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Abstract

A simple characterization of triple differential cross sections is needed for a systematic study of the nuclear matter collective flow in relativistic nucleus-nucleus collisions. Our analysis is based upon a fitting procedure, so that the triple differential distributions need not be measured in the whole momentum space. If the detector acceptance eliminates most spectator particles or if it is artificially restricted for doing so, this method leads to a flow characterization of the participant nuclear matter. The center-of-mass triple-differential momentum distributions are fitted to a simple analytical shape, namely an anisotropic Gaussian distribution. The adjusted parameters (flow angle and aspect ratios) are corrected for uncertainty in the event-by-event determination of the reaction plane azimuth (finite-number effects). Results are presented for neon-nucleus and argon-nucleus collisions at incident energy between 400 and 800 MeV per nucleon. Flow is already significant for light systems, and depends clearly upon the impact parameter.

Triple differential cross sections of proton-like particles (free protons as well as protons bound in light nuclei) have been measured for Ne-nucleus and Ar-nucleus collisions between 400 and 800 MeV per nucleon. These measurements were performed with the DIOGENE electronic 4 -detector [1] installed at the Saturne synchrotron in Saclay. They are restricted to the acceptance of the DIOGENE pictorial drift chamber [2], i.e. $20° < \theta < 132°$ in polar angle and kinetic energy larger than ~ 40 MeV. Collisions are sorted according to the multiplicity M of light charged particles, which is transformed [2] into a reduced impact parameter $\tilde{b} = b/(R_1 + R_2)$ where R_1 and R_2 are the projectile and target radii ($R = r_0 A^{1/3}$, $r_0 = 1.12$ fm). The transverse momentum analysis by Danielewicz and Odyniec [3] has been slightly adapted [2], because we are also dealing with asymmetric systems for which the center of mass of the participant system is not known a priori for each collision. After the event-by-event determination of the azimuth of the reaction plane, we obtain for each particle the two components of its transverse momentum $\vec{p}_\perp$, $p_{x'}$ in the estimated reaction plane and $p_{y'}$ out of the estimated reaction plane. Due to inaccuracies in the reconstruction of the reaction plane, these components are different from the components in and out of the true reaction plane. All the results about the measured triple differential distributions have to be corrected for the fluctuations $\Delta\phi$ of the azimuth of the estimated reaction plane around the azimuth of the true one. Such corrections can only be applied on average. They are based on estimates of the average values of $\cos\Delta\phi$ and of $\cos^2\Delta\phi$, made with the assumption that all correlations originate from the existence of the reaction plane. The average value of $\cos\Delta\phi$ is estimated according to reference [3]. In order to analyse not only the first but also the second moments of the distributions, we need an estimate of $\langle\cos^2\Delta\phi\rangle$. This is done along the lines of reference [4], using three-body correlations. Since the measured multiplicities are not very high (limited down to 6, and 40 at most), the corrections for finite number effects are rather important. Typically $\langle\cos\Delta\phi\rangle$ = 0.4-0.5 with a relative uncertainty smaller than 3 % and $\langle\cos^2\Delta\phi\rangle$ = 0.55-0.65 with a relative uncertainty between 5 and 15%.

In order to characterize rather completely, and independently of the detector cuts, the three-dimensional behaviour of the nuclear collective flow, we apply the following method to our results. The basic idea consists in fitting the $(p_z/m, p_{x'}/m)$ and $(p_z/m, p_{y'}/m)$ two-dimensional cross sections with two-dimensional Gaussian distributions [5]. The cross sections are evaluated in the center-of-mass reference frame for each multiplicity cut, p_z is the longitudinal momentum in this frame, and m is the proton mass. With this procedure there is not a complete use of the three-dimensional information. However, a three-dimensional Gaussian emission pattern, symmetric with respect to the reaction plane, would provide a simple summary of the complete information, and it reduces to two-dimensional Gaussian distributions for the in-plane and out-of-plane cross sections. The raw two-dimensional cross sections are strongly affected by the detector cuts at small values of $|p_{x'}|$ or $|p_{y'}|$ because, at any given value of p_z, the acceptance criterion corresponds to a minimum value of the transverse momentum, and not to a minimum value of either $|p_{x'}|$ or $|p_{y'}|$. If we apply the acceptance criterion to $|p_{x'}|$ for the in-plane cross section and to $|p_{y'}|$ for the out-of-plane cross section, we indeed lose some information, at small values of $|p_{x'}|$ or $|p_{y'}|$. However, the remaining information is completely free of any bias from the detector acceptance. The fitting procedure is thus performed on the $(p_z/m, p_{x'}/m)$ and $(p_z/m, p_{y'}/m)$ cross sections after the clean cut is applied to $|p_{x'}|$ and $|p_{y'}|$, respectively. These clean cross sections only span a limited region of phase space. However, in this limited region, at high enough transverse momentum, there should not be any contribution from the spectators of the collisions. This is an advantage when we are mostly interested in the emission pattern of the participants.

The parameters extracted from this analysis are one angle θ and two standard deviations τ_3 and τ_1 $(\tau_3 > \tau_1)$ for the in-plane cross sections, one angle θ' and two standard deviations τ_2 and τ for the out-of-plane cross sections. Since the in-plane and out-of-plane cross sections are not independent, but result from the integration of the same three-dimensional cross sections over $p_{y'}$ and $p_{x'}$ respectively, the parameters obtained from the two fits are related as follows :

$$\tau^2 = \tau_3^2 \cos^2\theta + \tau_1^2 \sin^2\theta$$

$$\theta' = 0° \ (\text{if } \tau_2 < \tau) \quad \text{or} \quad 90° \ (\text{if } \tau_2 > \tau)$$

This relation is well verified. The remaining parameters of the fit are one angle θ and three variances τ_3^2, τ_1^2 and τ_2^2, which can also be interpreted as the parameters of a three-dimensional Gaussian distribution, closely related to the flow angle and the eigenvalues obtained from a sphericity analysis. All these parameters are finally corrected for finite number effects, using the estimates of <cosΔφ> and <cos²Δφ>, and transformed into the true flow angle θ_F and the true variances σ^2_3, σ^2_1 and σ^2_2. Fitting not only the in-plane but also the out-of-plane cross sections, and taking into account the finite number effects, represent a net progress compared to our first attempt in the same direction of analysis [5]. With a χ^2 per degree of freedom varying between 1.5 and 3, the quality of the fits is not so bad, especially if we realize that the Gaussian distribution is a very simple one. Our cross sections are not corrected for distortions due to the resolution on the momentum measurements. This could explain why the fitted source velocity, for symmetric systems, is a little smaller than the center-of-mass velocity.

Typical results for the in-plane collective flow parameters, θ_F, σ_3 and σ_1, are illustrated with ellipses in Fig. 1 for asymmetric systems and several values of the impact parameter. The semi-axes of these ellipses are equal to $\sqrt{2}$ times the standard deviations σ_3 and σ_1. The flow angle θ_F increases when the impact parameter decreases, up to values as large as about 60°. The size of the ellipses, which reflects roughly the energy available per participant nucleon in the participant center-of-mass, decreases when the impact parameter decreases, in qualitative agreement with the simple picture that the projectile nucleons encounter more and more nucleons from the heavy target when the impact parameter decreases.

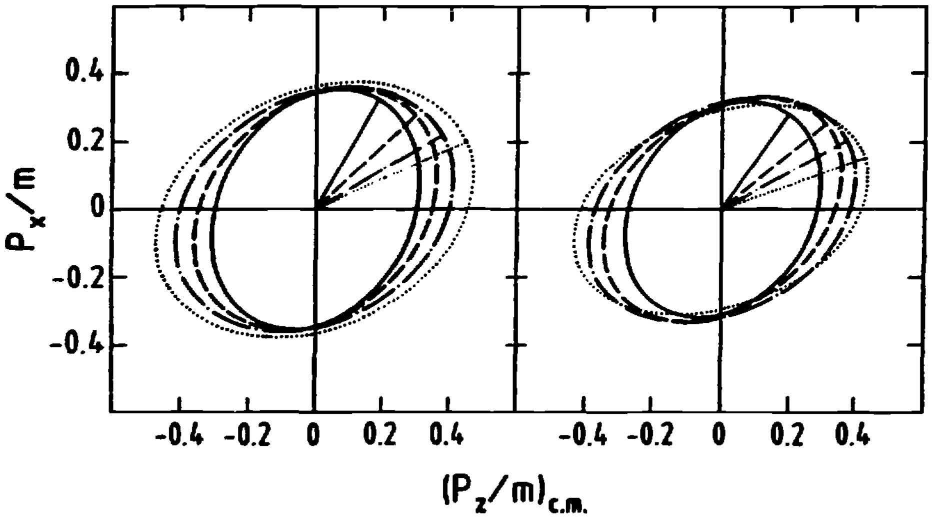

Fig. 1. Ellipses representing the two-dimensional Gaussian fits to the in-plane cross sections, for Ne + Pb collisions at 800 MeV per nucleon (left) at $\tilde{b}^2$=.05, .17, .30, .42 and for Ar + Pb collisions at 400 MeV per nucleon (right) at $\tilde{b}^2$ = .06, .20, .33, .46. Increasing $\tilde{b}^2$ values correspond successively to full, dashed, dot-dashed and dotted lines.

The shape of the emission pattern can be summarized with three quantities : the flow angle θ_F and two aspect ratios λ^2_{31} and λ^2_{31}, respectively equal to σ^2_3/σ^2_1 and σ^2_3/σ^2_2. Systematic results the flow angle θ_F are shown in Fig. 2 as a function of $\tilde{b}^2$. Except for the lightest system Ne + NaF, the flow angle θ_F is anticorrelated to $\tilde{b}^2$. For any given values of the projectile mass, incident energy and $\tilde{b}^2$, the flow angle is larger for heavier targets. At any value of $\tilde{b}^2$, for all projectile-target-energy combinations, the out-of-plane aspect ratio is smaller than the in-plane aspect ratio. This is in qualitative agreement with the observation that the mid-rapidity azimuthal distributions are peaked at 90° with respect to the reaction plane [6,7].

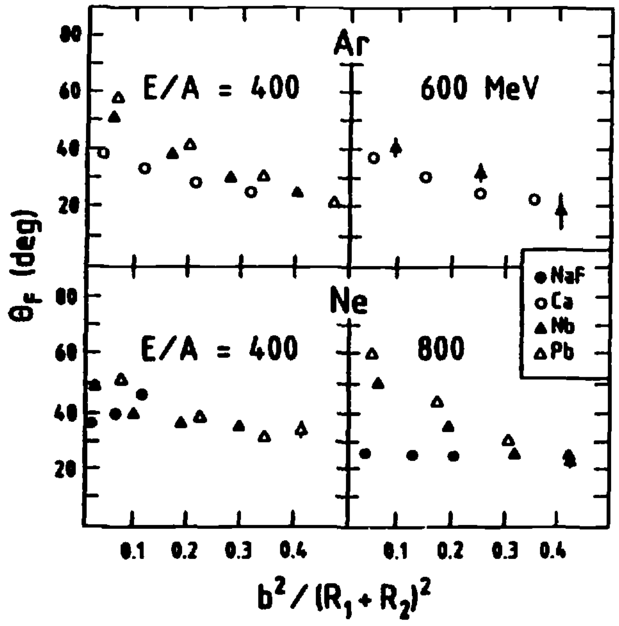

Fig. 2. Impact parameter dependence of the flow angle.

A comparison with predictions from intranuclear cascade calculations [8] is shown in Fig. 3 for the flow angle θ_F in argon-nucleus collisions. A simple filter is applied to the cascade outputs, including only the polar angle window and the kinetic energy threshold, but not including the full simulation of the DIOGENE biases, due to finite resolution of momentum measurements and inefficiencies of the track reconstruction. There is a huge difference between the experimental results and the cascade prediction, more important for more central collisions. It remains to be seen whether our results can be reproduced by more sophisticated models including the effects of the in-medium propagation of particles and the nuclear matter equation of state.

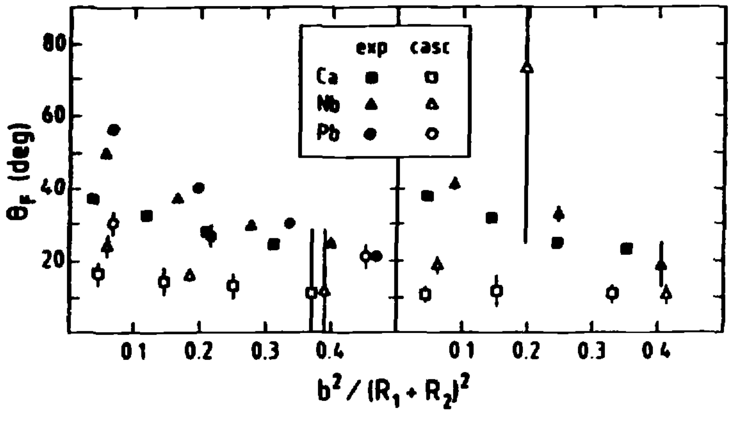

Fig. 3. Comparison between experimental results (filled symbols) and predictions of intranuclear cascade calculations (open symbols), concerning the impact parameter dependence of the flow angle, in argon-nucleus collisions at 400 (left) and 600 (right) MeV per nucleon.

When plotted in the plane $(\theta_F,\ r = 2\,\sigma_3^2/(\sigma_1^2 + \sigma_2^2))$, our data show a trend very similar to the results obtained by the streamer chamber collaboration [4] with a different method. Only the trends can be compared because the available data correspond to different energies. Flow angles were also reported by the Plastic Ball collaboration [9] after an event-by-event sphericity analysis. For the rather light system Ar + Ca they did not observe any peak at finite angle in the $dN/d(\cos\theta_F)$ distributions. This could appear as a contradiction with the rather large values (20-40°) that we measured (Fig. 2). However, it should be noted that the sphericity analysis is performed on all particles detected by the Plastic Ball, thus mixing the spectators and the participants. Moreover, the results of the event-by-event sphericity analysis are more strongly influenced by finite number effects than the event-by-event transverse momentum analysis for finding the reaction plane, followed by a sphericity analysis performed on the sum of the rotated events.

As a conclusion, two-dimensional Gaussian fits, performed on both in-plane and out-of-plane cross sections in order to summarize the participant emission pattern, give results (the flow angle and two aspect ratios) that should not be influenced by the detector biases. It has indeed been checked that, when applying more severe cuts to the momentum distributions, the fitted values of the three parameters stay almost compatible within uncertainties, even when the cut is so severe that 2/3 of the particles are lost. However other possible effects of the DIOGENE biases (momentum and double-track resolutions) remain to be evaluated. For argon-nucleus collisions, intranuclear cascade calculations predict too small flow angles. There is now an urgent need for a careful and systematic comparison between all our results and the predictions of more sophisticated models that incorporate explicitly the properties, or equation of state, of dense and hot nuclear matter, together with the propagation of particles inside this dense medium. For such a comparison, especially in order to ascertain the differences due to the variation of the stiffness of the equation of state, theoretical simulations with large enough statistics are needed, which requires a large amount of computer time.

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