exch., ...

We may need quark-gluon DOF to understand 3B repulsion.

→ Quark Meson Coupling,
Lattice QCD 3B force (HAL QCD),
Quark Cluster model (Nakamoto)

Fujiwara, Suzuki, Nakamoto ('07)
From 3-quark int. to 3B force

KMT interaction

\[ \mathcal{L} = g_D (\text{det} \Phi + \text{h.c.}) , \quad \Phi_{ij} = \bar{q}_j (1 - \gamma_5) q_i \]

- Responsible for U(1)$_A$ anomaly
- 3-body int. among u,d,s quarks
- \( g_D \) is fixed by \( \eta-\eta' \) mass diff.
  \[ \rightarrow g_D = -9.29 \quad \text{Hatsuda, Kunihiro ('94)} \]
  \[ -12.36 \quad \text{Rehberg, Klevanski, Hufner ('96)} \]
- Repulsive in \( \Lambda\Lambda \) system
  \[ \rightarrow \text{Pushes up } \Lambda \text{ particle energy.} \quad \text{Takeuchi, Oka ('91)} \]

Does the anomaly support NS?
3B potential from KMT interaction

AO, Kashiwa, Morita, arXiv:1610.06306
Lattice data: Doi et al. (HAL QCD) ('07)
3B potential from KMT: Repulsive enough?

Kohno ('12, '13)

Pauli

T. Doi

Quarks

Lattice QCD
Illinois-2
Urbana IX

A. Ohnishi @ QCS2017, Feb. 22, 2017, Kyoto
Summary

- Dense matter EOS is important in nuclear physics and astrophysics.
  - In compact star phenomena (neutron stars, supernovae, black hole formation, binary neutron star mergers), very dense matter would be created, and non-nucleonic hadrons and quarks may admix.
  - In heavy-ion collisions at $\sqrt{s_{NN}} = (5-20)$ GeV, very dense (and partially equilibrated) matter would be formed.

- Recent observation of the directed flow collapse ($dv_1/dy < 0$) seems to indicate softening of the EOS at high densities. This softening may signal a first-order QCD phase transition.

- Massive NSs imply stiff EOS at isospin asymmetric dense matter, and suggest (at least) one of 3B repulsive force, transition to stiff quark matter, or modified gravity is necessary.

- Can we understand the above two in a consistent manner?