Results from FOPI on nuclear collective flow in heavy ion collisions at SIS energies

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Results from FOPI on Nuclear Collective Flow in Heavy Ion Collisions at SIS energies

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2 FOPI detector overview

3 Experimental systematics
   • Directed flow
   • Elliptic flow

4 Data versus IQMD
   • Sensitivity to $\sigma_{nn}$?
   • Sensitivity to EoS?

5 Anisotropic flow from Lee-Yang Zeroes

6 Conclusion

Ca + Ca, Ni + Ni, Ru + Ru, Xe + CsI, Au + Au
90A MeV - 2A GeV
Motivations & Observables

Probing hot & dense hadronic matter

→ Nuclear Equation of State

- Collision dynamics
- In-medium effects: $\sigma_{\text{nn}}$, MDI

Global flow: $p_{x}^{\text{dir}} = \sum \text{sign}(y_{\text{cm}})Zu_{x} / \sum Z, \quad u_{x} = \beta_{x}\gamma$

Flow angle: $\theta_F$, Aspect ratios: $\lambda_{31}$ & $\lambda_{21}$

Differential flow: $\frac{dN}{d\varphi'} \sim 1 + 2v_{1}\cos(\varphi') + 2v_{2}\cos(2\varphi'), \quad \varphi' = \varphi - \varphi_{R}$
Systematics of Directed Flow & Stopping

Stopping:
\[ \frac{b}{b_{\text{max}}} < 0.15 \]
\[ \text{vartl} = \frac{\sigma^2(y_t)}{\sigma^2(y_z)} \]

Sideflow:
\[ \frac{b}{b_{\text{max}}} \approx 0.3 - 0.4 \]
\[ \text{max} \left[ (p_{x\text{dir}}^{(0)}) \right] \]

- Correlation between stopping & flow & pressure
- Evidence for incomplete stopping

- Stopping: maximum \( \sim 400\text{A MeV} \)
  decreasing towards higher beam energies
  rising with system size, no saturation
  below expectations from hydrodynamics
Systematics of Elliptic Flow

\begin{itemize}
  \item Transition from in-plane to out-of-plane preferred emission at low energies
  \item Maximum \( \sim 400A \text{ MeV} \) (depending on Pt)
  \item \( v_2 \) decreasing toward higher beam energies
\end{itemize}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{systematics.png}
\caption{\textbf{Au + Au, \( |y^{(0)}| < 0.1 \)}

\textbf{Z=1, all \( p_t^{(0)} \)}

\textbf{A\leq4, xA \( p_t^{(0)} > 0.8 \)}

\textbf{E_{beam}/A (GeV)}


\item Interplay between fireball expansion & spectator shadowing
\item Passing time decreasing at high beam energies
\item Influence of collision dynamics
\item Information on different stages of the collision
  \[ \Rightarrow \] High \( p_t \) particles messengers of high density phase

Shape parameters: Sensitivity to in-medium $\sigma_{nn}$?

- $\theta_F \rightarrow$ Directed flow
- $\lambda_{31} = f_3^2/f_1^2 \rightarrow$ Directed flow & Stopping
- $\lambda_{21} = f_2^2/f_1^2 \rightarrow$ Elliptic flow


Ru (400 AMeV) + Ru - Proton-likes - $< b_{geo} > = 1.1$ fm


Data favour in-medium $\sigma_{nn}$ close or slightly higher than $\sigma_{nn}^{free}$

$\Rightarrow$ Consistent with results on nuclear stopping

Sensitivity to the EoS parametrization

Soft EoS (with MDI & $\sigma_{\text{nn}}^{\text{free}}$) in best agreement with directed flow data for Au + Au & Xe + CsI at 400 AMeV

Difficulties of the model to reproduce directed flow versus system size & low $E_{\text{beam}}$ (90A MeV)

Proton elliptic flow in qualitative agreement with IQMD

Light fragments & IMF (Z>2) abundantly produced at SIS energies

Bound protons/all protons:
\[ \rightarrow 67\% \ (400A \ MeV) \rightarrow 33\% \ (1500A \ MeV) \]

\[ \Rightarrow \] Total baryon elliptic flow not described by any EoS
Flow from Lee-Yang Zeroes method

Genuine flow directly from correlation between many particles
⇒ Non-flow correlations due to quantum statistics, resonance decays, momentum conservation effects, ..., not neglected

□ Generating function:
\[
G(ir) = \langle \prod_j [1 + ir\omega_j \cos(n(\varphi_j - \theta))] \rangle_{\text{events}}
\]
where \( \ln G(ir) = \sum_{k=1}^{+\infty} c_k \frac{(ir)^k}{k!} \), \( c_k = \text{cumulant} \)

□ Find first zeroe (minimum), \( r_0^\theta \), of \( |G(ir)| \)
\( r_0^\theta \rightarrow \text{Asymptotic behaviour of } c_k \text{ in the expansion of } \ln G(ir) \)

□ “Integrated” flow: \( V_{\infty}^\theta \{\infty\} = \frac{j_{01}}{r_0^\theta} (\& \text{ averaged over } \theta) \)

□ Resolution parameter: \( \chi = \frac{V_{\infty} \{\infty\}}{\sigma} \)
→ \( \chi > 1 \): Lee-Yang zeroes should be used
→ \( 0.5 < \chi < 1 \): Important to optimize weights
→ \( \chi < 0.5 \): Large statistical errors, better to use cumulants

□ Differential flow:
→ Deduced from \( V_{\infty}^\theta \{\infty\} \text{ in harmonics multiples of } n \)

Detailed description in:

N. Borghini et al., nucl-th/0402053 (2004)
First application of Lee-Yang theory to FOPI data: Ru + Ru @ 1.69A GeV

- $\chi = 1.45 \Rightarrow$ Lee-Yang Zeroes theory can be used
- Clear indication of collective effects

- Non-flow effects from 4-particle correlations negligible
- Evidence for (small) momentum conservation effects on $v_1$
- Non-flow effects negligible for higher harmonics

Ongoing development $\rightarrow$ $\pi^\pm$ flow & influence of $\Delta$ decay?

(110 Millions central Ni + Ni @ 1.93A GeV)
Conclusion

Complete set of data at SIS energies measured with FOPI:

- Variation of beam energy from 90A MeV to 2A GeV
- Variation of system size from Ca to Au
- Variation of asymmetry in isospin (Ru/Zr)
- Variation of asymmetry in system size (Au/Ca & Pb/Ni)

- Main dependences of directed & elliptic flow are available
- New procedure of Lee-Yang Zeroes (& cumulants at SIS) successfully used for first time to analyze flow
- Correlations from non-flow effects negligible for protons & composite particles
- Most features of flow data reproduced qualitatively well by IQMD model but not in detail

- EoS is influencing different observables
- EoS is linked to in-medium NN interaction
  ⇒ momentum dependence, cross sections
- Non-equilibrium effects important