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THE BOUNCE OFF EFFECT AS A BAROMETER FOR HOT, DENSE MATTER IN FAST NUCLEAR COLLISIONS*

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The transverse momentum transfer (bounce-off effect) observed in fast nuclear collisions is studied in a simple model. The calculated momentum transfer is in agreement with experimental data. The bounce-off process is shown to be sensitive to the nuclear equation of state, $p(\rho,T)$, in the high-density, high-temperature region. We suggest using this for a systematic experimental investigation of compression phenomena in fast nuclear collisions. Such measurements could provide evidence for abnormal dense nuclear matter and quark matter.

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Experimental evidence for collective large transverse momentum transfer in high-energy heavy ion collisions has been reported recently by the GSI-LBL collaboration[1]. In these correlation experiments, collisions of ^{20}Ne projectiles with heavy targets (Au, U) were studied at $E_{lab} = 0.4$ and 2.1 GeV/n. Showers of fast, sidewards-deflected projectile fragments were observed in coincidence with heavy target fragments moving to $\theta_{lab} = 90^{\circ}$ in the opposite azimuthal direction. This experimental observation has been interpreted as being due to the highly inelastic bounce-off effect[2] in nuclear collisions at intermediate impact parameters.

In the nuclear fluid dynamical model[2-5] this process may be understood as follows: The hot, compressed nuclear matter in the impact region (the shock zone or "fireball" participant zone) acts like a compressed spring between the residual projectile- and target-like fragments. Owing to its large internal pressure, the hot, compressed matter expands and pushes the fragments apart from each other in the scattering plane. For nearly central collisions, on the other hand, no projectile and target residues survive the violent collision. The system disintegrates completely and an almost azimuthally symmetric fragment distribution results.[1-5]

Here we present a simple bounce-off model, which allows quantitative estimates of the transverse momentum transfer in violent nuclear collisions. The predicted momentum transfer agrees well with the experimental data.[1,6] In addition, we propose that the bounce-off effect may be utilized to study the influence of the nuclear equation of state on the reaction dynamics.

The bounce-off model requires, however, that the nucleon mean free path, $\lambda \lesssim 2$ fm, is small compared to the size of the system, 2R. Then the incident energy and longitudinal momentum can be randomized and thermal equilibrium, the prerequisite for hydrodynamics, can be established. (See the discussions in refs. 3-5.)

Some indications for fluid dynamical behavior seem to be found experimentally, e.g. the predominant sidewards emission of matter in nearly central violent collisions observed by Schopper and Baumgardt[4] and Stock et al[4]. Furthermore, it has been shown by Siemens and Kapusta[3] that the deuteron-to-proton ratios observed by Nagamiya et al[4] indicate a considerable entropy production in violent nuclear collisions. These findings seem to support our basic assumption of rapid dissipation of the incident energy at least in the spatially overlapping regions of the two colliding nuclei.

The geometrical aspects of our model are illustrated in Fig. 1. The transverse momentum transfer, $\Delta\vec{p}_\perp$, is calculated via

$$\Delta\vec{p}_\perp = -\int_{-\infty}^{\infty} \vec{F}(t)dt \quad , \tag{1}$$

where $\vec{F}$ is the force pushing the fragments apart. $\vec{F}$ can be estimated as the product of the internal pressure P of the hot, dense matter and the fragment surface area $\vec{S}$ exposed to the pressure:

$$\vec{F} = P\,\vec{S} \quad . \tag{2}$$

The pressure consists of two contributions, viz. the thermal pressure and the zero temperature part

$$P = P_C(\rho) + P_T(\rho,T) \quad . \tag{3}$$

It is well known[2-5] that for low bombarding energies $P_C(\rho)$ is by far the larger contribution, being related to the compression energy per nucleon E_C by

$$P_C(\rho) = \rho^2 \frac{\partial E_C}{\partial \rho} = \frac{K}{18\rho_0} (\rho^2 - \rho_0^2) \quad . \tag{4}$$

Here $K \sim 200$ MeV is the nuclear compression constant and $\rho_0 \sim 0.17\ \mathrm{fm}^{-3}$ is the groundstate density of nuclear matter.

For higher energies, above some 200 MeV/n, the <u>thermal</u> pressure dominates, which in a Fermi gas model is related to the thermal energy per nucleon

$$P_T = \frac{2}{3} \rho E_T \quad . \tag{5}$$

At this point we can already draw the conclusion that the bounce off must be triggered by the thermal pressure in the energy region investigated in Ref. 1 ($E_{lab} \geqslant 400$ MeV/n). In this energy region, the momentum transfer must therefore be sensitive mainly to the temperature dependence of the equation of state and to the magnitude of the temperature that is reached in the collision. (For a comparison with experiments at lower energies $E_{lab} \lesssim 200$ MeV/n, see Ref. 6 and Point 2 of the discussion below.) A crude estimate of the thermal energy per participant deposited in intermediate impact parameter collisions of two nuclei of not too different size is $E_T \approx E_{lab}/(4A_p)$, A_p being the projectile mass. The surface area exposed to the pressure is estimated to be

$$S = \pi r^2 \text{ with } r^2 = R_p{}^2 - b'^2 = R_T{}^2 - (b - b')^2 \tag{6}$$

where the notations are evident from Fig. 1a. The interaction time is approximately

$$\Delta t = \frac{1}{v} \left[(R_T + R_p)^2 - b^2 \right]^{1/2} \tag{7}$$

as illustrated in Fig. 1b, v being the projectile velocity in the lab system. Combining eqs. (1,2,4-7) gives the following result

$$\Delta p_\perp = \frac{2}{3} \rho \frac{E_{lab}}{4vA_p} \pi \left[R_p{}^2 - \left(\frac{b^2 - R_T{}^2 + R_p{}^2}{2b} \right)^2 \right] \left[(R_T + R_p)^2 - b^2 \right]^{1/2} \tag{8}$$

valid for not too high energies ($E_{lab} \gtrsim 0.2$ GeV/n). This can be written as

$$\Delta p_\perp = \frac{2}{3}\rho \frac{E_{lab}}{4vA_p} G(b) \tag{9}$$

where G(b) is a function of the impact parameter only. In particular, $\Delta p_\perp/p$ is independent of the bombarding energy (p denotes the beam momentum) and depends linearly on the compression achieved:

$$\frac{\Delta p_\perp}{p} = \tilde{G}(b) \cdot \frac{\rho}{\rho_0} \quad . \tag{10}$$

The transverse momentum transfer calculated from eq. (8) (using $\rho = \rho_0$) is shown in Table 1 for Ne + U collisions at $E_{lab} = 400$ MeV/n for various impact parameters. $\Delta p_\perp$ increases with the violence of the reaction, i.e., with decreasing impact parameter as

$$\Delta p_\perp \sim (R_R + R_p) - b \quad . \tag{11}$$

The momentum transfer predicted by this simple bounce-off model (Table 1) is found to be in good agreement with the experimentally observed values ($\Delta p_\perp \sim 1$-4 GeV/c).[1]

The important point in our argumentation is that $\Delta p_\perp/p$ factorizes in a function $\tilde{G}(b)$ containing the geometrical information and a factor carrying information on the compression reached in the collision [eq. (8-10)]. One could imagine that G(b) may be extracted from experimental data at fixed bombarding energy by comparing the measured $\Delta p_\perp$-distribution with geometrical estimates. It should be noted that the impact parameter dependence of $\Delta p_\perp$, as given in Table 1, is in agreement with the numerical results of Ref. 2 and of Bertsch and Amsden (Ref. 3) for their coefficient $\alpha^{(1)}$ measuring the azimuthal symmetry of the final particle distribution.

Once the geometrical factor, G(b), is known, one can go about determining the compression excitation function, $\rho(E_{lab})$. This is of great interest for various reasons:

(1) Hydrodynamical calculations[2-5] make detailed predictions about the compression reached in the intermediate stages of the collision. The final evaporation spectra yield only limited information on the maximum compression and temperature. According to our argument, however, the transverse momentum of large fragments is directly related to the initial compression, because this is the moment where the pressure is highest. By measuring the excitation function of large transverse momentum distributions (for massive fragments), one could test the bombarding energy dependence of the density $\rho(E_{lab})$.

(2) At low bombarding energies, E_{lab} = 20-200 MeV/n, the compression pressure $p_C(\rho)$ [eq. (4)] dominates[5] the thermal pressure and must be inserted into eq. (8). Recently, D. Scott[6] has shown that the "orbital deflection"[7] of projectile fragments in the reaction $^{16}O(E_{lab}$ = 90 MeV/n) + Au can be understood in the simple bounce-off model presented here. He deduced a compression $\rho/\rho_0 \approx 1.5$ from the data[7], in agreement with the values obtained in three-dimensional fluid dynamical calculations at this energy[5]. We would like to point out that evidence for large momentum transfers ($\Delta p \sim 1$ GeV/c) in this energy region is found also in preliminary data of the GSI-MPI Heidelberg collaboration.[7] A more detailed analysis of data of this type offers the opportunity to extract information on the properties of nuclear matter at moderate compression, the compression constant $K = 9\rho_0^2 \frac{\partial^2 E_C}{\partial \rho_0^2}$, and the related sound velocity $c_S = (K/9\,M_N)^{1/2}$ of nuclear matter.

(3) At higher incident energies, the achievable compression depends crucially on the stiffness of the nuclear equation of state. Accordingly, the program outlined above offers a way to measure systematically the equation of state at high density ($\rho \geqslant 2\rho_0$) and temperature. In particular, it has been shown[8] that possible phase transitions in compressed nuclear matter can soften the equation of state. This would imply a rather abrupt *increase*[5] in the attained density $\rho(E_{lab})$ at some threshold energy and, accordingly, contrary to first thought, a much stronger *thermal* pressure. We conclude that a sudden softening of the nuclear equation of state would result in a drastic change of the transverse momenta transferred to the bounce-off fragments. This can show up in dramatic effects, should a density isomer exist[8], i.e., if there was a secondary minimum in the equation of state.

(4) The bootstrap model[9] suggests that at very high energies $E_{lab} >>$ 1 GeV/n, most of the available excitation energy is transformed into massive hadronic resonances rather than into heat. Therefore, the pressure is decreased considerably. Hence, in this model one expects a strong reduction of the bounce-off effect at bombarding energies of several GeV/n.

(5) If eventually quark matter is formed at sufficiently high bombarding energies,[10] a pronounced enhancement of high transverse momenta results from the transition from the hadron gas with $P_T = 2/3\ \rho E_T$ to the ultra-relativistic quark gas with $P_T = 1/3\ \rho E^*$. (E^* contains also the rest energy of the nucleons in terms of kinetic energy of the quarks.) A strong increase of the deflection angles is to be expected. We would, however, like to make a remark of caution: little is known about the influence of the temperature on the (negative) bag pressure. More understanding of the dynamics of quark bags is required before really trustworthy predictions can be made.

In conclusion, we have shown that the highly inelastic bounce-off process can be understood as the result of the strong compression of matter in violent nuclear collisions. The bounce-off effect may be utilized to investigate the compression phenomena in fast nuclear collisions. It could be applied to discriminate between different equations of state of nuclear matter and to search for exotic states of dense, hot matter (quark matter, pion-condensates, density isomers, etc.). Above all, the scattered fragments are direct witnesses of the initial, hot part of the reaction, and as such they deserve much future attention.

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Table 1: Impact parameter dependence of the calculated transverse momentum transfer $\Delta p_\perp(b)$ for the reaction ^{20}Ne (393 MeV/n) + ^{238}U

b [fm]	10.5	10	9.5	9	8.5	8	7.5	7
$\Delta p_\perp$[GeV/c]	0.09	0.56	1.19	1.89	2.59	3.24	3.81	4.25

Figure caption:

Fig. 1 illustrates the geometrical notations used in the text.

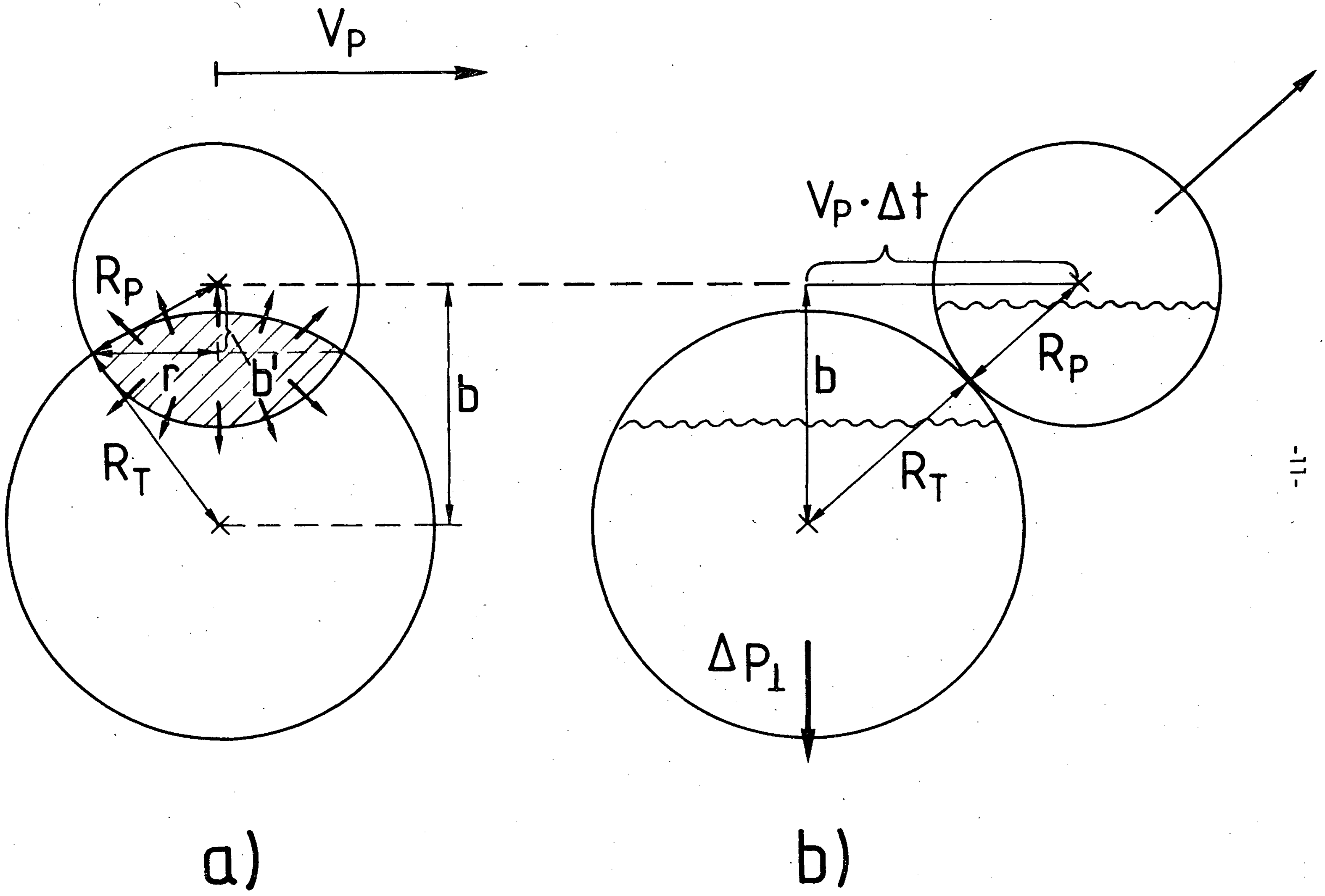

Fig. 1

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