Isospin diffusion in semi-peripheral $^{58}Ni+^{197}Au$ collisions at intermediate energies (II): Dynamical simulations

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Abstract

We study isospin effects in semi-peripheral collisions above the Fermi energy by considering the symmetric $^{58}Ni+^{58}Ni$ and the asymmetric reactions $^{58}Ni+^{197}Au$ over the incident energy range 52-74 A MeV. A microscopic transport model with two different parameterizations of the symmetry energy term is used to investigate the isotopic content of pre-equilibrium emission and the N/Z diffusion process. Simulations are also compared to experimental data obtained with the INDRA array and bring information on the degree of isospin equilibration observed in Ni + Au collisions. A better overall agreement between data and simulations is obtained when using a symmetry term which linearly increases with nuclear density.

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I. INTRODUCTION

Collisions between nuclei with different charge asymmetries may carry important information on the structure of the nuclear equation of state (EOS) symmetry term in density regions away from the normal value, that may be encountered along the reaction path [1, 2]. For instance, the symmetry energy behaviour influences reaction processes, such as fragmentation, pre-equilibrium emission, N/Z equilibration between the two collisional partners [3–11]. Among the sensitive observables, in semi-peripheral collisions, one can look at the isotopic content of light particle and IMF emission and at the asymmetry (N/Z) of the reconstructed quasi-projectiles (QP) and quasi-targets (QT) [7, 8, 12]. The degree of equilibration, that is related to the interplay between the reaction time and the typical time for isospin transport, can give information about important transport properties, such as drift and diffusion coefficients, and their relation with the density dependence of the symmetry energy.

In this paper we undertake this kind of investigations by studying isospin transport effects on the reaction dynamics in collisions with impact parameter between 4 and 12 fm. Two systems, with the same projectile, ^{58}Ni, and two different targets (^{58}Ni and ^{197}Au), are considered at incident energies of 52 AMeV and 74 AMeV. The N/Z ratio of the two composite systems is N/Z=1.07 for Ni+Ni and N/Z=1.38 for Ni+Au. The choice of the two systems and beam energies will allow us to study isospin effects in different conditions of charge (and mass) asymmetry and how they evolve as a function of the energy deposited into the system. In the symmetric Ni + Ni system isospin effects are essentially due to the pre-equilibrium emission. On the contrary, in the charge (and mass) asymmetric reactions, one can observe isospin transport between the two partners. The dependence of these mechanisms on the symmetry energy behaviour is discussed.

The paper is divided into three sections. In a first part (Section II), we describe the model used and we present the results obtained, then we discuss the role of the isospin degree of freedom on the reaction dynamics and the comparison with some experimental data (Section III). Conclusions are drawn in Section IV.

II. RESULTS OF BNV CODE

A. Evolution in phase space

We follow the reaction dynamics solving the BNV transport equation, that describes the evolution of the one-body distribution function according to the nuclear mean-field and including the effects of two-body collisions [13]. The test-particle prescription is adopted, using the TWINGO code [14]. The main ingredients that enter this equation are the nuclear matter compressibility, the symmetry energy term and its density dependence and the nucleon-nucleon cross section. Here we will consider a compressibility modulus K =200 MeV and two different prescriptions for the behaviour of the symmetry energy, in order to study the sensitivity of the results to the considered parameterization: an "asy-stiff" case for which the potential symmetry term linearly increases with nuclear density ($E_{sym}(\rho) = E_{sym}(\rho_0)(\rho/\rho_0)$), where ρ_0 is the nuclear saturation density, and an "asy-soft" case using the SKM^* parameterization which exhibits a $(\rho/\rho_0)^{0.6}$ dependence (see [5] for more details). The free nucleon-nucleon cross section with its angular, energy and isospin dependence was used. For the two reactions, we have ran different impact parameters, from b = 4 fm to b = 10 fm for the Ni+Ni system and from b = 4 fm to b = 12 fm for the Ni+Au system. For each impact parameter 10 events were produced (one event represents already the mean trajectory of the reaction), for the two cases of symmetry energy parameterization. In the following, except for figures 1 and 2, the results shown will be averaged over the 10 events for each impact parameter. This reduces the fluctuations due to the use of a finite number of test particles in the simulations. In figures 1, 2 is displayed the time evolution of density contours in the reaction plane, for two impact parameters and the two parameterizations of the symmetry energy term, asy-soft and asy-stiff .

In general the asy-stiff EOS can be linked to a more repulsive dynamics. Indeed, in this case, the system feels a stronger repulsion in the first stage of the collisions, due to the increased value of the symmetry energy above normal density. However, in proton-rich systems, the larger value of E_{sym} can lead also to a larger pre-equilibrium proton emission. Hence finally, due to lowering of Coulomb repulsion among the reaction partners, they can interact for a longer time, favouring the occurrence of dissipative mechanisms [15].

Indeed, in the 52 AMeV Ni+Ni case, at t = 80 fm/c (b = 5 fm), a more dissipative neck

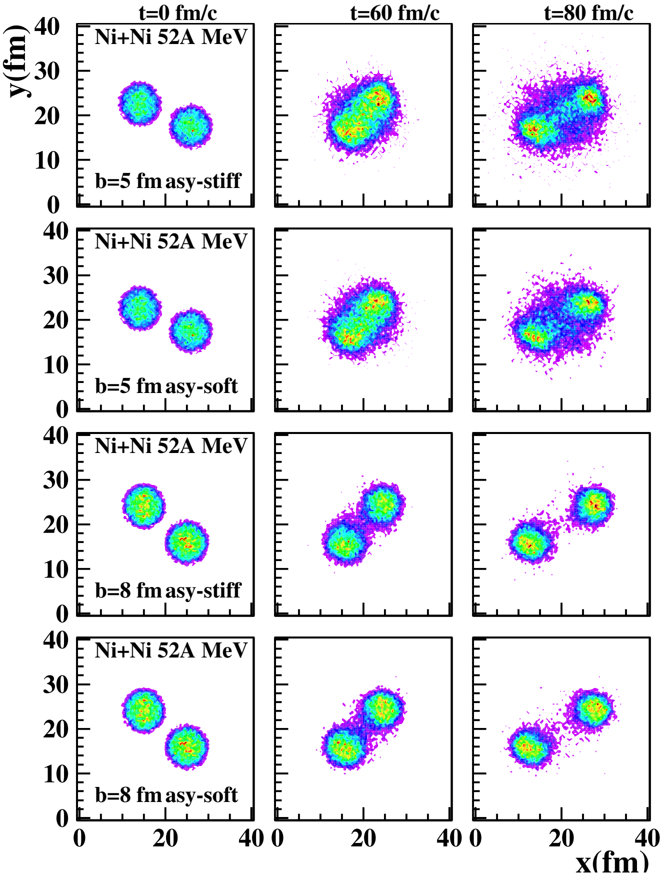

FIG. 1: (color online) Density plots for Ni+Ni collisions at 52 AMeV

dynamics is observed in the asy-stiff case. At b = 8 fm the reaction shows essentially a binary character for both EOS. Similar effects are observed for the Ni+Ni reaction at 74 AMeV. In the Ni+Au case, we face a different situation, since now the system is neutron-rich, apart from the fact that it is also asymmetric in mass and has a larger size. For neutron-rich colliding ions the asy-soft choice leads to a little more dissipative dynamics. We can see in figure 2 that at $b = 5$ fm, the reaction appears quite dissipative and it is difficult to distinguish the projectile from the target, especially in the soft case. At $b = 10$ fm, the collision is essentially binary. One can see some particles in between projectile and target regions, mostly due to pre-equilibrium emission and the two EOS give very similar results. However, in general the difference on the reaction path between the asy-soft and asy-stiff choice appears quite small and one has to explore the behaviour of other observables more sensitive to the symmetry energy.

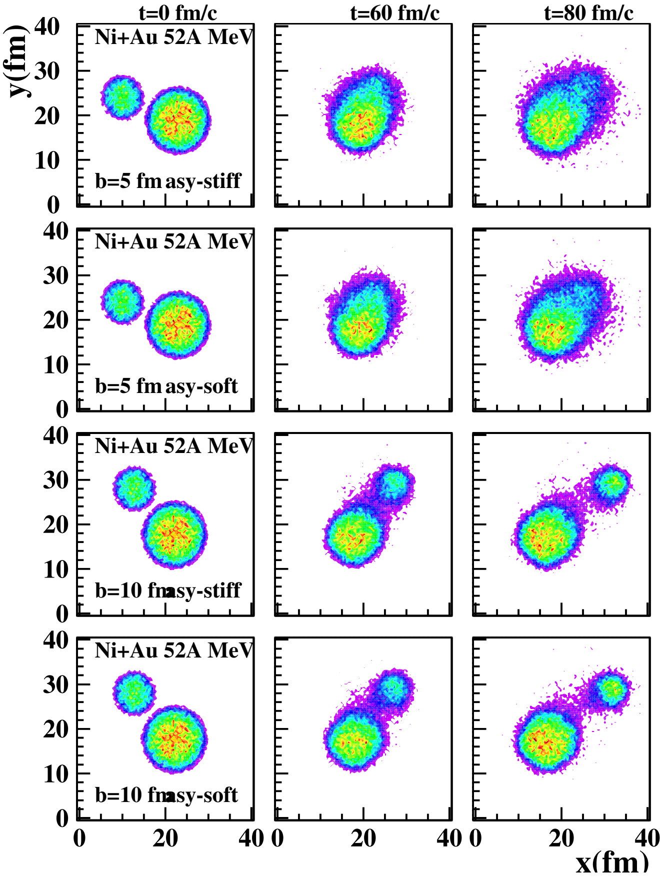

FIG. 2: (color online) Density plots for Ni+Au collisions at 52 AMeV

B. Observables

1. Mass and excitation energy of primary QP/QT

We have simulated the reactions until $t = 200$ fm/c. The properties of the two main partners of the collision are considered at the time when they re-separate after interaction. We will call this time t_{sep}. At t_{sep}, which differs for each impact parameter, QP and QT are well defined. A clusterization procedure (in $\vec{r}$ space) was used to separate the different products of the reaction [16]. Due to the mean-field approximation, only heavy fragments and IMF's can be reconstructed with this procedure in a reliable way, while the yield of complex particles is underestimated and the number of free nucleons overestimated. Thus we can obtain the mass, charge and excitation energy of the two main partners and all possible fragments. The mass and the excitation energy of QT and QP are represented in fig. 3 for the two systems, the two energies and the two choices of symmetry energy term, as a function of the impact parameter.

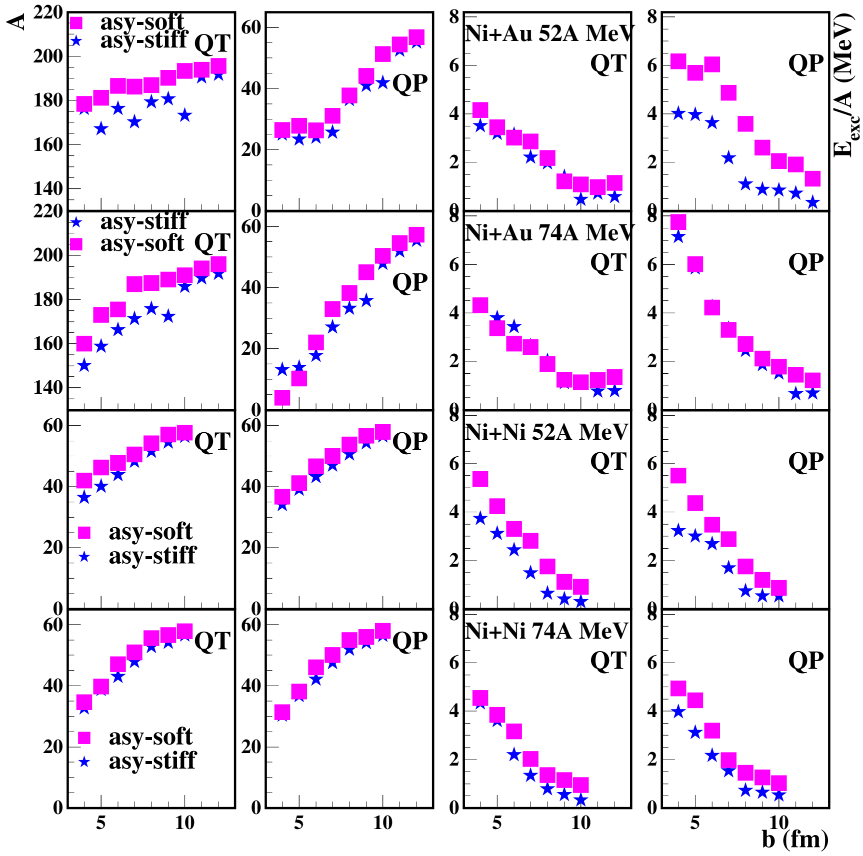

FIG. 3: (color online) Masses (columns 1 and 2, left) and excitation energy per nucleon (columns 3 and 4, right) of the quasi- target and the quasi-projectile as a function of the impact parameter, for the two reactions and the two energies. The stars correspond to the asy-stiff case and the squares to the asy-soft case.

The mass of QT and QP decreases when going towards more central collisions. This is due firstly to pre-equilibrium particle emission. Moreover, in some cases, an IMF can originate from the overlap region. For the Ni+Ni system the mass of both QP and QT is little sensitive to the choice of the interaction. On the contrary for the Ni+Au system the two equations give different results for the QT. For both incident energies the mass in the asy-soft case is higher than in the asy-stiff case. Indeed with the asy-stiff equation the production of an IMF between the two partners is more probable, with respect to the re-absorption of the neck region. This IMF comes essentially from the target; thus its emission does not affect the mass of the QP, whose mass is then independent of the chosen equation of state.

The excitation energy per nucleon of QT and QP becomes higher for central collisions in all cases. For the symmetric Ni+Ni system, the energies of the two partners are equal, as expected. They do not depend on the EOS at 74 AMeV, while they are higher with the asy-soft EOS at 52 AMeV, due to the less energetic pre-equilibrium emission in this case. In the Ni+Au system, at 52 AMeV, the excitation energies of the QP strongly depend on the EOS, indicating that more dissipation occurs in the asy-soft case. The effect is less evident on the QT side, as expected, since the percentage of nucleons involved in dissipative mechanisms (in these semi-peripheral collisions) is less for the system with the largest mass. It is interesting to notice also that, at 74 AMeV, the QT keeps almost the same value of excitation energy as the one obtained at 52 AMeV, while only for the QP an increase of excitation energy is observed for the most central collisions. At 74 AMeV the two asy-EOS lead to very similar results.

Globally, at the highest incident energy and for both systems, probably due to the shorter interaction times, no influence of the EOS appears on the excitation energies. Conversely the symmetry term does act on the excitation energies at 52 AMeV.

2. N/Z ratio of the quasi-projectile

Let us turn to isospin dependent observables, such as the N/Z ratio of the quasi-projectile. The isospin ratio of the projectile, ^{58}Ni, and of the composite Ni+Ni system is 1.07 while that of the Au target and of the Ni+Au system is respectively 1.49 and 1.38. After collision the isospin content of the QP is expected to depend on the target, remaining unchanged for the symmetric system, and lying somewhere between those of the projectile and of the composite system, depending on the interaction and the isospin equilibration times for the Ni+Au system. This observable is represented in fig. 4.

The N/Z ratio increases with the centrality of the collision for the two systems and the two energies.

For the proton-rich Ni+Ni system the variation of N/Z with centrality is small, and attributed to pre-equilibrium emission. Little dependence on the EOS appears at 52 AMeV, while N/Z grows slightly higher at 74 AMeV for the stiff case. Indeed, with a stiff EOS, more protons are emitted during the pre-equilibrium stage. This effect increases with the inci-

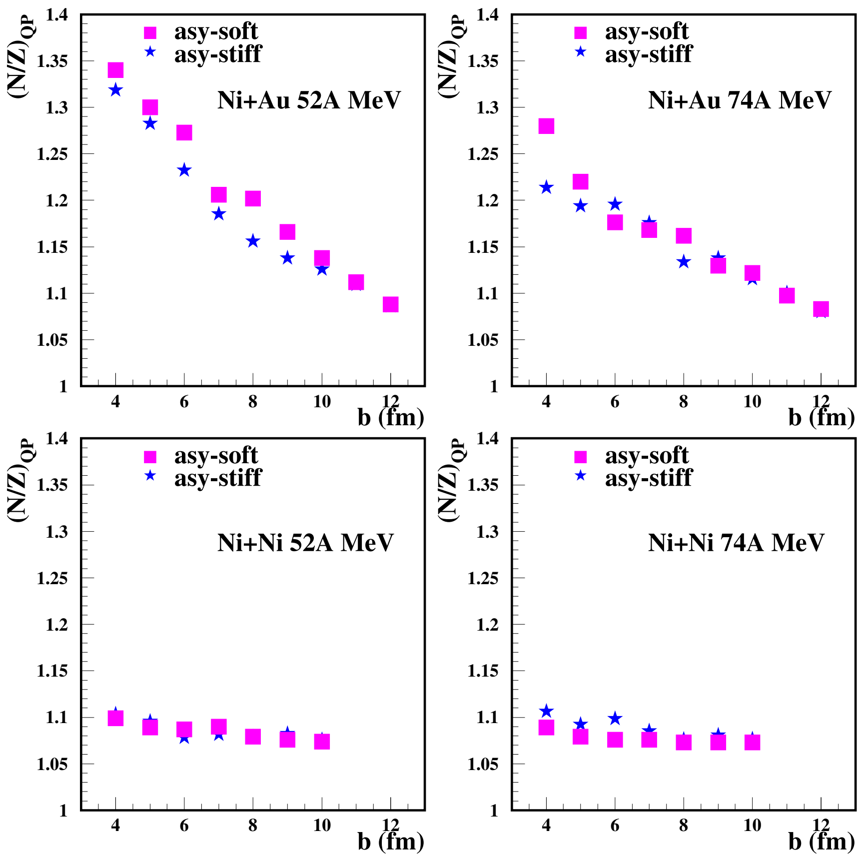

FIG. 4: (color online) Isospin ratio of the quasi-projectile as a function of the impact parameter, for the two reactions and the two energies. The stars correspond to the asy-stiff case and the squares to the asy-soft case.

dent energy. On the contrary, the asy-soft case tends to emit more preequilibrium neutrons leading to a lower N/Z ratio [17]. The evolution with centrality is much more pronounced for the neutron-rich and asymmetric Ni+Au system. In addition to pre-equilibrium effects, isospin transport takes place between the two partners of the collision, which increases with the violence of the collision. N/Z is always higher in the asy-soft than in the asy-stiff case (which is less dissipative, as seen above) for the two energies. Thus the N/Z diffusion appears related to the degree of dissipation reached in the system and to the driving force provided by the symmetry term of the nuclear EOS, that speeds up the isospin equilibration among the reaction partners [2, 7, 9]. The largest value reached, at b=4 fm, is lower at 74 AMeV than at 52 AMeV; this may be attributed to the shorter reaction times, and to the fact that the collision becomes more transparent. It must be underlined that isospin equilibration is nearly reached at the lower energy for the soft EOS, at b=4 fm. An asy-soft EOS thus favours isospin equilibration between the two partners, as found also in other recent theoretical investigations [6, 7, 9, 18].

In conclusion we can say that the effect of the EOS on the quasi-projectile N/Z content appears essentially in two ways: in an asymmetric system (Ni+Au case) the effect will be seen mostly on the isospin equilibration between the two partners of the collision, whereas for a symmetric system, the effect will react essentially on the pre-equilibrium emission.

III. COMPARISON WITH EXPERIMENTAL DATA

A. Excitation energy

In order to compare results of the present model with experimental data collected with the INDRA detector, the same sorting must be adopted [12]. The energy dissipated in the reaction was chosen, calculated in the same way as in the experimental analysis, where it is determined from the relative velocity between QT and QP. The correlation between the calculated dissipated energy normalized to the centre of mass energy - called $E_{diss}/E_{c.m.}$ in the following - and the impact parameter is displayed in fig. 5. In all cases the two quantities are strongly correlated, which confirms that E_{diss} is a good measure of the centrality of the collision. It should be stressed that a given relative dissipation $E_{diss}/E_{c.m.}$ corresponds for the different reactions to different impact parameters. The correlation does not depend much on the employed equation of state, although for the Ni+Au system a tendency towards more dissipation in the asy-soft case starts to be visible below b=5 fm. So, this sorting variable does not reflect exactly the dissipation energy deposited into the system, that, as seen in fig. 5, does depend on the asy-EOS, especially for the 52 AMeV reactions. This is due to the fact that, in the evaluation of E_{diss} , the effects of pre-equilibrium emission are neglected.

With the help of the dissipated energy E_{diss} as a sorting variable, the behaviour of some observables can be followed versus the violence of the collision. For comparisons between calculated and experimental data the hot primary quasi-projectiles were cooled down with the proper part of the SIMON code [19].

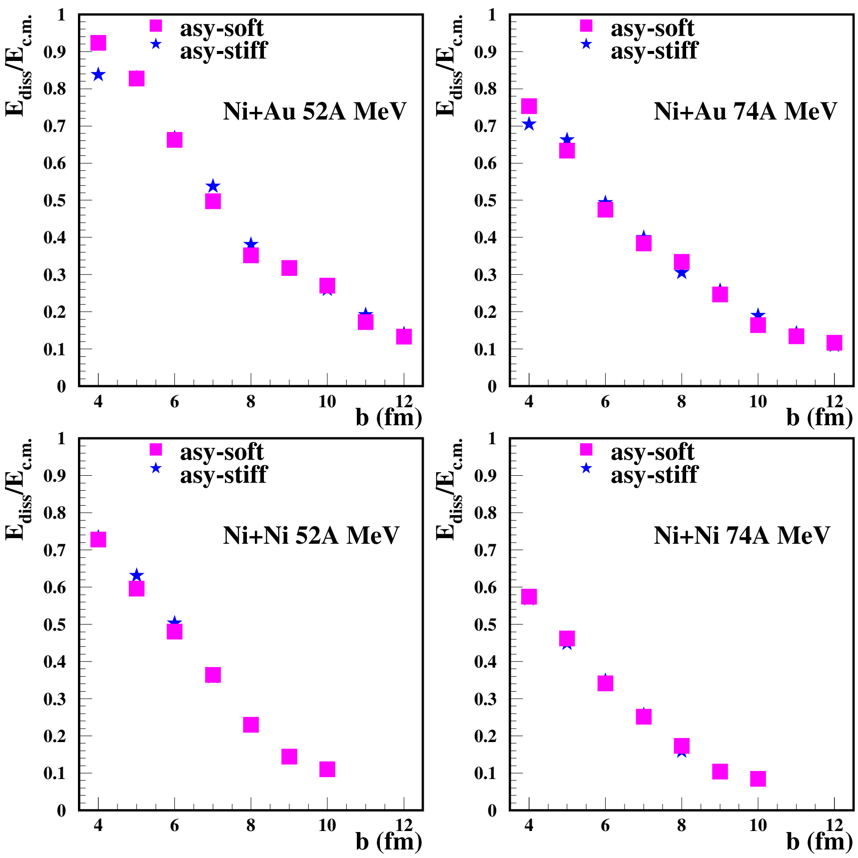

FIG. 5: (color online) Correlation between $E_{diss}/E_{c.m.}$ and the impact parameter, for the two reactions and the two energies. The stars correspond to the asy-stiff case and the squares to the asy-soft case.

B. Charge of the quasi-projectile

Fig. 6 shows the calculated charge of primary QP (defined at t_{sep}) as a function of dissipation. Fragments coming from the neck region were not considered in the evaluation of Z_{QP}; it was however checked that taking them into account changes very slightly the QP charge values: the variation remains within the statistical errors, which are represented only in the asy-stiff case in fig. 6 for a better visibility. These errors only exceed the size of the symbols for the more dissipative collisions.
As expected, Z_{QP} decreases with the increase of E_{diss} for the two systems and the two energies. For the Ni+Au system the charge decreases down to $Z \approx 10$ at 52 AMeV, and to $Z \approx 5$ at 74 AMeV, due to a larger pre-equilibrium emission (see sect II.B.1). For the Ni+Ni system the charge remains higher ($Z \approx 17$ and $Z \approx 15$ for 52 AMeV and 74 AMeV

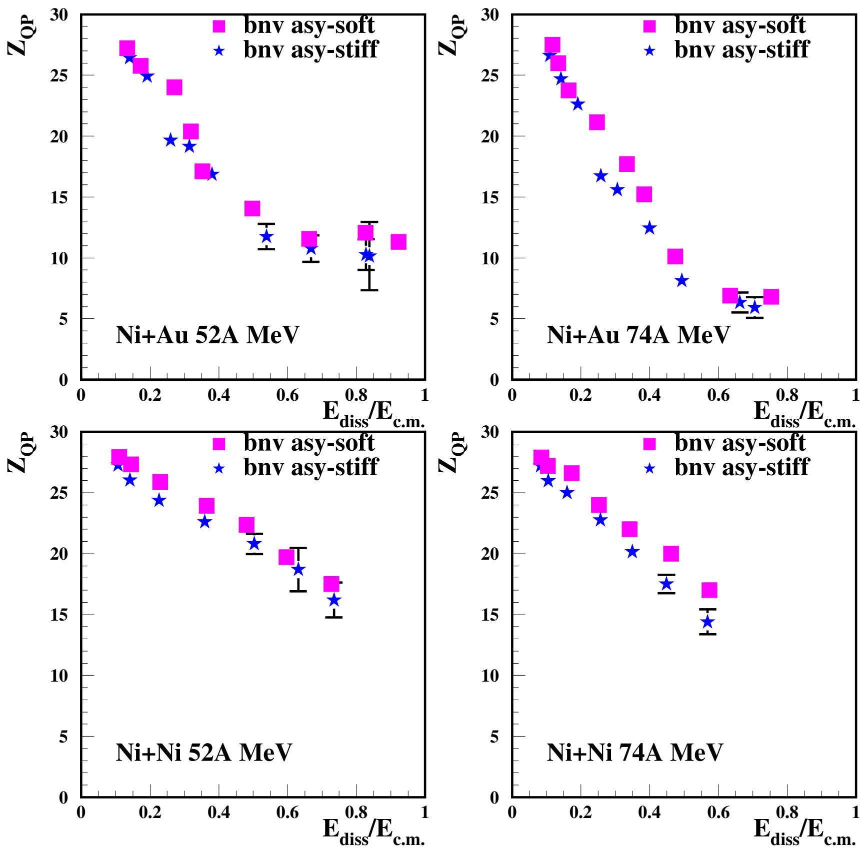

FIG. 6: (color online) Calculated charge of the primary quasi-projectile vs $E_{diss}/E_{c.m.}$, for the two reactions and the two energies. The stars correspond to the asy-stiff case, the squares to the asy-soft case.

respectively), even at similar percentages of dissipation of the available energy. The two equations of state give rather similar behaviours. However the soft equation of state gives results that are systematically above the ones obtained in the stiff case. The comparison of the charge of the final QP residue, obtained with the two asy-parameterizations, with the experimental values is shown in fig. 7. For experimental data, averages and variances of the distribution of the heaviest fragment measured by INDRA [12] are displayed. Because of geometry and trigger effects (see [12]) the more peripheral collisions were strongly rejected for the Ni+Ni system, leading to an apparent decrease of the charge of the detected QP for the lower values of the excitation energy. At higher dissipation, for the two systems, data well follow the theoretical trend and charges of final QP are within the variance distributions of the data. In all cases one can stress that the agreement between calculation

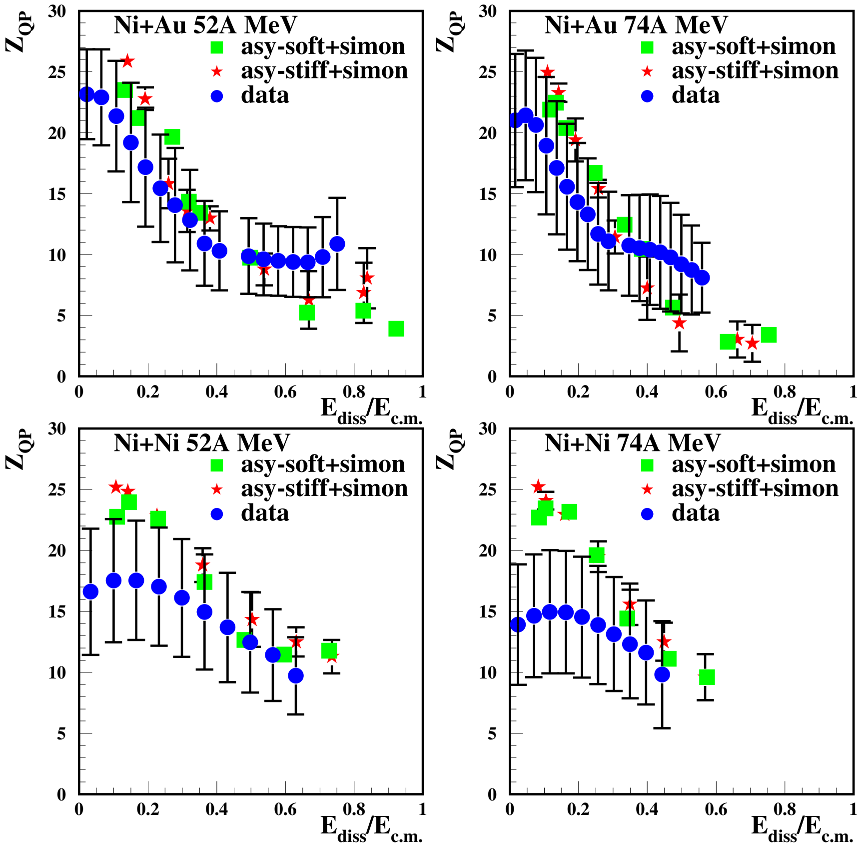

FIG. 7: (color online) Charge of the quasi-projectile residue vs $E_{diss}/E_{c.m.}$, for the two reactions and the two energies. The squares correspond to the asy-soft case+SIMON, the stars to the asy-stiff case+SIMON and the circles to the experimental data.

and experiment is better for the more central collisions.

C. N/Z ratio as a function of the dissipation

The N/Z ratio of primary QP as a function of E_{diss} is reported in fig. 8. The lines represent the results of a linear fit. These results, plotted versus b, were already discussed in sect.II.B.2; the observed trends are not modified when the dissipation is used as a scale for the violence of the collision (see also sect. III.A). Particularly, N/Z equilibration is nearly reached in the Ni+Au system at 52 AMeV, with an asy-soft EOS, when about 80% of the available energy has been dissipated. In the same figure are also plotted the results concerning the de-excitation step, with the variable called $(N/Z)_{CP}$ defined for experimental data.

Isotopes included in the calculation of the variable are those evaporated by the hot QP. The values of $(N/Z)_{CP}$ are always smaller than the N/Z of the primary QP. At low dissipation, in all cases, the value starts at 1 instead of 1.07, due to the dominance of α particles. The evolution of $(N/Z)_{CP}$ with $E_{diss}/E_{c.m.}$ is generally flatter than the $(N/Z)_{QP}$, however the differences between the results of the two parameterizations are more pronounced for $(N/Z)_{CP}$, with respect to $(N/Z)_{QP}$, especially at 52 AMeV. This is because excitation energies are larger in the asy-soft case and this favours the emission of neutron-richer particles, thus enhancing the effect due to the larger N/Z value observed in the asy-soft case for the QP. Only for the reaction Ni+Ni at 74 AMeV, where the N/Z of the QP is higher in the asy-stiff case, the effects due to the de-excitation modify the initial trend imposed by the dynamical evolution. For the Ni+Au case at 52 A MeV, for instance, the slopes associated with the evolution of $(N/Z)_{QP}$ and $(N/Z)_{CP}$ with $E_{diss}/E_{c.m.}$, obtained with the two parameterizations, differ by 20% and 40%, respectively. $(N/Z)_{CP}$ is thus a good witness of isospin transport effects and is sensitive to the asy-EOS, though no direct conclusion concerning the reach of isospin equilibration among the two reaction partners can be derived from this variable. It should be noticed that the difference observed for $(N/Z)_{QP}$, between the two parameterizatons, is in agreement with recent calculations performed on other systems in the same energy range [18].

A comparison of calculated and experimental values of $(N/Z)_{CP}$ is shown in fig. 9. The results presented in the accompanying paper [12] correspond to open circles; they are above the calculated $(N/Z)_{CP}$ at low dissipation but values get closer at high dissipation. We remind that these experimental values correspond to particles forward emitted in the nucleon-nucleon frame, because of the difficulty to define a QP source. For comparison with the values calculated with BNV+SIMON, we need a variable more representative of the QP de-excitation properties. In this aim a second experimental value of $(N/Z)_{CP}$ was built with particles forward emitted in the QP frame. The values are remarkably close to the BNV+SIMON data, for all systems, particularly for the asy-stiff case. They are lower than those built with particles emitted forward of the N-N velocity at low dissipation which indicates that indeed mid-rapidity emission is more neutron-rich for the complex particles considered in the variable $(N/Z)_{CP}$. Both experimental values (forward N-N and forward QP) present the same trend, namely no or very little evolution with dissipation for Ni+Ni, and an increase with the violence of the collision for Ni+Au. For Ni+Au at 52 AMeV, they become equal at high dissipation. This gives a strong experimental indication that N/Z equilibration has been reached.

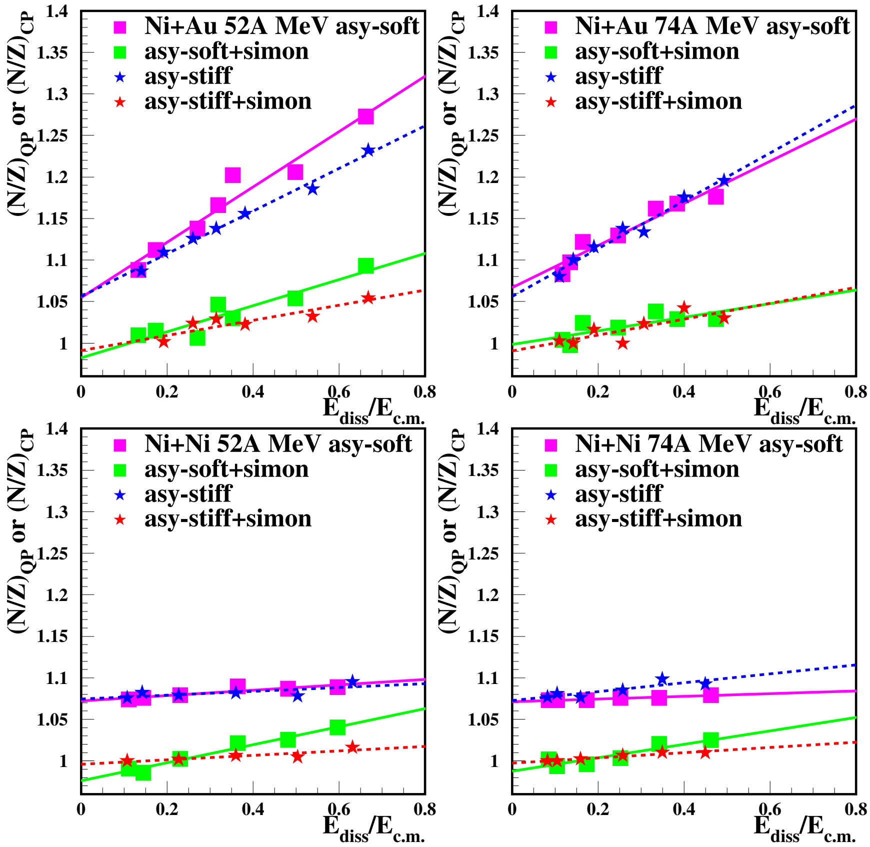

FIG. 8: (color online) Isospin ratio of the quasi-projectile vs $E_{diss}/E_{c.m.}$, for the two reactions and the two energies. For the asy-stiff calculation, black stars and dotted lines display $(N/Z)_{QP}$ and grey stars and dotted lines the $(N/Z)_{CP}$ (BNV calculation followed by SIMON). Same conventions for the asy-soft case displayed by squares and full lines. The lines correspond to linear fits.

D. Summary of the main findings

Following the comparison between calculations with two EOS and between calculations and experimental data, several important points can be stressed.

- BNV calculations show a very good correlation between the impact parameter and the variable E_{diss} calculated as in experiment: E_{diss} appears as a good indicator of the violence of the collision.

- The differences between the two EOS are small, which reflects the fact that in the studied

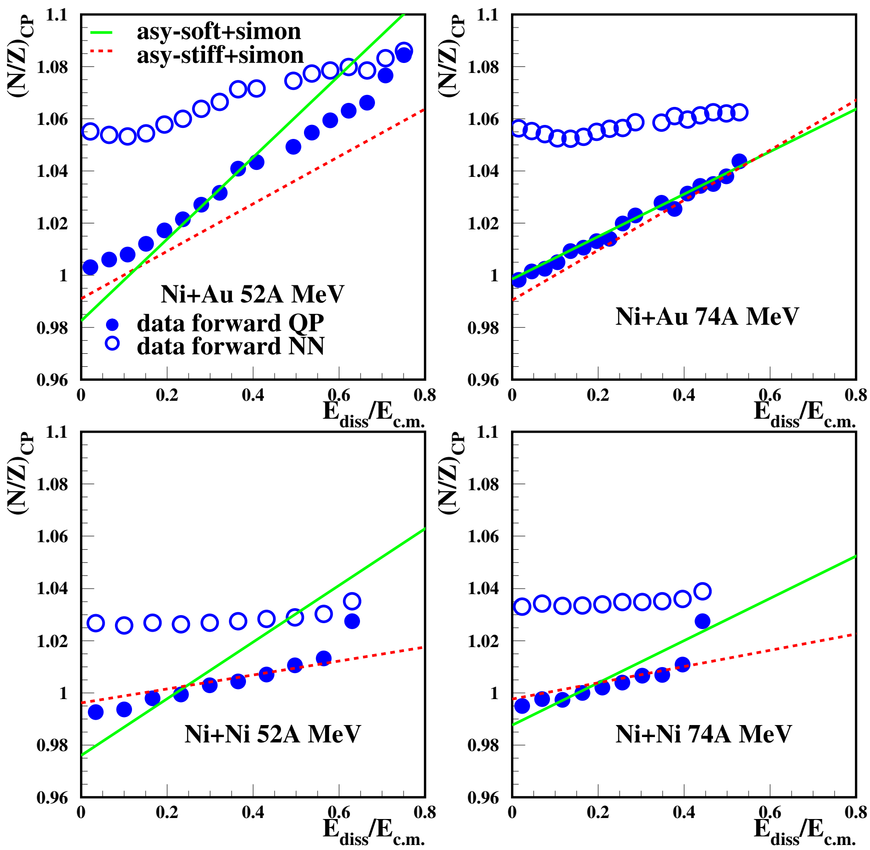

FIG. 9: (color online) Isospin ratio of complex particles for Ni quasi-projectile vs $E_{diss}/E_{c.m.}$, for the two reactions and the two energies. Circles correspond to the experimental data, open for data forward of the N-N velocity [12], full for data forward in the QP frame. Dotted lines and full lines as in fig. 8.

collisions nuclear densities keep values close to the normal one.

- The secondary decay effect is very important and, in almost all cases, it reduces the sensitivity of the proposed isospin observable $(N/Z)_{CP}$ with $E_{diss}/E_{c.m.}$.

- Calculations support the experimental observation of the significant increase of the (N/Z) observable for QP in the Ni+Au reactions as a function of the centrality of the collisions. This appears related to isospin equilibration between the two reaction partners.

- The value of $(N/Z)_{CP}$ calculated with BNV+SIMON well matches the experimental data obtained from the forward emitted products in the QP frame for the whole dissipation range studied. This indicates that the products emitted forward in the QP frame are well representative of the QP de-excitation properties.

- Globally the asy-stiff case better matches the experimental data for both systems. In particular, the behaviour of $(N/Z)_{CP}$ with respect to $E_{diss}/E_{c.m.}$ is better reproduced by the asy-stiff interaction. A similar interaction with free nucleon-nucleon cross section was also used in a BUU transport code to well reproduce isospin diffusion deduced from an isoscaling analysis for ^{124}Sn+^{112}Sn at 50 AMeV[9].
- BNV calculations show that isospin equilibration is quasi-reached at the higher dissipation (impact parameter around 5 fm) for the Ni+Au system at 52 AMeV. The same conclusion can be directly deduced experimentally from the observation that the $(N/Z)_{CP}$ forward of the N-N velocity and forward in the QP frame become equal.
- Finally, the isospin equilibration time for reactions in the Fermi energy domain, as considered here, can be estimated at 130 ± 10 fm/c; this time is the time interval when the di-nuclear system remains in interaction, for the most dissipative binary collisions studied at 52 AMeV.

IV. CONCLUSION

In this paper we have studied isospin effects in semi-peripheral nuclear collisions above the Fermi energy, with different conditions of mass and charge asymmetry, using different equations of state : asy-soft and asy-stiff. In this aim, we have compared results obtained on quasi-projectiles, in two different reactions with the same projectile: ^{58}Ni + ^{58}Ni and ^{58}Ni + ^{197}Au, at incident energies of 52 and 74 AMeV. The present analysis is an alternative to both the isoscaling analysis obtained from an average experimental impact parameter [7, 9] and the pre-equilibrium neutron-to-proton ratios which correspond to events distributed over an impact parameter range [11, 20, 21]. Here we study isospin transfer as a function of dissipation or centrality in collisions for two beam energies, looking directly at the average isotopic content of the emitted light particles. Simulations show that for the Ni + Ni system, the N/Z of the quasi-projectile is essentially determined by proton rich pre-equilibrium emission, and so the N/Z slightly increases with centrality. The effect is more pronounced using an asy-stiff equation of state. For the Ni+Au system isospin transport takes place and the N/Z is larger in the asy-soft case. Excitation energies are also larger in the asy-soft case, increasing the N/Z of the emitted particles. Hence in the Ni+Ni case we observe a kind of compensation between the trend imposed by the dynamical evolution and the secondary decay, while in the Ni+ Au case, the two effects act in the same direction. Finally we find a better overall agreement with experimental data for the asy-stiff case corresponding to a symmetry term linearly increasing with nuclear density. Moreover more precise information concerning the isospin equilibration time, as compared to the conclusions of the experimental joint paper, is obtained. At 52 AMeV for the Ni+Au and the most dissipative collisions we can infer from the data-model comparison that isospin equilibration is reached at 130 $\pm$ 10 fm/c. Another very interesting result comes out from the present study: as far as the N/Z content is concerned, the chemical composition of the quasi-projectile forward emission appears as a very good representation of the composition of the entire quasi-projectile source. Such an observation seems to validate a posteriori this kind of selection frequently used to characterize the properties of quasi-projectiles.

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