PHYSICAL REVIEW C VOLUME 57, NUMBER 3 MARCH 1998

Effects of charge symmetry on heavy ion reaction mechanisms

M. Colonna,[1] M. Di Toro,[1] G. Fabbri,[2] and S. Maccarone[1]
[1]Laboratorio Nazionale del Sud, Via S. Sofia 44, I-95123 Catania, Italy
and Universitá di Catania, Catania, Italy
[2]Dipartimento di Fisica, Universitá di Firenze and INFN, Sezione di Firenze, Firenze, Italy

(Received 9 October 1997)

We suggest several possibilities to study the properties of the symmetry term in the nuclear equation of state from radioactive beam experiments. Collision simulations with a stochastic transport approach, where asymmetry effects are suitably introduced, are presented. The dynamical response of an interacting highly asymmetric nuclear matter can be studied, taking advantage of the neutron skin structure. The main reaction mechanisms, from fusion to deep inelastic and fragmentation, appear quite sensitive to the form of the symmetry term of the effective force used, opening some new appealing experimental perspectives. Finally new features of fragment production are presented, due to the onset of chemical plus mechanical instabilities in dilute asymmetric nuclear matter. [S0556-2813(98)06002-6]

PACS number(s): 25.70.−z, 21.30.−x, 21.65.+f

I. INTRODUCTION

The present and future availability of radioactive beams in many laboratories all around the world has driven a large interest in nuclear structure features of beta-unstable nuclei. There are, however, several expectations based on the fact that the nonequilibrium dynamical behavior of nuclear systems can be also strongly influenced by charge asymmetry. A quantitative study of this point, trying to pin down the most sensitive observables in reaction mechanisms, is the aim of the present paper. We will try to show that collisions of very asymmetric nuclei can lead to unique information on the symmetry term of the nuclear equation of state (EOS) and on the structure of asymmetric nuclear matter in regions far from normal density. In this way we can put some experimental constraints on the theoretical predictions used in astrophysical contexts [1], where such information is essential in understanding the properties of neutron stars [2–5]. Moreover, there are quite stimulating predictions on new phases of asymmetric nuclear matter in regions far from normal density, which eventually could be reached during the reaction dynamics. The onset of coupled mechanical and chemical instabilities is envisaged [6,7], which would lead to clear experimental signatures. Finally we stress the fundamental interest in the role of heavy mesons in hot and dense asymmetric nuclear matter, which could be checked in a relativistic mean field approach [8].

In the very last years some first data have appeared on isospin effects in reaction dynamics, with a few theoretical analyses, on charge equilibration [9,10], collective flows [11–13], fragment production [14–17], and preequilibrium emissions [18]. See also the recent reviews in [19,20]. Although the data are of inclusive type and the theoretical studies do not focus on the effect of different charge symmetry terms, a noticeable dependence of the reaction mechanisms on charge asymmetry emerges quite clearly. In this paper we will concentrate our analysis on the possibility of extracting some direct information on the symmetry term, discussing the following main results: (i) At relatively low beam energies the competition between fusion and deep-inelastic processes is strongly affected. (ii) With increasing energy, using a stochastic transport theory we see directly the onset of new instabilities and effects on fragment production.

In Sec. II we introduce the theoretical framework and we discuss how the nuclear equation of state is affected by the symmetry term. In Sec. III we present several simulations obtained using exotic beams and we expecially discuss the dependence of the results on the considered effective force. Conclusions and perspectives are drawn in Sec. IV.

II. STOCHASTIC BOLTZMANN-NORDHEIM-VLASOV CODE FOR CHARGE ASYMMETRIC NUCLEAR DYNAMICS

We solve numerically microscopic transport equations [21–26] using a new code that includes fluctuations and asymmetry effects [27]. A density-dependent symmetry term is used also in the ground state construction of the initial conditions; isospin effects on the nucleon-nucleon cross section and Pauli blocking are consistently evaluated. In order to simplify the analysis of the most sensitive observables a local mean field of the Skyrme-like form has been used:

$$U(\rho)=A(\rho/\rho_0)+B(\rho/\rho_0)^{\sigma}+C(\rho)(\rho_n-\rho_p)/\rho_0\tau_z, \quad (1)$$

with A,B,σ parameters corresponding to a soft EOS ($K=200$ MeV, SKM parameters [28]) and with two different choices for the density dependence of the symmetry term:

$$C=32\ \text{MeV: ASY-STIFF choice,}$$

$$C/\rho_0=a+b\rho \ \text{ with } a=481.7\ \text{MeV fm}^3,$$

$$b=-1638.2\ \text{MeV fm}^6\text{: ASY-SOFT choice.}$$

We remark that the two parametrizations give close values for the symmetry energy at normal total density $\rho_0=0.17\ \text{fm}^{-3}$. In the lower density region they are quite similar while at higher densities the difference is noticeable. The asy-soft symmetry energy shows a decrease and actually it changes sign at density $\rho\approx 2\rho_0$. This parametrization is typical of SIII forces. The effects on the EOS of asymmetric

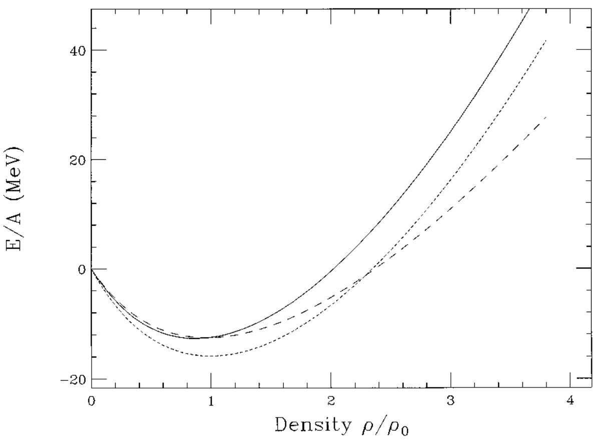

FIG. 1. The nuclear equation of state, at zero temperature, for symmetric nuclear matter (dotted line) and for nuclear matter with asymmetry $I=1/3$ using the asy-soft parametrization (dashed line) and the asy-stiff parametrization (solid line).

nuclear matter can be seen in Fig. 1 where we show the total energy per nucleon as a function of the density for two values of the asymmetry parameter $I=(N-Z)/A$: $I=0$ (symmetric nuclear matter) and $I=1/3$ ($N=2Z$).

While the EOS in general softens, as expected, with asymmetry, we see a clear difference in the stiffness at $I=1/3$ for the two different choices. Of course the difference increases for larger asymmetries. One of the aims of this paper is to show that reaction mechanisms at medium energies are sensitive to this effect, although we will certainly not reach high compression regions. The main idea is to get a very asymmetric piece of nuclear matter in the interacting zone, just taking advantage of the neutron (proton) skin structure of beta-unstable nuclei and considering reaction mechanisms particularly sensitive to a ‘‘skin-skin’’ interaction.

We would like to stress that for some reaction mechanisms, fragmentation and deep inelastic mainly, it is quite important to have a dynamical approach which includes fluctuations in a consistent way. Indeed we expect the dynamical outcome to be strongly influenced by the different stiffness of the EOS as we already well know from symmetric nuclear matter results [29,30]. In our stochastic mean field approach fluctuations are introduced in a new way, just starting from a local equilibrium assumption in a phase space cell [27]. This new procedure has been checked in the case of incomplete fusion events, just comparing the obtained variances with statistical predictions. At higher energies, the results on neck fragmentation processes can be checked by making a comparison with Boltzmann-Langevin-type simulations [31,32].

III. RESULTS

A. Fusion−deep-inelastic competition

The aim of this investigation is to study the dominant dissipative reaction mechanisms associated with different parametrizations of the symmetry term. We have started our analysis at relatively low energies. Moreover, we have considered medium-light radioactive beams which will be likely available in this energy region from SPIRAL [33] and other projects. In order to see the competition between binary events and heavy residue formation we have chosen an intermediate impact parameter $b \approx 0.4 b_{\mathrm{max}}$. We have compared the mean trajectories (i.e., averaged over many events) of the collisions ^{46}Ar ($N/Z=1.56$)$+^{64}$Ni ($N/Z=1.22$), neutron-rich systems, versus ^{46}V + ^{64}Ge ($N=Z$, proton rich) at 30 MeV/nucleon and $b=4$ fm.

Figure 2 shows the time evolution of density projection on the reaction plane for the neutron-rich system with the two choices of the symmetry term parametrization. The difference is quite evident. In the asy-soft case we have a stronger interaction between the two partners, a larger dissipation of the relative energy, and the systems enters a fusion path. The asy-stiff case is more repulsive; we have less dissipation and eventually the dinuclear system breaks on a relatively short time scale.

These results suggest that it might be possible to extract information on the stiffness of the symmetry term by measuring the relative rate of fusion events. Moreover, for the asy-soft case we expect more interaction time available for charge equilibration. This means that also for binary events we will see the final fragments emerge with more similar N/Z ratios and in general with more neutrons emitted since more are excited. At variance, for a stiff symmetry term the two final fragments will keep more memory of the entrance channel conditions. This point will be also discussed in Sec. III B.

For the isobaric proton-rich system a quite unexpected new feature appears; see Fig. 3. Now the asy-soft parametrization leads to a dominant deep-inelastic mechanism, Fig. 3(a). This could be predicted from two combining effects: (i) larger Coulomb repulsion and (ii) a larger number of nucleon-nucleon collisions (more n-p couples, which see a larger cross section) which reduces the main nucleon-exchange dissipation mechanism [34]. The quite amazing result is in Fig. 3(b) for the asy-stiff case. Since here overall we have $I=0$, we would not expect any difference, while in fact now the most probable events are of fusion type. A way to understand this result is that the two quite exotic nuclei ^{46}V and ^{64}Ge develop a proton skin which is overlapping in the interaction zone. The protons in the asy-stiff case see a stronger repulsive mean field and are more easily emitted. As a consequence, the Coulomb repulsion between the two partners decreases and fusion can be easily reached. This interpretation seems to be confirmed by the proton and nucleon emission pattern in the two collisions; see Fig. 4. Only the proton-rich case indeed shows a clear difference in the number of emitted protons between asy-soft and asy-stiff parametrizations.

From the previous discussion the importance of neutron-proton skin formation in the final determination of the main reaction mechanism is clear. This is an interesting point since in this way we can also have a direct connection between reaction mechanisms and the low density part of the EOS for asymmetric nuclear matter, which gives the skin structure on the surface of β-unstable nuclei. In other words, from reaction rates we could get independent information on effective interactions used to make predictions on n,p drip lines.

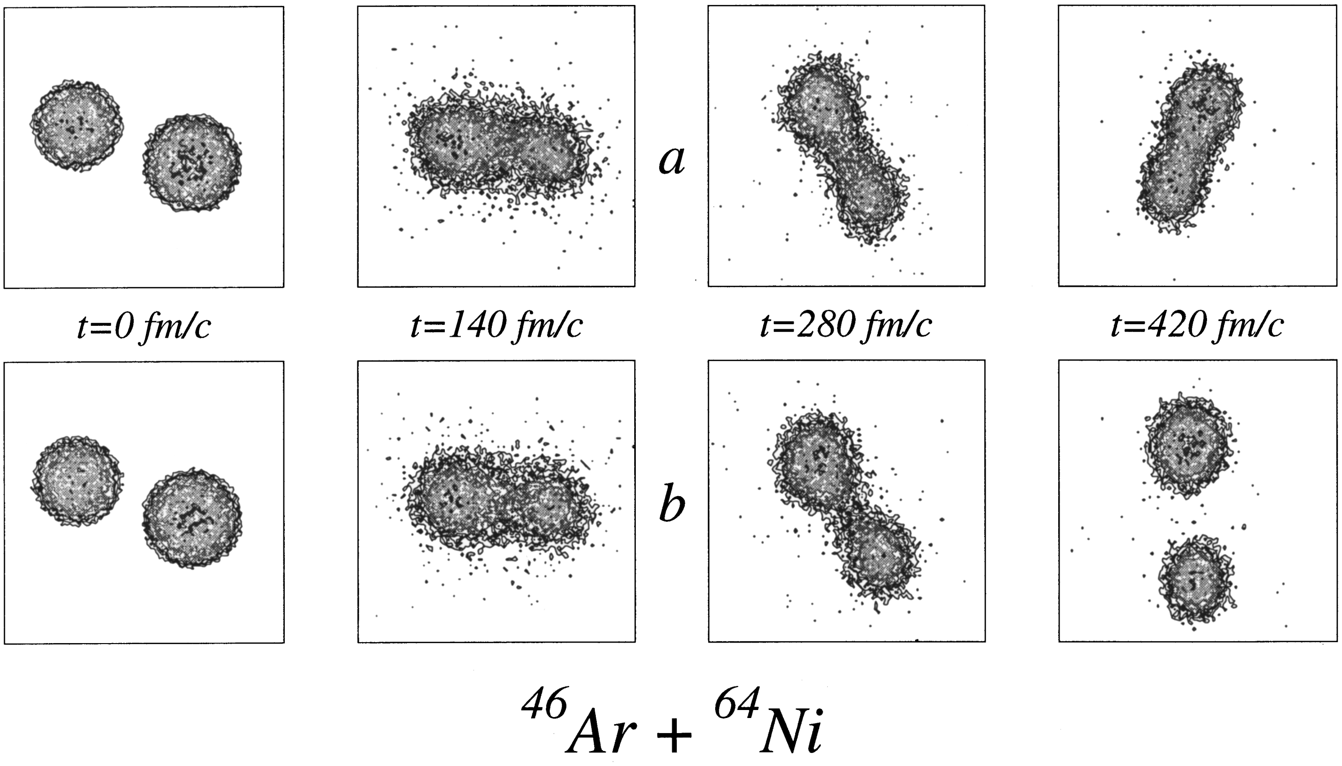

FIG. 2. Contour plots of the density in the reaction plane for ^{46}Ar+^{64}Ni at 30 MeV/nucleon, $b = 4$ fm, in the asy-soft case (a) and asy-stiff case (b). The size of the box is 30 fm.

B. Deep-inelastic–fragmentation competition

At higher beam energy, 50 MeV/nucleon, we have studied collisions of quite exotic nuclei, ^{60}Ca+^{60}Ca. Collisions between neutron-rich isotopes of calcium have already been studied [35], showing that preequilibrium emission is sensitive to the isospin strength. Our aim is different. In this paper we study the effects of symmetry energy on the onset of a multifragmentation evolution of the system. First of all, the

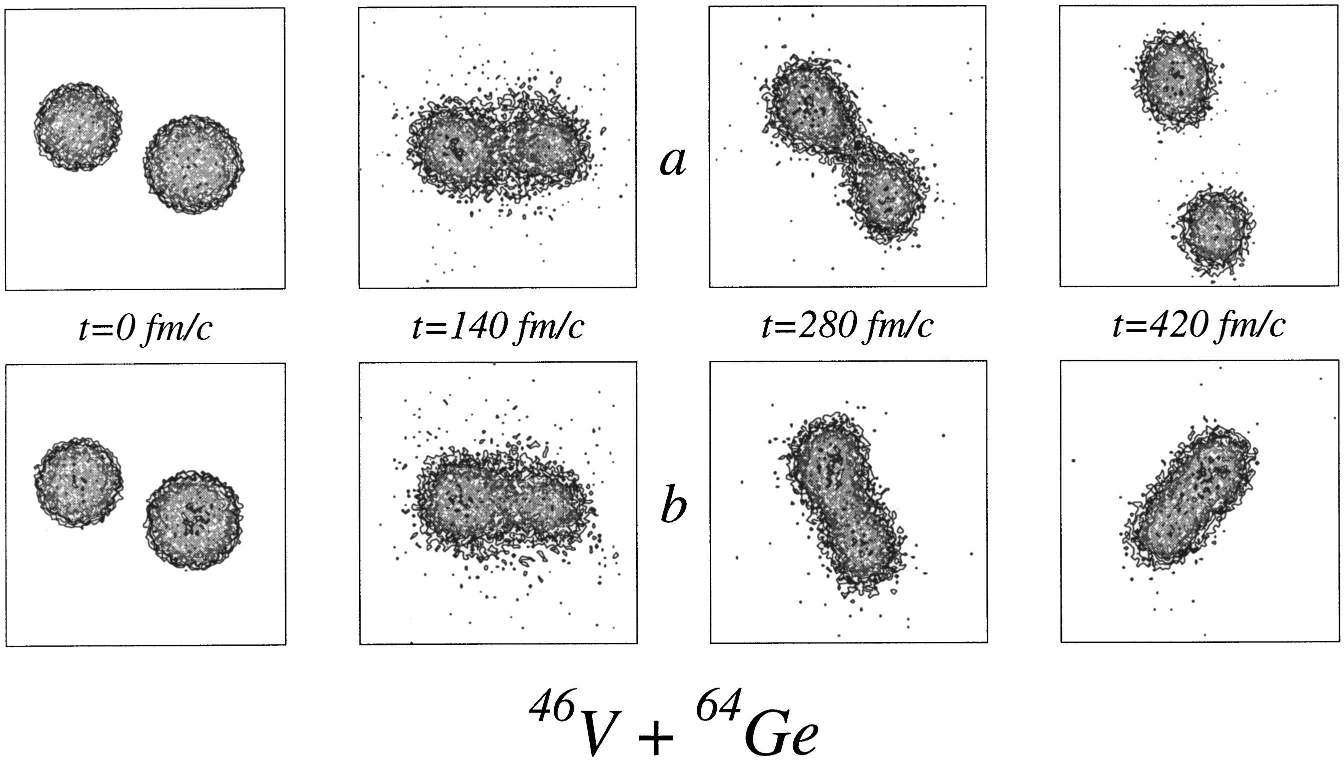

FIG. 3. The same as Fig. 2 for ^{46}V+^{64}Ge.

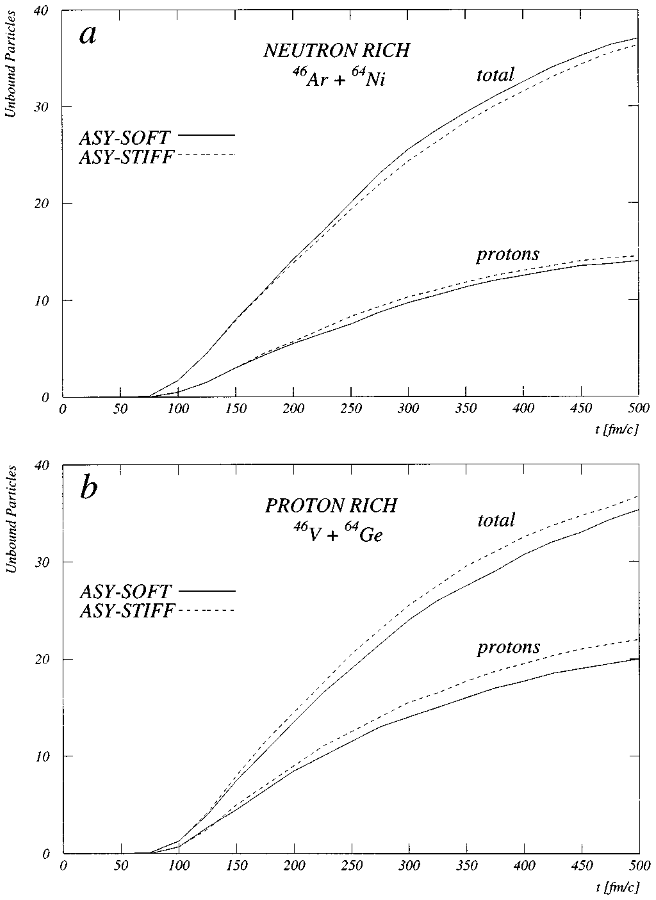

FIG. 4. Time evolution of emitted protons and nucleons for ^{46}Ar $+ ^{64}$Ni (a) and ^{46}V$+ ^{64}$Ge (b), at the same energy and impact parameter of Fig. 2. Dashed line, asy-stiff case; solid line, asy-soft case.

^{60}Ca nucleus should show a very clear neutron skin, as predicted by Hartree-Fock calculations almost independently of the used effective interaction [36]. In our iterative procedure (see Ref. [24]) to construct the initial conditions we also reproduce a quite nice neutron skin effect; see Fig. 5.

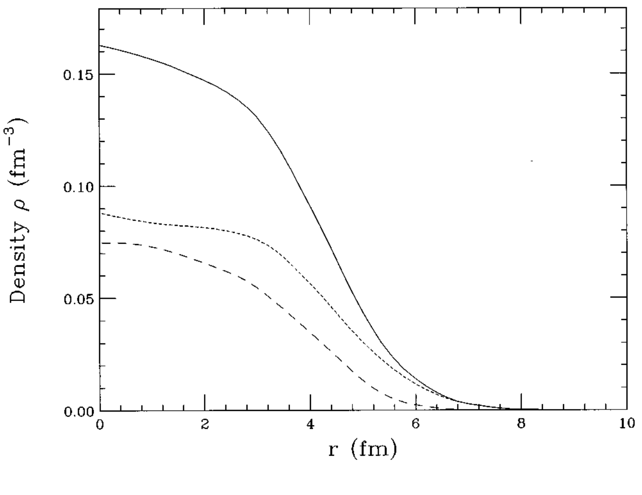

FIG. 5. Profiles of proton (dashed line), neutron (dotted line), and total (solid line) density for a nucleus of ^{60}Ca in the ground state.

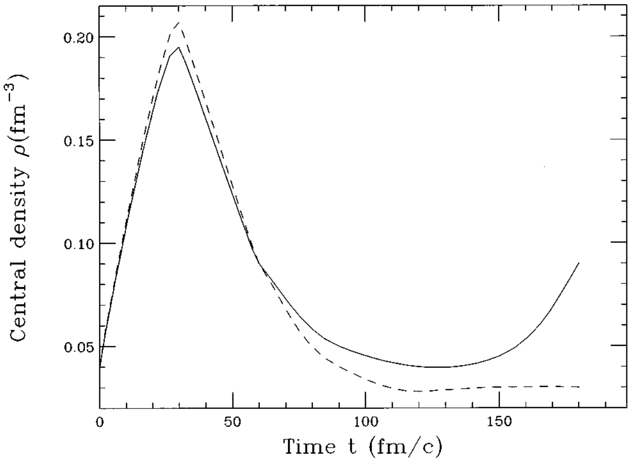

FIG. 6. Time evolution of the central density obtained for the reaction ^{60}Ca$+ ^{60}$Ca at 50 MeV/nucleon, $b = 0$. Dashed line, asy-soft case; solid line, asy-stiff case.

We therefore expect to observe quite enhanced asymmetry effects for ‘‘skin-skin’’ type of collisions at intermediate impact parameter.

Figure 6 shows an interesting result for central collisions, too. This is not surprising since in any case the overall asymmetry parameter is $I = 1/3$. For central collisions between relatively light ions we expect to have a quite large transparency and consequently the EOS effects should be reduced. In order to increase the stopping power we have performed a calculation, just doubling the nucleon-nucleon cross sections.

In Fig. 6 we report the density evolution for two events, asy-stiff and asy-soft, with the same initial conditions, in a space cell of a 3 fm side around the system center of mass. We can infer that the asy-soft and asy-stiff calculations lead to quite different reaction mechanisms for central events.

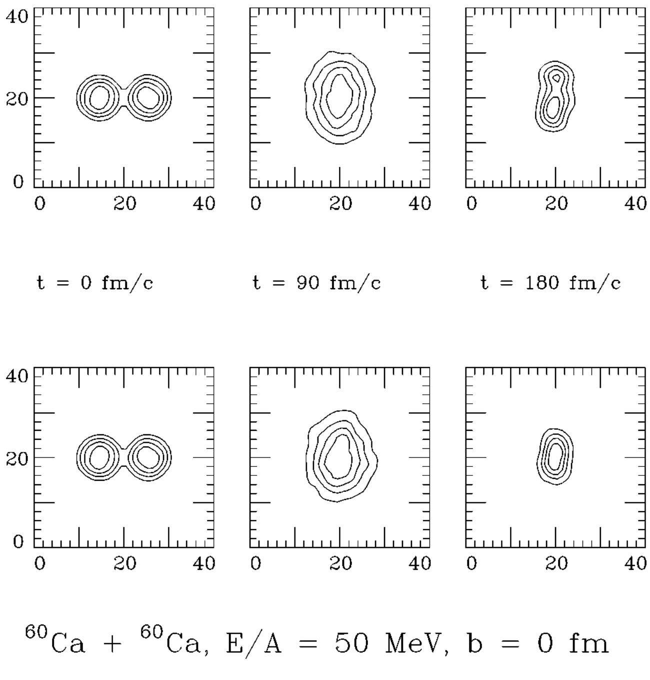

FIG. 7. Contour plots of the density in the reaction plane for ^{60}Ca$+ ^{60}$Ca at 50 MeV/nucleon, $b = 0$ in the asy-soft case (top) and asy-stiff case (bottom). The size of the box is 40 fm.

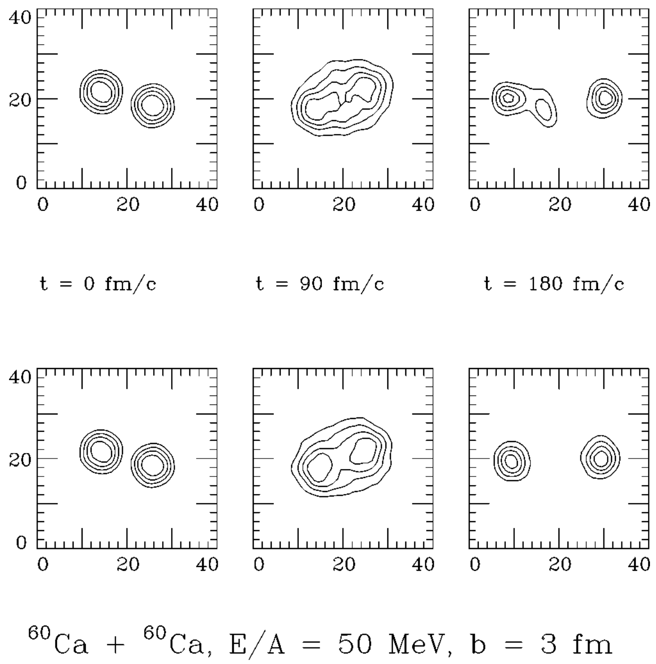

FIG. 8. Contour plots of the density in the reaction plane for $^{60}\mathrm{Ca}+{}^{60}\mathrm{Ca}$ at 50 MeV/nucleon, $b=3$ fm, in the asy-soft case (top) and asy-stiff case (bottom). The size of the box is 40 fm.

The asy-stiff trajectory has a smaller compression and then undergoes monopole oscillations: The system will cool down via particle emission and then a fused residue will be formed. In the asy-soft trajectory the initial density oscillation is larger and we expect a larger dynamical effect from two-body collisions with the onset of a disklike instability [37]: The nuclear matter in the interacting zone goes deeply into the low density region, spinodal instabilities develop, and the system will follow a multifragmentation evolution. Contour plots of the density are presented in Fig. 7. The effect is clearly seen in our calculations, which contain dynamical fluctuations.

As already said, due to the neutron skin effect, the dynamical differences will be also more pronounced for semicentral collisions. In Fig. 8 we present two events, asy-stiff and asy-soft, at $b=3$ fm. At final interaction times the asy-stiff case is binary while in the asy-soft parametrization neck instabilities develop and we have fragments dynamically produced in the neck region [30,38 and references therein] and in general larger variances in the projectilelike and targetlike remnants. The isotopic structure of the final products will be also different in the two cases. As in the lower energy discussion presented above, the asy-stiff repulsion will keep a larger N/Z ratio in the projectilelike fragment (PLF) and targetlike fragment (TLF) ‘‘spectators.’’ In the asy-soft case our results seem to indicate a substantial equality in the N/Z ratios of the PLF and TLF remnants and of the fragments produced in the neck region, although the latter should be more neutron rich. A stimulating interpretation could be related to a dynamical effect that tends to restore the charge symmetry in spinodal instabilities of asymmetric nuclear matter (see Refs. [6,39]). We should observe an essentially charge symmetric clusterization surrounded by a neutron gas.

At a larger impact parameter binary events of a deep-inelastic type are dominant in both cases. Now the important observables are the ones related to the dissipation rate, masses, and charge asymmetries of the two final fragments. Also the widths will be sensitive to the symmetry term parametrizations, because of the different dissipation as well as the possibility of some instability contribution. We finally remark that the influence of the symmetry term on the number of nucleon-nucleon collisions in the first stage of the reaction should also lead to noticeable effects on preequilibrium emission and bremsstrahlung photon production.

IV. CONCLUSIONS AND PERSPECTIVES

Starting from simulations of reaction dynamics performed with a new transport code, where isospin and fluctuation effects are suitably accounted for, we have shown that dissipative heavy ion collisions at medium energies are strongly sensitive to the density dependence of the symmetry term in the nuclear equation of state. Important properties, such as the rates associated with the different reaction mechanisms, ranging from incomplete fusion to deep-inelastic processes and neck fragmentation, are significantly affected. In particular, we suggest to investigate the competition between incomplete fusion and deep-inelastic events in the case of low energy collisions and between binary events and dynamical emission of intermediate mass fragments (IMF’s) at higher energy. Several other observables related to the dissipation degree reached during the collision can also lead to important information on the symmetry term. For instance, one can look at the masses, the N/Z ratios of the final projectilelike and targetlike fragments, deflection functions, and so on. In central and semicentral reactions, where it is possible to observe the prompt production of several IMF’s, the N/Z ratio distribution of the fragments produced in the neck region is affected by the density dependence of the symmetry term. This study could also give information on the time scales involved in the fragmentation process and on the degree of equilibration reached during the collision.

A possibility is emerging of obtaining in accelerator laboratories important information on the symmetry term of large astrophysical interest. It appears essential to have good radioactive beams available at intermediate energies and to perform more exclusive experiments.

ACKNOWLEDGMENTS

We gratefully acknowledge intense and stimulating discussions within the ISO-DYN working group, international working group on isospin effects on nuclear dynamics. This work was supported in part by the Commission of the European Community, under Contract No. ERBFMB I-CT-960654.

[1] I. Bombaci, in *Perspectives in Theoretical Nuclear Physics*, edited by S. Rosati *et al.* (Edizioni ETS, Pisa, 1996), p. 223; M. Prakash *et al.*, Phys. Rep. **280**, 1 (1997).

[2] G. Baym, H.A. Bethe, and C.J. Pethick, Nucl. Phys. **A175**, 225 (1997); I.M. Irvine, *Neutron Stars* (Oxford University Press, New York, 1978).

[3] C.J. Pethick and D.G. Ravenhall, in *The Lives of Neutron Stars*, edited by M.A. Alpar *et al.*, Vol. 450 of NATO Advanced Study Institute, Series C (Plenum, New York, 1995), pp. 59–70.

[4] V.A. Urpin, in *The Lives of Neutron Stars* [3], pp. 163–166.

[5] G. Fabbri and F. Matera, Phys. Rev. C **54**, 2031 (1996).

[6] M. Colonna, M. Di Toro, and A. Larionov, Phys. Lett. B (submited).

[7] Bao-An Li and C.M. Ko, Nucl. Phys. **A618**, 498 (1997): H. Mueller and B.D. Serot, Phys. Rev. C **52**, 2072 (1995).

[8] M.M. Sharma, G.A. Lalazissis, W. Hillebrandt, and P. Ring, Phys. Rev. Lett. **72**, 1431 (1994); P.G. Reinhard and H. Flocard, Nucl. Phys. **A584**, 467 (1995).

[9] S.J. Yennello *et al.*, Phys. Lett. B **321**, 15 (1994).

[10] Bao-An Li and S.J. Yennello, Phys. Rev. C **52**, R1746 (1995).

[11] Bao-An Li, Z. Ren, C.M. Ko, and S.J. Yennello, Phys. Rev. Lett. **76**, 4492 (1996).

[12] R. Pak *et al.*, Phys. Rev. Lett. **78**, 1022 (1997).

[13] R. Pak *et al.*, Phys. Rev. Lett. **78**, 1026 (1997).

[14] J.F. Dempsey *et al.*, Phys. Rev. C **54**, 1710 (1996).

[15] G.J. Kunde *et al.*, Phys. Rev. Lett. **77**, 2897 (1996).

[16] L.G. Sobotka, Phys. Rev. C **50**, R1272 (1994).

[17] G. Kortemeyer, W. Bauer, and G.J. Kunde, Phys. Rev. C **55**, 2730 (1997).

[18] Bao-An Li, C.M. Ko, and Z. Ren, Phys. Rev. Lett. **78**, 1644 (1997).

[19] G. Westfall, in Proceedings of the VI Nucleus-Nucleus Conference, Gatlinburg, 1997 [Nucl. Phys. A (in press)].

[20] Bao-An Li, C.M. Ko, and W. Bauer, Int. J. Mod. Phys. E (to be published).

[21] H. Stoecker and W. Greiner, Phys. Rep. **137**, 277 (1986).

[22] G.F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).

[23] W. Bauer, C.K. Gelbke, and S. Pratt, Annu. Rev. Nucl. Part. Sci. **42**, 77 (1992).

[24] Ch. Gregoire *et al.*, Nucl. Phys. **A465**, 315 (1987).

[25] A. Bonasera, F. Gulminelli, and J. Molitoris, Phys. Rep. **244**, 1 (1994).

[26] A. Guarnera, Computer code TWINGO, Ph.D. thesis, Caen University, 1996.

[27] M. Colonna *et al.*, in *Critical Phenomena and Collective Observables*, edited by S. Costa *et al.* (World Scientific, Singapore, 1997), p. 369.

[28] H. Krivine, J. Treiner, and O. Bohigas, Nucl. Phys. **A336**, 155 (1980).

[29] M. Colonna and Ph. Chomaz, Phys. Rev. C **49**, 1908 (1994).

[30] M. Colonna, M. Di Toro, and A. Guarnera, Nucl. Phys. **A589**, 160 (1995).

[31] M. Colonna *et al.*, Phys. Rev. C **47**, 1395 (1993).

[32] S. Maccarone *et al.* (unpublished).

[33] D. Guerrau, in Proceedings of the XXIV Hirschegg Workshop, Hirschegg, 1996, edited by W. Noeremberg *et al.* (unpublished); D. Guerrau, in ''Nouvelles du Ganil Report'' 96/97.

[34] V. Baran *et al.*, in Proceedings of the Fusion 97, edited by D. Hinde *et al.* [J. Phys. G **23**, 1341 (1997)].

[35] M. Farine, T. Sami, B. Remaud, and F. Sebille, Z. Phys. A **339**, 363 (1991).

[36] F. Catara, E. Lanza, M.A. Nagarajan, and A. Vitturi, Nucl. Phys. **A614**, 86 (1997).

[37] L.G. Moretto and G.J. Wozniak, Annu. Rev. Nucl. Part. Sci. **43**, 371 (1993), and references therein.

[38] J. Toke *et al.*, Phys. Rev. Lett. **77**, 3514 (1996), and references therein.

[39] V. Baran, A. Larionov, M. Colonna, and M. Di Toro, Nucl. Phys. A (in press).