INDRA@GSI : COLLECTIVE FLOW FROM FERMI TO RELATIVISTIC ENERGIES

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Abstract

Directed flow for the ^{197}Au + ^{197}Au reactions at incident energies between 40 and 150 AMeV has been measured using the 4π multi-detector INDRA at the GSI facility. In particular, the bombarding energy at which the elliptic flow switches from in-plane to out-of-plane enhancement has been determined to be around 100 AMeV in good agreement with the result obtained by the FOPI Collaboration. The new data allows also to extend the experimental excitation function of v_2 to lower energies.

1 INTRODUCTION

Collective motion of decompressing excited nuclear matter formed in heavy ion collisions has a long history of more than two decades of research (see e.g. [1] for a review) and is still drawing attention of nuclear physicists. The main reason of this continuous interest is the presumed link of the collective phenomena to the nuclear matter equation of state, including possible insight into momentum dependence of nuclear interactions as well as the in-medium effects (see e.g. [2] for a review).

The main aim of this contribution is to present the results of the flow analysis applied to the data on Au+Au collisions at energies from 40 to 150 AMeV obtained using the INDRA detector [3] and the beams from the SIS synchrotron at the GSI, and also to relate them to the existing data.

2 CENTRALITY SELECTION

Following previous investigations of symmetric heavy ion collisions [4, 5], we use in the following the total transverse energy, $E_{12}^{\perp}$, of light charged particles (LCP, Z≤2) as an impact parameter selector.

Collisions associated with the most central 5% of the reduced impact parameter have been grouped in bin ❽, the remaining part of the $E_{12}^{\perp}$

spectrum has been divided into 7 equal bins, with bin ❶ corresponding to the most peripheral collisions. See [6] for more details. In the following, bins ❼ and ❽ have been merged in order to increase the statistics for the most central collisions.

3 SQUEEZE ANGLE

Squeeze angle, Ψ_{sq}, is defined as an angle between the middle eigenvector of the kinetic energy tensor and the reaction plane [7]. It can be regarded as a very global observable characterizing the preferential directions of emission of particles and fragments around mid-rapidity.

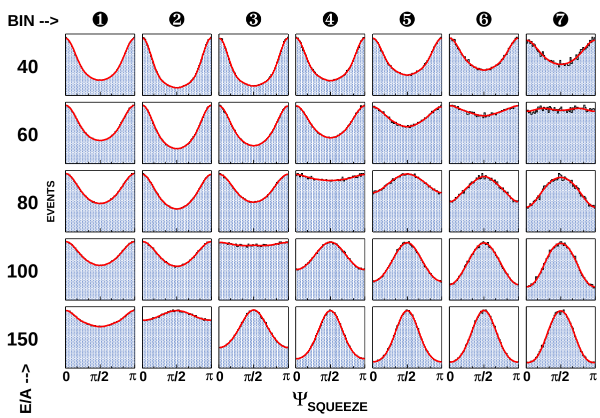

Figure 1: Squeeze angle distributions for incident energies from 40 to 150 AMeV (from top to bottom) and centrality bins from peripheral (left) to central (right).

Fig. 1 shows the trends of the squeeze angle distributions as a function of incident energy and centrality. Minima at $\pi/2$ characterize the events with preferential in-plane emission, while peaks at $\pi/2$ characterize those with preferential out-of-plane emission near mid-rapidity. The smooth lines superposed on the distributions represent the fits performed with the Fourier expansion formula: $N(\Psi_{sq}) \propto 1 + q_2 \cos(2\Psi_{sq}) + q_4 \cos(4\Psi_{sq}) + q_6 \cos(6\Psi_{sq})$. This formula has been used to analyze the curvature of the distributions at $\Psi_{sq} = \pi/2$.

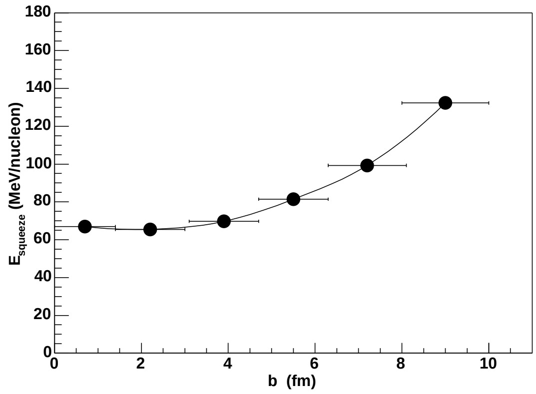

Figure 2: Transition energies at which the Ψ_{sq} distributions switch from concave to convex.

Fig. 2 shows the transition energies at which the second derivative of the distributions from Fig. 1 calculated at $\pi/2$ changes its sign, as a function of impact parameter. The horizontal error bars mark the impact parameter ranges corresponding to consecutive centrality bins.

As can be seen, the transition energy from in-plane to out-of-plane emission near mid-rapidity, measured through a global observable Ψ_{sq}, amounts to about 65 AMeV for central collisions and increases with the impact parameter.

4 EVENTS IN VELOCITY SPACE

Collective phenomena and associated transitions can be viewed directly from the events presented in velocity space.

Fig. 3 presents 3 projections of the 3 dimensional distribution of transverse velocity (x) vs rapidity (y) for fragments with $3 \leq Z \leq 6$ produced in semi-peripheral collisions. The columns present the projections on the reaction plane (left), on the plane containing the beam axis but perpendicular to the reaction plane (middle) and a slice at mid-rapidity perpendicular to the beam axis (right). The reaction plane was reconstructed using the kinetic energy tensor and excluding the particle of interest from the reconstruction (leading to “1 plane per particle” method as pointed out in [8]). The distribution in the upper left panel (40 AMeV) shows that this reconstruction method may lead to negative sideward flow values (strong emissions on the negative

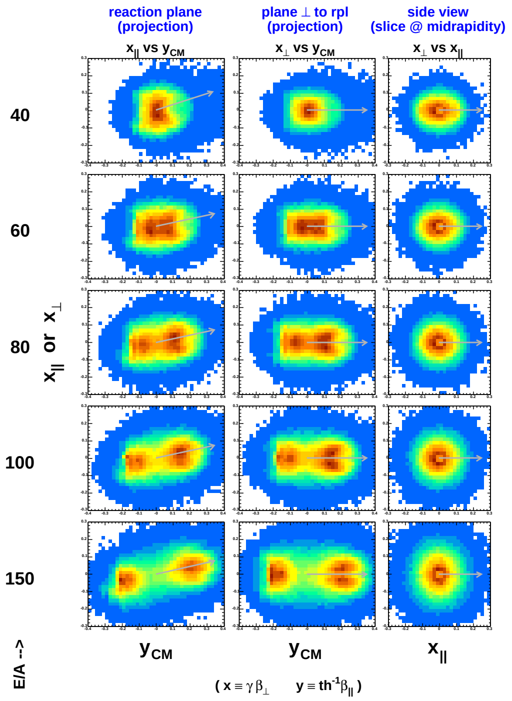

Figure 3: Distribution of fragments with $3 \leq Z \leq 6$ in velocity space measured for semi-peripheral (bin ❸) Au+Au collisions at energies from 40 to 150 AMeV (top to bottom). The arrows point in the direction of the main flow tensor eigenvector.

side of the reaction plane). On the other hand, the right column shows a transition from the in-plane emission at mid-rapidity at 40 AMeV (the ellipse elongated in the direction defined by the reaction plane in the projection perpendicular to the beam axis), to out-of-plane emission at 150 AMeV (the ellipse perpendicular to the reaction pane).

Performing the Fourier analysis of the azimuthal distributions with respect to the reaction plane, one can get more quantitative information about the above observations.

5 SIDEWARD FLOW

Directed flow can be conveniently characterized in terms of rapidity, and possibly transverse momentum, dependent Fourier coefficients (see e.g. [9] or [10] and refs. therein) extracted from the azimuthal distributions of the reaction products, measured with respect to the reconstructed reaction plane: $\frac{dN}{d\phi} \propto 1 + 2\mathrm{v}_1\cos(\phi) + 2\mathrm{v}_2\cos(2\phi)$. In this representation the first two Fourier coefficients, v_1 and v_2, characterize the sideward and elliptic flow, respectively.

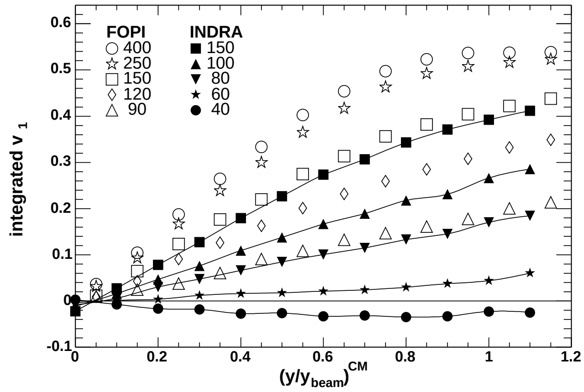

Figure 4: v_1 for Z=2 particles integrated over p_T as a function of scaled rapidity. The open and filled symbols represent the FOPI and the INDRA data, respectively. The numbers in the legend indicate the beam energies per nucleon, in MeV.

Fig. 4 presents the rapidity dependence of the parameter v_1 for Z=2 particles extracted from the INDRA data (filled symbols), for an impact parameter range of about 3–4.5 fm, superposed on the corresponding distributions measured by the FOPI collaboration [11] (open symbols) for 2–5.3 fm impact parameter range. Both data sets represent here the values uncorrected for the reaction plane dispersion.

As can be seen both measurements fit together. This can be verified especially by looking at the data for 150 AMeV incident energy (squares) which has been measured in both experiments. In the case of the INDRA data, the reaction plane has been reconstructed using the flow-vector method [12], excluding the particle of interest ("1 plane per particle") and correcting for the momentum conservation effects [13].

An intriguing feature of sideward flow that can be observed in Fig. 4 is its negative value at 40 AMeV. A similar observation has been reported in [8] for the "1 plane per particle" method, and given possible physical and (or) method related origins. In the present case, the negative flow value is most likely due the method of reaction plane reconstruction and reflects the fact that close to the balance energy, E_{bal}, where the sideward flow is very weak, the imperfect isolation of the correlations due to momentum conservation may lead to enhanced anti-correlation resulting in a flip of the orientation of the reaction plane. Thus, extraction of sideward flow in the vicinity of E_{bal} needs a special care, and possibly new methods of subtracting the non-flow correlations, such as e.g. the one suggested in [10] for high energy collisions.

In particular, one should be careful when applying the “1 plane per particle” method of reaction plane reconstruction, in order to extract E_{bal} by extrapolating to 0 the flow values measured exclusively above or below E_{bal}. Such an extrapolation would most likely yield the “0-crossing” energy rather than the energy corresponding to the actual minimum of flow. This minimum can in principle be negative, as shown in [8] for lighter systems. Thus, in order to extract unambiguously E_{bal} one needs the values of flow measured both, below and above its minimum.

6 ELLIPTIC FLOW

Fig. 5 shows a compilation of 3 data sets measured by the Plastic Ball [7] (crosses), FOPI [14] (circles) and INDRA (stars), representing the excitation function of the elliptic flow at mid-rapidity for Z≤2 particles, in the rotated reference frame and for mid-central collisions (4–6 fm for FOPI and about 4.5–6.5 fm in the case of INDRA). All the presented data points represent values uncorrected for the reaction plane dispersion. The INDRA data has been analyzed in this case in the same way as the Plastic Ball data by using the kinetic flow tensor method and excluding the particle of interest from the reaction plane reconstruction. The impact parameter has been estimated, as in the case of Fig. 4, using the $E^{\perp}_{12}$ global observable.

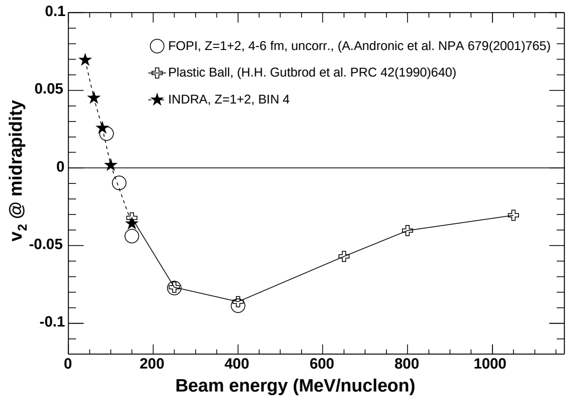

Figure 5: v_2 measured at mid-rapidity for Z≤2 particles in the rotated reference frame. The crosses, circles and stars represent the Plastic Ball, the FOPI and the INDRA data, respectively.

As one can see, all 3 data sets constitute a coherent systematics of v_2. Moreover, the INDRA data confirms the FOPI value of the transition energy to be around 100 AMeV for Z≤2 and mid-central Au+Au collisions, and as a result, these experiments set a reliable constraint for transport models which aim at fixing the basic parameters of nuclear interactions from flow observables.

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