Kinetic Energy Flow in Nb(400A MeV) + Nb: Evidence for Hydrodynamic Compression of Nuclear Matter

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A kinetic-energy–flow analysis of multiplicity-selected collisions of ^{93}Nb($E_{\rm lab}=400A$ MeV) + ^{93}Nb is performed on the basis of the nuclear fluid dynamical model. The effects of finite particle numbers on the flow tensor are explicitly taken into account. Strong sidewards peaks are predicted in $dN/d\cos\theta_F$, the distribution of event by event flow angles. This is in qualitative agreement with recent data from the "Plastic Ball" electronic detection system. Cascade simulations fail to reproduce the data.

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Little is known to date about the properties of nuclear matter at finite temperatures and densities other than the ground-state density, $n_0=0.15$ fm^{-3}. Experimental information on the unexplored domain is being sought by analysis of high-energy collisions of heavy nuclei. One of the first predicted signatures for hydrodynamic compression is the sidewards splash of nuclear matter in head-on collisions of massive equal nuclei[1]: As a result of the pressure buildup, the highly excited nuclear matter expands into the vacuum perpendicular to the beam axis, i.e., to 90° in the center-of-momentum system. Collisions of massive equal nuclei, however, could not be studied experimentally in the past. Only recently have ions with mass $A>40$ been accelerated at the BEVALAC to bombarding energies of several hundred megaelectronvolts per nucleon.

In this Letter we report a detailed analysis of the reaction ^{93}Nb($E_{\rm lab}=400A$ MeV) + ^{93}Nb based on nuclear fluid dynamics and intranuclear cascade simulations. The theory is compared to the recent experimental data of Ritter *et al.*,[2] who studied this system with the "Plastic Ball" 4π electronic detector system.

Preferential sidewards emission of fragments from central collisions of high-energy nuclei had been reported previously for very asymmetric reactions, e.g., C+Ag and Ne+U: Early particle track detector experiments[3] yielded peaks in the angular distribution of alpha particles emitted from central C+Ag reactions, and the double differential cross sections of light fragments (p, d, t) emitted from high-multiplicity selected collisions of Ne(393A MeV)+U exhibit sidewards maxima,[4] in accord with predictions of the fluid dynamical model.[5] Other theories, such as the intranuclear cascade and the thermal model, yield forward-peaked angular distributions,[6] in contrast to those data.

Recently it has been proposed to observe the collective flow directly via a kinetic-energy–flow analysis[7,8] on an event-by-event basis. The sensitivity[8] of the flow analysis for very heavy systems to the properties of nuclear matter at high densities and excitation energies is particularly fascinating. The basic idea of the flow analysis is to measure event by event the momenta of all (charged) particles. Such an analysis can be done experimentally only with 4π detector systems such as emulsion, streamer chamber, or the plastic ball. Once this information is available, the momenta are transformed into the center-of-momentum frame and the direction of the maximum kinetic energy flow is determined by performing a principal-axis transformation.

The kinetic-energy–flow tensor F_{ij},

$$F_{ij}=\sum_\nu p_i p_j/2m_\nu,$$

insures that composite fragments ν contribute to the matter flow tensor with the correct weight relative to nucleons.[9]

In the hydrodynamic calculations,[8] the reaction volume is divided into cells characterized by a mean flow velocity, $v(r)$, a local temperature $T(r)$, and a local baryon number $n(r)$. When the baryon density in a cell falls below a freezeout value during the expansion it contributes an amount $\frac{1}{2}(\bar{p}_i\bar{p}_j/m + \delta_{ij}T)$ to the flow tensor. Thus, for hydrodynamics F_{ij} is the sum of a collective flow tensor $\bar{F}_{ij} = \bar{p}_i\bar{p}_j/2m$ and a stochastic part $\delta_{ij}E_T/3$. Note that the aspect ratio of the principal values of the flow tensor is brought closer to unity by thermal smearing, whereas the flow angle θ_F is not affected by temperature.

The general behavior of the flow pattern in the fluid dynamical model is as follows: The flow angle θ_F rises smoothly from 0° at large impact parameters to 90° at $b=0$. Since the contribution of zero impact parameters to the actual experiment is negligible, the theory has to sample over a range of finite impact parameters before it can be compared to the data.

The major cause of concern for a direct comparison of the data to the hydrodynamical predictions is, however, the finite multiplicity, $M < 50$, of emitted fragments: There are substantial finite-number distortions[10] to the kinetic-energy–flow analysis for multiplicities $M < 100$. Therefore, a direct comparison of the conventional "infinite–particle-number" hydrodynamics with the "raw" finite-multiplicity experimental data is inhibited. Only for very massive systems such as uranium on uranium could the finite–particle-number distortions be considered reasonably small. There are two ways out of this dilemma: The first is to correct for the finite-multiplicity distortions in the experimental data via an unfolding procedure, which extrapolates the data to the thermodynamic limit, i.e., towards infinite particle number. The second method, applied in this work, incorporates the finite-multiplicity effects via a Monte Carlo procedure into the theory. This is done by random sampling of a given fragment multiplicity from the momentum-space distribution of the flow tensor as obtained from the fluid dynamical calculation. This procedure has the distinct advantage that the detector efficiencies can be folded into the theoretical analysis, thus allowing for an unbiased, direct comparison of theory and data. In particular, the restriction to light fragments $Z \leq 2$, the low-energy cutoff ($E^{\rm cut}/A < 25$ MeV), and the backward-angle acceptance hole of the Plastic Ball ($\theta_{\rm lab}^{\rm cut} > 160°$) have been taken into account in the present analysis.

Figure 1 shows the distribution of flow angles, $dN/d\cos\theta_F$, thus obtained in comparison with the experimental data and the intranuclear cascade calculation.[2,11] The fragment yield calculation performed after the breakup of the fluid yields average multiplicities from $M=35$ at $b=6$ fm to $M=46$ at

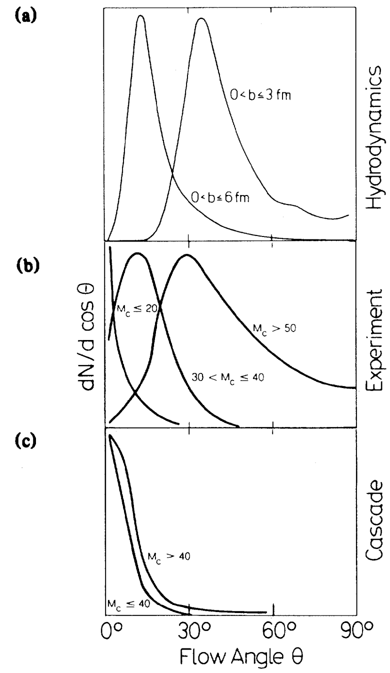

FIG. 1. Distributions of flow angles $dN/d\cos\theta_F$ for the reaction ^{93}Nb(400A MeV) + ^{93}Nb. (a) Result of the hydrodynamical calculation. The finite-multiplicity distortions are taken into account. The given impact-parameter ranges correspond to the multiplicity cuts indicated at the experimental curves below [(b)]. (b) Plastic Ball data (Ref. 2) for various multiplicity cuts at the curves. (c) Result of the cascade simulation (Refs. 2 and 11) after multiplicity selection.

$b=0$. The dispersion of multiplicities around these values has not been taken into account. The theoretically obtained high-multiplicity triggered events, corresponding to the small impact parameters ($b=0$ to 3 fm), compare favorably with the high-muliplicity selected experimental data. Both exhibit average sidewards flow angles of $\theta_F = 30°$, whereas the high-multiplicity selected events of the cascade calculation[2,11] exhibit strongly forward-peaked distributions. It is surprising that the predicted 90° flow[1,8] can be observed neither in the data nor in the fluid calculation. This is due to the rapid falloff of θ_F for $b > 0$: $dN/d\cos\theta$ is dominated by contributions from $b \approx 2$–3 fm. Only for much heavier systems, e.g., U+U, would this range of b values reveal flow angles $\theta_F \gtrsim 60°$. The intermediate multiplicities ($30 < M < 40$) correspond to larger impact parameters, $b < 6$ fm in the hydrodynamical plus statistical breakup calculation. The experimentally observed decrease of the average flow angle ($\theta_F = 15°$) is well reproduced by the fluid dynamical calculation. The lowest interval of multiplicities, $M < 20$, corresponds to large impact parameters, where the projectile and target remnants cause the strong 0° peak in $dN/d\cos\theta_F$.

In summary, nuclear fluid dynamics predicts a peak in the angular distributions of the flow tensors for collisions of Nb on Nb, which shifts to larger angles with increasing multiplicity. The agreement with the new data is very encouraging for the ongoing program aimed at extracting high-density nuclear properties from nuclear collision data. In the future the study of the detailed dependence of atomic number on the *triple* differential cross section on beam energy and multiplicity will be essential for more quantitative conclusions.

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