PROBING THE DEGREE OF EQUILIBRATION ATTAINED IN RELATIVISTIC HEAVY-ION COLLISIONS[1]

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Abstract

We present a method to extract direct experimental information on the degree of equilibration reached in central heavy-ion collisions. The proposed method relies on a new type of high precision measurement which makes use of the isospin (N/Z) degree of freedom. The N/Z is used as a tracer to attribute the measured nucleons (on average) either to the target or to the projectile nucleons. Results for Ru(Zr)+Zr(Ru) reactions at 400A MeV show that the global equilibrium is not reached even in the most central collisions. Quantitative measures of stopping and mixing are extracted. They are found to exhibit a quite strong sensitivity to the in-medium (n,n) cross section used in microscopic transport calculations.

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I. Introduction

The degree of projectile-target equilibration is one of the key questions in understanding the complex reaction mechanisms governing central heavy-ion collisions at relativistic energies. This question has profound implications on the theoretical concepts used to describe the collision process. It is still an open question whether the widely applied, at least local if not global, equilibrium assumption is valid [1, 2], or whether significant non-equilibrium effects rather require the application of more elaborated non-equilibrium dynamical models [2, 3, 4]. This issue of equilibration is expected to be influenced by in-medium effects (such as Pauli blocking, Fermi motion) on the 'hard' scattering processes, by early 'soft' deflections in the momentum-dependent mean fields, and by finite-size (corona) effects. An understanding of all these effects is a prerequisite for a quantitative extraction of the equation-of-state (EOS) from nucleus-nucleus collisions.

At relativistic energies (0.1 to 2.0 AGeV), experimental investigations of the degree of equilibration were concentrated, up to now, on the measurement of the phase space distributions of the reaction products. Observables of interest were the width of rapidity distributions [3, 5] or the overall shape of the source [6, 7]. The sensitivity of such observables is however reduced by effects like rescattering during the late phase of expansion.

In the present work, we have designed an experimental method to explore directly, in a model independent approach, the degree of projectile-target equilibration achieved during the collision. The proposed method relies on a new type of high precision measurement which makes use of the isospin (N/Z) degree of freedom. The N/Z is used as a tracer to attribute the measured nucleons (on average) either to the target or to the projectile nucleons. This idea has been applied in an experiment [8] performed recently with the FOPI apparatus, where we have measured all the four combinations of $^{96}_{44}$Ru and $^{96}_{40}$Zr nuclei, both as projectile and target, at the same incident energy of 400A MeV.

After a brief description of the experimental conditions and the criteria used to select central collisions, we will introduce the new tracer method and the observables extracted from the experiment. Then, we will report on the experimental results and we will discuss them in the framework of the Isospin Quantum Molecular Dynamics (IQMD) model [9].

II. Experimental conditions and event selection

Four different combinations of $^{96}_{44}$Ru and $^{96}_{40}$Zr nuclei, both as projectile and target, were investigated at the heavy-ion synchrotron SIS at GSI-Darmstadt using the FOPI

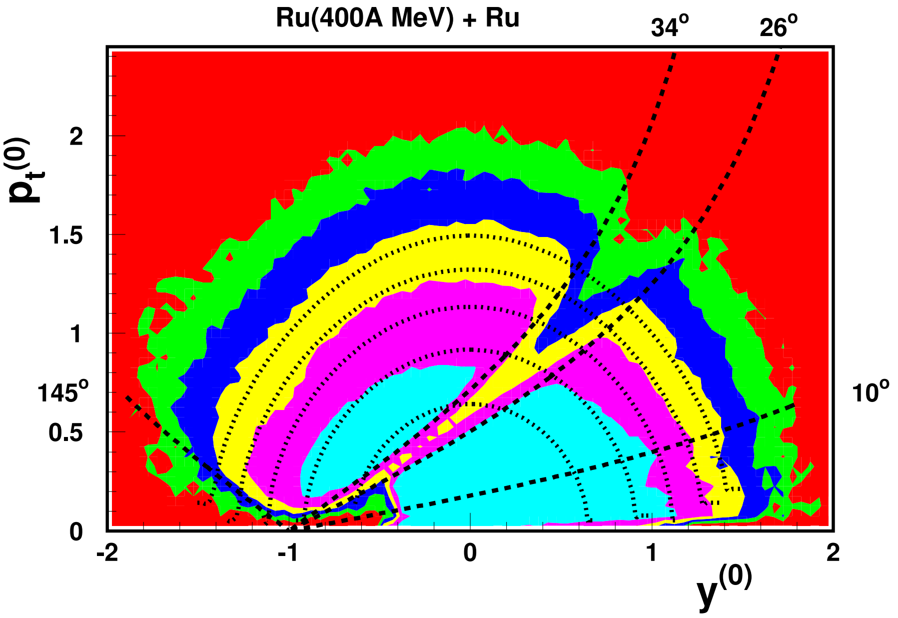


Figure 1: *Invariant cross section in the* $(y^{(0)}, p_t^{(0)})$ *plane of* $Z = 1$ *particles measured in the CDC and the TOF-wall, under the* $E_{\rm RAT} > 1.4$ *centrality cut.* $y^{(0)}$ *is the normalized rapidity,* i.e. *the particle* c.m. *rapidity divided by the projectile rapidity in the* c.m. *system.* $p_t^{(0)}$ *denotes the normalized transverse momentum,* i.e. *the particle transverse momentum per nucleon divided by the* c.m. *projectile momentum per nucleon. The grey levels correspond to different logarithmic cuts in the invariant cross section. The dashed lines show the acceptance of the CDC* ($34° < \theta_{\rm lab} < 145°$) *and the HELITRON* ($10° < \theta_{\rm lab} < 26°$) *detector components. The circles correspond to constant* c.m. *energies per nucleon: from the inner to the outer, 40, 80, 120, 160 and 200A MeV.*

apparatus [10, 11]. All four reactions were measured at the the same bombarding energy of 400A MeV

The reaction products were detected at forward angles by the TOF-wall and the HELITRON drift chamber and at backward angles by the Central Drift Chamber (CDC). Particles of interest in the present work were: i) tritons and ^{3}He emitted at laboratory angles $10° < \theta_{\rm lab} < 28°$, identified by combining the TOF-wall and the HELITRON and ii) protons and deuterons emitted at backward angles ($34° < \theta_{\rm lab} < 145°$), identified by the CDC. These particles constitute a large fraction of the emitted charge, about 40%, 30%, 10% and 10% for p, d, t and ^{3}He, respectively.

Central collisions were selected using the E_{RAT} criterion [6, 7, 12], i.e. the ratio of the sum of the transverse kinetic energies to the sum of the longitudinal kinetic energies. E_{RAT} is determined event wise by including all detected particles: $E_{\mathrm{RAT}} = \sum_{\mathrm{i}=1}^{\mathrm{M}} E_{\mathrm{t}}^{\mathrm{i}} / \sum_{\mathrm{i}=1}^{\mathrm{M}} E_{\mathrm{l}}^{\mathrm{i}}$, where $E_{\mathrm{t}}^{\mathrm{i}}$ and $E_{\mathrm{l}}^{\mathrm{i}}$ are the transverse and longitudinal kinetic energies of the particle i and M is the number of detected particles. It was shown in previous works [7, 12], that by requiring large E_{RAT} values one can isolate samples of highly central events. The $E_{\mathrm{RAT}} > 1.4$ cut used here corresponds to about 1.5% of the total reaction cross section and to a geometrical impact parameter $b_{\mathrm{geom}} \leq 1.3$ fm in a sharp-cut-off approximation.

Fig.1 shows that the events selected under the $E_{\mathrm{RAT}} > 1.4$ condition exhibit, in a representation of center-of-mass (c.m.) rapidity versus transverse momentum, a nearly isotropic source for the observed hydrogen ($Z = 1$) products. This is in agreement with previous observations [5, 6, 7, 13].

III. (N/Z)-ratio as a probe for the degree of equilibration

III.1 The (N/Z)-tracer method

The method relies on the investigation of reactions between colliding nuclei with the same mass but different isospin content. We have measured all the four combinations of $^{96}_{44}$Ru and $^{96}_{40}$Zr nuclei: $^{96}_{44}$Ru on $^{96}_{40}$Zr, $^{96}_{40}$Zr on $^{96}_{44}$Ru, $^{96}_{44}$Ru on $^{96}_{44}$Ru and $^{96}_{40}$Zr on $^{96}_{40}$Zr. The choice of Ru and Zr isotopes takes advantage of an almost unique possibility offered by the periodic table of stable isotopes, while searching for two isobars of the largest possible N/Z difference (the N/Z ratio is equal to 1.18 and 1.40 for $^{96}_{44}$Ru and $^{96}_{40}$Zr, respectively) which can be used both as projectile and target. The bombarding energy ($400A$ MeV) was chosen at the minimum of the (n,n) cross section where the relative motion is significantly larger than the Fermi motion, but sufficiently low to avoid inelastic (n,n) channels, while the (n,n) angular distribution is almost isotropic.

Let us first introduce the main idea of the (N/Z)-tracer method. Assume that we are observing the final number of protons, Z in a given cell of the momentum space. The expected yield Z^{Ru} measured for the Ru+Ru reaction is higher than Z^{Zr} of the Zr+Zr reaction since Ru has 44 protons as opposed to 40 for Zr. Such measurements using identical projectile and target deliver calibration values Z^{Ru} and Z^{Zr} for each observed cell. In the case of a mixed reaction, Ru+Zr or Zr+Ru, the measured proton yield Z takes values intermediate between the calibration values (Z^{Ru}, Z^{Zr}). If e.g. Z is close to Z^{Ru} in a Ru+Zr reaction, means that the cell is populated predominantly from nucleons of the Ru-projectile while if it is close to Z^{Zr} it is mostly populated from nucleons of the Zr-target. In this way it is possible to trace back the relative abundance of target to

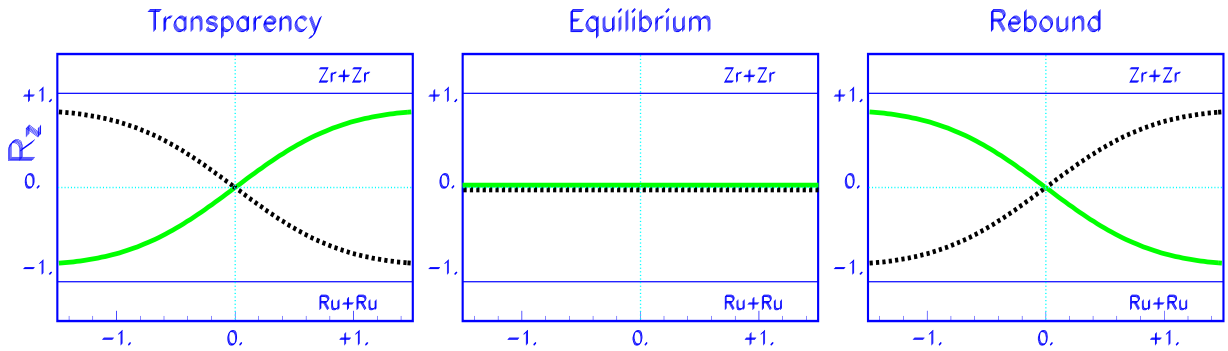


Figure 2: *Relative abundance R_Z as a function of the normalized* c.m. *rapidity. The curves illustrate the trends expected for the mixed reactions: Ru+Zr (dashed) and Zr+Ru (full). Three different scenarios are shown: transparency, equilibrium and rebound.*

projectile nucleons contributing to a given cell.

The following definition for the relative abundance of the projectile-target nucleons has been adopted:

$$R_Z = \frac{2 \times Z - Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}}{Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}} \tag{1}$$

By definition the ratio R_Z takes +1 for Zr+Zr and −1 for Ru+Ru. Fig.2 illustrates the expected dependences of R_Z as a function of the c.m. rapidity. In the case of full equilibrium in a mixed reaction, R_Z would be equal to 0 (equal number of projectile and target nucleons) everywhere independently of the location of the cell in the phase space. Note that 'equilibrium' means here the complete mixing of projectile and target nucleons. In a transparency scenario the value of R_Z for Zr(beam) on Ru(target) is expected to be positive in the forward ($y^{(0)} > 0$) c.m. hemisphere and negative in the backward ($y^{(0)} < 0$) c.m. hemisphere; while for the other mixed reaction Ru(beam) on Zr(target) one expects negative values in the forward region and positive values in the backward region. A rebound scenario would correspond to an inverted situation as compared to the one described above for transparency.

The (N/Z)-tracer method presents several important advantages:

- The four reaction combinations are investigated, under identical experimental conditions so that the ratios are insensitive to systematic uncertainties due to the apparatus. The errors are essentially of statistical nature and profit from the high yield in the considered cell.

- The mixed reaction Zr+Ru is the same as Ru+Zr except that target and projectile are inverted: this allows forward-backward cross-checks of the apparatus which in addition can also be obtained from the symmetric Ru+Ru and Zr+Zr reactions.
- Using the four reactions the full information needed can be obtained by measuring only within the c.m. backward or only the c.m. forward hemisphere.

III.2 Experimental evidence for non-equilibrium effects

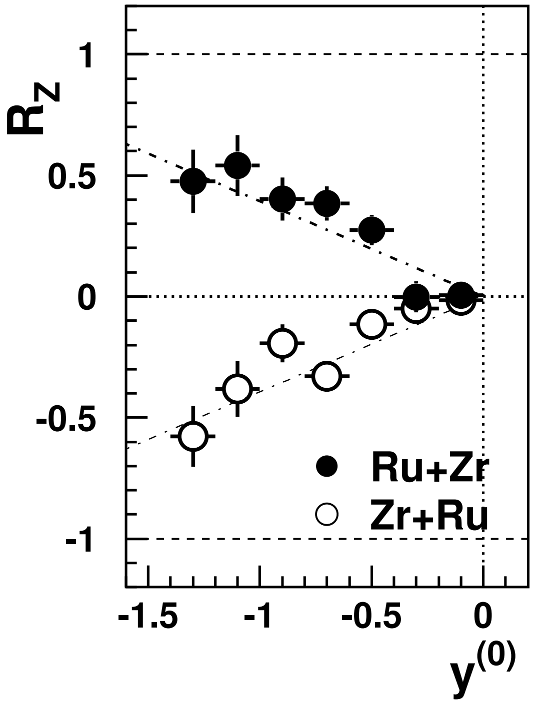
Fig.3 shows the relative abundance R_Z extracted from the data in the case of highly central collisions ($E_{RAT} > 1.4$). The R_Z-ratio is obtained according to equation (1) with Z being the sum of the number of detected free protons plus the number of protons detected within the deuterons. The experimental results are presented in the backward c.m. hemisphere. In this backward region, the influence of background due to the oxygen content of the (ZrO_2) target is negligible.

It is interesting to notice that the inversion of projectile and target changes, as expected, the sign of the R_Z-values; besides that both results agree within errors. Note also that at $y^{(0)} = 0$, one observes for both mixed reactions a value of R_Z close to 0 as expected in this rapidity region where projectile and target nucleons must be completely mixed. All these observations accredit the reliability of the (N/Z)-tracer method and its sensitivity.

As can be seen in Fig.3, the method allows us to map the degree of mixing between projectile and target nucleons across a large region of the phase space. The results show clearly a substantial departure from the expected trend for a complete mixing scenario (indicated by the horizontal dotted line in Fig.3). They are consistent with the presence of sizeable transparency effects.

This evidence for non-equilibrium effects is also observed in Fig.4a which shows the centrality dependence of the R_Z-ratio. Here, data are presented within a wide c.m. rapidity range: $-0.75 \leq y^{(0)} \leq -0.25$. The impact parameter $b_{\rm geom}$ is derived by integrating over the measured cross section as a function of E_{RAT} or of the charged particle multiplicity. The observed trend corroborates the picture of an incomplete mixing between projectile and target nucleons which persists up to the end of the collision, an observation that holds even for the most central collisions, for $b_{\rm geom} \to 0$. Note on the other hand that, as expected, the magnitude of transparency effects increases with increasing impact parameters.

Figure 3: *Relative abundance R_Z as a function of the normalized* c.m. *rapidity. The experimental results are shown for both isospin asymmetric reactions Ru+Zr (full circles) and Zr+Ru (open circles) in the case of highly central collisions. The error bars correspond to statistical uncertainties. The horizontal dashed lines indicate the values of $R_Z = +1$ and -1 corresponding to the isospin symmetric reactions Zr+Zr and Ru+Ru, respectively.*



Similar conclusions can be also drawn from the inspection of Fig.4b. Here the relative abundance ratio is extracted from another observable, the ratio of tritium to ^{3}He (t/^{3}He), which is also sensitive to the N/Z ratio. The t/^{3}He ratio was measured in the forward c.m. hemisphere using HELITRON and TOF-wall profiting from a good time-of-flight particle identification [10, 11]. The quantity $R_{\mathrm{t}/^3\mathrm{He}}$ is defined in a similar way as for R_{Z}, using equation (1) with Z being replaced by the t/^{3}He ratio. Except for an off-set of $R_{\mathrm{t}/^3\mathrm{He}} = -0.27 \pm 0.07$ for the t/^{3}He-ratio, one observes qualitatively the same trend as for the R_{Z}-ratio. Such an off-set can be understood from a non-linear dependence of the t/^{3}He ratio as a function of isospin. We find that, for $N > Z$, an empirical dependence of the t/^{3}He ratio of $[1 + 100 \times \left(\frac{N-Z}{N+Z}\right)^{2.5}]$ describes the known systematics [14] and satisfies the measured off-set of -0.27.

Fig.5 displays the overall rapidity-density distribution $\mathrm{d}N/\mathrm{d}y^{(0)}$ measured in central Ru+Ru collisions. This distribution (circles in Fig.5) was obtained by extrapolating the measured transverse momentum spectra, within the backward detector acceptance, using the thermal blast model proposed by Siemens and Rasmussen [15]. The forward part of the distribution (open circles) was deduced by assuming a backward/forward symmetry.

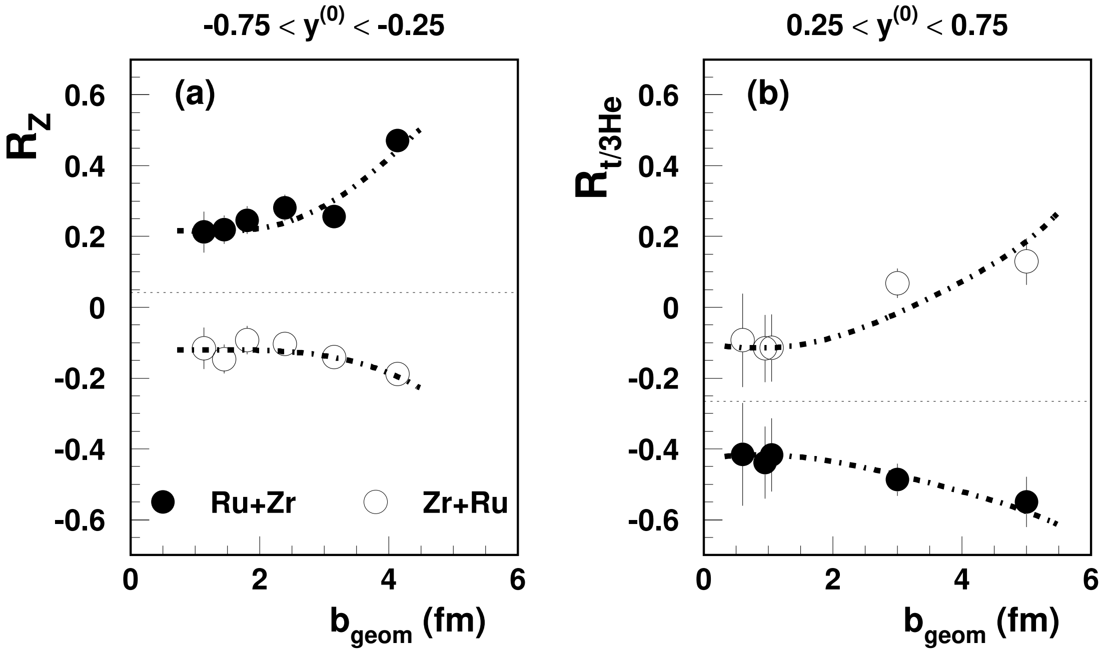


Figure 4: *R_Z (left panel) and $R_{t/^3He}$ (right panel) as a function of the geometrical impact parameter. They are determined in the* c.m. *rapidity range $-0.75 \leq y^{(0)} \leq -0.25$ and $0.25 \leq y^{(0)} \leq 0.75$, respectively. The horizontal dotted lines correspond to the values ($R_Z = 0.04$ and $R_{t/^3He} = -0.27$) at halfway between the Ru+Zr and Zr+Ru experimental points in the $b_{geom} \leq 1.5$ fm region. The dotted-dashed lines are just to guide the eye.*

As stated before, the R_Z-ratio gives a measure of the relative abundance of projectile and target nucleons. This can be used to deconvolute the overall rapidity distribution into separated distributions for the projectile and for the target nucleons. For this purpose we use the dashed-dotted line ($\pm 0.393\ y^{(0)}$) in Fig.3 which describes an average of both measurements for Ru+Zr and Zr+Ru reactions. For each rapidity bin, the number of projectile (target) nucleons is obtained as $N_{pr} = 0.5\ (1 + 0.393\ y^{(0)})\ N$ ($N_{tr} = 0.5\ (1 - 0.393\ y^{(0)})\ N$).

After deconvolution of the overall $dN/dy^{(0)}$ distribution, a shift between the two deduced rapidity distributions (see Fig.5) emerges, demonstrating that a memory of the initial target-projectile translatory motion survives throughout a central collision. Transparency effects are clearly visible here with more projectile nucleons in the forward c.m. hemisphere and more target nucleons in the backward c.m. hemisphere.

In order to characterize with few numbers the information contained in the separated projectile (or target) distribution, we define the following quantities:

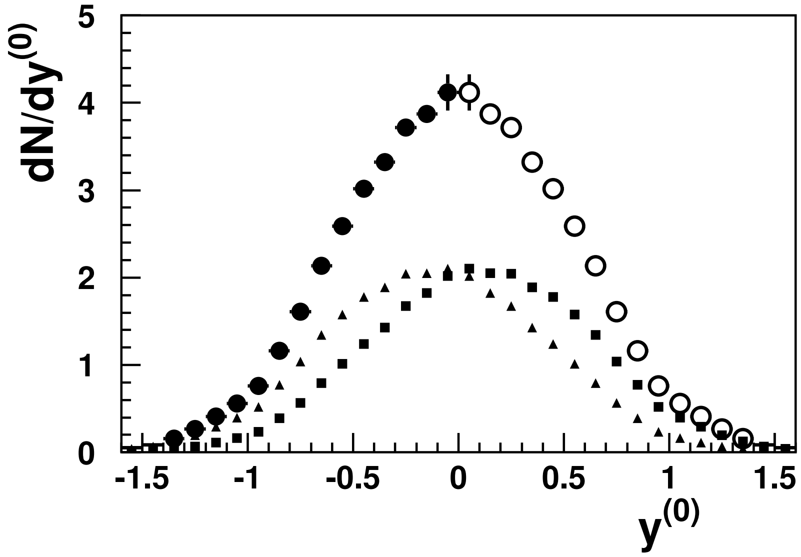


Figure 5: *Experimental* c.m. *rapidity distribution (circles) of protons, free plus those detected within the deuterons, in central Ru+Ru collisions. Data points in the backward hemisphere (full circles) were obtained from the CDC detector. Those in the forward region (open circles) were obtained by assuming a backward/forward symmetry. The two other distributions have been obtained by unfolding the overall distribution into 'projectile' (squares) and 'target' (triangles) components.*

- A shift $\langle y^{(0)}_{\rm pr}\rangle$ of the mean value with respect to mid-rapidity; $\langle y^{(0)}_{\rm pr}\rangle = 0$ corresponds to full stopping and full thermo/chemical equilibrium, while $\langle y^{(0)}_{\rm pr}\rangle = 1$ corresponds to the initial projectile rapidity without any stopping; positive values of $\langle y^{(0)}_{\rm pr}\rangle$ are expected for transparency, negative values for a backward rebound of the projectile nucleons from the target.

- A mixing value $M_{\rm pr} = (N_f - N_b)/(N_f + N_b)$, where N_f is the number of projectile nucleons emitted forward and N_b backwards; $M_{\rm pr}$ is a measure of non-equilibrium effects.

- A width of the unfolded distribution, $\sigma_{\rm pr}$.

These quantities provide a quantitative information of the strength of the non-equilibrium effects. This is, as we will see in the next section, very convenient in order to

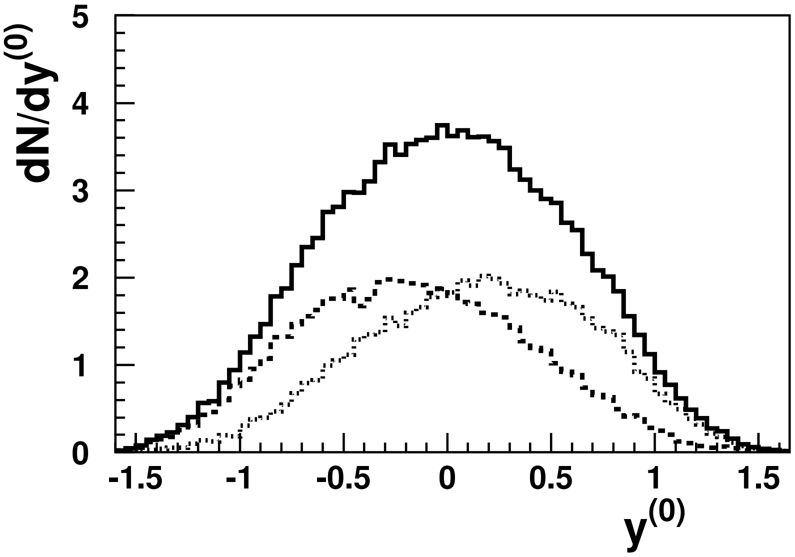


Figure 6: *Calculated* c.m. *rapidity distribution (solid histogram) of nucleons emitted in central ($b \leq 1fm$) Ru(400A MeV)+Ru collisions. The two other distributions have been obtained by tagging projectile (dotted) and target (dashed) nucleons in the model.*

discuss the experimental results within the framework of theoretical models.

IV. Comparison to IQMD model predictions

We have compared the data to the predictions of the IQMD-model [9]. The latter is a version of the Quantum Molecular Dynamics (QMD) model [1, 3] which takes into account isospin degrees of freedom into the cross sections and the Coulomb interaction. Calculations were made using a stiff EOS, with a compressibility coefficient $K = 380$ MeV, and momentum dependent interactions (MDI). The impact parameter was limited to $b \leq 1fm$, a condition similar to the centrality selection applied to the data.

Fig.6 shows the rapidity-density distributions predicted for the Ru(400A MeV)+Ru reaction. The separated distributions were obtained here by tagging [16] the projectile and target nucleons in the calculations. As can be seen in the figure, the model also predicts a sizeable transparency: there is no complete overlap of the projectile and rapidity distributions. The predictions are in qualitative agreement with the data (Fig.5).

	tagged	N/Z-tracer	N/Z-tracer + filter
$\langle y_{\mathrm{pr}}^{(0)} \rangle$	0.16	0.15	0.15
σ_{pr}	0.55	0.55	0.56
M_{pr}	0.23	0.22	0.21

Table 1: *Mean value $\langle y_{\mathrm{pr}}^{(0)} \rangle$, width σ_{pr} of the projectile rapidity distribution (in $y^{(0)}$ units) and mixing observable M_{pr} calculated for the Ru+Ru reaction using the IQMD model (see text for more details).*

Before going to more quantitative comparisons with the data, it is interesting to examine, within the model, the reliability of the (N/Z)-tracer method. To this end, we compare in Table 1 the values obtained by applying the (N/Z)-tracer method to those extracted directly from the projectile rapidity distribution obtained by tagging the nucleons in the model. As can be seen (Table 1), the results of both calculations are very similar. This confirms clearly the validity of the (N/Z)-tracer method. Moreover, the effect of the detector filter (last column in Table 1) is found to be negligible. This is due to the fact that the method relies on relative quantities.

Calculations using different model parameters are presented in Table 2 together with the experimental results. As can be seen, both observables $\langle y_{\mathrm{pr}}^{(0)} \rangle$ and M_{pr} exhibit a quite strong sensitivity to the in-medium (n,n)-cross section ($\sigma_{\mathrm{nn}}^{\mathrm{med}}$) used in the calculations. A reduction of 50% of the (n,n)-cross section ($\sigma_{\mathrm{nn}}^{\mathrm{med}} = 0.5 \times \sigma_{\mathrm{nn}}^{\mathrm{free}}$) leads to an increase of both $\langle y_{\mathrm{pr}}^{(0)} \rangle$ and M_{pr} by about a factor of 2. This strong sensitivity to $\sigma_{\mathrm{nn}}^{\mathrm{med}}$ was also reported recently in the framework of different microscopic transport approaches [16, 17]. It is also interesting to notice in Table 2 that MDI effects act against equilibration: HM parametrization gives larger values of $\langle y_{\mathrm{pr}}^{(0)} \rangle$ and M_{pr} as compared to those obtained with the H parametrization. On the other hand, the influence of the stiffness of the EOS is found to be very weak: HM and SM calculations lead, within statistical uncertainties, to the same results.

The best agreement with the data is obtained for a value of $\sigma_{\mathrm{nn}}^{\mathrm{med}}$ slightly higher, by about 20%, than the free (n,n)-cross section ($\sigma_{\mathrm{nn}}^{\mathrm{free}}$). This indicates that, within this model, a significant modification of the (n,n)-cross section in the nuclear medium is to be excluded.

	data	IQMD HM $\sigma_{\rm nn}^{\rm free}$	HM $0.5\times\sigma_{\rm nn}^{\rm free}$	HM $1.2\times\sigma_{\rm nn}^{\rm free}$	H $\sigma_{\rm nn}^{\rm free}$	SM $\sigma_{\rm nn}^{\rm free}$
$\langle y_{\rm pr}^{(0)}\rangle$	0.11	0.16	0.33	0.11	0.10	0.16
$\sigma_{\rm pr}$	0.52	0.55	0.59	0.54	0.52	0.56
$M_{\rm pr}$	0.17	0.23	0.43	0.16	0.15	0.22

Table 2: *Comparison between data and different IQMD model predictions. Systematic errors on the values of $\langle y_{\rm pr}^{(0)}\rangle$ and $M_{\rm pr}$ extracted from the data are about 10%. IQMD calculations are obtained by tagging projectile and target nucleons in the model. HM stands for a hard equation-of-state and momentum dependent interaction; H stands for a hard equation-of-state without momentum dependent interaction and SM stands for a soft equation-of-state ($K = 200$ MeV) and momentum dependent interaction. $\sigma_{\rm nn}^{\rm free}$ is the free (n,n) cross section (default value in the model).*

V. Summary and conclusion

In this contribution, we have reported on a new method to explore experimentally the degree of equilibration reached in central heavy-ion collisions. The proposed method relies on a new type of high precision measurement which makes use of the isospin degree of freedom. This idea has been applied in an experiment performed recently with the FOPI apparatus, where we have measured all the four combinations of ${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr nuclei, both as projectile and target, at the same incident energy of $400A$ MeV.

We have shown that using this method one can extract information on the relative abundance between projectile and target nucleons. By doing so, the degree of mixing between projectile and target nucleons was mapped over a broad portion of the phase space. The results clearly indicate that the global equilibrium is not reached even in the most central collisions. They are consistent with the presence of sizeable transparency effects. This evidence for non-equilibrium effects has been observed from the analysis of two different experimental observables: the number of measured protons and the t/^{3}He ratio.

The (N/Z)-tracer method allowed us to deconvolute the experimental rapidity-density distribution $\mathrm{d}N/\mathrm{d}y^{(0)}$ into separated distributions for the projectile and for the target nucleons. Quantitative measures of stopping and mixing were extracted from the separated rapidity distributions and the obtained values were compared to different predictions of the IQMD model. The best agreement between data and model calculations was found for a value of the (n,n)-cross section slightly higher, by about 20%, than the free (n,n)-cross section. This indicates that, within this model, a significant modification of the (n,n)-cross section in the nuclear medium is to be excluded.

In conclusion, the proposed experiment and method demonstrate a high sensitivity to non-equilibrium effects, which are found to persist up to the end of a reaction even in the most central collisions. This confirms the necessity to use non-equilibrium dynamical calculations for studies of in-medium effects and of the EOS of high density nuclear matter.

Acknowledgements

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