CLUSTERIZATION AT SIS ENERGIES NON-EQUILIBRIUM EFFECTS AND FLOW BACK-INFLUENCE

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Abstract

Observations obtained with the FOPI detector system indicate that 1) that clusterization probabilities in expanding participant matter (in contrast to spectator matte) is system-size dependent and 2) that complete nucleon mixing is not achieved in central collisions

1 Introduction

The FOPI Collaboration studies central heavy-ion reactions in the SIS energy range (0.1 to 2 AGeV) using a 4π particle detection system [1, 2]. Light Charged Particles (LCP), Intermediate-Mass Particles (IMF), as well as pions and kaons are identified using a combined magnetic rigidity, time-of-flight and energy-loss analysis. Our general aim is to study hot and compressed nuclear matter in this energy regime. In view of the subject of this workshop, data in the lower incident energy range E/A=100 to 400 AMeV will be stressed here. In this energy range nucleonic excitations are not yet important, although measurable, however the phenomenon of 'flow' [3] in all its variants, is emerging and rising rapidly with incident energy. An interesting question, concerning multifragmentation, is whether flow phenomena influence the process of cluster formation or breaking. We shall first briefly revise the flow situation and point to the difficulties of understanding both the flow and the chemical composition of the hot expanding fireball on a consistent basis. This will raise the question of non-equilibrium features. Two recent FOPI experiments studying

1. the system-size dependence of multifragmentation (separating 'spectators' and 'participants')
2. the mixing in chemically (N/Z) asymmetric systems

will be described.

2 Brief reminder: Flow and clusterization

Flow is a term borrowed from hydrodynamics, which is a macroscopic discipline. In the physics of heavy-ion collisions 'flow' is used, or misused, to refer to a number of phenomena which encompass azimuthal asymmetries in momentum space populations (for non-central collisions) and particle-mass dependent kinetic energy or transverse-momentum distributions in central collisions ('radial' flow). Some of the older data have been reviewed elsewhere [3]. Such phenomena are very prominent at SIS energies and are *rapidly varying* in the energy range $E/A = 100 - 400$ MeV.

The asymmetric forms of 'flow' are maximal in collisions with intermediate impact parameters. They imply the existence of a 'reaction plane' which is usually determined with the well established transverse-momentum method [4]. Formally, the azimuthal (ϕ) distributions, taking the reaction plane as reference, are Fourier analysed, the $\cos\phi$ terms quantizing the in-plane 'sideways' flow, the $\cos 2\phi$ term telling us whether particle emission preferentially is into or out of the plane.

Flow is partially washed out by chaotic or thermal motion. The latter is minimized when looking at heavier particles. Fig. 1 shows the rapid evolution of sideways (in-plane) flow with incident energy using heavy clusters ($Z > 2$) to quantify the so-called flow-angle [5]. Spectacular evidence for the rapid rise also of the other ($\cos 2\phi$) component (nowadays dubbed elliptic flow) is shown in Fig.2. The onset of the preferential out-of-plane emission [6] is roughly at 100 A MeV (and actually goes back into the plane somewhere above 2 AGeV [7]). The transition from in-plane to preferential out-of-plane emission turns out to be a complex, theory-challenging function of the particle type, the centrality and the transverse momentum [6].

'Radial' flow, which implies a position-momentum correlation, is hard to define properly in the experimental situation, in which spatial information can only be deduced indirectly [8]. Usually, radial flow is inferred from observing mass dependent kinetic energy spectra (an example is given in Fig.3) in very central collisions and in phase-space regions outside the 'spectator' peak. Hydrodynamically inspired fits [10, 9, 11] to the data reproduce the spectra well (solid lines in Fig.3). One deduces flow energies on the order of $30\% - 60\%$ of the available kinetic energy. The main problem with this hydrodynamical point of view, is that the remaining energy, interpreted as local thermal energy, is too high to 'explain' the still copious clusterization with statistical models [11] (Fig.4).

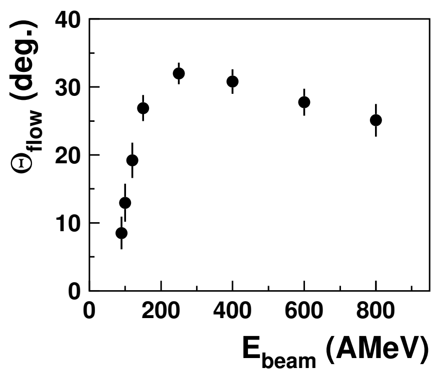

Fig. 1. Sideflow excitation function.

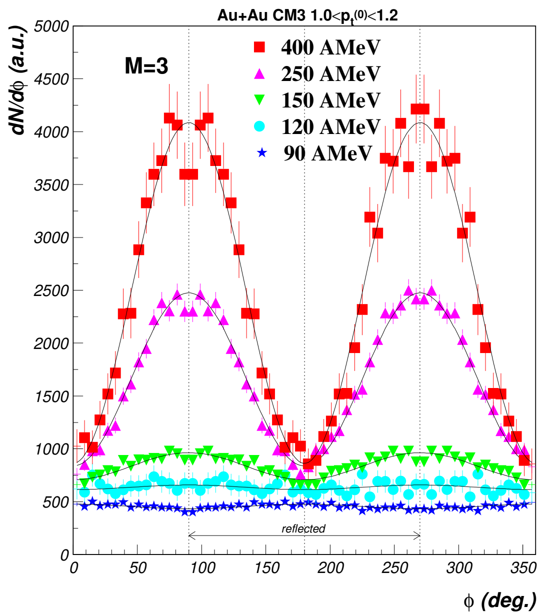

Fig. 2. Mass-3 azimuthal distributions near midrapidity .

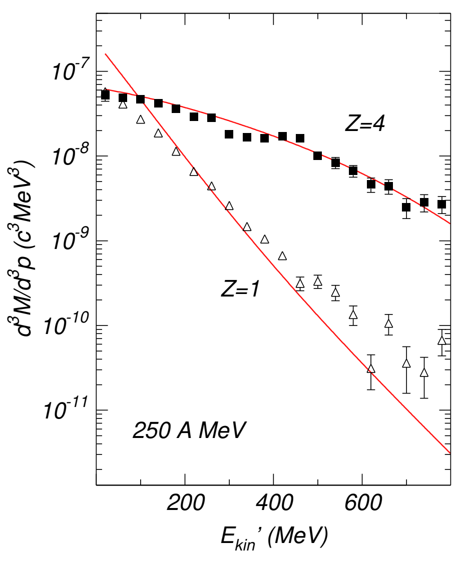

Fig. 3. Kinetic energy spectra of Z=1 and Z=4 fragments in central collisions.

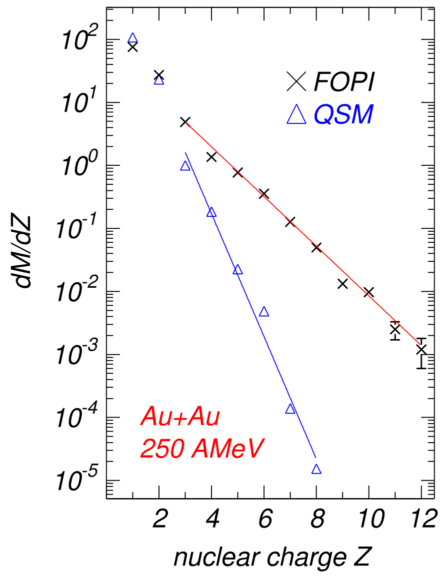

Fig. 4. Comparison of experimental (FOPI) charge distributions with hydrothermal estimate.

Transition to transport models, not limited by the local equilibrium assumption, seems mandatory, as we shall corroborate even further with new observations. In the past the IQMD model calculations [12, 13] have been unable, though, to reproduce the observed IMF multiplicity. Modern developments are promising: a new cluster finding algorithm presented in this workshop [14] seems to be successful. One has tried to overcome the lack of quantum fluctuations in these quasi-classical simulations by introducing either so-called Quantum-Langevin methods [15] or by using Antisymmetrized Molecular Dynamics [16].

3 Energy and size dependences in multifragmentations

In order to obtain additional information on the mechanism of multifragmentation, the FOPI Collaboration has studied the fragment distributions varying the system size, the incident energy and roughly separating the sources into 'spectators' and 'participants'. In a preliminary approach [17], we have separated the sources along the rapidity axis: using the scaled rapidity $y^{(0)}$, we have taken fragments with $0 < y^{(0)} < 0.5$ to be 'participants', fragments with $y^{(0)} > 0.5$, to be 'spectators' ($y^{(0)}$ is the scaled rapidity, zero being midrapidity, $+1$ (-1) the projectile (target) rapidity). This separation is coarse and can be improved by invoking the full 3d momentum space distribution (i.e. the reaction plane).

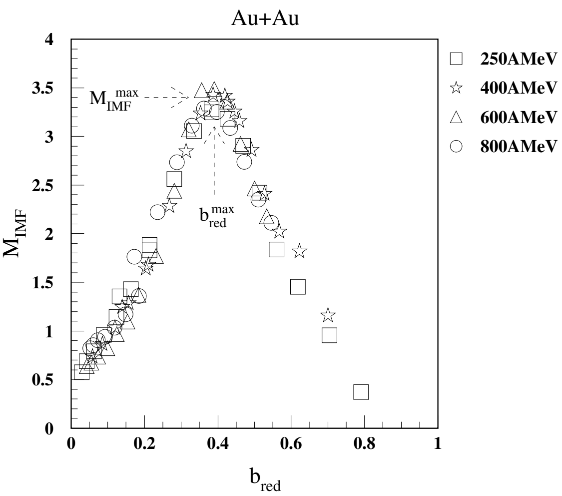

Fig.5 IMF multiplicity vs reduced impact parameter in spectator matter: high incident energies

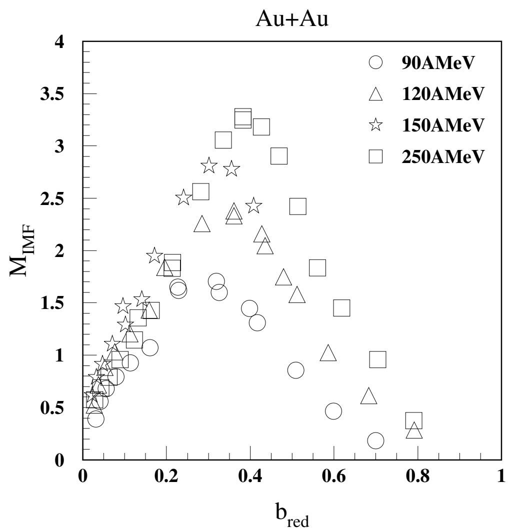

Fig. 6 Same as Fig.5 : low incident energies

3.1 The 'spectators'

Three figures serve to illustrate the main observations. We plot the average multiplicity M_{IMF} versus the reduced impact parameter $b_{red} = b/b_{max}$. Impact parameter selection was done by a combined analysis of global charged-particle multiplicities, transverse energies and directivity [11, 17]. We observe the features well known from ALADIN work [18]. In our case however, due to apparatus limitations, the data are undistorted only below b_{red}=0.6. For Au+Au 'universality' [18] as a function of incident energy E/A is seen for $250 \leq E/A \leq 800$ (Fig. 5). This universality is lost below 250 AMeV (Fig. 6). Above 200 AMeV universality is, roughly, also kept if the size is varied from Ni+Ni, to Zr+Zr, to Xe+CsI and finally to Au+Au (Fig. 7). Note that these observations are nicely complementary to the work of the ALADIN collaboration.

1. We extend the 'spectator' studies to lower incident energies
2. We vary the system size, not by varying the asymmetry of the system (keeping the same projectile), but rather by varying in a symmetric system, both projectile and target, thus keeping the same geometry (in scaled units). This simplifies the theoretical comparison of different systems considerably.

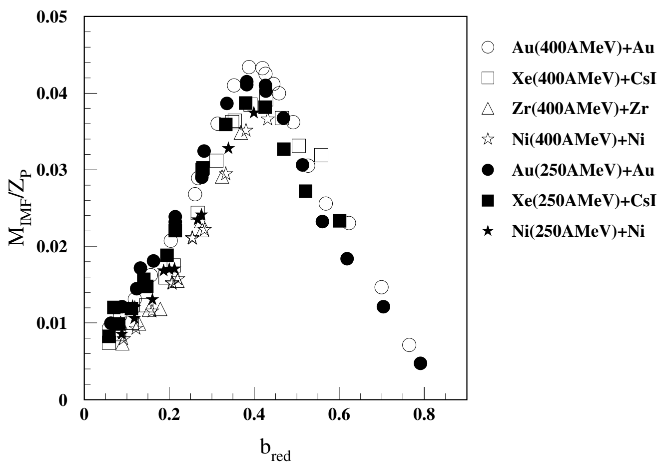

Fig. 7 Same as Fig.5: system size variation

Our main conclusion: 'spectator' universality (as far as the yields of IMF fragments are concerned) *improves* as the incident energy is raised. Considering the Fermi time (see later) this is what one would intuitively expect.

3.2 The 'participants'

To keep 'spectator' contamination low, we have, in addition to the midrapidity condition, $y^{(0)} \leq 0.5$, concentrated on very central collisions, $b_{red} \leq 0.1$ and, for apparatus reasons, on the forward hemisphere in the c.o.m.. Fig. 8 summarizes the data for $E/A = 150$ and 400 A MeV. One sees the familiar [11] exponential yield curves as a function of the fragment's nuclear charge Z, the slopes becoming steeper as the incident energy is raised. The new observation is that the slopes also become steeper, i.e.heavier fragments relatively rarer, in smaller systems. The number of IMF's *per unit of incoming charge* is higher for Au+Au than for Ni+Ni, Fig. 9 . The lack of universality *increases* with incident energy, in contrast to spectator physics. As the system size for the smallest system, Ni+Ni (A=116), is still large compared to typical IM sizes (5-15), (there are also relatively more alpha particles in the Au+Au system), and in view of the contrasting observations for the 'spectators', this is not a trivial observation.

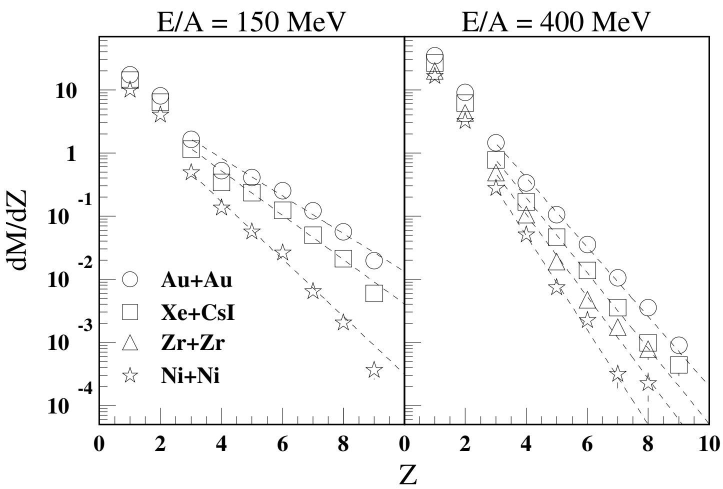

Fig. 8 Nuclear charge distributions in participant matter.

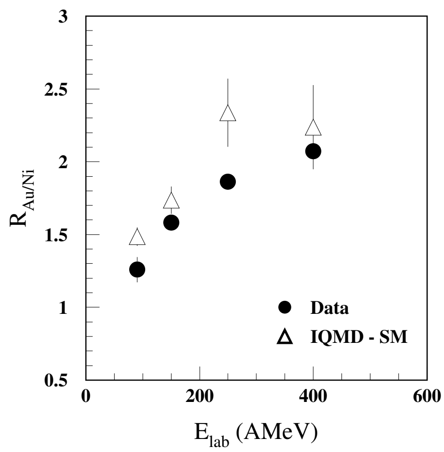

Fig. 9 Ratio of specific IMF multiplicities for Au+Au over Ni+Ni as a function of incident energy in participant matter.

A full understanding must wait for the completion of a flow study as a function of the system size. Preliminary analyses show that radial flow is also system-size dependent: it is larger for heavier systems. The rapid rise of flow with E/A has been stressed already. Thus, *flow seems to favour clusterization.* If one interpretes radial flow hydrodynamically, one can tentatively conclude that the cooling action of *bulk* expansion, visible by flow creation, is responsible for the higher condensation in larger systems. Clearly, this interpretation is preliminary.

4 Equilibration in chemically asymmetric systems

Valuable insight into the question of equilibration can be gained by studying systems, that, while mass symmetric, are isospin asymmetric. We have performed a so called 'mixing experiment' using four mass 96+96 systems Ru+Ru, Zr+Zr, Ru+Zr and Zr+Ru at 400 and 1500 AMeV. Only the 400 AMeV data will be discussed here. ^{96}Ru has just about 10% more protons than ^{96}Zr (44 versus 40). Experiments must therefore be able to combine high statistics and small systematic errors. Very naively, if Ru was to impinge on Zr and if complete transparency were nature's choice, then, after the collision, we should be able to count 44 protons (Ru) in the forward rapidity hemisphere, and we should find the 40 protons of Zr at backward rapidities. In the extreme limit of a complete 'rebound' (predicted by one-fluid non-viscous hydrodynamics, as we shall see), just the opposite would be observed, while 'complete mixing' would show up as a 'white' distribution.

A more complete description of this experiment will soon be available [19]. Let me summarize some of the results in two figures. Two observables have been considered and looked at in various parts of the three(!)-dimensional momentum-space. Fig. 10 shows for very central collisions the result of 'proton-counting' (including those in clusters!) for the four systems as a function of the center-of-mass polar angle. The transverse-momentum vs rapidity distributions of emitted protons indicate the apparent dominance of *one* nearly isotropic source located at midrapidity. To quantify conveniently the 'degree of mixing' we first study the symmetric systems Ru+Ru and Zr+Zr and renormalize in each angle bin the observable to +1 (Zr), resp. −1 (Ru). Using this normalization, we then study the asymmetric systems Ru $\rightarrow$ Zr and the 'inverse' reaction Zr $\rightarrow$ Ru. As can be seen the two asymmetric systems converge to the expected mixed value (zero) only near 90°, where they *must* converge. As soon as one leaves the 90° interval, the proton counting observable tends to the value expected for transparency, the sign being opposite for the Ru+Zr and Zr+Ru systems, as it should be for internal consistency.

An alternative way of demonstrating this partial transparency is to use instead the triton to ^{3}He ratio (Fig. 11). Again one proceeds by looking at the symmetric system first, normalizes the difference to ±1 and then studies the asymmetric systems. This time we fix the phase-space region: we look at to $y^{(0)} = 0.25 - 0.75$. We now vary the centrality from impact parameters below 1 fm (ER6) to about 8 fm (M2). Note again that effects can only be expected away from midrapidity. We find that our second observable again indicates partial transparency, although the effect is least pronounced for the most central collisions. One can show by the way [17] that the 'fully mixed' value should be somewhat below the zero line in Fig. 11, near (-0.20).

What can we conclude? We believe these types of data are important for at least two reasons.

1) it is good to have a signature of partial memory of the past: this puts a constraint on dynamic models; these models must show that they can realistically cope with the observed partial transparency, independently whether its origin is connected with the surface corona and possibly even with insufficient stopping volume. Reactions with heavy ions *always* concern finite sizes and corona effects. Already in the static case (nuclear ground state masses) the corrections to bulk properties (of interest in astrophysics) are large. In the dynamic case these corrections could be essential.

2) If the system is not fully equilibrated at the *end* of the evolution, we expect it to be even less equilibrated at earlier stages, i.e. at maximum compression. Hence the pressure expected from the nuclear equation of state (EOS) is not fully developed, which in turn will lead to decreased flow at the end of the evolution. *Transparency may mock up a 'soft' EOS.* Transport models used to extract information on the EOS must therefore correctly reproduce the observed partial transparency (be it bulk and/or surface transparency).

Clearly, corona effects must be one of the reasons for observing partial transparency, although they are subtle: for the most central collisions they do not appear as an obvious structure close to target or projectile rapidity. Various transport calculations shedding light on the mixing problem have already been done. In Fig. 12 we show results that I have deduced from recent work of Hombach et al.[20]. Using a periodic box condition the authors have determined the equilibration time for nucleon mixing in the SIS energy range. They find times on the order of 40 to 10 fm/c decreasing with increasing incident energy (see the Figure). Comparing this with the passing time ($2R/u$) (R projectile radius, u four-velocity), and the Fermi-time (typical time for a nucleon to cross the system due to its Fermi-motion), we can conclude from this study that the passing time might indeed be somewhat to short for equilibration below 500 AMeV. The relative transparency at lower energies is intimately connected with the importance of Pauli blocking and the still frozen nucleonic degrees of freedom. (The mobility implied by the Fermi time is important for the communication between 'participants' and 'spectators') .

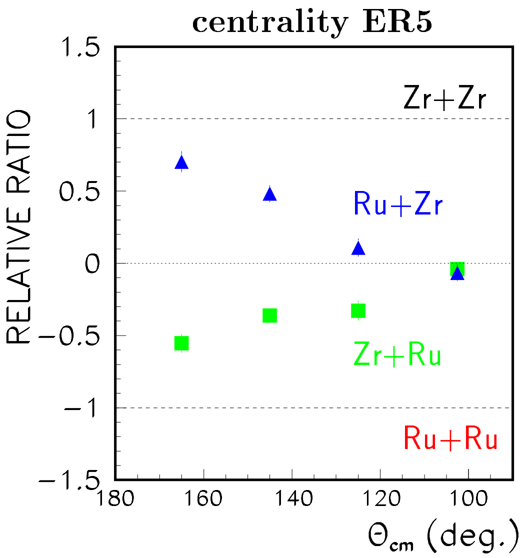

Fig. 10 Proton counting as a function of polar angle (see text).

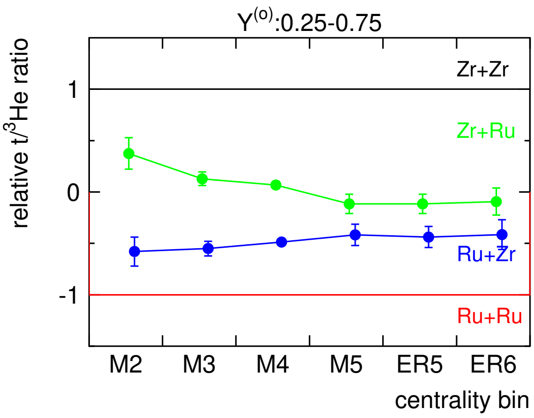

Fig. 11 Normalized triton/^{3}He ratios as a function of centrality.

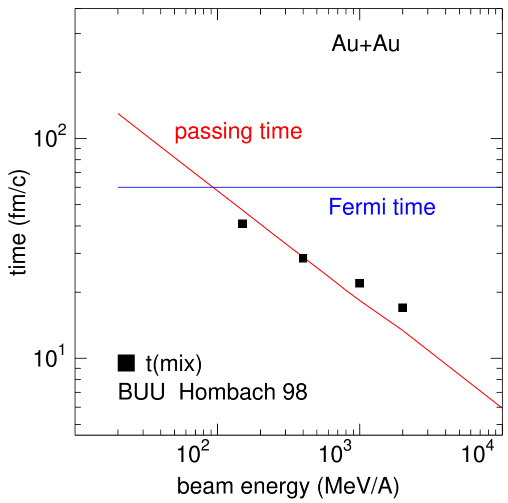

Fig. 12 Passing time, Fermi time and mixing time (symbols) as a function of beam energy.

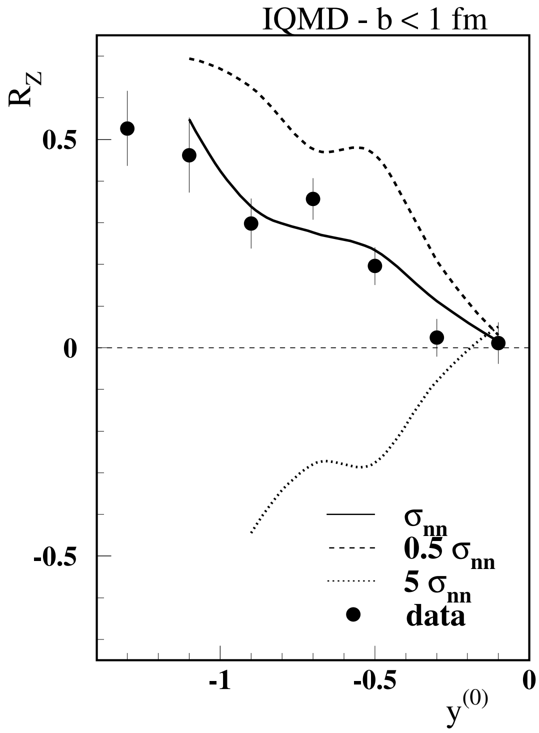

Fig. 14 Comparison of the proton counting observable with various IQMD simulations.

Transparency is sensitive to the medium-modified nucleon-nucleon elastic scattering cross sections σ_{nn}. Fig. 13 shows momentum-space distributions for Ru+Ru at 400 AMeV obtained using the IQMD transport code [13] with two extreme, but instructive, assumptions: for the left panel we used [17] $0.5 * \sigma_{nn}$ and for the right panel $5 * \sigma_{nn}$ (σ_{nn} are free-scattering cross sections from the literature). We note that the code of course applies the usual Pauli-blocking weights in the collision term [12]. This takes care of some, but not all in-medium effects.

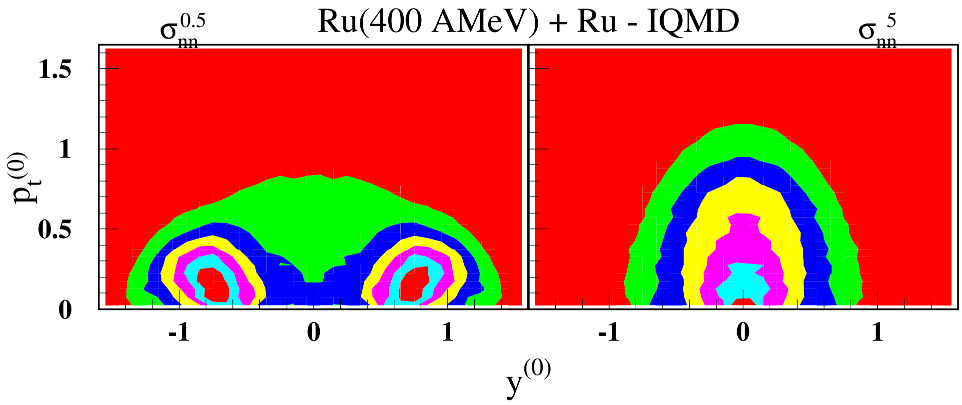

Fig. 13 Momentum space distributions in a transparency and a hydro-shock (right) scenario.

The two (impact parameter zero) cases illustrate vividly the transparent and the 'hydro-shock' alternatives. In the former case one still sees 'spectatator' sources, in contrast to experiment. In the latter case, almost instant equilibration leads to highly oblate event shapes with increased particle emission at 90° (c.o.m.): the true 'squeeze-out' predicted in the early seventies [21]. The consequences for our proton counting observable are seen in Fig. 14. In particular the hydro-shock scenario leads to a rebound, the opposite of what we observe. The data are in between the two scenarios (although closer to the 'transparent' scenario) and are in impressive agreement with IQMD predictions using the nominal σ_{nn} (solid curve). It is important to realize that only a *fraction* of the flow-creating pressure expected from ideal hydrodynamics is achieved in a heavy ion collision! This makes the experimental determination of the EOS a very difficult, very subtle task.

Finally,let me give special credit for the work presented here to A. Andronic, P. Crochet, B. de Schauenburg, Y. Leifels, and, of course, F.Rami.

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