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Jets of Nuclear Matter from High Energy Heavy Ion Collisions*

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Abstract: The nuclear fluid dynamical model with final thermal breakup is used to study the reactions $^{20}Ne + {}^{238}U$ and $^{40}Ar + {}^{40}Ca$ at $E_{LAB} = 390$ MeV/n. The calculated double differential cross sections $d^2\sigma/d\Omega dE$ are in agreement with recent experimental data. However, it is shown that the azimuthal dependence of the triple differential distributions $d^3\sigma/dEd\cos\theta d\phi$, to be obtained from 4π exclusive experiments with single event analysis, can yield considerably deeper insight into the collision process and allow for snapshots of the reactions. Strongly correlated jets of nuclear matter are predicted.

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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. Several features of the data [1] are in qualitative agreement with three-dimensional (3D) nuclear fluid dynamical (NFD) calculations [3]. This is of great importance as it might indicate the presence of strong compression effects in nuclear collisions inherent in the NFD model [2-6].

Here we analyze the reactions $^{20}Ne + ^{238}U$ and $^{40}Ar + ^{40}Ca$ at E_{LAB} = 390 MeV/n [1]. We emphasize the great importance of 4π exclusive measurements for the understanding of the basic reaction mechanisms. Jets of nuclear matter are predicted. The NFD model we use includes [6] compressibility, an effective density dependent n-n interaction, Fermi pressure, internal excitations, a realistic treatment of the nuclear binding and surface properties, and the final thermal breakup [7-9]. Nuclear viscosity and thermal conductivity [8-11] have been neglected as in all previous 3D 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 Maxwell Boltzmann momentum distribution in each fluid element by the corresponding collective flow velocity into the laboratory [8-9]. This 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 $\rho_{BU} \sim 0.5\ \rho_0$ [7-9].

In order to estimate the differences between light and heavy fragment production, distributions for free nucleons (p,n) are also calculated [9]. This is done by shifting down the Fermi distributions of the nucleons in each fluid element according to the corresponding binding energy and evaporating the high momentum tails having internal energy $\varepsilon \geqslant mc^2$ only [9]. These prescriptions lead to reasonable agreement with calculations assuming chemical equilibrium to describe the breakup into various light nuclei [12].

Figure 1 shows contours of the calculated double differential invariant nucleon cross section in the rapidity-transverse momentum plane $y_{\|}/p_T$ together with the multiplicity selected observed proton inclusive cross sections [1] for the reaction ^{20}Ne (393 MeV/n) + ^{238}U. The theoretical results for b = 4 fm are consistent with the high multiplicity selected experimental data with an estimated mean $\bar{b} \approx 4$ fm [1]. In particular, the "emission pattern" [1], i.e., the positions of the maximum cross section at given p_T, and its shift with p_T agrees rather well (dashed lines). In agreement with the data [1], the calculated angular distributions of low energy particles ($E_{Kin} \sim 10$ MeV) show a broad maximum at large angles ($\theta_{LAB} \approx 75^o$), which shifts forward with increasing nucleon energy while the height decreases. A detailed quantitative comparison is presently inhibited, since the data result from a complicated folding of impact parameter dependent multiplicity distributions [1]. This can not easily be incorporated into the theoretical calculations, e.g., by simply assuming a sharp cut-off impact parameter $b = 4.5$ fm [5]. The qualitative features of the calculated ϕ averaged contour plots, however, do not change dramatically with impact parameter, once violent collisions with $b < 6$ fm are selected. The emission pattern shifts only towards slightly larger angles when b is decreased. This means, unfortunately, that ϕ averaged double differential cross sections are of limited value for obtaining information on 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 [13-16], can provide more specific dynamical information.

Figure 2 shows the triple differential cross sections $d^3\sigma/d\cos\theta d\phi dE$ in the scattering plane, i.e., the $y_{\parallel}/p_T$ plane at $\phi = 0^o/180^o$, for the reaction ^{20}Ne(393 MeV/n) + ^{238}U at various impact parameters b. For head-on collisions, $b = 0$ fm, the two maxima at $p_T/m \sim 0.1-0.2$ indicate the azimuthally symmetric large angle sidewards emission of matter with temperatures $T < 10$ MeV, caused by the strong shockwave [2,3]. At intermediate impact parameters, a considerable azimuthal asymmetry appears. A strong maximum at smaller transverse and longitudinal velocities indicates the presence of a large chunk of cold, slowly moving matter, namely the target residue at $\phi = 180^o$. A flat local maximum in the projectile hemisphere ($\phi = 0^o$) at larger p_T and $y_{\parallel}$ 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 $\Delta\phi \sim 40^o$. The apparent large collective transverse and longitudinal momentum transfer (the bounce off process [3,6,13,15]) results from the high pressure in the "participant" head shock zone, pushing the nuclear residues apart to opposite directions ($\Delta\phi \sim 180^{o}$). 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 $P(\rho,T)$ [17]. 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/n) + ^{40}Ca shows a similarly strong forward-backward peaked distribution at large b. The ϕ-averaged double differential invariant nucleon cross sections exhibit a structureless "fireball" distribution at smaller impact parameters ($b \sim 2$ fm), i.e. the contour lines in the $y_{\parallel}/p_T$ plane are circles centered around y_{cm}. 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 in the scattering plane defines the jet axis, which rotates around y_{cm} as a function of impact parameter b. The angle, $\theta_{jet}(b)$, of the jet axis with respect to the beam direction is given in Table 1. It is directly connected to the "emission pattern" [1] in the cm frame, thus giving the direction of the main fluid flow.

The mean momentum perpendicular to the jet axis may serve as a measure for the temperature in the system. The distance between the maxima, i.e. the mean momentum along the jet axis, will be influenced by the transport properties of the matter. For example, a large viscosity slows down the motion in the jet directon. Thus an event shape analysis [21] in terms of thrust and sphericity might be appropriate for 4π exclusive experiments.

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 jet patterns give way to an azimuthally symmetric disk of nuclear matter, expanding towards 90° in the cm system [18]. It eventually results in doughnut-shaped triple differential cross sections symmetric around the beam axis. The strong collective transverse matter flow [18] with large mean velocity $p_T/m \sim 0.4$ is caused by the high pressure in the shock region, in analogy to the intermediate impact parameters. Remnants from the squeeze-out can still be seen at small, but finite impact parameters, $b \lesssim 2$ fm, thus giving rise to additional out-of-plane jet structures at $\theta_{cm} \sim 90^{\circ}$, $\phi \sim 90^{\circ}$ (four jet events [19]).

The "chemical" composition in various regions of phase space is another observable of great importance, which may yield information on the nuclear equation of state [20]. Since the temperature in the shock zone is much higher than the temperatures in the projectile and target remnants, we expect the predominant emission of free nucleons from the "fireball". Hence, the 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 effect is seen in Fig. 2, b = 4 fm, comparing the distribution of all particles with the free nucleon distribution. The latter is less structured and resembles a large fraction of the thermal background in the particle distribution. The distribution of the bound nuclei may be roughly estimated by subtracting the free nucleon distribution from that of all particles. One is thus led to the conclusion that the collective effects should be observable most clearly in, e.g., the α particle distributions. It might be useful to note that first indications for predominant sidewards emission were observed using α-particle detection [2] and that recent data on deuteron and triton emission [15] show sharper sidewards maxima than the protons [1]. Therefore, a detailed calculation of the cluster formation, e.g. in a chemical equilibrium model [12], 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. Exclusive 4π experiments with single event analysis and special emphasis on production and correlations of the emitted fragments can provide snapshots of bulk motion, mass and temperature distributions and energy flux in violent nuclear collisions.

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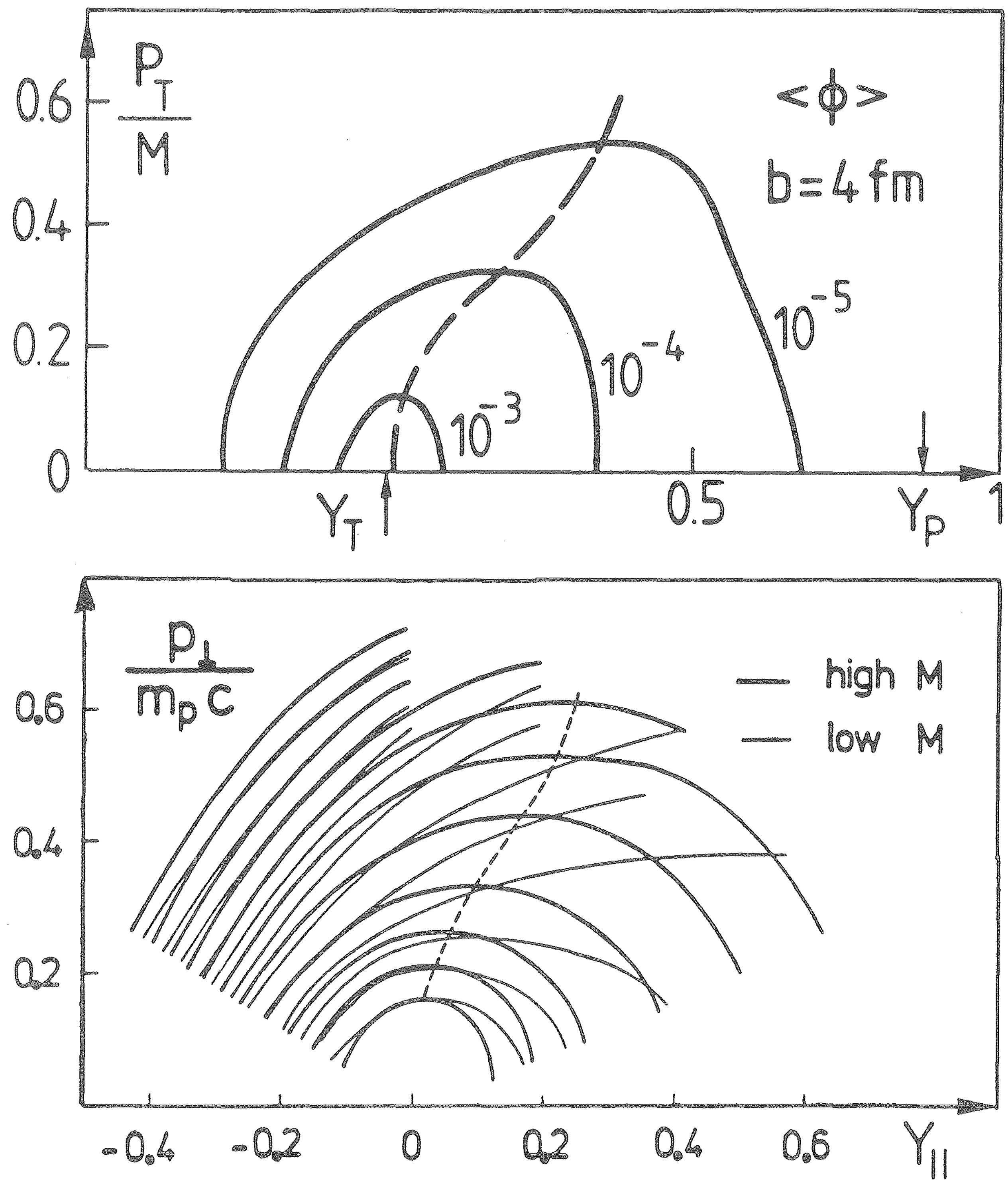
Table 1: The jet angle, θ_{jet}, relative to the beam axis as a function of impact parameter at E_{LAB} = 390 MeV/n

b[fm]	0	2	3	4	6	8
Ne + U	90°	68°	--	45°	26°	7°
Ar + Ca	90°	44°	28°	17°	2°	--

Figure Captions

Fig. 1) Contour diagrams in the plane of transverse momentum p_T in units of $p_T/(m_N c)$ and rapidity $y_{\parallel} = 1/2 \ln [(E + p_{\parallel})/(E - p_{\parallel})]$ for the reaction $^{20}Ne + {}^{238}U$ at $E_{LAB} = 393$ MeV/n.
Compare the calculated invariant nucleon cross section $\frac{1}{p}d^2\sigma/d\Omega dE$ [n/MeV^2 sr c^{-1}] at b = 4 fm with the measured proton cross sections for peripheral collisions (low associated multiplicities M, thin lines) and "central" collisions with an estimated mean $\bar{b} \approx 4$ fm (high M, thick lines) [1]. Note that in the upper and lower part of the figure, one and five lines respectively are drawn for each decade of cross section.

Fig. 2) Azimuthally dependent triple differential particle cross sections $\frac{1}{p}d^3\sigma/dEd\cos\theta d\phi$ [n/MeV^2 sr c^{-1}] at various impact parameters for the same reaction as above. Shaded areas indicate flat local maxima. The lower right frame shows the distribution of free nucleons at b = 4 fm to be compared with the distribution of all particles in the lower left frame.



Ne ⟶ U $E_{LAB} = 393$ MeV/n

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Fig. 1

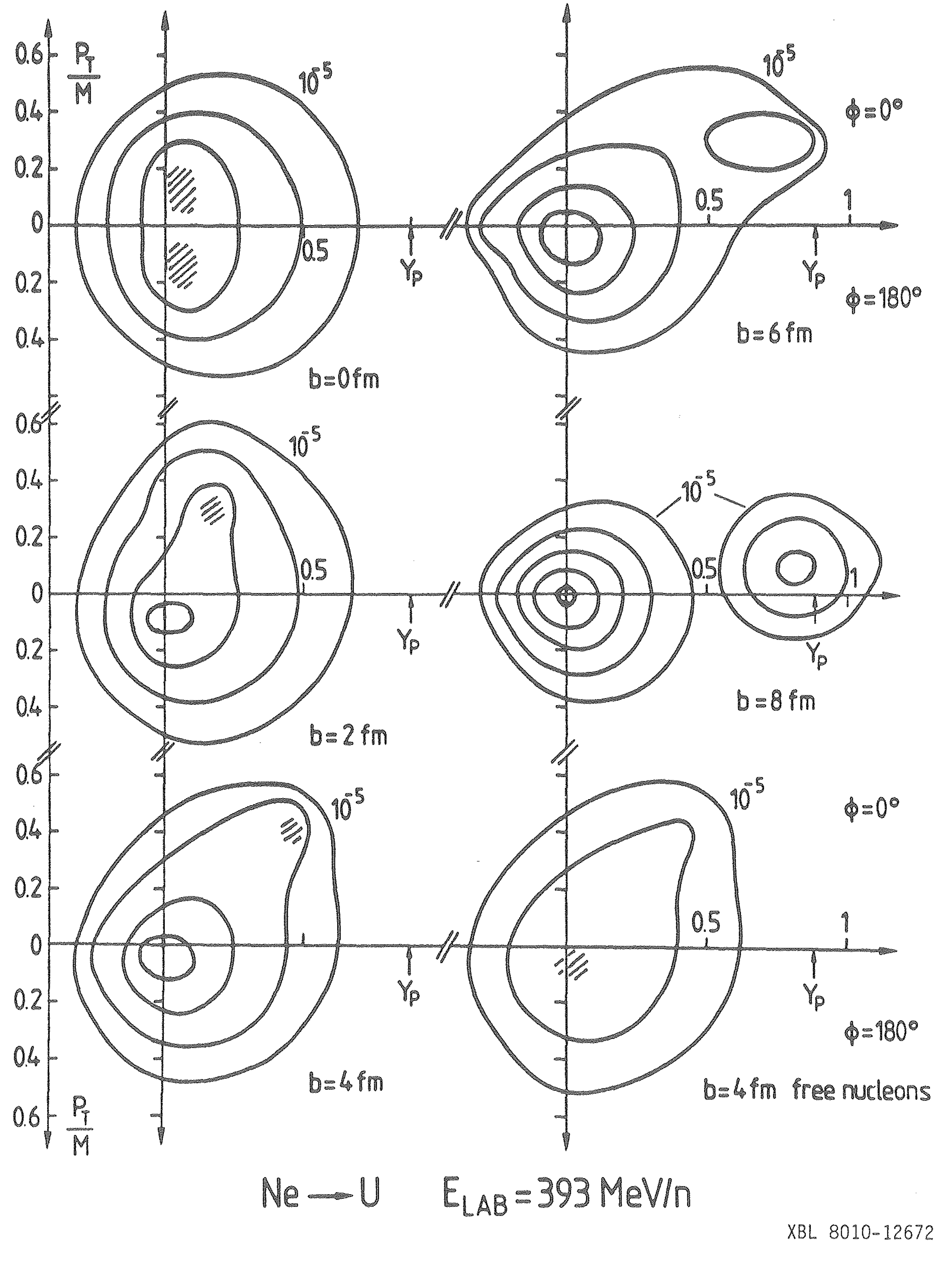

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Fig. 2