Collective Flow Observed in Relativistic Nuclear Collisions

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The reactions Ca + Ca and Nb + Nb at 400 MeV/nucleon have been studied at the Bevalac using the "Plastic Ball" spectrometer. A global analysis of the events shows two nontrivial collective flow effects: the bounceoff of the projectile fragments, and the side-splash of the intermediate-rapidity fragments for the higher-multiplicity Nb + Nb events. Neither effect is seen in a knockon cascade calculation. A simulation with an event-generating statistical model has been done in order to extract the magnitudes of the effects.

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The study of the equation of state of nuclear matter is one of the main objectives of relativistic heavy-ion physics. A signature of the compression effects predicted by an equation of state would be collective flow of the nuclear matter upon reexpansion. Data from 4π detectors like the "Plastic Ball" are ideally suited to studying the emission patterns and event shapes which might be able to reveal this effect and distinguish between predictions of cascade and hydrodynamical models.

Thrust[1-3] and sphericity[3,4] analyses have been used in high-energy physics.[5] Because the thrust vector cannot be calculated analytically, the sphericity method generally has been used.[6] The sphericity tensor

$$F_{ij} = \sum_{\nu} p_i(\nu) p_j(\nu) w(\nu)$$

is calculated from the momenta of all measured particles for each event. It is appropriate to chose the weight factor $w(\nu)$ in such a way that composite particles have the same weight per nucleon as the individual nucleons of the composite particle at the same velocity. In this paper the weight $w(\nu) = 1/2m(\nu)$ as proposed in Ref. 4 (kinetic energy flow) is used. Other coalescense-invariant weights such as $1/p(\nu)$ have been proposed[3] and have been used in our analysis with similar results. The sphericity tensor approximates the event shape by an ellipsoid whose orientation in space and whose aspect ratios can be calculated by diagonalization.

The shapes predicted by hydrodynamical and intranuclear cascade calculations are quite different. The hydrodynamical model predicts prolate shapes along the beam axis for only grazing collisions. With decreasing impact parameter the flow angle increases, and reaches 90 deg (with oblate shapes) for zero-impact-parameter events.[1,2,4] This behavior is independent of projectile and target mass. Cascade calculations on the other hand predict zero flow angles at all impact parameters.[4]

Fluctuations due to finite particle effects are a big obstacle in extracting information from a flow analysis. Recently, Danielewicz and Gyulassy[7] have shown that those distortions strongly depend on multiplicity and that the flow angle θ, if properly weighted by the Jacobian ($\sin\theta$), is much less severely shifted towards higher values than the aspect ratios. A rigorous comparison of experimental data with predictions is only possible if the theory calculates all observed quantities by generating a large random sample of complete events. Those events have to be filtered individually with the known experimental acceptance and efficiency of the detector.[8] Most models, however, have not yet reached sufficient sophistication: Cascade models do not include composite particles and hydrodynamical codes do not yet produce complete events with fluctuations. We use a statistical model to simulate the data by fitting a small number of parameters which describe the main features.

At the Bevalac, collisions of Ca + Ca and Nb + Nb at 400 MeV/nucleon have been studied with the Plastic Ball/Plastic Wall detector.[9] The Plastic Ball covers the angular region between 10 and 160 deg. It consists of 815 detectors where each module is a ΔE-E telescope capable of identifying the hydrogen and helium isotopes and positive pions. The ΔE measurement is performed with a 4-mm-thick CaF_2 crystal and the E counter is a 36-cm-long plastic scintillator. Both signals are read out by a single photomultiplier tube. Because of the different decay times of the two scintillators, ΔE and E information can be separated by gating two different analog-to-digital converters at different times. The positive pions are additionally identified by measuring the delayed decay. The Plastic Wall, placed 6 m downstream from the target, covers the angular range from 0 to 10 deg and measures time of flight, energy loss, and position of the reaction products. In addition, the information from the inner counters (0 to 2 deg) is used to produce a trigger signal.[10] Thin metal targets of 50 to 200 mg/cm^2 have been used in the experiments.

Approximately 50 000 events accumulated with a minimum-bias trigger have been analyzed for each case. The events have been classified according to charged-particle multiplicity. The energy flow tensor[4] in the center-of-mass system has been determined and diagonalized for each individual event. The distribution of the flow angle θ (angle between the major axis of the flow ellipsoid and the beam axis) is shown in Fig. 1 for different multiplicity selections. A striking difference between the Ca and Nb data can be observed. For all but the highest multiplicity bins the distribution of the flow angles for the Ca data is peaked at 0 deg. For Nb, however, there is a finite deflection angle increasing with increasing multiplicity. The same analysis has been performed with filtered events from a cascade code calculation[11] (Fig. 1). For both systems studied the distributions are always peaked at 0 deg. It is not so evident that the Ca + Ca collision differs from its simulation with the cascade model, whereas a new collective phenomenon definitely appears in the larger-mass system which is not accounted for by the present cascade models.

In this analysis each event was parametrized by an ellipsoid, but it is of interest to study the shapes in more detail. The fact that finite flow angles are seen in the data indicates that in those events a reaction plane exists that is defined by the flow axis and the beam axis. All events can be rotated by the azimuthal angle ϕ determined by the flow analysis so that their individual reaction planes all fall into the x-z plane, with the z axis being the beam axis. For those rotated events the invariant cross section in the reaction plane $[d^2\sigma/dy\, d(p_x/m)]$[1,12] can be plotted, where p_x is the projection of the perpendicular momentum into the reaction plane and y is the center-of-mass rapidity. Figure 2 shows this plot for a selected multiplicity bin for 400-MeV/nucleon Ca + Ca and Nb + Nb data, together with cascade calculations. The depletion near target rapidities ($y \simeq -0.45, p_x \simeq 0$) is due to limited experimental acceptance for low-energy particles in the laboratory system. This depletion enhances the flow angles artificially but does not change the reaction plane. The cascade plot is symetric around the beam axis, whereas the Ca and Nb in-plane data plots are clearly asymmetric. The highest level contour, near projectile rapidity and just above the horizontal axis, results largely from the projectile remnants and in-

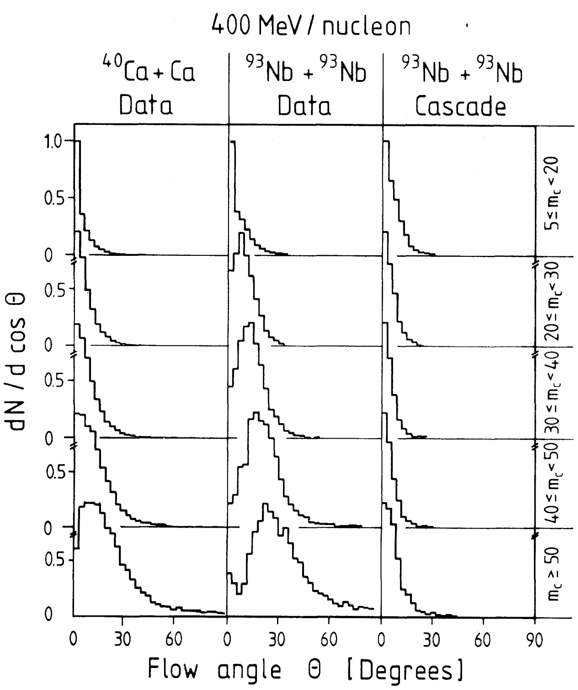

FIG. 1. Frequency distributions of the flow angle θ for two sets of data and a cascade calculation for different multiplicity bins. For the case of Ca the multiplicities are half the indicated values.

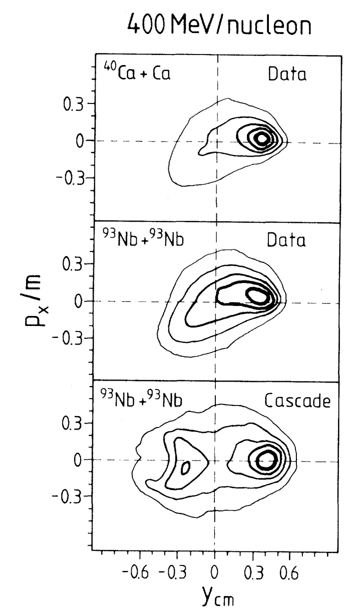

FIG. 2. Contour plots (equally-spaced linear contours without offset) of p_x/m as a function of c.m. rapidity for multiplicities selected between 40 and 49 charged particles for Nb and 20 and 24 for Ca.

dicates a definite bounceoff effect. The data show that the multiplicity dependence of the orientation of the outer contour lines from the lower left to the upper right follows the trend indicated by the flow-angle distributions (Fig. 1). However, the position of the bounceoff peak from the projectile remnants changes only slightly with multiplicity. Thus one can conclude that the strong sideward peaking seen in Fig. 1, which we will call side splash, is mainly due to the midrapidity particles. It should be noted that the bounceoff and side-splash effects appear to be in the same plane. There is also the possibility that the increased prominence of projectile fragments at low multiplicity could contribute to the decreasing splash angle.

The bounceoff in the projectile rapidity region has been further analyzed by looking at the peak in its p_x and its y distribution as a function of charged particle multiplicity. The parallel component is peaked below the beam rapidity whereas the p_x distribution indicates a perpendicular momentum component of about 50 MeV/c per nucleon. The bounceoff process is therefore a slowing down of the projectile fragments and a sidewards deflection in the reaction plane.

The comparison of the experiment with hydrodynamical calculations[1] is not straightforward as the impact parameter can be related to multiplicity only via event-generating models. The hydrodynamical prediction of the flow angle seems to be qualitatively in agreement with the measurement, but the present models do not predict two separate effects as seen in the data.

In order to extract the magnitude of these collective effects, the data have been fitted with the statistical event simulation code of Fai and Randrup,[13] suitably modified to include the two collective effects seen. The bounceoff is simulated by adding a perpendicular and a parallel momentum transfer to the spectators with an impact-parameter dependence which peaks at intermediate impact parameters. This effect alone fits the bounceoff but does not suffice to describe the distribution of flow angles and the shape of the midrapidity contours. The midrapidity region has therefore been parametrized with two fireballs moving away from each other. The direction is such that for peripheral collisions the collective motion is along the beam axis and for zero impact parameter it is perpendicular to the beam axis. To be exact, the tangent of the angle of the collective motion was taken as $[(1-v)/v]^{1/2}$ where v is the fraction of the maximum impact parameter. The collective momentum per nucleon fitted is of the order of 120 MeV/c. With these parameters the distribution of the flow angles can be fairly well reproduced, but the ratio between the number of participants and spectators in the contour plots is not yet well described. It can be further estimated that roughly 10% of the total kinetic energy available in the center-of-mass system is contained in collective motion. This modest amount of collective motion explains why it is extremely difficult to observe the effect in inclusive data. This value is not in contradiction with the larger amount of compressional energy deduced from pion multiplicity measurements[14] as our method is not capable of detecting isotropic flow[15] and also during the expansion phase some collective energy may be transformed into thermal energy.

The Plastic Ball data show for the first time two different collective effects: the bounceoff in the fragmentation region and the side-splash of the participants. It is now a challenge to models that include collective phenomena, like the hydrodynamical model, to explain those effects and to relate them to compression and density,[16] and thus to the equation of state of nuclear matter.

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