SYSTEM SIZE AND ISOSPIN EFFECTS IN CENTRAL HEAVY-ION COLLISIONS AT SIS ENERGIES [a]

Fouad RAMI

Institut de Recherches Subatomiques, IN2P3-CNRS, Université Louis Pasteur
B.P.28, F-67037 Strasbourg Cedex 2, France

for the FOPI Collaboration

IPNE Bucharest, CRIP Budapest, LPC Clermont-Ferrand, GSI Darmstadt, FZ-Rossendorf Dresden, Universität Heidelberg, ITEP Moscow, KI Moscow, University of Seoul, IReS Strasbourg, University of Warsaw, RBI Zagreb

1 INTRODUCTION

Much interest has been devoted, for the last two decades, to the investigation of the bulk properties of hot and dense nuclear matter produced in energetic heavy-ion collisions. Despite the tremendous progress accomplished so far [1], the dynamical collision process is not yet sufficiently understood to extract unambiguous information on the fundamental properties of nuclear matter and the underlying equation of state. Further studies both experimentally and theoretically are therefore still needed. In this context, a large systematic study of different symmetric reactions has been achieved recently with the FOPI detector [2] at the SIS accelerator of GSI-Darmstadt, where different entrance channel parameters (the size of the system, its isospin and the beam energy) were varied. The production of intermediate mass fragments (IMFs) and the degree of equilibration attained during the collision were among the main aspects of interest. By varying the size of the interacting nuclei, one can explore the influence of phenomena like stopping, compression and decompression on the formation of IMFs, which is expected to be particularly important in central collisions [3]. A deep understanding of the mechanism of IMF production, the so-called "multifragmentation", is of special interest as it might be related to the possible occurence of a liquid-gas phase transition in finite nuclear systems. Using, on the other hand, different combinations of equal mass projectile and target nuclei which differ only by their isospin content, one can investigate the degree of mixing of projectile and target nucleons. This offers a very promising method to probe the question of whether or not a global equilibrium is reached during the collision, which is the basic assumption in applying statistical concepts to describe the dissociation of the nuclear system. This issue is also of high interest in a microscopic approach of the collision process as the degree of mixing

[a] Presented at 14^{th} Winter Workshop on Nuclear Dynamics, Snowbird, Utah, 31 Jan - 7 Feb 1998

of projectile and target nucleons is expected to be particularly sensitive to the elementary in-medium interactions [4].

2 MULTIFRAGMENT DECAY OF THE NUCLEAR FIREBALL : SOURCE SIZE DEPENDENCE

The production of IMFs in energetic heavy-ion collisions is currently the object of intensive experimental and theoretical investigations. This is motivated by the fact that the underlying mechanism might result in a liquid-gas phase transition. In central collisions at beam energies of a few hundred MeV/nucleon, the production of IMFs is strongly influenced by the large amount of collective expansion energy built up into the system. The measured fragment yields were found to be systematically correlated with the collective flow energy [3,5]. Dynamical transport models [6] show that during a central collision the nuclear system is first compressed and heated and then it expands and cools down. In this approach, the reorganisation of nucleons into clusters (clusterization) takes place during the expansion and cooling stage. On the other hand, statistical models assuming a late IMF formation, at freeze-out densities of $\rho/\rho_0 \sim 1/3$ where ρ_0 is the normal nuclear matter density, can be also considered to describe the multifragment decay of the nuclear system formed in central collisions if the collective expansion motion is taken into account [5].

In the present work, we investigate the influence of expansion on fragment formation by comparing the IMF production in four different symmetric systems with masses ranging from $A_P = A_T = 58$ to 197 (A_P and A_T are the masses of, respectively, the projectile and the target nuclei). One expects, indeed, an increase of dynamical effects due to the compression-decompression process with increasing size of the interacting system. Moreover, the use of a relatively small size system (Ni+Ni) allows also to explore the surface geometry effects in the clusterization process.

The data presented here were taken in a serie of experiments performed over the last three years using the phase II setup of the FOPI detector, where four symmetric reactions, Ni+Ni, Ru+Ru, Xe+CsI and Au+Au, were measured at beam energies going from 90 A MeV to 400 A MeV. IMFs ($3 \leq Z \leq 12$) were detected in the forward wall [2] covering laboratory polar angles below 30°, corresponding to the coverage of a very large fraction of the forward center-of-mass (c.m.) hemisphere.

The collision impact parameter was estimated, in a sharp cut-off approximation, from the measured cross sections. Two centrality selection criteria were used : i) the charged particle multiplicity measured with both the forward wall and the central drift chamber [2] and ii) the ratio E_{RAT} of the sum of the transverse kinetic energies to the sum of the longitudinal kinetic energies in the forward c.m. hemisphere. The combination of these two criteria allows the coverage of a broad range of impact parameters. The first one is more appropriate for the selection of semi-central collisions, while the second is much more efficient for isolating the most central events. The reliability of this combined procedure

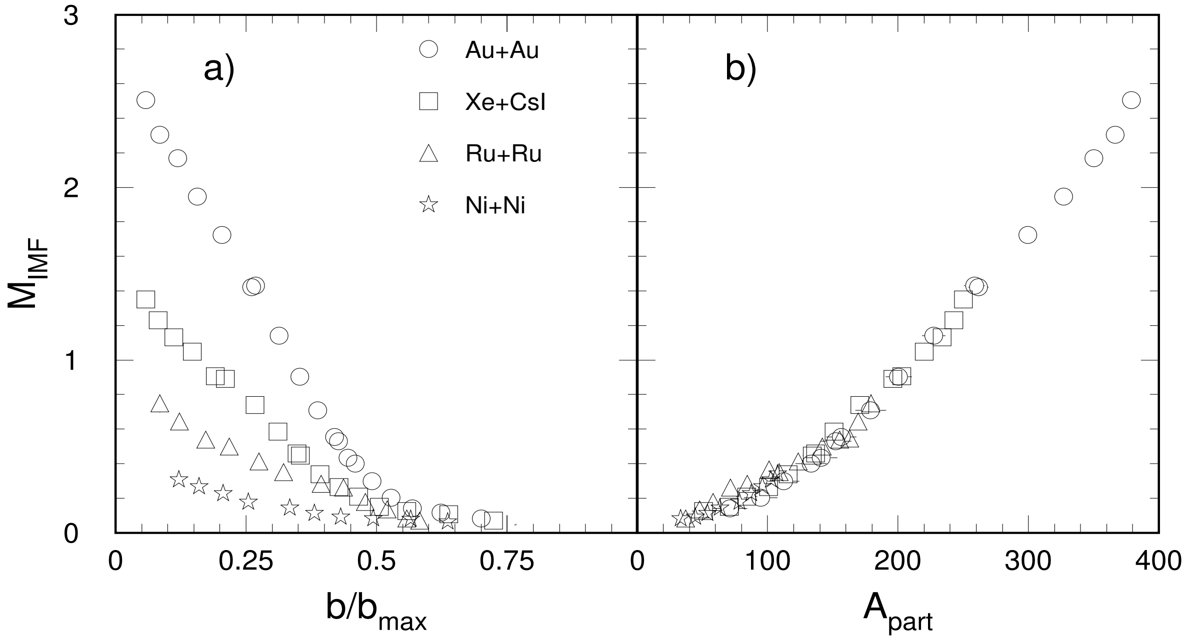

Figure 1: IMF multiplicity as a function of a) the reduced impact parameter (b/b_{max}) and b) the mass of the participant source (A_{part}). M_{IMF} were measured in the forward c.m. hemisphere and then multiplied by a factor of 2. The data are shown at the same incident energy of E/A = 400 MeV for all four reactions. Statistical uncertainties are smaller than the size of the symbols. Horizontal error bars in b) correspond to an uncertainty of 0.05 fm on the nuclear radius which was taken equal to $r_0 = 1.14 fm$.

was successfully checked [5,7] in the framework of the Quantum Molecular Dynamics model [8].

To study the emission of IMFs from the participant source formed in semi-central collisions, we have imposed a rapidity condition $|y^{(0)}| \leq 0.5$, where $y^{(0)}$ is the c.m. particle rapidity normalised to the rapidity of the projectile. Using this cut, an exponential fall off of the fragment charge distributions is obtained [9]. It is worth, on the other hand, to notice that by applying a similar rapidity condition ($y^{(0)} > 0.5$) to select the spectator component, we found [7] that the results exhibit the universal behaviour typical of the decay of the spectator matter [10,11].

Fig.1a shows the correlation between the mean multiplicity of IMFs (M_{IMF}) emitted from the participant region and the collision centrality. To allow for a direct comparison of the four measured reactions, the results are plotted as a function of the reduced impact parameter (b/b_{max}, where b_{max} is the maximum impact parameter). As can be seen (Fig.1a), one observes for all systems the expected trend characterized by a gradual decrease of M_{IMF} with increasing impact parameters. In order to see how this trend is related to the size of the participant source, we have estimated, for each reaction, the number of participant nucleons A_{part}. A_{part} at a given impact parameter was calculated from the geometrical overlap between the colliding nuclei, assuming a uniform density profile. The result, shown in Fig.1b, is spectacular. One sees that the 4 sets of experimental points overlap remarkably well if the IMF multiplicity is plotted against the average number of participant nucleons. This clearly shows, for the first time, that the IMF multiplicity scales with the size of the emitting source independently of the mass of the projectile+target system. Such an observation seems to indicate that the presence of spectator matter in semi-central collisions does not influence the production yields of IMFs in the participant region. This is consistent with the expansion-shadowing scenario which was suggested from the study of the azimuthal distributions of mid-rapidity particles [12]. Spectator remnants would, therefore, act only as shadowing objects [12,13] whose presence hinders the emission of particles in the reaction plane, favouring therefore their out-of-plane emission.

The observation in Fig.1b of a rapid increase (faster than a linear dependence) of M_{IMF} as a function of the size of the emitting source suggests that the IMF production is enhanced in heavy systems. This striking effect is clearly visible in Fig.2 where highly central collisions were selected by requiring a low directivity [3] in addition to a large E_{RAT} (> 0.7) ratio. In this figure, the average multiplicity of IMFs scaled to the charge of the emitting source is plotted against the mass of the source. The latter was considered as composed of the total mass ($A_{part} = A_P + A_T$) and charge ($Z_{part} = Z_P + Z_T$) of projectile and target. No rapidity cut was applied here as the contribution of the spectator components is low in highly central collisions. As one can see (Fig.2), $M_{IMF}/(Z_P + Z_T)$ increases with the size of the emitting source. IMF production in Au+Au is larger than in Ni+Ni by about a factor of 1.5 and 2 at, respectively, 150 A MeV and 400 A MeV. This enhanced production of IMFs in heavy systems might be attributed to stronger collective expansion and cooling effects in heavier systems. It could be also associated with the role of the "surface to volume" effect in the clusterization process.

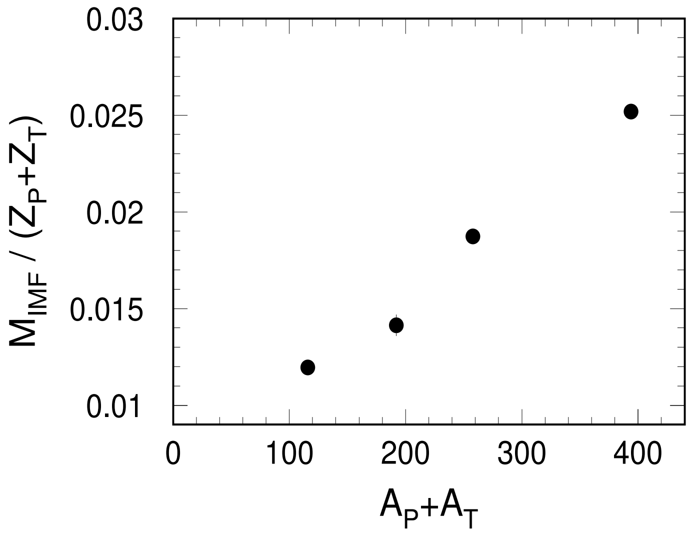

Figure 2: Normalised IMF multiplicity as a function of the mass of the interacting projectile+target system. The data are shown for highly central collisions at an incident energy of E/A = 400 MeV.

In order to examine the respective influences of the above mentioned effects on the formation of IMFs, we have compared the data to the predictions of a multifragmentation model [14] where clusters are formed in an expanding nuclear system by a coalescence mechanism. In the framework of this model, the nuclear system is considered as a finite 3-dimensional space taken as a cube subdivided into A cubic cells of equal size (A being the number of nucleons of the system). Each nucleon is placed randomly into a cubic cell. The size of the cell is fixed by the density of the system. Nucleons in this geometrical configuration are subjected to a random thermal motion, assuming a common temperature, and a collective expansion motion with a linear velocity profile. They are interacting by means of two body short and long range potentials [14]. The cluster recognition is based on bond criteria for pairs of neighbouring particles. One calculates the relative energy between two neighbouring nucleons. If this relative energy is negative then the two nucleons are bound into a cluster, otherwise they remain free. In practical calculations, there are three input parameters in the model : the temperature T of the system, its density ρ and the mean collective expansion energy E_{coll}. We assumed that IMFs are formed in a late stage of the collision when the density is relatively low ($\rho/\rho_0 = 1/3$). The temperature and the mean collective energy were adjusted to reproduce, respectively, the experimental fragment charge distribution and the measured mean kinetic energies [7]. Detector cuts were taken into account by filtering the calculations through the acceptance of the FOPI apparatus [2]. For Au+Au central collisions at a beam energy of E/A = 150 MeV, the best agreement between data and model predictions was obtained for $T = 14MeV$ and $E_{coll} = 20AMeV$.

The mean IMF multiplicities measured in central collisions of Ni+Ni, Xe+CsI and Au+Au at 150 A MeV are compared in Fig.3 to the results of two different calculations. The dotted curve was obtained using the same values of $T = 14MeV$ and $E_{coll} = 20AMeV$ for all three reactions. As can be seen, the theoretical predictions fail to reproduce the data although a slight reduction of the normalised IMF multilpicities from heavy to light systems is predicted by the calculations. The predicted reduction of IMFs in light reactions is due to geometrical effects since only the size of the system changes in these calculations. Light systems have a larger surface to volume ratio which leads to a stronger suppression of IMFs on the surface.

In order to reproduce the data (dashed curve in Fig.3), we had to adjust the model parameters (T and E_{coll}) independently for each reaction. The extracted values of T and E_{coll} are depicted in Fig.4 as a function of the mass of the interacting system. Going from heavy to light reactions, the temperature increases while the collective energy decreases. It follows therefore that in the framework of the present calculations, the relative suppression of IMFs observed in light systems is mainly due to the fact that the fraction of the total c.m. energy which is converted into the collective expansion motion increases with increasing size of the interacting system. As we will see in the next section, stopping of projectile and target nuclei might not be complete in light systems. Such an effect should be, therefore,

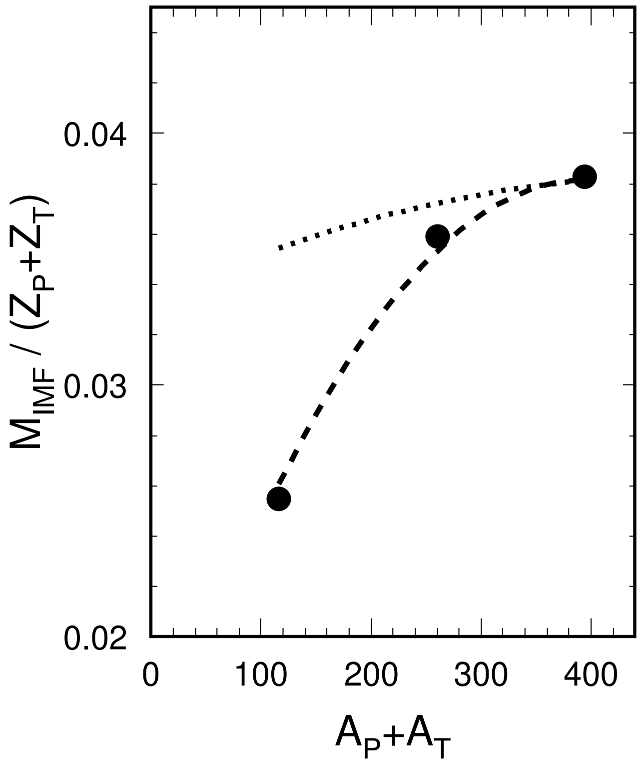

Figure 3: Normalised IMF multiplicity as a function of the mass of the interacting projectile+target system. The data are shown for highly central collisions at an incident energy of E/A = 150 MeV. The curves are two different predictions of a multifragmentation model [14] (see text for more details).

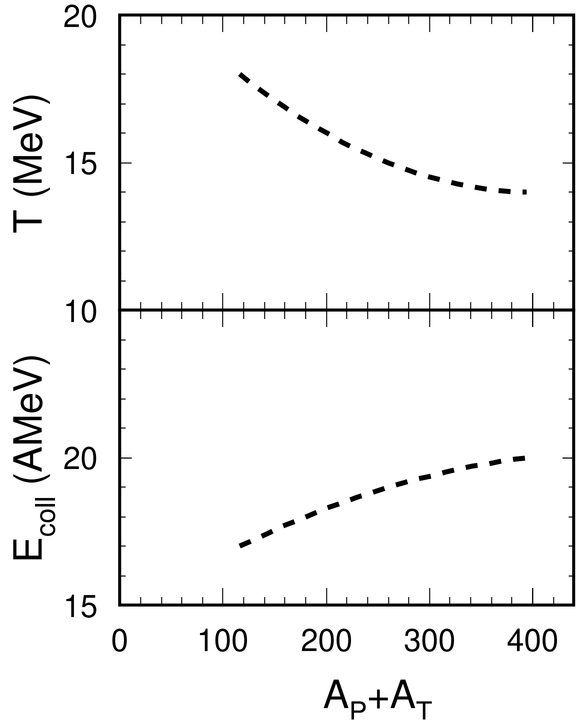

Figure 4: Temperatures and mean collective energies leading to the best agreement between data and model calculations (dashed curve in Fig.3).

considered in more elaborated interpretations of the data.

This simple static model seems to reproduce surprisingly many features seen in the data providing a possible explanation for the observed suppression of IMFs in light systems. It should be very interesting to pursue these studies by confronting our data to the outcome of microscopic transport models where the collision dynamics, the degree of stopping and the reorganisation process of nucleons into clusters are intimately connected.

3 ISOSPIN ASYMMETRY AS A DIRECT EXPERIMENTAL PROBE FOR GLOBAL EQUILIBRIUM

In the calculations discussed in the preceding section, we have considered IMF formation in an idealized thermalized system made up of all initial projectile and target constituents, disregarding therefore any form of preequilibrium emission. The latter effect may, however, play an important role in particular at high bombarding energies [15]. On the other hand, the shape of the rapidity distributions measured for IMFs in central Au+Au collisions was found to be compatible with a complete stopping, while the data from a lighter system (Ni+Ni) suggests a sizeable transparency effect [16].

This raises the longstanding question to know whether the colliding nuclear system attains a full thermo-chemical equilibrium during the collision process. Up to now, this crucial question was examined only on the basis of comparisons of experimental data to global equilibrium model predictions. Here, we report on a direct experimental method to test one of the prerequisite conditions for global equilibrium, namely the complete chemical mixing of projectile and target nucleons. The idea relies on the investigation of different combinations of equal mass projectile and target nuclei which differ only by their isospin content. This was investigated recently by Bass et al [4] within the framework of Quantum Molecular Dynamics model calculations.

The data presented here were obtained in an experiment performed recently at SIS/ESR-Darmstadt, using the phase II configuration of the FOPI apparatus. Taking advantage from the availability of the ^{96}Ru and ^{96}Zr nuclei both as projectile and target, we have measured the four projectile/target combinations : ^{96}Ru beam on ^{96}Ru target, ^{96}Zr beam on ^{96}Zr target, ^{96}Ru beam on ^{96}Zr target and ^{96}Zr beam on ^{96}Ru target. $^{96}_{44}Ru$ and $^{96}_{40}Zr$ nuclei were chosen for their large isospin difference; the N/Z ratio is equal to 1.18 and 1.40 for $^{96}_{44}Ru$ and $^{96}_{40}Zr$, respectively. The experiment was carried out at two bombarding energies of 400 A MeV and 1580 A MeV. Here we focus only on the 400 A MeV data. Those at the higher energy are not yet completely analysed. By measuring all four reactions under the same experimental conditions, one can eliminate the systematic errors due to detector inefficiencies and biases. The use of the two symmetric combinations ^{96}Ru on ^{96}Ru and ^{96}Zr on ^{96}Zr is essential for calibration purposes. The investigation of both mixed reactions,

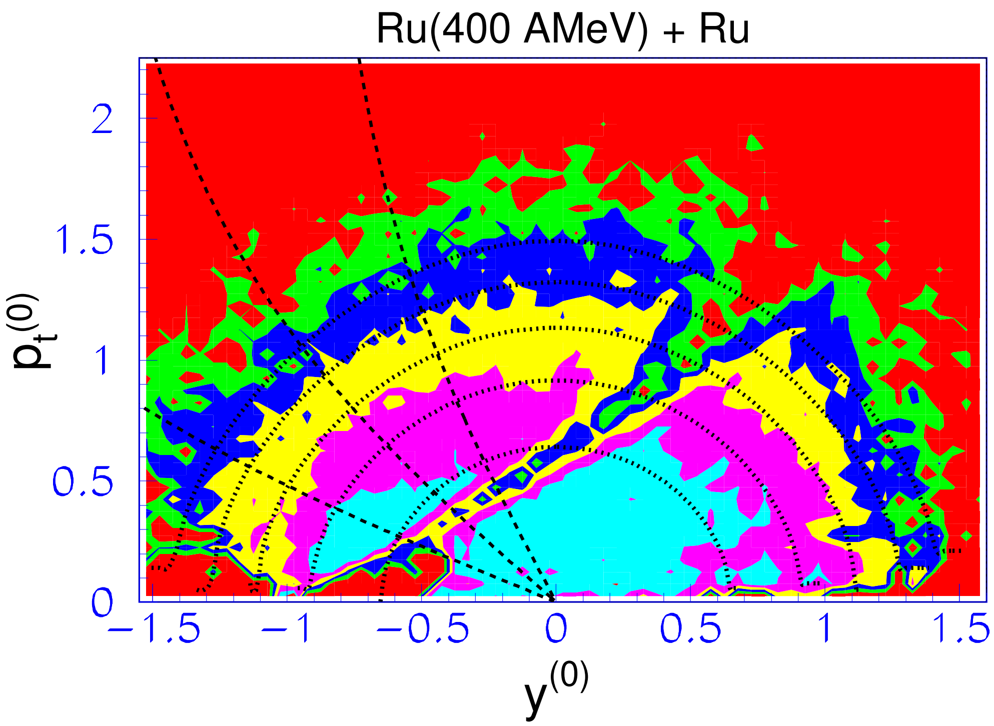

Figure 5: Invariant cross section in the ($p_t^{(0)}$, $y^{(0)}$) plane of p-like particles under the $E_{RAT} > 0.7$ centrality cut. The different grey levels correspond to different logarithmic cuts in the invariant cross section. The curves show different c.m. polar angle limits. The circles correspond to constant c.m. energies per nucleon : 40, 80, 120, 160 and 200 AMeV.

which are physically identical, allows one to check the consistency of the method.

The calculations of Bass et al [4] were presented in terms of the neutron to proton ratio, which is not measurable within our setup. Instead, we consider here another observable, i.e. the proton-like multiplicity (M_p) in different regions of the phase space, which is also sensitive to the isospin asymmetry and the way projectile and target nucleons interpenetrate and mix each with others. Keeping constant the mass of projectile and target nuclei, the number of proton-like particles should correlate with the charge (or the isospin) of the emitting source. If the emission occurs from the projectile (or the target) then the multiplicity of p-like particles must be related to the charge of the projectile Z_P (or the target Z_T). This would correspond to a transparency or a rebound scenario. In the other extreme situation where the emittor is a chemically equilibrated single source, then one expects that the p-like multiplicity should be correlated with the charge of the total initial system ($Z_{TOT} = Z_P + Z_T$) and independent of that of the projectile and target nuclei.

Fig.5 shows a typical distribution of the invariant cross section of p-like particles emitted in central collisions in the "$p_t^{(0)}$ versus $y^{(0)}$" representation[b]. Central collisions were selected eventwise by requiring an $E_{RAT} > 0.7$ cut corresponding to about 2% of the total

[b] $p_t^{(0)}$ is the particle transverse momentum normalised to the projectile momentum and $y^{(0)}$ is the particle c.m. rapidity scaled to the projectile rapidity.

reaction cross section. The observed event shape is nearly isotropic which seems to point to a high degree of stopping. The accuracy in the measurements of relative p-like multiplicities is illustrated in Fig.6. The multiplicity of p-like particles was extracted by including only $Z = 1$ and $Z = 2$ particles which constitute a very large fraction of the nuclear matter emitted in highly central collision at the bombarding energy under investigation (E/A = 400 MeV). The distributions plotted in Fig.6 include all p-like particles detected in the backward c.m. hemisphere. As expected, the Ru+Ru ($Z_P = Z_T = 44$) distribution is shifted towards higher multiplicities with respect to the one measured for Zr+Zr ($Z_P = Z_T = 40$). Furthermore, the ratio of the measured mean values $< M_p^{Ru} > / < M_p^{Zr} >= 1.095$ is very close to the value of 1.1 (= 44/40) that one would expect if the experimental conditions, within the covered phase space region, do not change from one system to another. It is also interesting to point out that the results for the two other mixed reactions (not shown in the figure) lie in between those of Ru+Ru and Zr+Zr.

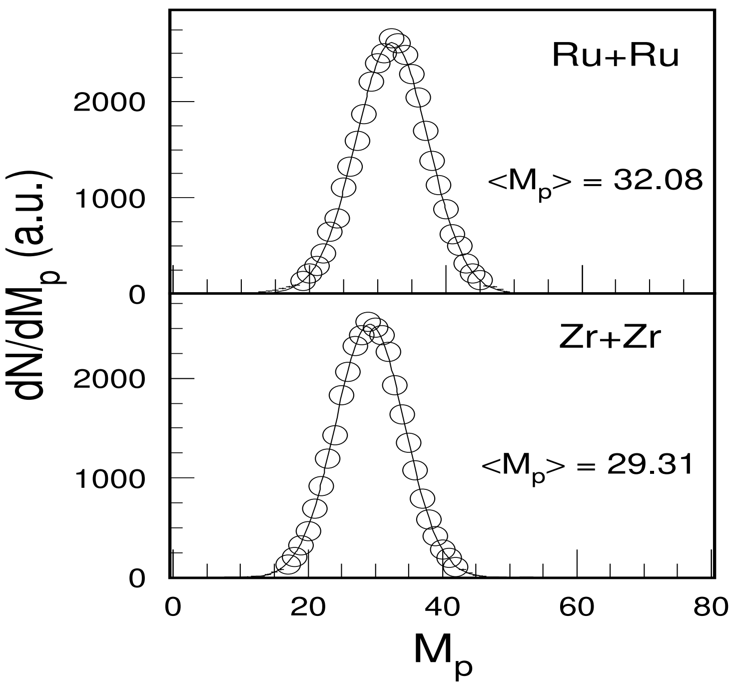

Figure 6: p-like multiplicity (M_p) distributions. M_p is the number of p-like particles per event detected in the backward hemisphere within the FOPI acceptance. The data are shown for both Ru+Ru and Zr+Zr reactions, under the cut $E_{RAT} > 0.7$. The mean values are indicated in the figure.

In order to facilitate the comparison between the experimental results obtained for all four systems, we introduce the relative ratio R defined for a given reaction, with a mean p-like multiplicity M_p, as :

$$R = (2 \times M_p - M_p^{Zr} - M_p^{Ru})/(M_p^{Zr} - M_p^{Ru})$$

where M_p^{Zr} and M_p^{Ru} are the mean p-like multiplicities of, respectively, Zr+Zr and Ru+Ru symmetric reactions.

By definition, the ratio R takes $+1$ for the Zr+Zr reaction and -1 for the Ru+Ru reaction. In the case of the mixed systems, the value of R will depend on the underlying physics scenario. If the emission occurs from a fully chemically equilibrated fireball, then one should find R close to 0 for both mixed reactions. In a transparency scenario the value of R for Zr(beam) on Ru(target) is expected to be close to $+1$ and -1 in, respectively, the forward ($y^{(0)} > 0$) and backward ($y^{(0)} < 0$) c.m. hemispheres; while the one of Ru(beam) on Zr(target) is expected to take -1 and $+1$ in, respectively, the forward and backward c.m. hemispheres. A rebound scenario would correspond to an inverted situation as compared to the one described above for transparency.

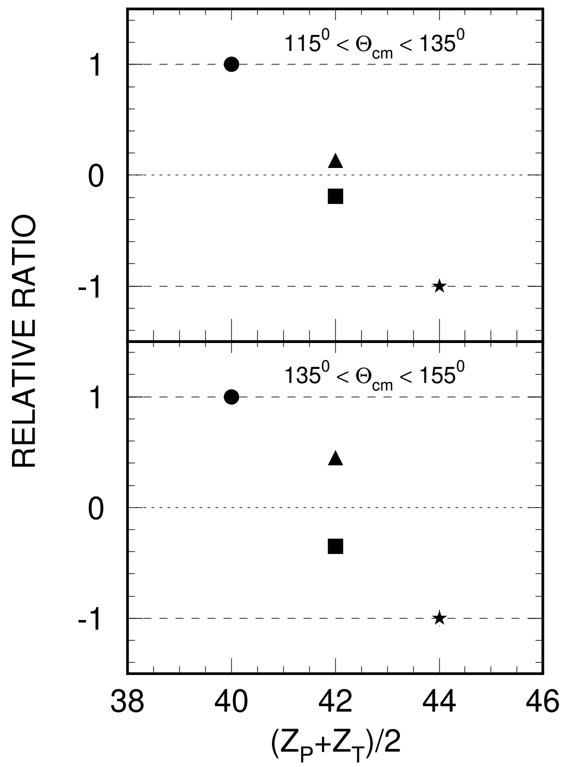

Figure 7: Relative ratio R (defined in the text) as a function of half the total charge of the "projectile+target" system. R is shown in two different phase space regions. Circles : Zr on Zr; squares : Zr on Ru; triangles : Ru on Zr and stars : Ru on Ru. The error bars correspond to statistical uncertainties only. The systematic errors are, within the acceptance of the detector, eliminated thanks to the use of the same experimental setup for all four reactions.

The results are shown in Fig.7, where the relative ratio R is plotted as a function of half the total charge ($Z_P + Z_T/2$), in two phase space regions (see Fig.5). In the upper part, polar c.m. angles between 115° and 135°, were selected. In this region where the contribution of spectator is expected to be negligeable, the relative ratio R is found to be nearly the same for both mixed reactions and very close to the value $R = 0$ corresponding to a full mixing of the projectile and target nucleons. This clearly indicates that the nuclear matter in this phase space region does not keep a memory of the initial projectile/target composition. Similar conclusions were also drawn from an analysis of the same data in terms of the $t/^3He$ ratio [17].

Going towards more backward angles (lower part of Fig.7), one sees that the relative ratio, for the two mixed systems, strays significantly from the equilibrium point with opposite signs for both reactions. The value of R for Ru on Zr is positive, while the one for the inverted reaction (Zr on Ru) is negative. Such an observation is compatible with a transparency effect, where some of the projectile (target) nucleons are not stopped by the target (projectile).

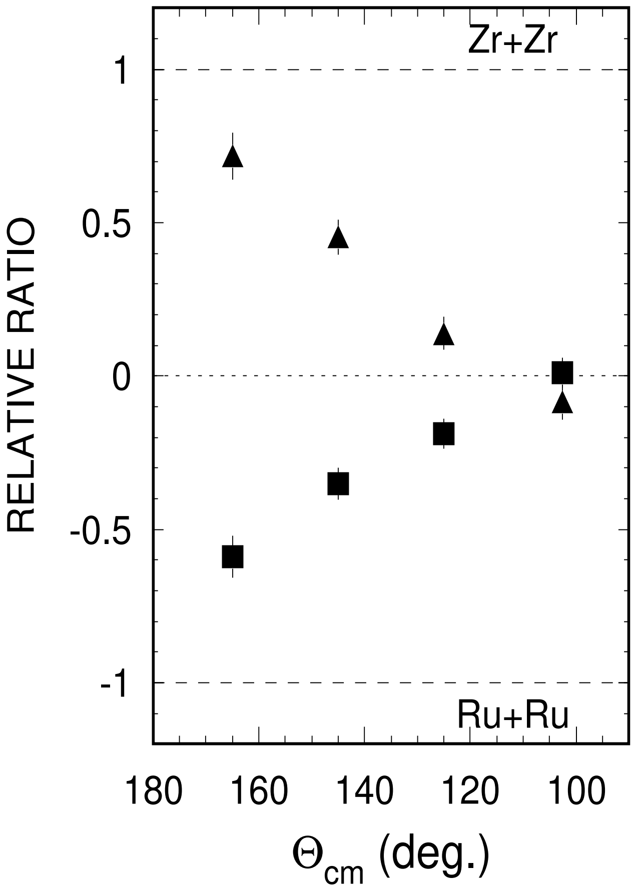

Figure 8: Relative ratio R as a function of the c.m. polar angle in the backward hemisphere. Squares : Zr on Ru and triangles : Ru on Zr.

Fig.8, showing the θ_{cm} dependence of the relative ratio, evidences much better the manifestation of non-equilibrium effects in these reactions. Indeed, one observes a clear gradual increase of the ratio R when going from the most central "equilibrated" phase space part to the region where spectator matter is expected to be present. Again, the transparency scenario is reinforced by the observation of positive and negative R values for, respectively, Ru on Zr and Zr on Ru reactions. A rebound effect would lead to the opposite trend.

The impact parameter dependence of the relative ratio in the region around the target rapidity is depicted in Fig.9. Two important observations can be made : i) The ratio R decreases with increasing centralities which confirms the sensitivity of the method and ii) Even in the most central collisions, one still observes a significant transparency effect.

Thus the experimental observations reported above reveal an incomplete mixing of projectile and target nucleons even in the case of the most central collisions. This observation

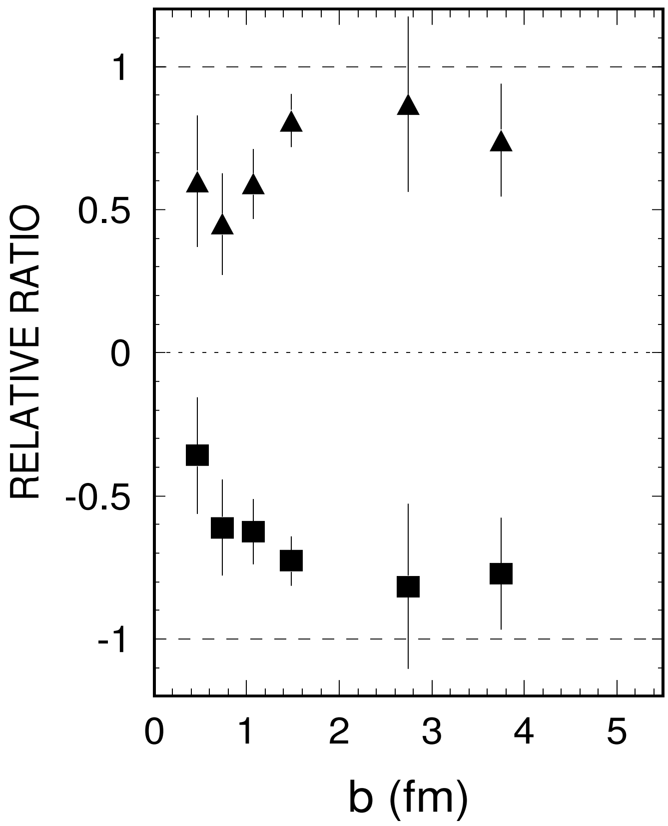

Figure 9: Relative ratio R as a function of the collision impact parameter. The data are shown in the phase space region delimited by $-1.2 \leq y^{(0)} \leq -0.8$ and $0.2 \leq p_t^{(0)} \leq 0.6$ (see Fig.5). Squares : Zr on Ru and triangles : Ru on Zr.

calls into question the applicability of statistical concepts to describe the disassembly of the nuclear fireball and underscores the importance of non-equilibrium effects. Furthermore, the availability of such data should enable us to put constraints on the in-medium nucleon-nucleon cross section [4]. It will be, therefore, very interesting to confront these experimental results with the outcome of dynamical transport models.

4 SUMMARY AND CONCLUSIONS

We have presented new results from the FOPI experiment at SIS/ESR. The main emphasis was placed on two aspects : the IMF emission from the hot and dense participant region and the degree of equilibration reached during the collision.

The IMF yields in the participant region were found to scale with the size of the emitting source independently of the mass of the initial "projectile+target" system. This observation suggests that in semi-central collisions the multifragment decay of the hot and dense central region is not significantly influenced by the presence of the spectator remnants. We have also shown that the production of IMFs is reduced in light systems. An analysis within the framework of a simple multifragmentation model [14] allowed us to attribute this suppression effect to the influence of the collective expansion motion which decreases going from heavy to light systems.

We have reported, on the other hand, on a recent experiment where four different reactions using different combinations of ^{96}Ru and ^{96}Zr nuclei both as target and projectile were measured at an incident energy of 400 A MeV. It was shown that, within the context of this experiment, the measurements of relative proton-like multiplicities can provide a direct quantitative measure of the degree of mixing of projectile and target nucleons. The first experimental results reveal sizeable transparency effects even in the case of the most central collisions.

Acknowledgments

It is a pleasure to thank all members of the FOPI Collaboration. Most of the results presented in this paper are extracted from the Ph.D. thesis of Béatrice de Schauenburg. The author wishes also to thank Jean Richert and Pierre Wagner for valuable and inspiring discussions.

References

[1] See, for example, Proceedings of the "International Research Workshop on Heavy-Ion Physics at Low, Intermediate and Relativistic Energies using 4π Detectors" Poina-Brasov, Romania, World Scientific Publishing Co., 1997, edited by M.Petrovici, A.Sandulescu, D.Pelte, H.Stöcker and J.Randrup.

[2] A. Gobbi et al., Nucl. Inst. Meth. A 324 (1993) 156.

[3] S.C. Jeong et al., Phys. Rev. Lett. 72 (1994) 3468.

[4] S. Bass, et al, GSI annual report 1994, p.66.

[5] W. Reisdorf et al., Nucl. Phys. A612 (1997) 493.

[6] J. Aichelin, Phys. Rep. 202 (1991) 233.

[7] B. de Schauenburg, Thesis, Strasbourg, France (1998) and to be published.

[8] C. Hartnack et al., submitted to Z. Phys.A.

[9] C. Kuhn et al., Phys. Rev. C48 (1993) 1232.

[10] A. Schüttauf et al, Nucl.Phys. A607 (1996) 457.

[11] W. Trautmann, these proceedings.

[12] P. Crochet et al., Nucl. Phys. A624 (1997) 755.

[13] F. Rami for the FOPI Collaboration, in the same Proceedings as in reference 1, p.160.

[14] B. Elattari et al, Nucl.Phys. A592 (1995) 385.

[15] W. Neubert et al. for the FOPI Collaboration, in the same Proceedings as in reference 1, p.176.

[16] G.S. Wang et al., GSI annual report 1996, p.50.

[17] Y. Leifels et al., GSI annual report 1997.