The Role of Femtoscopy in Constraining the Eq. of State of High-Baryon-Density Matter

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Femtoscopy Theory (one slide)

\[ C(\vec{p}_1, \vec{p}_2) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} \]
\[ = C(\vec{v}_{cm}, \vec{q}) \]
\[ = \int d^3r S(\vec{v}_{cm}, \vec{r}) |\phi_q(\vec{r})|^2 , \]

\[ S(\vec{v}_{cm}, \vec{r}) = \frac{\int d^3r_1 d^3r_2 f_{cm}(\vec{v}_{cm}, \vec{r}_1, t)f_{cm}(\vec{v}_{cm}, \vec{r}_2, t)\delta(\vec{r}_1 - \vec{r}_2 - \vec{r})}{\int d^3r_1 d^3r_2 f_{cm}(\vec{v}_{cm}, \vec{r}_1, t)f_{cm}(\vec{v}_{cm}, \vec{r}_2, t)} \]

“SOURCE FUNCTION” measures phase space cloud, not source!!!

GOAL: Measure \( C(\vec{p}_1, \vec{p}_2) \) to infer \( S(\vec{v}_{cm}, \vec{r}) \)

For identical bosons: \( |\phi|^2 = 1 + \cos(2\vec{q} \cdot \vec{r}) \)

Strong/Coulomb makes inversion more complicated
Basic Idea

Softer EoS → Longer Lifetime

Longer Lifetime → $R_{out} > R_{side}$ & $R_{beam}$ increases

Longer $R_{out}$ → Narrow C.F.

$R_{out} \sim \sqrt{R_{side}^2 + v^2 \tau^2}$

Two-Pion Correlation Function


Outward

Sideward

no phase transition

with phase transition
Phase Transition at Low Energy

neutron-neutron correlations at 25A MeV and 58A MeV

S. Gaff et al, PRC58, 2161 (98)

Sensitivity to EoS (realistic calc.s)

The figure shows the sensitivity of the calculated radii of the phase space cloud to the equation of state (EoS). The graphs display the ratio of the outgoing radii to the side radius as a function of the transverse momentum ($k_t$) for Au+Au collisions at 100A GeV. The data are compared with different EoS models:

- **1st order EoS**: This model assumes a first-order phase transition with a latent heat. It predicts a large increase in the radius ratio, indicating a significant change in the phase-space distribution.
- **Lattice EoS**: This model is based on lattice gauge theory and provides a more realistic equation of state, especially near the phase transition points.
- **STAR** model: This includes hydrodynamic and cascade calculations, which are used to model the initial expansion and thermalization of the system.

The figure highlights the importance of using realistic EoS models to accurately describe the phase-space distributions in heavy-ion collisions. Other corrections, such as initial flow, shear viscosity, and a better wave function, are also discussed.
Role of Femtoscopy in Global Analysis

Pionic femtoscopy provided most of resolving power of EoS

S.P. E.Sangaline, P.Sorensen & H. Wang, PRL 2016

E. Sangaline & S.P, PRC 2016

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The Review of Particle Physics [15]

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FIG. 1. Twenty pion, kaon and proton spectra as measured strains some integrated measure of the overall sti...
Evidence of EoS Stiffening & Softening from $v_1$, $v_2$

$v_1$ rises and falls with beam energy

A. Sorensen et al., nucl-th2301.13253
Bayesian Analysis of $\nu_1$, $\nu_2$

Calculations has some questions:
- momentum dependence of potential
- role of string/flux-tubes on $\nu_1$
Evidence of stiffness for $\rho \sim 3\rho_0$ from neutron star observations
— $c_s^2$ higher for neutron-rich matter
Source Radii vs Beam Energy

REMARKABLE!
Lowering beam energy below 19.6 GeV yields higher speed of sound despite higher $p/\pi$ ratio!
UrQMD vs STAR/HADES

Stiffer EoS looks better!

P.Li, J.Steinheimer, A.Kittiratpattana, M.Bleicher & Q.Li
Where to go from here...
Which Beam Energies?

- Lower BES (FXT) energies and HADES energies:
  - explore up to $\lesssim 3\rho_0$ without becoming QGP
  - can then avoid hydro

- Isospin degree of freedom:
  - crucial for astrophysical correction
  - FRIB - 400 program?
What to Measure

emphas on sensitivity to EoS

1. Pions
   - tilt and azimuthal sensitivity
   - away from mid-rapidity
     (important at lower energy)

2. Protons & Kaons
   - also good shape sensitivity

3. Non-identical particles
   - $S(\vec{r})$ not reflection symmetric
What to Calculate
emphasis on sensitivity to EoS

READY TO GO:
1. CoRAL (Correlations Analysis Library)
   — Calculates 3D Correlations
   — Wide variety of species pairs
   — Need only provide OSCAR output
   — Not turnkey, but easily adaptable

2. Emulation software for Bayesian Analysis
   — Smooth Emulator
     (developed at MSU for BAND Collab.)
   — Initial state parameters, EoS, viscosity
     need to be simultaneously analyzed

TO DO:
1. Improve Transport Theory
   — Momentum dependence
   — Initial stopping
   — Parameterize possibilities
     for Bayesian analysis

2. Improve data/model comparisons
   — Extracting Gaussian radii for pp…
   — Compare angular decompositions?
What to take away from this talk

I. The physics of high-baryon density in hadron phase is fundamentally interesting
   — Eq. of state
   — Astrophysical connection

II. Femtoscopy will play large role in that effort!