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Jets of nuclear matter from high energy heavy ion collisions

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The fluid dynamical model is used to study the reactions ^{20}Ne$+^{238}$U and ^{40}Ar$+^{40}$Ca at $E_{\rm lab}=390$ MeV/nucleon. The calculated double differential cross sections $d^2\sigma/d\Omega\, dE$ exhibit sidewards maxima in agreement with recent experimental data. The azimuthal dependence of the *triple* differential distributions, to be obtained from an event-by-event analysis of 4π exclusive experiments, can yield deeper insight into the collision process: Jets of nuclear matter are predicted with a strongly impact-parameter-dependent thrust angle $\theta_{\rm jet}(b)$.

NUCLEAR REACTIONS Ar+Ca, Ne+U, $E_{\rm lab}=393$ MeV/nucleon, fluid dynamics with thermal breakup, double differential cross sections, azimuthal dependence of triple differential cross sections, event-by-event thrust analysis of 4π exclusive experiments.

Recent measurements of proton cross sections with high associated multiplicities[1] provide further evidence for predominant sidewards emission of fragments[2] from high-energy heavy ion collisions. This might indicate the presence of strong compression effects, which are predicted in the nuclear fluid dynamical (NFD) model.[2-6] Here we present the first quantitative comparison of an NFD calculation with the multiplicity triggered experimental data.[1] The NFD model[3] includes a realistic treatment of the nuclear binding[6] and the final thermal breakup.[7-9] Nuclear viscosity and thermal conductivity[8-11] have been neglected as in all previous three-dimensional calculations because of numerical expenditure; the thermal energy is produced by shock heating.[3-6] Azimuthally (ϕ) averaged double differential particle cross sections $d^2\sigma/d\Omega\, dE$ and ϕ-dependent *triple* differential distributions $d^3\sigma/d\cos\theta d\phi\, dE$ are calculated, boosting the internal (Maxwell Boltzmann) momentum distribution $f(k)=f(\rho,T)$ in each fluid element by the corresponding collective flow velocity into the laboratory.[8] The proton distributions are calculated by allowing only the emission of unbound particles with $\epsilon \geq m_p c^2$, $\epsilon(k)$ being the total energy per proton in the rest frame of each fluid element. The freezeout is done in a late stage in the reaction, so that the final distributions depend only negligibly on the exact value of the breakup density $\rho_{\rm BU}\sim 0.5\rho_0$.[7-9]

Figure 1(a) shows the measured angular distributions of protons emitted from high multiplicity selected (i.e., central) collisions of ^{20}Ne (393 MeV/nucleon)$+^{238}$U.[1] The data exhibit sidewards maxima; forward emission is strongly suppressed. The angular distributions of protons and summed charges as calculated in the present work are in agreement with the data [see Fig. 1(a)]. It is important to point out that the sidewards maxima are predicted to be even more pronounced for the summed charges than for protons. In fact, such a behavior has been found in experiments with α-particle detectors.[2] Also, the high multiplicity selected angular distributions of ^{2}H and ^{3}H (Ref. 15) show sharper sidewards peaking than the protons. On the other hand, cascade calculations, which treat reactions of heavy nuclei as a sequence of independent free nucleon-nucleon collisions,[3,12,13] predict, in general, strongly forward peaked proton distributions even when small impact parameters are selected,[3,12] in contrast to the data.[1,15] The qualitative disagreement of the data and the cascade calculations[3,12,13] points out that it is necessary to incorporate realistic many-body interactions[14] of nucleons in dense nuclear matter into a microscopic approach to high energy heavy ion collisions.

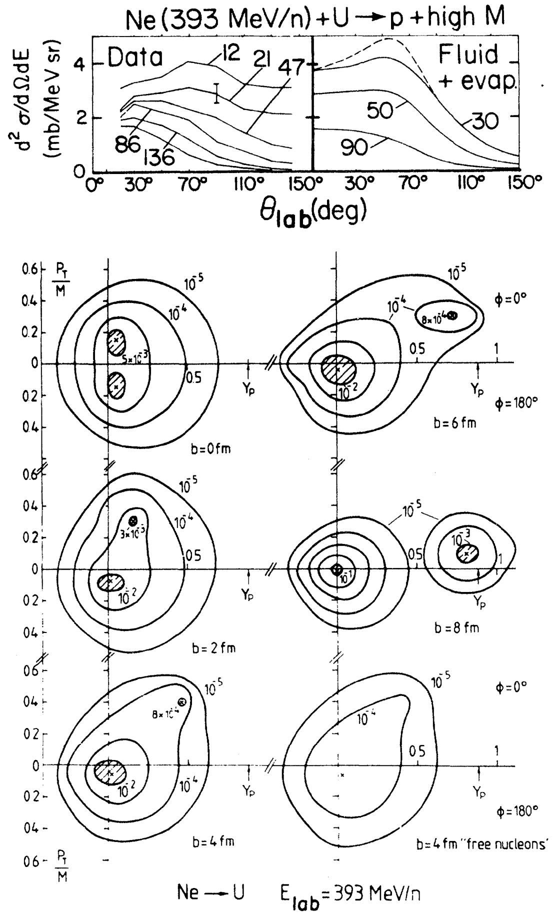

FIG. 1. (a) The angular distributions of protons emitted from central (high multiplicity selected) collisions of ^{20}Ne (393 MeV/nucleon)+^{238}U are shown. The experimental data (left) exhibit sidewards maxima and are in agreement with the results of the fluid dynamical calculation (right) with an impact parameter cut at $b_{\max}=1.5$ fm. The dashed line indicates the results for summed charges (multiplied by 0.2 to fit in the figure). The numbers indicate the kinetic energy (laboratory) of the emitted protons, respectively. (b) Azimuthally dependent *triple* differential invariant particle cross sections $1/p\, d^3\sigma/dE\, d\cos\theta d\phi$ (nMeV^{-2} sr$^{-1}c^{-1}$) in the scattering plane $\phi=0°/180°$ at various impact parameters. Shown are contour diagrams in the plane of transverse momentum p_T in units of $p_T/(m_N c)$ and rapidity $y_{\|}=\frac{1}{2}$ ln $[(E+p_{\|}1/P d)/(E-p_{\|})]$ for the reaction ^{20}Ne+^{238}U at $E_{\mathrm{lab}}=393$ MeV/nucleon. Shaded areas indicate flat local maxima. The lower right frame shows the proton distribution at $b=4$ fm to be compared with the distribution of all particles in the lower left frame.

The qualitative features of the ϕ-averaged distributions calculated in the present work, however, do not change dramatically with impact parameter, once violent collisions with $b \lesssim 4$ fm are selected. This means, unfortunately, that ϕ-averaged double differential cross sections are of limited value for obtaining information on details of the reaction dynamics and on the nuclear equation of state.[5,6] Therefore, we next consider whether the *azimuthal dependence* of the differential cross sections, to be obtained from 4π exclusive experiments with single event analysis,[15] can provide more specific dynamical information.

Figure 1(b) shows the *triple* differential cross sections $d^3\sigma/d\cos\theta d\phi\, dE$ in the scattering plane, i.e., the $y_{\|}/p_T$ plane at $\phi=0°/180°$, for the reaction ^{20}Ne (393 MeV/nucleon)+^{238}U at various impact parameters b. For head-on collisions, $b=0$ fm, the two maxima at $p_T/m \approx 0.1-0.2$ indicate the azimuthally symmetric large angle sidewards emission of cold ($T<10$ MeV) matter.[6] At intermediate impact parameters, a considerable azimuthal asymmetry appears. A strong maximum at small transverse and longitudinal velocities indicates the presence of a large chunk of cold, slowly moving matter, namely, the target residue at $\phi=180°$. A flat local maximum in the projectile hemisphere ($\phi=0°$) at larger p_T and $y_{\|}$ reflects some sidewards deflected fragments of the beam particles. The spread of the maxima in ϕ depends strongly on b; for intermediate b it is on the order of $\Delta\phi \sim 40°$. The apparent large collective transverse and longitudinal momentum transfer (the bounce off process[6,15]) results from the high pressure in the "participant" head shock zone, pushing the nuclear residues apart to opposite directions ($\Delta\phi=180°$). This process is of great importance, as it intimately connects the momentum transfer to be observed in bounce off events with the quantity of central interest, namely, the nuclear equation of state $P(\rho,T)$.[16] At large impact parameters ($b>6$ fm) the invariant cross sections peak more closely to the initial projectile and target momenta. Maxima at *finite* p_T are found even in the azimuthally *averaged* particle cross sections.

The symmetric system ^{40}Ar (388 MeV/nucleon)+^{40}Ca shows a similarly forward-backward peaked distribution at large impact parameters. At smaller b, the ϕ-averaged double differential invariant proton cross sections exhibit a structureless "fireball" distribution, i.e., the contour lines in the $y_{\|}/p_T$ plane are circles centered around $y_{\mathrm{c.m.}}$. However, we observe in the *triple* differential cross sections again a symmetric two jet structure at finite p_T being superimposed on the broad thermal "fireball" background. The connection between the two jet maxima—the jet axis—immediately yields the direction of the main momentum flow relative to the beam axis. It thus defines the angle θ_{jet} in the c.m. frame at which the thrust

$$T=\max_{\vec{n}} \sum_i |\vec{p}_i \cdot \vec{n}| / \sum_i |\vec{p}_i| \qquad (1)$$

occurs, which has been introduced to analyze jetting phenomena in e^+-e^- collisions.[17] Here $\vec{p}_i$ is the momentum of each fragment and $\vec{n}$ is a unit vector pointing in any direction. The thrust angle, θ_{jet}, is strongly impact parameter dependent (see Table I): For both Ar+Ca and Ne+U it is 0° at large b and increases to 90° for central collisions.

The measurement of the *triple* differential cross section can yield, however, considerably *more* information about the collision dynamics than the thrust analysis alone: The distance between the jet maxima, i.e., the mean momentum along the jet axis, may serve as a measure of the transport properties of the matter: For example, a large viscosity slows down the collective fluid motion in the jet direction. There are many other features of the reaction dynamics which are only accessible by detailed inspection of the *triple* differential cross sections: For head-on collisions of equal nuclei, the compression in the shock zone is maximized, and most of the matter participates in the strong compression. The two-jet patterns give way to an azimuthally symmetric disk of nuclear matter, expanding towards 90° in the c.m. system.[18] It eventually results in doughnut-shaped (toroidal) triple differential cross sections symmetric around the beam axis. The strong collective transverse matter flow[18] with large mean velocity, $p_T/m \approx 0.4$ is caused by the high pressure in the shock region, in analogy to the intermediate impact parameters. Remnants from the squeezeout can still be seen at small, but finite impact parameters, $b \sim 2$ fm, thus giving rise to additional *out-of-plane* jet structures—*four-jet-events*—at $\theta_{\text{c.m.}}=90°$, $\phi=90°$, as the outflow of the compressed matter perpendicular to the scattering plane is not hindered by "spectator" matter. These predictions, however, do not take into account the limitations (e.g., considerable fluctuations) of Eulerian fluid dynamics when applied to light systems: microscopic calculations[12–14] for C+C and Ne+Ne indicate large nonequilibrium contributions. However, while the cascade calculations[12,13]—based on free n-n collisions—do not show a considerable transverse momentum transfer even for heavy nuclei, many body calculations with realistic n-n interactions[14] predict hydrodynamic features such as the 90° sideways peaking for systems with $A_T, A_P \gtrsim 40$. Unfortunately, the heaviest presently available projectiles have a mass $A_p \approx 40$. Heavier symmetric systems should be more suitable for a quantitative comparison to the present predictions.

TABLE I. The center-of-mass jet angle, θ_{jet}, relative to the beam axis as a function of impact parameter at $E_{\text{lab}}=390$ MeV/nucleon.

b (fm)	0	1	2	3	4	6	8
Ne+U	90°	82°	73°	60°	47°	24°	7°
Ar+Ca	90°	62°	42°	28°	19°	6°	0°

Beyond the jet analysis, the "chemical" composition[19] in various regions of phase space is another observable of great importance, which may yield information on the nuclear equation of state. Since the temperature in the shock zone is much higher than the temperatures in the projectile and target remnants, we predict the emission of predominantly unbound nucleons from the "fireball." Hence, the actual jet structure is much more pronounced for bound nuclei (e.g., α, ^{12}C). The reason for that is twofold: Clusters are heavier and thus have a smaller thermal velocity than nucleons at the same temperature, so that their distributions are not broadened as much by thermal effects. In addition, they are produced preferentially in the "cold" parts of the matter distribution, which for the bounce off is just the central part of the projectile and target residues. This is illustrated by comparing the distribution of all particles to the proton distribution in Fig. 1(b). The latter is less structured and resembles a large fraction of the thermal background in the particle distribution. One is thus led to the conclusion that the collective effects should be observable most clearly in, e.g., the α particle distributions.[2] Therefore, a detailed calculation of the cluster formation, e.g., in a chemical equilibrium model,[19] is required for a quantitative comparison with future 4π exclusive experiments.

In conclusion, we have shown that *triple* differential particle cross sections offer a unique tool for the investigation of the complicated reaction dynamics in high energy heavy ion collisions. The combination of the jet analysis with the composition analysis in 4π exclusive experiments, with special emphasis on production and correlations of the different nuclei emitted, can provide snapshots of bulk motion, mass, and temperature distributions, as well as energy and momentum flux in violent nuclear collisions.

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