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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 $^{20}\text{Ne} + ^{238}\text{U}$ and $^{40}\text{Ar} + ^{40}\text{Ca}$ at $E_{\text{LAB}} = 390 \text{ MeV/n}$. Calculated double differential cross sections $d^2\sigma/d\Omega dE$ are in agreement with recent experimental data. It is shown that azimuthally dependent triple differential cross sections $d^3\sigma/dEd \cos\theta d\phi$ 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 [2] for predominant sideways emission of fragments from high-energy heavy ion collisions. The reported forward shift of the maxima in the angular distributions and the decrease in the absolute value with increasing fragment energy are in qualitative agreement with three-dimensional (3D) nuclear fluid dynamical (NFD) calculations [3], which predict strong compression effects in nuclear matter [3-6]. Quantitative comparisons were lacking because of the fact that the cross sections were calculated by taking into account the hydrodynamical flow velocities only at a late stage of the collision [3-6]. At the final stage the nuclear fluid has non-negligible temperatures and the thermal velocities must be added to the fluid flow [7-9]. In this letter, the 3D NFD model including final thermal breakup is used to analyze the reactions $^{20}\text{Ne} + ^{238}\text{U}$ and $^{40}\text{Ar} + ^{40}\text{Ca}$ at $E_{\text{LAB}} = 390 \text{ MeV/n}$.

The calculated double differential cross sections are in qualitative agreement with the data. We propose that considerably more information can be gained about the collision process by investigating triple differential cross sections $d^3\sigma/dE d\phi d\cos\theta$ of different fragments in single event 4π analysis: the azimuthally dependent cross sections reflect in a unique way the bulk motion and energy flux in the collision process. Information on the density, velocity, temperature and entropy distributions can possibly be obtained by comparing the triple differential cross sections of different clusters. Strongly correlated jets

of nuclear matter are predicted in violent reactions. Experimental analysis of the jet phenomena is in progress.

The fluid dynamical model used here has been discussed in some detail elsewhere [6]. We note only that compressibility and effective, density dependent n-n interactions, Fermi pressure and internal excitations, and a realistic treatment of the nuclear binding and surface properties are included. 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 only [3-6]. Thermal emission of particles from the decompressed system is calculated in a late stage of the reaction, so that the final distributions depend only negligibly on the exact value of the breakup density $\rho_S \sim 0.5\rho_0$ [7-9]. Double and triple differential particle cross sections are obtained by assuming a Maxwell Boltzmann distributions $f(\vec{r}, \vec{k})$ for the momentum distribution of each fluid element and boosting it to the lab system by the collective flow velocities $\vec{V}(\vec{r})$ [7-9].

In order to estimate the differences in the production of light and heavy fragments, unbound nucleon cross sections [9] are also calculated. This is done by shifting the Fermi distributions of the nucleons according to the binding energy of each fluid element and evaporating only the high momentum tails with $\epsilon \geq mc^2$ [9]. These prescriptions lead to reasonable agreement with recent calculations assuming chemical equilibrium to describe the break up into various light nuclei [12].

Figure 1 shows contours of the calculated double differential invariant nucleon cross section in the rapidity-transverse momentum plane $y_{\parallel}/p_{\perp}$ together with the measured multiplicity selected 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 positions of the maximum cross section at given p_T and their shift with p_T agree rather well (dashed lines). The calculated angular distributions of the nucleons show a broad maximum at $\theta_{\text{LAB}} \approx 75^\circ$ for low energy nucleons $E_{\text{Kin}} = 10$ MeV. The maximum shifts forward with increasing nucleon energy, toward $\theta_{\text{LAB}} \approx 45^\circ$ at $E_{\text{Kin}} = 90$ MeV, while the height decreases. These findings are in qualitative agreement with the data [1]. Furthermore, the peaks of the particle distributions are narrower than those of the nucleons. This is consistent with the reduction in the peak width observed experimentally [15] when going from emitted protons to deuterons and, even more, to tritons. A quantitative comparison is presently not possible, because the data result from a complicated folding of impact parameter dependent multiplicity distributions [1], which 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. This means, unfortunately, that double differential cross sections are of limited value for obtaining information on the reaction dynamics and on the nuclear equation of state [5,6]. We therefore consider next whether the azimuthal dependence of the differential cross sections can provide more specific dynamical information.

Figure 2 shows the triple differential cross sections in the $y_{||}/p_T$ plane at $\phi = 0^\circ/180^\circ$ (in the scattering plane) for the reaction discussed above at various impact parameters b . Strong peaking of the invariant cross sections close to the initial projectile and target positions are observed for $b = 8$ fm. Apparently the resulting thermal excitation and momentum transfers are rather small. For head-on collisions, $b = 0$ fm, the two equal maxima at $p_T/m \sim 0.1-0.2$ indicate the azimuthally symmetric sideways emission of rather cold matter ("Machshock" [2]). The high temperatures in the head shock lead to a depletion at small p_T and to a broad thermal background at higher p_T . At intermediate impact parameters, the spectra broaden as compared to $b = 8$ fm, indicating higher thermal excitation. The projectile and target maxima shift from the collision axis to finite p_T , reflecting the highly inelastic bounce-off effect [3,6,9,13-15]: One recognizes a rather sharp maximum in $d^3\sigma/dEd\cos\theta d\phi$ at the target side ($\phi = 180^\circ$) at low transverse and longitudinal momentum, while the projectile hemisphere ($\phi = 0^\circ$) shows a broader maximum at $P_T/M \approx 0.2-0.4$, shifting to smaller rapidities with decreasing b . The narrow maximum at $\phi = 180^\circ$ indicates the presence of a large

chunk of rather cold, slowly moving matter, i.e., the target residue. The projectile and target matter in the directly hit head shock region blows apart after impact and is seen as broad thermal distribution. The high pressure in the head shock region results in a large collective momentum transfer to the target residue and to the remnants of the projectile. The sideways deflected projectile fragments, seen as the smaller maximum in $d^3\sigma/dEd\cos\theta d\phi$ at $\phi = 0^\circ$, are emitted from a zone of low temperatures.

Because of their low temperatures, the remnants of projectile and target must be observable as jets of predominantly bound nuclei, e.g. ^4He , while hot zones will predominantly emit free nucleons. These different phase space distributions of various components can provide information on the density, temperature, entropy and velocity distributions by careful experimental single event 4π analysis. The distributions of particle production rates, e.g., π/p and p/d ratios [22], reflect the temperature and entropy distributions in a collision, which are strongly dependent on the nuclear equation of state [6,7,10,12,21,22]. Therefore, we emphasize the importance of particle identification in future 4π experiments. This can also be seen by comparing the particle distribution with the unbound nucleon distribution (see Fig. 2, $b = 4$ fm). The distribution of free nucleons are less structured, being broader and resembling the high p_T background. The contribution of the bound nuclei can be roughly estimated by subtracting the free nucleon distribution from the all matter distribution.

One recognizes that the prominent feature of the reaction process at intermediate impact parameters, namely the bounce off, is most likely to be observed in the triple differential distributions of clusters (e.g., ^4He). They represent the jet structure most strongly. Also the calculated ϕ averaged double differential cross sections show considerably narrower angular distributions (i.e., sharper maxima) compared to the free nucleons (see above). A quantitative comparison with the data [15], however, asks for a detailed calculation of the cluster formation, e.g. in a chemical equilibrium model [12]. Indications for jetting phenomena are found experimentally [13-15] in Ne-induced reactions with Au and U nuclei, which show strong 180° azimuthal correlations between heavy target fragments and a jet of fast light particles being emitted in the opposite direction. Experimental analysis of the focusing of the jets in E , θ and ϕ is presently underway [14,16]. The calculated triple differential particle cross sections for the system ^{40}Ar (388 MeV/n) + ^{40}Ca show a symmetric two-jet structure being superimposed on a broad thermal background. The ϕ averaged double differential nucleon cross sections again exhibit a rather structureless "fireball" distribution at small impact parameters $b \sim 2$ fm and are forward-backward peaked at large b in agreement with the experimental findings [1]. The two jet maxima at $\phi = 0^\circ/180^\circ$ shift towards larger p_T with decreasing impact parameters, almost on a circle around y_{cm} in the $p_T/y_{\parallel}$ plane, possibly providing an alternate explanation of two particle correlation measurements [17].

Correlations are apparently not only caused by free n-n collisions (as assumed previously [18]), but also by the collective matter flow [19]. For head-on collisions, the jets convert to the azimuthally symmetric ring of nuclear matter moving towards 90° in the cm system [20,21]. Remnants of this ring can still be seen at small, but finite impact parameters, thus giving rise to additional out-of-plane jet structures [21] at small impact parameters. Preliminary calculations [21] indicate that the jets and in particular their "chemical" composition are sensitive to the details of the reaction dynamics and to the nuclear equation of state, while the double differential cross sections are rather insensitive especially after impact parameter averaging[5,6].

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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Figure Captions

Fig. 1) Contour diagrams in the plane of transverse momentum in units of $p_T/(m_N c)$ and rapidity $y = 1/2 \ln [(E + p_{\parallel})/(E - p_{\parallel})]$ for the reaction $^{20}\text{Ne} + ^{238}\text{U}$ at $E_{\text{LAB}} = 393 \text{ MeV/n}$.

Compare the calculated invariant nucleon cross section $1/p d^2\sigma/d\Omega dE$ [$\text{n/MeV}^2 \text{ sr c}^{-1}$] at $b = 4 \text{ fm}$ with the measured proton cross sections for peripheral collisions (low associated multiplicities M , thin lines) and "central" collisions with an estimated mean $\bar{b} \approx 4 \text{ fm}$ (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 resolving triple differential particle cross sections $\frac{1}{p} d^3\sigma/dE d\cos\theta d\phi$ [$\text{n/MeV}^2 \text{ sr c}^{-1}$] at various impact parameters for the same reaction as above. Shaded areas indicate maxima not exceeding the background by one decade. The lower right frame shows the distribution of nucleons at $b = 4 \text{ fm}$ to be compared with the distribution of all particles in the lower left frame.

Ne $\rightarrow$ U $E_{\text{LAB}} = 393 \text{ MeV/n}$

XBL 8011-7415

Fig. 1.

XBL 8010-12672

Fig. 2.