Constraining the Equation of State of Asymmetric Nuclear Matter with Collective Flow Measurements

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Equation of State (EOS): relationship between Energy, Pressure, Temperature, Density and Isospin Asymmetry of Nuclear Matter
The dense nuclear overlap is ellipsoidal at the beginning of heavy ion collisions.

Pressure gradient is largest in the shortest direction of the ellipsoid.

The initial spatial anisotropy evolves via interactions and density gradients to momentum-space anisotropy.

\( \Rightarrow \) Collective Flow
Collective Flow in the “Real” World!

Interplay between
a) The collision geometry
b) The relative magnitude of the time for development of the transverse expansion
c) The passage time for removal of the shadowing of participant hadrons by the projectile and target spectators

gives rise to dependence on E, b, pt, y ...
Characterising Collective Flow: Event Plane Method

Fourier expansion of particle azimuthal distribution relative to reaction plane

\[ E \frac{d^3 N}{dp^3} = \frac{1}{2\pi} \frac{dN}{p_{t}dp_{t}dy} \left( 1 + \sum_{n=1}^{3} 2v_n \cos(n[\phi - \Psi_R]) \right) \]

\[ v_1 = <\cos(\phi - \phi_R)> \quad \text{directed flow} \]
\[ v_2 = <\cos 2(\phi - \phi_R)> \quad \text{elliptic flow (} v_2 > 0 \text{ in-plane, } v_2 < 0 \text{ out-of-plane)} \]

Reaction plane (\( \phi_R \)) unknown. Measure \( \phi_E \) in experiment via Q-vector method.

Can calculate systematically the correction for reaction plane dispersion (fluctuations):

\[ V_n^{exp} = <\cos n(\phi - \phi_E)> = v_n^{corr} <\cos n\Delta \phi> \quad \text{where } <\cos n\Delta \phi> = <\cos n(\phi_R - \phi_E)> \]
Determination of Reaction Plane and Correction for Dispersion

Experimental Q-vector defines reaction plane $\phi_E$ event-by-event

Construct Q for two random sub-events: $\Delta \phi_E = \phi_1 - \phi_2$

Gaussian model, J.Y. Ollitrault, nucl-ex/9711003

Assumes sub-events are independent, isotropic, equivalent and normally distributed.

$$\frac{dN}{d\Delta \phi_R} = \frac{e^{-\chi^2/2}}{2} \left\{ \frac{2}{\pi} \left[ 1 + \chi^2/2 \right] + \chi^2/2 \left[ I_0(z) + L_0(z) \right] + \chi^2/2 \left[ I_1(z) + L_1(z) \right] \right\},$$

$$\langle \cos n \Delta \phi \rangle = \frac{\sqrt{\pi}}{2} \chi e^{-\chi^2/2} \left[ I_{n+1/2} \left( \frac{\chi^2}{2} \right) + I_{n+1} \left( \frac{\chi^2}{2} \right) \right],$$
Excitation Function of Integrated Elliptic Flow ($v_2$)

Comparison of Collective Flow to Transport Model Calculations

- BEVALAC and AGS data
  - Comparison to BUU transport model calculations
  - Additional constraints on $m^*$ and $\sigma_{nn}$
Experimental Constraints on EOS for Nuclear Matter

Symmetric

Model Dependence of Elliptic Flow

- Model dependence in determination of equation of state from flow observables
- More stringent constraints on the EOS of symmetric nuclear matter should be pursued
Experimental Constraints on EOS for Nuclear Matter

Symmetric

Asymmetric

Sensitivity of Elliptic Flow to Symmetry Energy at High Densities

Comparison to FOPI fragment yield data

- UrQMD transport model adapted to intermediate energies (Q. Li et al.)
- Clustering algorithm ($\Delta r = 3.0$ fm; $\Delta p = 275$ MeV/c)

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$

$$= 22\text{MeV} \cdot \left(\frac{\rho}{\rho_0}\right)^\gamma + 12\text{MeV} \cdot \left(\frac{\rho}{\rho_0}\right)^{2/3}$$

- asy-stiff: $\gamma = 1.5$
- asy-soft: $\gamma = 0.5$
Measurements of Neutron and Proton Elliptic Flow

- SIS@GSI
- LAND + FOPI forward wall
- Au+Au at 400, 600, 800 AMeV
- Re-analysis of data sets and comparison to UrQMD transport models

FOPI Forward Wall

- Highly segmented $\Delta E$-time-of-flight wall
- Full azimuthal angle coverage at polar angles from $1^\circ$ to $30^\circ$
- 764 scintillators, 188 thin $\Delta E$ detectors (gas and thin scintillator) in front
- Velocity and Z of fragments determined by $\Delta E$ and TOF

LAND Neutron Detector

- Plastic scintillator / Fe converter sandwich structure
- Plastic scintillator veto detector in front of LAND
- $\sigma_t < 250$ ps
- $\sigma_{x,y,z} \approx 3$ cm

- neutrons and protons in same detector
- reduce errors due to different detector acceptances

Azimuthal Distributions for Au+Au at 400 AMeV

- **Target rapidity region**
  - In-plane flow
  - $\phi_R - \phi = 180^\circ$
  - $v_1$ large, $v_2$ small

- **Mid-rapidity region**
  - Out-of-plane flow
  - $\phi_R - \phi = 90^\circ$ and $270^\circ$
  - $v_1$ small, $v_2$ large

- **Projectile rapidity region**
  - In-plane flow
  - $\phi_R - \phi = -180^\circ$
  - $v_1$ large, $v_2$ small

Background subtraction for neutrons
Results at 400 AMeV

- mid-peripheral (5.5 ≤ b ≤ 7.5 fm)
- integrated over 0.3 ≤ p_t/A ≤ 1.3 GeV/c
- \( \gamma = 0.9 \pm 0.4 \)
- moderately soft symmetry term
- what does this imply?
- combined central to mid-peripheral
- 0.25 ≤ y/y_p ≤ 0.75
Comparison of n-p Elliptic Flow with $\pi^-/\pi^+$ Particle Production

- Comparison of $\pi^-/\pi^+$ ratios measured with FOPI to IBUU04 transport model
  - super-soft symmetry energy ($x=1; \gamma < 0.5$)
- Comparison of neutron-proton elliptic flow data to UrQMD model
  - moderately soft symmetry energy ($x=0; \gamma = 0.9 \pm 0.4$ at $\rho/\rho_0 \sim 2$)
- Recent re-analysis of FOPI $\pi^-/\pi^+$ ratios with ImQMD
  - hard symmetry energy ($x=-1; \gamma = 2$)
Conclusions

• Collective flow can probe EOS of nuclear matter at high densities

• Constraints extracted for symmetric nuclear matter
  • Model dependence...
  • More stringent constraints on symmetric matter should be pursued

• Collective flow can provide constraints on asymmetric nuclear matter
  • Neutron-proton elliptic flow
  • First constraints from FOPI-LAND data $^{197}$Au+$^{197}$Au at 400 AMeV
    • $\gamma = 0.9 \pm 0.4$ (moderately soft)
    • Limited statistics

• Future Work
  • FOPI-LAND data $^{197}$Au+$^{197}$Au at 600, 800 AMeV under analysis
  • New experiment performed at GSI in May 2011
    • $^{197}$Au+$^{197}$Au, $^{96}$Ru+$^{96}$Ru, $^{96}$Zr+$^{96}$Zr at 400AMeV
    • See talks by P. Russotto, S. Santoro (Sunday afternoon)
  • Future prospects at FAIR with R3B
    • See talk by M. Chartier (Sunday afternoon)