Directed flow in heavy-ion collisions as a probe of the first order phase transition

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in collaboration with

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- Introduction: Negative dv1/dy at √s_{NN}~10 GeV
- Hadronic transport model with Softening Effects
- Summary

QCD Phase Diagram

RHIC, LHC, Early Universe

0

T

CP

QGP

Heavy-Ion Collisions (BES, FAIR, NICA, J-PARC)

ρ₀

ρ_B

CSC
QCD Phase Diagram

RHIC, LHC, Early Universe

Sym. Nucl. Matter
Pure Neut. Matter
Neutron Star

$\delta = (N-Z)/A$

$T$
$\rho$
$\rho_0$

QGP
Heavy-Ion Collisions (BES, FAIR, NICA, J-PARC)

CSC

Quark Matter

A. Ohnishi @ Reimei-HI 2016, Aug. 9, 2016
QCD phase transition

QCD phase transition at top RHIC & LHC energies = Crossover → One of Next Grand Challenges = Discovery of 1st or 2nd order phase transition in QCD

Signals of QCD phase transition at J-PARC energies ($\sqrt{s_{NN}} = 5-10$ GeV)?

- (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 ($k\sigma^2$) and collective flow ($dv_1/dy$)
Net-Proton Number Cumulants & Directed Flow

STAR Collab. PRL 112(’14)032302

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

QGP → Hadrons
Final State Observables
Cumulants, ...

Hadrons → 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 → Sensitive to the EOS in the early stage.
- Becomes smaller at higher energies.

How can we explain non-monotonic dependence of $dv_1/dy$? → Softening or Geometry

$$v_1, \langle p_x \rangle$$

$$v_1 = \langle p_x / p \rangle = \langle \cos \varphi \rangle$$
SPS(NA49) vs RHIC(STAR)

**SPS (NA49), $\sqrt{s_{NN}} = 8.9$ GeV**

C. Alt et al. (NA49), PRC68 ('03) 034903

Mid-central: Green

Hadronic Transport w/ MF

M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72 ('05) 064908

**RHIC(STAR), 7.7-39 GeV**

L. Adamczyk et al. (STAR), PRL 112(2014)162301
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 → Controversial!
  - Yes, in three-fluid simulations. → Thermalization?
    - Y. B. Ivanov and A. A. Soldatov, PRC91('15)024915; P. Batyuk et al., 1608.00965.
  - No (for semi-central collisions), in transport models incl. hybrid.
    - Exception: B.A.Li, C.M.Ko ('98) with FOPT EOS

We investigate the directed flow at J-PARC energies in hadronic transport model with / without mean field effects and with / without softening effects via attractive orbit.
Hadronic Transport with Softening Effects
**Transport Model**

- Microscopic Transport Models
  - Boltzmann equation
    - with (optional) potential effects
    - *E.g. Bertsch, Das Gupta, Phys. Rept. 160(88), 190*

- 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
  - Potential term → Mean field effects in the framework of RQMD/S
    - *Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.
Mean Field Potential

Skyrme type density dependent + momentum dependent potential

\[ V = \sum_i V_i = \int d^3r \left[ \frac{\alpha}{2} \left( \frac{\rho}{\rho_0} \right)^2 + \frac{\beta}{\gamma + 1} \left( \frac{\rho}{\rho_0} \right)^{\gamma + 1} \right] + \sum_k \int d^3r d^3p d^3p' \frac{C_{ex}^{(k)}}{2\rho_0} \frac{f(r,p)f(r',p')}{1 + (p - p')^2/\mu_k^2} \]

<table>
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<tr>
<th>Type</th>
<th>(\alpha) (MeV)</th>
<th>(\beta) (MeV)</th>
<th>(\gamma)</th>
<th>(C_{ex}^{(1)}) (MeV)</th>
<th>(C_{ex}^{(2)}) (MeV)</th>
<th>(\mu_1) (fm(^{-1}))</th>
<th>(\mu_2) (fm(^{-1}))</th>
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<td>2.02</td>
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</tbody>
</table>

Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908.

A. Ohnishi @ Reimei-HI 2016, Aug.9, 2016

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Comparison with RHIC data on $v_1$

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.

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).

\[ P = P_f + \frac{1}{3TV} \sum_{(i,j)} (q_i \cdot r_i + q_j \cdot r_j) \]
(Virial theorem)

- With attractive orbit, particle trajectories are bended toward denser region.
  \[ \rightarrow \text{Attractive orbit scattering simulates time evolution with softer EOS!} \]

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

Directed Flow with Attractive Orbits

Nara, Niemi, AO, Stöcker ('16)

Softening!
Softening: Where and How much?


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

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

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

J. Steinheimer, J. Randrup, V. Koch, PRC89('14)034901.
\[ \Delta P = -\frac{\rho}{3(\delta \tau_i + \delta \tau_j)} (p_i' - p_i)^\mu (x_i - x_j)_\mu \]

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

Nara, Niemi, AO, Stöcker ('16)

H. Sorge, PRL82('99)2048.
Summary

- We may see QCD phase transition (1\textsuperscript{st} or 2\textsuperscript{nd}) signals at BES (or J-PARC) energies in baryon number cumulants and $v_1$ slope.

- Hadronic transport models cannot explain negative $v_1$ slope below $\sqrt{s_{\text{NN}}} = 20$ GeV.

  - Geometric (bowling pin) mechanism becomes manifest at higher energies (JAM, JAM-MF, HSD, PHSD, UrQMD, ....).

- Hadronic transport with EOS softening can describe negative $v_1$ slope below $\sqrt{s_{\text{NN}}} = 20$ GeV.


  - Attractive orbit scattering simulates EOS softening (virial theorem).

  - We need more studies to confirm its nature.

    First-order phase transition ? Crossover ? Forward-backward rapidities ? MF leading to softer EOS ?

- We need “re-hardening” at higher energies, e.g. $\sqrt{s_{\text{NN}}} = 27$ GeV.
Thank you!
Directed Flow

\[ F = \frac{d\langle P_x \rangle}{dy} \]

\[ F_y \text{ (MeV/c)} \]

\[ \text{Beam Energy (GeV/A)} \]

Mean Field + Attractive Orbit

MF + Attractive Orbit make $dv_1/dy$ negative at $\sqrt{s_{NN}} \sim 10$ GeV
v1 is sensitive to highest density regime

Nara, Niemi, AO, Stöcker ('16)
“Softening” should take place at $\sqrt{s_{NN}} = 11.5$ GeV $\rightarrow \rho/\rho_B \sim (6-10)$

- Attractive orbit
- Larger interactions
- Higher T at later times
How about $v_2$?

Do we see softening effects in other observables, e.g. $v_2$?

Yes, attractive orbits reduces proton $v_2$ by $\sim 0.2$%.
(but there is no qualitative change.)
**Relation to Neutron Star Matter**

We may need early transition (2-5 $\rho_0$) to quark matter to solve the hyperon puzzle. contradicting?

→ Temperature effects ($T \sim 0$ MeV & 100 MeV)

Isospin chem. pot. (Weaker transition with finite $\delta\mu$)

Hyperon repulsion may push up the transition density.

AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284

H. Ueda, T. Z. Nakano, AO, M. Ruggieri, K. Sumiyoshi, PRD88('13),074006
Negative $dv_1/dy$ around $\sqrt{s_{NN}} \sim 10$ GeV

Yes in Hydrodynamics

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

Black: Crossover, Red: 1st

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

V. P. Konchakovski, W. Cassing, Y. B. Ivanov, V. D. Toneev, PRC90('14)014903