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Prominent transverse flow of clusters in stopped Au (150 *A* MeV) + Au reactions

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ABSTRACT :

Stopped Au (150 *A* MeV) + Au collisions have been measured with the FOPI-Detector at GSI by imposing an upper limit on the ratio of the global longitudinal momentum to the collected charge within an event. The ejectiles, in particular those with Z > 3, have a rapidity close to mid-rapidity and exhibit angular distributions in the centre-of-mass strongly peaking around 90° thus suggesting an enhancement of the flow in the transverse direction. Fits to the data and comparisons with QMD calculations indicate an averaged collective velocity in the transverse direction equal to 0.12 *c*. Significance of the determined velocity and temperature values is discussed.

The origin of the collective behaviour of nuclear matter in the collisions of heavy-nuclei, leading practically to a complete stopping in the centre-of-mass of the two reactants, is one of the most interesting questions addressed by the new generation of relativistic heavy-ion reactions. Indeed it offers the best chance for a large highly excited and compressed volume of nuclear matter and the means for studying the collective flow in the peculiar case where sideward and squeeze-out emissions merge. Signals for an explosion-like phenomenon where the thermal agitation is added to a large collective motion has been recognised [1]. Yet the accurate sharing between thermal and collective energy as well as the space distribution of this flow remain to be determined.

Experimentally such a study is a difficult one since it demands the selection of very low ($b \leq 1$ fm) impact parameter reactions, hence the elaboration of specific criteria adapted to this requirement. Up to now, several approaches for isolating, if not exclusively fully stopped, at least fairly low b reactions have been elaborated. Among them one should retain as the most effective *i)* a large charged particle multiplicity combined with an homogeneous azimuthal distribution of the momentum of the emitted products, the so-called PM5D1 selection[2], *ii)* a ratio of the multiplicity of the clusters (Z ≥ 3) having a rapidity $y/y_p \leq 0.5$ to that of all Z ≥ 3 clusters exceeding 50 %, i.e. the CE4 and CE5 event types[3,4], *iii)* a large ratio of the transverse to the longitudinal kinetic energy in the centre-of-mass forward hemisphere, namely the ERAT5 cut[5]. When studying the possible transversal enhancement of the flow, this latter criterion might influence the results, due to acceptance effects of the FOPI Detector[6] specially at large polar angles. In the present work a new criterion has been used. Since collisions of full-stopping type imply quite a weak longitudinal momentum $p_{//}$ for the ejectiles in the centre-of-mass, we have calculated the

$$PL = \left(\sum_i p^i_{//}\right) / Z_{total} \Big]_{y>0}^{p_t<0.6} \qquad (1)$$

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distribution event by event. The sum runs over the *i* members of an event in the forward centre-of-mass hemisphere and Z_{total} is the corresponding total collected charge. Hence the distribution is, in a way, weighted by the entireness of the events and, in principle, does not involve any transverse-momentum pre-requisite else than implicit energy conservation. In fact, in order to avoid distortion of the phase space introduced by the detector boundary limit at $\theta = 30°$, the transverse momenta have been limited to $(p_t / A)/(p_p / A_p) \leq 0.6$. This turns out to be of an appreciable effect essentially for $Z \leq 3$. The PL distribution[7] of the PM5 set of events shows a broad structure extending from zero up to ~ 0.52 GeV/*c* (the projectile momentum divided by Z_{total}) with a maximum around PL = 0.33 GeV/*c*. By restraining PL to less than an upper limit such as one selects half as many events as with the PM5D1 (~ 25 mb, the so-called PL7 cut), one retains only strongly stopped collisions. This is clearly evidenced in

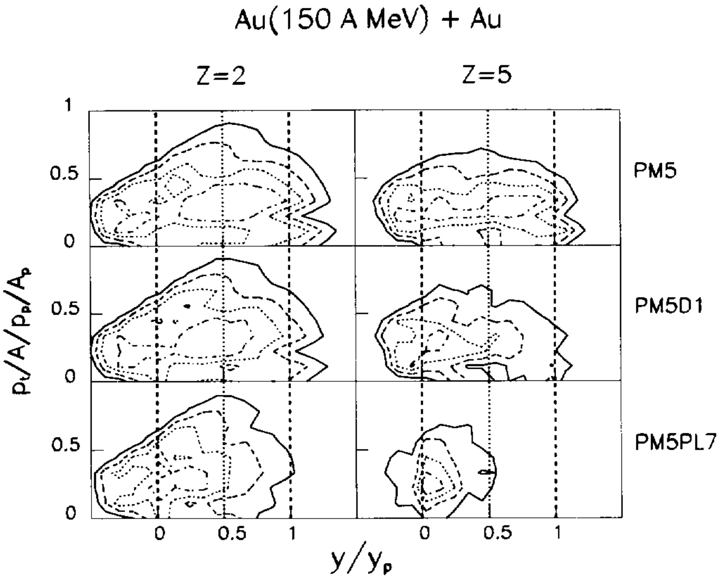

Fig. 1

Figure 1 showing, from top to bottom, the contour plots of the transverse momentum per nucleon as a function of rapidity for Z = 2 and 5 fragments elaborated with the PM5, PM5D1 and PM5PL7 cuts, respectively. The PM5D1 set has been shown[4] to contain different classes of events constituted of different relative fractions of participant and spectator decays, from substantial projectile-like and participant components to nearly exclusive participant one. It means a variety of collisions from fairly central to fully stopped as also predicted by QMD[2]. PM5PL7, which favours the selection of this latter class of reactions without introducing any extra concept expressing the participant belonging like an upper limit on *y*, appears very effective for heavy clusters but also for light products. Filtered QMD calculations[8] at *b* = 1 fm show striking similarity to the PM5PL7 data, supporting the approach to select stopped collisions by gating on the mean longitudinal momentum in one hemisphere.

With the PM5PL7 criterion the $dN/d(\cos\theta_{cm})$ centre-of-mass polar-angle distributions, corrected for threshold and acceptance effects, have been determined. An example of them is shown (dots) in Figure 2 (middle section) for the Z = 4-6 fragments. For consistency with the $p_t < 0.6$ limit set before the fragment's kinetic energy has been taken $\leq 9\,A$ MeV. A strong

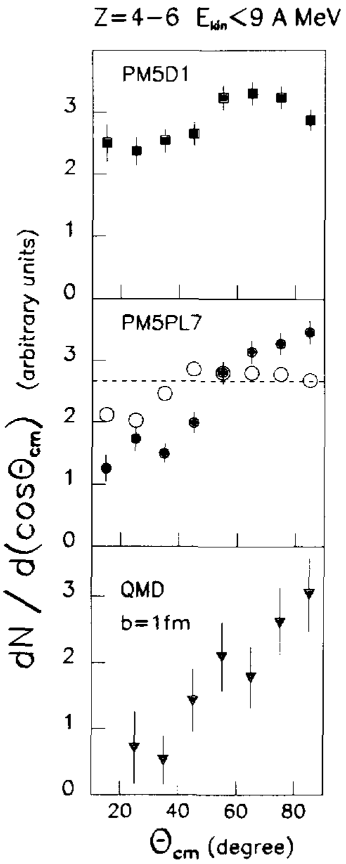

Fig. 2

anisotropy is observed with a peaking around $\theta_{cm} = 90°$. For comparison purpose the corresponding distribution obtained with PM5D1 is shown in the upper part of the figure : a more modest effect is visible with a maximum at angles around 70°. Fluctuations in finite-multiplicity events may lead to an artificial anisotropy. This effect has been studied with an explosion model[9]. Indeed fluctuations in "isotropic" events lead to some fraction (normalised to the same number of particles as in the data) of these latter which fulfils the PM5PL7 criterion (open circles in Figure 2, the horizontal dotted line corresponds to a perfect isotropy). However, these events explain only 20% of the $N(\theta = 90°/\theta = 0°) \approx 3$ measured effect. QMD calculations[8] performed at $b = 1$ fm (lower frame of Figure 2) predict a strong anisotropy consistent with that experimentally observed. This behaviour remains measurable for all ejectiles, including lighter down to $Z = 2$ although less marked, and suggests for stopped collisions an enhancement of the nuclear matter flow around the plane orthogonal to the beam direction. Such an effect has also been predicted in earlier calculations[10].

In order to quantify this trend we have analysed the invariant $(1/p_t).(dN/dp_t)$ transverse momentum distributions whose an example (dots) is given in Figure 3 for the $Z = 4$-6 fragments. This distributions, not corrected for acceptance effect in the figure, departs from a straight thermal distribution, which should be centred at $p_t = 0$, suggesting that a collective expansion has to be added to the thermal agitation. A very simple analysis consisting of fitting filtered Monte Carlo distributions to the data have been performed[4, 11]. As described in details before[4] these distributions depend in the azimuthal plane on two free parameters, the transverse flow velocity $\vec{V}_t^{flow}$ and the temperature T, as

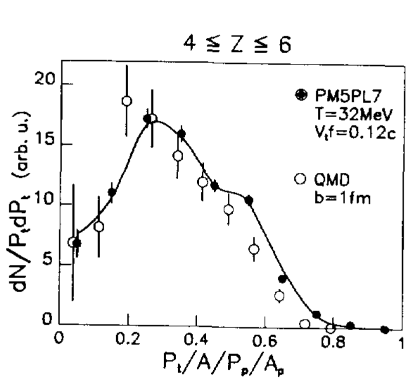

Fig. 3

$$\left(\frac{\eta}{\pi}\right)^{3/2} v_t \int_0^{2\pi} e^{-\eta\left[(\vec{v}_t - \vec{v}_t^{flow})^2 + \vec{v}_l^{\,2}\right]} d\varphi \qquad (2)$$

with $\vec{V}_t = \vec{V}_t^{th} + \vec{V}_t^{flow}$, $\eta = M/2kT$ and by assuming that M=2Z. The fit (solid curve in Figure 3) to the data is very good and leads to $V_t^{flow} = 0.12c$. Nearly identical results have been obtained[4, 11] for all individual $3 \le Z \le 9$ experimentally measured. QMD calculation[8] for the same set of Z's at $b = 1$ fm, also shown in Figure 3 (open circles), leads to quite a comparable distribution. This analysis indicates that in stopped collisions all ejectiles are prominently emitted into the azimuthal plane. It is corroborated by studies[4] applied to 2D-plots, like $(p_t$-$y)$. Such a result may appear somewhat in conflict with other experimental[12, 13] or theoretical[13, 14] works which conclude rather to a spherical expansion. However, the other analyses involve a dominant Z $\leq$ 2 component, susceptible to come partly from the deexcitation of the projectile-like zone as well as from secondary decay of excited products,

rendering the centre-of-mass angular distributions nearly isotropic, hence the data compatible with a radial flow interpretation.

It is essential to notice that the temperature extracted here is high (32 MeV), at large variance with other determinations (~ 8 MeV) from a statistical treatment of the decaying system[15]. It is also appreciably larger than those (~ 25 MeV, $V_t^{flow} = 0.10c$) derived from an analysis, comparable to that presented here, applied to QMD calculations[8] for $b = 0$. Since the system is not fully equilibrated one may speculate about the concept of a "kinetic temperature" departing from the thermodynamic one. The clue resides in the fact that too simplistic the approach used here assumes, as many others, an homogenous emitting source with a single temperature for almost the whole system. However, QMD calculation[16] indicates varying density and local temperatures over the reaction volume in the compression as well as in the expansion phase. Accordingly, the measured final momentum distributions are superpositions of the flow velocity distribution $V^{flow}(\bar{r})$ and of thermal velocities resulting from local temperature $T(\bar{r})$ at freeze-out. Any temperature determination from fitting final spectra is strongly affected by the assumptions on the freeze-out conditions and may consequently not express thermostatic quantities relevant for the nuclear equation of state. Alternative approaches are presently under investigation.

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