Isospin asymmetry as a probe of stopping and equilibration in heavy-ion collisions*

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A new experimental approach to explore the degree of equilibration reached in central heavy-ion collisions is presented. It 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 obtained from the data. Comparisons are made with microscopic transport model calculations and information on the in-medium (n,n) cross section is extracted.

1. INTRODUCTION

The study of the degree of equilibration between projectile and target nucleons is of crucial importance in understanding the complex reaction mechanisms governing central heavy-ion collisions. This issue 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 [2–4]. The degree of projectile-target 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.

Experimentally, investigations of this question 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 this contribution, we propose a new experimental method allowing to explore directly, in a model independent approach, the degree of projectile-target equilibration achieved during the collision. The 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

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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. The new N/Z-tracer method will be introduced in Section 2. Then, we will report (Section 3) on the observation of non-equilibrium effects in Ru + Zr reactions and we will discuss the experimental results in the framework of the Isospin Quantum Molecular Dynamics (IQMD) model [9]. The main conclusions will be given in Section 4.

2. 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 experiment [8,10] was performed recently at the heavy-ion synchrotron SIS at GSI-Darmstadt using the FOPI apparatus. Details about the experimental conditions can be found in ref. [11,12]. 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 projectile nucleons contributing to a given cell.

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

$$R_{\mathrm{Z}} \quad = \quad \frac{2 \times Z - Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}}{Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}} \qquad (1)$$

By definition the ratio R_{Z} takes $+1$ for Zr+Zr and -1 for Ru+Ru. 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 c.m. hemisphere and negative in the backward c.m. hemisphere; while for the other mixed reaction Ru(beam) on Zr(target) one expects negative values

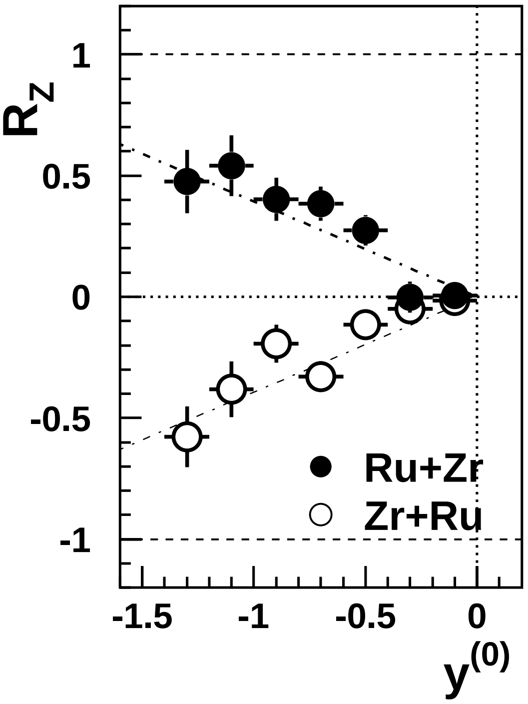

Figure 1. Relative abundance R_Z as a function of the normalized c.m. rapidity $y^{(0)}$ ($y^{(0)}$ is the particle rapidity divided by the projectile rapidity in the c.m. system). The experimental results are shown for both isospin asymmetric reactions Ru+Zr (full circles) and Zr+Ru (open circles) in 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.

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: i) 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. ii) 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. iii) 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.

3. EXPERIMENTAL EVIDENCE FOR NON-EQUILIBRIUM EFFECTS

Fig.1 shows the relative abundance R_Z extracted from the data in the case of highly central collisions corresponding to a geometrical impact parameter range $b_{\text{geom}} \leq 1.3$ fm in a sharp-cut-off approximation. The collision centrality was selected using the E_{RAT} criterion [8,10], i.e. the ratio of the sum of the transverse kinetic energies to the sum

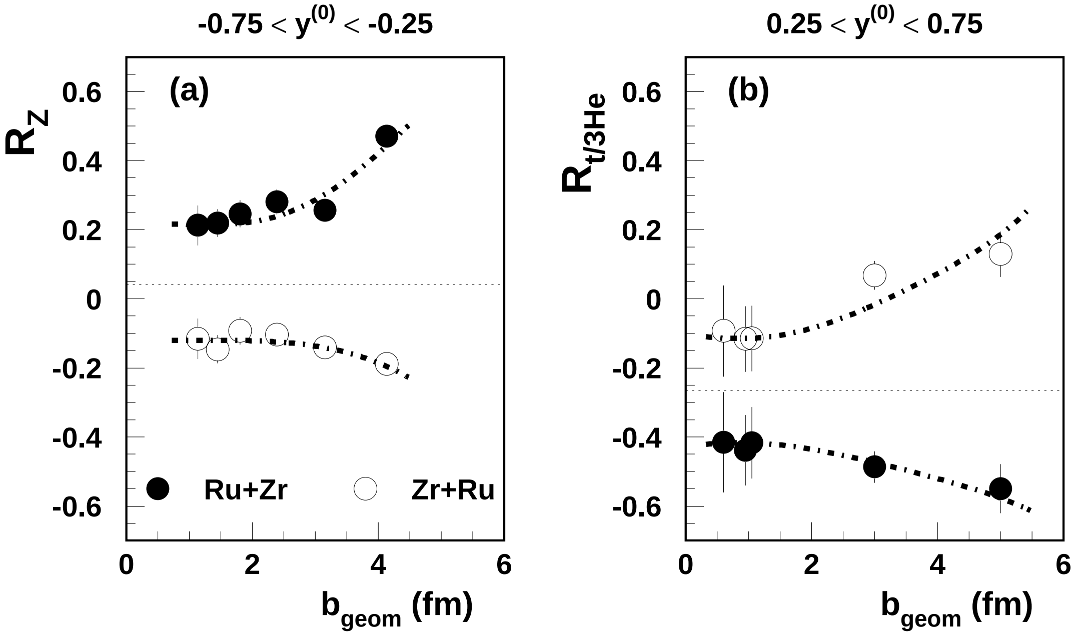

Figure 2. R_Z (left panel) and $R_{t/^3\mathrm{He}}$ (right panel) as a function of the geometrical impact parameter. The horizontal dotted lines correspond to the values ($R_Z = 0.04$ and $R_{t/^3\mathrm{He}} = -0.27$) at halfway between the Ru+Zr and Zr+Ru experimental points in the $b_{\mathrm{geom}} \leq 1.5$ fm region. The dotted-dashed lines are just to guide the eye.

of the longitudinal kinetic energies. 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 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.1, 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.1). They are consistent with the presence of sizeable transparency effects.

This evidence for non-equilibrium effects is also observed in Fig.2a 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_{geom} is derived by integrating over the measured cross section as a function of E_{RAT} or of the charged particle multi-

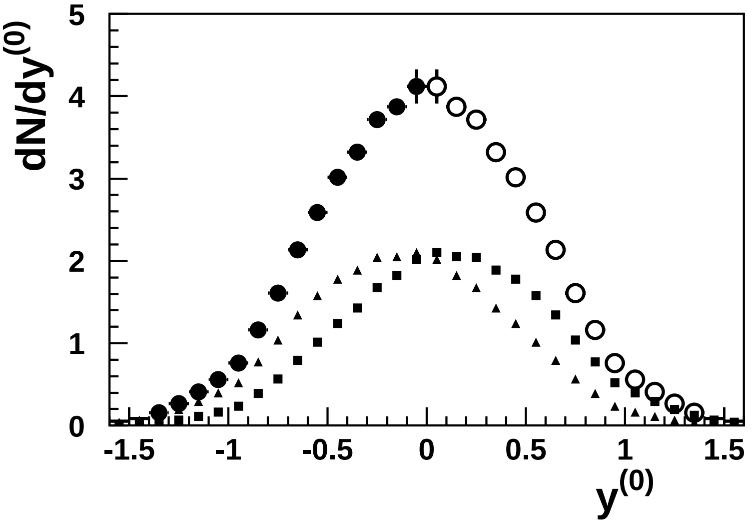

Figure 3. Experimental c.m. rapidity distribution (circles) of protons, free plus those detected within the deuterons, in central Ru+Ru collisions. Data points in the backward hemisphere (full circles) were obtained from the CDC detector. Those in the forward region (open circles) were obtained by assuming a backward/forward symmetry. The two other distributions have been obtained by unfolding the overall distribution into 'projectile' (squares) and 'target' (triangles) components.

plicity. 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 $b_{\rm geom} \rightarrow 0$. Note on the other hand that, as expected, the magnitude of transparency effects increases with increasing impact parameters.

Similar conclusions can be also drawn from the inspection of Fig.2b. 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 [11,12]. The quantity $R_{\rm t/^3He}$ is defined in a similar way as for $R_{\rm Z}$, using equation (1) with Z being replaced by the t/^{3}He ratio. Except for an off-set of $R_{\rm t/^3He} = -0.27 \pm 0.07$ for the t/^{3}He-ratio, one observes qualitatively the same trend as for the $R_{\rm Z}$-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 [13] and satisfies the measured off-set of -0.27.

Fig.3 displays the overall rapidity-density distribution dN/d$y^{(0)}$ measured in central Ru+Ru collisions. This distribution (circles in Fig.3) was obtained by extrapolating the measured transverse momentum spectra, within the backward detector acceptance, using the thermal blast model of Siemens and Rasmussen [14]. The forward part of the distribution (open circles) was deduced by assuming a backward/forward symmetry. 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.1 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 $N_{\rm pr} = 0.5\ (1 + 0.393\ y^{(0)})\ N$ ($N_{\rm tr} = 0.5\ (1 - 0.393\ y^{(0)})\ N$). After deconvolution of the overall $\mathrm{d}N/\mathrm{d}y^{(0)}$ distribution, a shift between the two deduced rapidity distributions (see Fig.3) 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.

Table 1
Comparison between data and different IQMD model predictions. Systematic errors on the values of $\langle y^{(0)}_{\rm pr}\rangle$ 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. $\sigma^{\rm free}_{\rm nn}$ is the free (n,n) cross section (default value in the model).

		IQMD				
	data	HM $\sigma^{\rm free}_{\rm nn}$	HM $0.5 \times \sigma^{\rm free}_{\rm nn}$	HM $1.2 \times \sigma^{\rm free}_{\rm nn}$	H $\sigma^{\rm free}_{\rm nn}$	SM $\sigma^{\rm free}_{\rm nn}$
$\langle y^{(0)}_{\rm pr}\rangle$	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

In order to characterize with few numbers the information contained in the separated projectile (or target) distribution, we define the following quantities: i) 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. ii) 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. iii) 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 very convenient in order to compare the experimental results to theoretical predictions. Table 1 shows such comparisons in the framework of the Isospin Quantum Molecular Dynamics (IQMD) model [9]. IQMD 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. As can be seen in Table 1, both observables $\langle y_{\rm pr}^{(0)} \rangle$ and $M_{\rm pr}$ exhibit a quite strong sensitivity to the in-medium (n,n) cross section ($\sigma_{\rm nn}^{\rm med}$) used in the calculations. A reduction of 50% of the (n,n) cross section ($\sigma_{\rm nn}^{\rm med} = 0.5 \times \sigma_{\rm nn}^{\rm free}$) leads to an increase of both $\langle y_{\rm pr}^{(0)} \rangle$ and $M_{\rm pr}$ by about a factor of 2. This strong sensitivity of mixing observables to $\sigma_{\rm nn}^{\rm med}$ was also reported recently in the framework of different microscopic transport approaches [15,16]. It is also interesting to notice in Table 1 that MDI effects act against equilibration: HM parametrization gives larger values of $\langle y_{\rm pr}^{(0)} \rangle$ and $M_{\rm pr}$ 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 $\sigma_{\rm nn}^{\rm med}$ slightly higher, by about 20%, than the free (n,n) cross section ($\sigma_{\rm nn}^{\rm free}$). This indicates that, within this model, a significant modification of the (n,n) cross section in the nuclear medium is to be excluded.

4. SUMMARY AND CONCLUSION

In this contribution, we have presented 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 this method allows the relative abundance between projectile and target nucleons to be mapped across a large domain 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. Quantitative measures of stopping and mixing were extracted from the data 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 seems to exclude a significant change of the (n,n) cross section in the nuclear medium.

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