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Fast nucleon emission as a probe of the momentum dependence of the symmetry potential

J. Rizzo, M. Colonna,* and M. Di Toro

Dipartimento di Fisica e Astronomia, Laboratori Nazionali del Sud INFN, Universita' di Catania Via S. Sofia 62, I-95123 Catania, Italy

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We investigate the structure of the nonlocal contributions to the potential part of the symmetry term of the nuclear equation of state (EOS). Such momentum dependence of the symmetry potential leads to a splitting of the effective masses of protons and neutrons in asymmetric matter that will directly affect the nucleus-nucleus reaction dynamics. Based on microscopic transport simulations we suggest some rather sensitive observables in collisions of neutron-rich (unstable) ions at intermediate energies. In particular we focus the attention on preequilibrium nucleon emissions. We discuss interesting correlations between the N/Z content of the fast emitted particles and their rapidity or transverse momentum, that show a nice dependence on the prescription used for the effective mass splitting.

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I. INTRODUCTION

Effective interactions have been extensively used in transport codes to gain knowledge about nuclear matter properties in conditions far from equilibrium. They predict very different behaviors for some physical properties, such as the momentum dependence of the mean field in the isoscalar and isovector channels (see Refs. [1,2] for recent reviews).

In general, the momentum dependence of the potential is strictly related to the concept of in-medium reduction of the nucleon mass. In particular, the nonlocal part of the symmetry potential has become an interesting subject of investigation, because it leads to a splitting of the masses of different nucleonic species in asymmetric nuclear matter (ANM). The sign itself of such splitting is in fact still a rather controversial problem [3–5] among different theory approaches. Thus, from the experimental point of view, a more quantitative evaluation of the n/p mass splitting is required.

Aim of the present work is to search for new *selectively* sensitive observables. As discussed in the rest of the introduction, this project appears interesting, in particular for the fundamental implications on our knowledge of the effective interactions.

In the nonrelativistic frame, considering separately the local and nonlocal contributions to the potential part of the symmetry energy, a sharp change is observed, for instance, going from the earlier Skyrme forces to the Lyon parametrizations, with almost an inversion of the signs of the two contributions [2]. The important repulsive nonlocal part of the Lyon forces leads to a completely different behavior of the neutron matter EOS, of great relevance for the neutron star properties. Actually this substantially modified parametrization was mainly motivated by a rather puzzling feature in the spin channel of the earlier Skyrme forces, the collapse of polarized neutron matter [6–9]. In correspondence the predictions on the momentum dependence of the symmetry term are quite different. A very important consequence for the reaction dynamics is the expected inversion of the sign of the n/p effective mass splitting, i.e., in the Lyon forces neutron effective masses are below the proton ones for n-rich matter. At variance, the more microscopic nonrelativistic Brueckner-Hartree-Fock (BHF) calculations are leading to opposite conclusions [10–12].

In the relativistic approaches we have also a variety of predictions. The trend $m^*_D(n) < m^*_D(p)$, for the Dirac effective masses is expected from relativistic Dirac-Brueckner-Hartree-Fock (DBHF) calculations [13–15] and in general from the introduction of scalar isovector virtual mesons in relativistic mean field (RMF) approaches [16,17]. However, the comparison between relativistic effective (Dirac) masses and nonrelativistic effective masses requires some attention, see Chap. 6 of [2] and references therein. In fact, though the neutron Dirac mass is below the proton one, in correspondence the nonrelativistic Schroedinger mass splitting can have any sign. Indeed this is just the case of the very recent DBHF analysis of the Tübingen group [15,18]. Such puzzling effect is related to the intrinsic momentum dependence of the nucleon self-energies, it is then beyond the RMF approach and it represents a very important test of the treatment of Dirac-Brueckner correlations. All that clearly shows that sensitive experimental observables are largely needed.

The sign of the splitting will directly affect the energy dependence of the so-called Lane potential, i.e., the difference between (n, p) optical potentials on charge asymmetric targets, normalized by the target asymmetry [19]. A decreasing behavior is observed in the case $m^*_n > m^*_p$, whereas a positive slope is obtained in the opposite case. An important physical consequence of the negative slopes is that isospin effects on the optical potential tend to disappear at energies just above 100 MeV (or even change the sign for "old" Skyrme-like forces). Moreover, we expect a crossing of the two prescriptions at low energies, i.e., low momentum nucleons will see exactly the same Lane potentials, as shown in detail in Ref. [5].

From the analysis of low-energy nucleon-nucleus scattering data and charge exchange reactions there is a rather general consensus on a slightly negative slope of the Lane potential (at normal density), see Refs. [19–24]. However because of

*Electronic address: colonna@lns.infn.it

the relevant implications discussed before we think that it is worthwhile to look for other independent reaction observables sensitive to the nucleon mass splitting, even at abnormal densities. For the latter point heavy ion collisions (HIC) in the intermediate energy range, i.e., roughly from 20 to 200 A MeV, appear rather suitable.

In any case our opinion is that it would be important to confirm the results derived from neutron/proton optical potentials at low energies. The main point is the presence of large error bars, mainly because of the use of indirect methods to extract such information from data. In particular the effects because of the mass splitting appear of the same order of the uncertainty on the determination of the local contribution to the symmetry energy. Moreover at low energies, because of the crossing discussed before, the expected differences between positive and negative slopes are within the error bars.

Finally we have to remark that a good fit of neutron scattering data on ^{208}Pb at 96 MeV has been recently obtained even within a Dirac optical model phenomenology (Madland potential) [25]. The corresponding Lane potential, derived from a nonrelativistic reduction, shows an increasing energy slope [26,27]. Our point is that more scattering data are needed at higher energies (around/above 100 MeV) to improve the systematics to clearly disentangle between the two trends of the Lane potential and of the effective mass splitting.

We note that these properties of the interaction will also in general affect the dynamical evolution of heavy-ion collisions. The idea is then to get some indipendent information just by looking at suitably selected reaction observables. We can expect important effects on transport properties (fast particle emission, collective flows) of the dense and asymmetric nuclear matter that will be reached in exotic (radioactive) beam collisions at intermediate energies. Indeed such energy range is particularly interesting because we can directly probe dynamical effects of the mass splitting at high densities and momenta.

Here we focus on the study of preequilibrium emission in neutron-rich central collisions at 50 and 100 MeV/A. We will see that the energy dependence of the N/Z content of fast-emitted particles is rather sensitive to the sign of the effective mass splitting. Hence it would be possible to answer many fundamental questions in isospin physics by looking at appropriate observables in intermediate energy HIC.

II. DETAILS OF THE INTERACTION

To directly test the influence of the Schroedinger effective mass splitting we present results from reaction dynamics at intermediate energies analyzed in a nonrelativistic transport approach, of Boltzmann-Nordheim-Vlasov (BNV) type, see Refs. [2,28]. The isovector momentum-dependent (IsoMD) effective interaction is derived via an asymmetric extension of the Gale-Bertsch-DasGupta (GBD) force [29,30].

The energy density can be parametrized as follows (see also [1,10]):

$$\varepsilon = \varepsilon_{\rm kin} + \varepsilon(A', A'') + \varepsilon(B', B'') + \varepsilon(C', C'') \qquad (1)$$

where $\varepsilon_{\rm kin}$ is the usual kinetic energy density and

$$\begin{aligned} \varepsilon(A', A'') &= (A' + A'' I^2)\frac{\varrho^2}{\varrho_0} \\ \varepsilon(B', B'') &= (B' + B'' I^2)\left(\frac{\varrho}{\varrho_0}\right)^{\sigma} \varrho \qquad (2) \\ \varepsilon(C', C'') &= C'(\mathcal{I}_{NN} + \mathcal{I}_{PP}) + C''\mathcal{I}_{NP}. \end{aligned}$$

The variable $I = (N - Z)/(A)$ defines the isospin content of the system, given the number of neutrons (N), protons (Z), and the total mass $A = N + Z$; ϱ is the nuclear matter density (ϱ_0 is the saturation value). The momentum dependence is contained in the $\mathcal{I}_{\tau\tau'}$ terms, which are integrals of the following form:

$$\mathcal{I}_{\tau\tau'} = \int d\vec{p}\, d\vec{p}'\, f_\tau(\vec{r}, \vec{p}) f_{\tau'}(\vec{r}, \vec{p}') g(\vec{p}, \vec{p}'),$$

where $f_\tau(\vec{r}, \vec{p})$ are the nucleon phase space distributions and $g(\vec{p}, \vec{p}') \equiv (\vec{p} - \vec{p}')^2$. This choice of the function $g(\vec{p}, \vec{p}')$ corresponds to a Skyrme-like behavior and it is suitable for BNV simulations. We use a soft equation of state for symmetric nuclear matter [compressibility modulus $K_{NM}(\varrho_0) = 215$ MeV]. In this frame we can easily adjust the parameters to have the same density dependence of the symmetry energy but with two opposite n/p effective mass splittings, similar to the ones predicted respectively by the early Skyrme forces [7] and the later Skyrme-Lyon parametrizations [8]. As a result we can separately study the corresponding dynamical effects [3].

A good way to visualize the physical meaning of the mass splitting is to look at the kinetic energy dependence of the Lane potential $U_{\rm Lane} = (U_n - U_p)/2I$ [19]. As already noted in the introduction, its slope depends on the value and sign of the mass splitting (see Ref. [5] for details). In Fig. 1 we plot the Lane potential with the parameters corresponding to the two choices of the sign of the n/p mass splitting (shown in the insert for the $I = 0.2$ asymmetry). In the two cases, the absolute value of the splitting is exactly the same (the

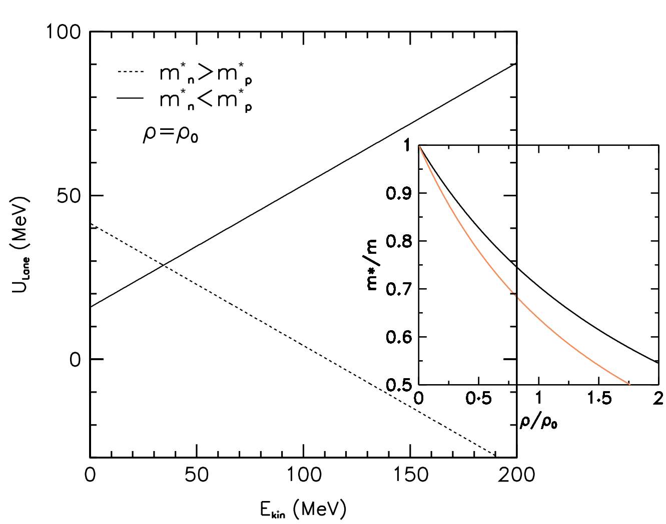

FIG. 1. (Color online) Energy dependence of the Lane potential for the used parametrizations. (Inset) The effective mass splitting, related to the slope of the Lane potential (for the asymmetry $I = 0.2$).

difference between neutron and proton masses is ∼10% at normal density); only the sign is different. The upper curve reproduces the Skyrme-Lyon (in particular SLy4,Sly7) results, the lower (dashed) the SIII,SKM* ones.

From the figure we can immediately expect for nucleons with kinetic energy around 100 MeV very different symmetry effects: an enhancement (with larger neutron repulsion) in the $m_n^* < m_p^*$ case vs. a disappearing (and even larger proton repulsion) in the $m_n^* > m_p^*$ choice. Moreover, we can see a crossing of the two prescriptions at low energy: this means that low-momentum nucleons feel almost the same Lane potential. Thus it is important to choose the appropriate dynamical observables to clearly see the effect of the mass splitting, e.g., to look at observables where neutron/proton mean fields at high momentum are playing an important role.

III. ISOTOPIC CONTENT OF THE FAST NUCLEON EMISSION

We have performed *ab initio* simulations of central collisions at intermediate energies of *n*-rich systems, in particular ^{132}Sn $+^{124}$ Sn at 50 and 100 *A* MeV, at impact parameter $b = 2$ fm. We have employed either an *asy-stiff* or an *asy-soft* density dependence of the symmetry energy, corresponding to different slopes around normal density, with an increasing symmetry repulsion in the *asy-stiff* case [31]. The aim of our work is to select reaction observables more sensitive to the momentum (nonlocal part) than to the density (local part) dependence of the symmetry term.

Performing a local low density selection of the test particles ($\rho < \rho_0/8$) we can follow the time evolution of free nucleon emissions (gas phase) and the corresponding asymmetry. The results are shown in Fig. 2 [where $I(t) \equiv (N - Z)/A$ of the gas phase at each time step] for the 50 *A* MeV reaction. The solid line gives the initial asymmetry of the total system.

We find an interesting behavior for the isospin content of the nucleonic gas: at early times (up to about 60 fm/c), during the (high-density) compression phase, the *asy-stiff* choice leads to higher gas isospin asymmetry than the *asy-soft* one; later we can see an inversion of this trend, because of contributions to the nucleon emission coming from low-density regions in the expansion phase while fragments are forming. This is the well-established isospin distillation, characteristic of the liquid-gas phase transition in asymmetric matter, which leads to a more neutron-rich gas phase. Such process is more effective in the *asy-soft* choice, see Refs. [2,31] and references therein. Finally we can define a kind of *freeze-out* time for the fast (dynamical) nucleon emission (preequilibrium and expansion mechanisms). After this time free nucleons will be mostly coming from evaporation of primary reaction products. From Fig. 2 we can estimate this *freeze-out* time for the gas phase around 100 fm/c. We see that, because of the larger contribution in the expansion stage, the gas phase at *freeze-out* is more asymmetric in the *asy-soft* case, in agreement with previous independent estimations [32].

In conclusion we can see that free nucleons are always emitted during the reaction dynamics. The previous analysis

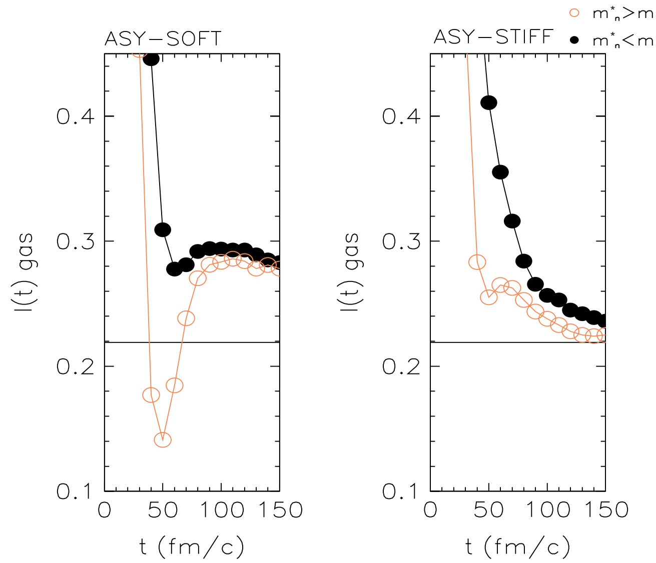

FIG. 2. (Color online) Gas asymmetry as a function of time in a central collision ^{132}Sn $+^{124}$ Sn at 50 *A* MeV for two opposite choices of mass splitting. (Left panel) *asy-soft* EOS; (right panel) *asy-stiff* EOS.

allows us to distinguish two qualitative different mechanisms for the fast nucleon emission: in the compression stage and in the expansion up to *freeze-out*. This distinction is of interest because the corresponding free nucleons will carry information from different density/momentum regions of excited nuclear matter. As shown in the following a nice experimental selection can be based on the nucleon transverse momenta. We call the end of “preequilibrium” emission the time-step corresponding to the end of the compression for two main reasons, the observed local equilibration in momentum space and the corresponding onset of the distillation process.

The gas-asymmetry evolution analyzed before is mainly because of the local part of the symmetry energy, but for both choices of the density stiffness of the symmetry term we clearly see also the influence of the mass splitting, resulting in a reduced fast neutron emission when $m_n^* > m_p^*$. The effect is more pronounced during the early stages of the reaction (up to 60 fm/c), when the most energetic particles are emitted [33] and the momentum-dependent part of the mean field is more effective. The two effects we have just discussed, the former related to the density dependence, the latter to the momentum dependence of the symmetry potential, can be singled out in the transverse momentum distribution of the N/Z content of the gas phase.

In Figs. 3 and 4 we report the N/Z of the “gas” at two different times, $t = 60$ fm/c (end of the preequilibrium emission), and $t = 100$ fm/c (roughly the *gas freeze-out* time). We present the transverse momentum dependence for a fixed central rapidity $y^{(0)}$ (normalized to projectile rapidity). In Fig. 3 we show the results without the mass splitting effect, i.e., only taking into account the different repulsion of the symmetry term (the initial average asymmetry is $N/Z = 1.56$).

At early times (left panel of Fig. 3), when the emission from high-density regions is dominant, we see a difference because

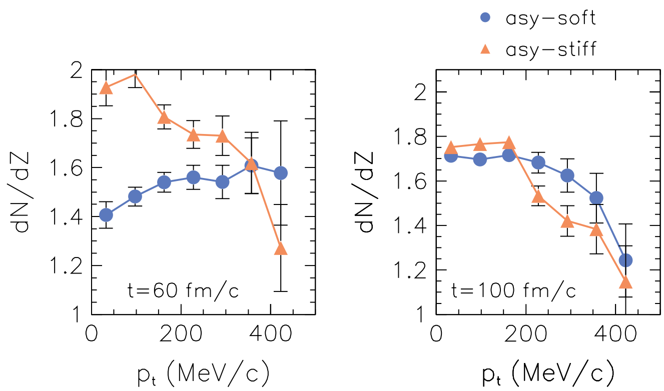

FIG. 3. (Color online) Transverse momentum dependence of the neutron/proton ratio in the rapidity range $|y^{(0)}| \leqslant 0.3$ for a central reaction ^{132}Sn $+^{124}$ Sn at 50 *A* MeV. Comparison between two choices of symmetry energy stiffness at the two different times defined in the text.

of the larger neutron repulsion of the *asy-stiff* choice. The effect is reduced at higher p_t's because of the overall repulsion of the isoscalar momentum dependence. Finally at the *gas freeze-out* time (right panel) the difference is less pronounced, because isospin distillation is coming into play during the expansion phase and it is more efficient in the *asy-soft* choice (see before). This result is a nice indication that low p_t nucleons are mainly coming from low-density regions.

When we introduce the mass splitting, the difference in the isotopic content of the gas, for the larger transverse momenta, is very evident at all times, in particular at the *freeze-out*, of larger experimental interest, see Fig. 4. As expected the $m_n^* > m_p^*$ choice sharply reduces the neutron emission at high p_t's. Conversely, low-momentum nucleons show a behavior that is consistent with Fig. 3, mainly ruled by the local part of the symmetry potential at low densities.

We have repeated the analysis at higher energy, 100 *A* MeV, and the effect appears nicely enhanced, see Fig. 5. The observed differences for nucleons at high p_ts already appear at early times: because these momentum regions are populated mostly during the early stages of the reaction (cfr. [33]) we finally get a permanent signal of the dynamical isovector effect of the interaction. We note a decreasing

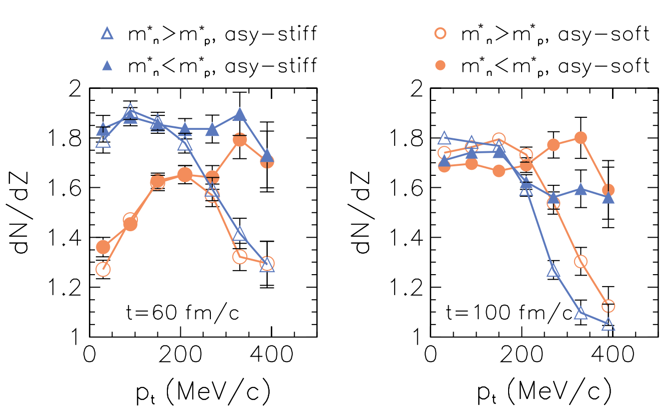

FIG. 4. (Color online) Same as described in the legend to Fig. 3, for two opposite choices of mass splitting.

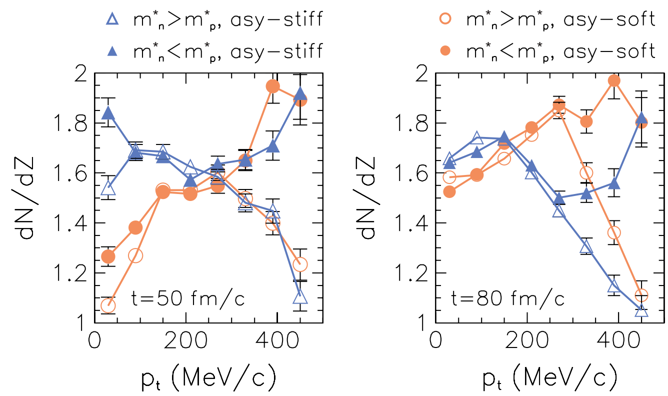

FIG. 5. (Color online) Same as Fig. 4, but for an incident energy of 100 *A* MeV [note the reduced pre-equilibrium (left panel) and freeze-out (right panel) times].

behavior of the N/Z content of pre-equilibrium emission versus the transverse momentum, because of a larger neutron attraction, in the $m_n^* > m_p^*$ case, whereas in the opposite case we get a flat, or even increasing, trend.

The *N/Z* of emitted particles has been studied also as a function of rapidity (see Fig. 6). It is possible to see that, at 50 fm/c (end of the preequilibrium emission at this beam energy), differences between the two prescriptions are present at all rapidities, though more pronounced for faster particles, as expected. We note the opposite behavior of the two mass splitting signs. Going to 80 fm/c (new *gas freeze-out* time), the differences at small rapidity almost disappear, whereas the different effects already shown at 50 fm/c for large rapidities are kept and are even enhanced. The behavior observed as a function of rapidity is quite similar to the trend already seen as a function of the transverse momentum. The different mass splitting sign leads to different results, expecially for particles with larger rapidity or, in a given rapidity bin, with larger transverse energy. Using the $m_n^* < m_p^*$ prescription, the N/Z content of fast emitted particles is enhanced, whereas it is reduced in the opposite case. This is fully consistent with the expectations deduced from the Fig. 1 at the end of Sec. II.

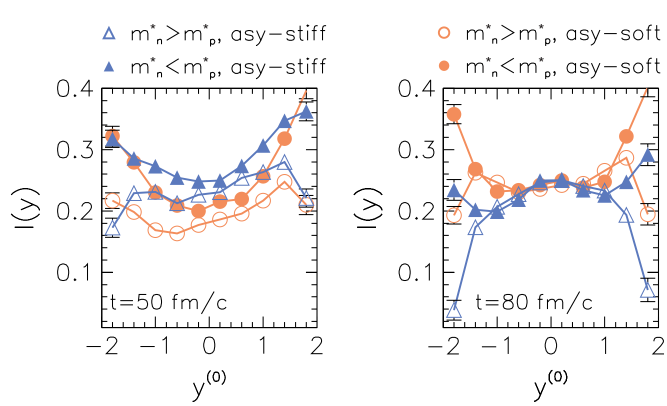

FIG. 6. (Color online) The asymmetry of fast-emitted particles as a function of rapidity, for the reaction ^{132}Sn $+^{124}$ Sn at 100 MeV/*A*, $b = 2$ fm.

Similar results have been obtained in Ref. [34] at 400 A MeV in a different IsoMD model, restricted to the $m_n^* > m_p^*$ choice.

IV. CONCLUSIONS

Our aim has been to find selective observables particularly sensitive to dynamical effects of the nucleon effective mass splitting in asymmetric nuclear matter, which is determined by the momentum dependence of the symmetry potential. We have performed transport simulations for reactions of interest for the new radioactive beam facilities at intermediate energies.

From our results it appears that the isospin content of pre-equilibrium emitted nucleons at high transverse momentum, or large rapidity, is rather sensitive to this property of the mean field. Thus it can be a good observable to learn about fundamental properties of the nuclear interaction, such as its momentum dependence in the isovector channel. In particular, it is found that the $m_n^* > m_p^*$ splitting leads to a decreasing behavior of the N/Z of emitted particles versus rapidity or transverse energy, whereas the opposite splitting is associated with a flat (or even increasing) trend.

A quantitative analysis appears also possible and is of great interest because new regions at abnormal densities and high momenta could be probed.

We remark finally that such observables of experimental interest could be investigated even in absence of information about neutron emissions by looking at the correlation between kinematical properties and isotopic content of light clusters emitted during the early stage of the collision. Promising indications in this direction are coming from cluster coalescence studies of the fast-emitted nucleons, see Refs. [33,35].

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