Fast nucleon emission as a probe of the isospin momentum dependence

J. Rizzo, M. Colonna, M. Di Toro
Laboratori Nazionali del Sud INFN,
Via S.Sofia 62, I-95123 Catania, Italy
Dipartimento di Fisica e Astronomia,
Università di Catania
E-mail: colonna@lns.infn.it

In this article we investigate the structure of the non-local part of the symmetry term, that leads to a splitting of the effective masses of protons and neutrons in asymmetric matter. Based on microscopic transport simulations we suggest some rather sensitive observables in collisions of neutron-rich (unstable) ions at intermediate (RIA) energies. In particular we focus the attention on pre-equilibrium 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 behaviours for some physical properties, such as the momentum dependence of the mean field in the iso-scalar and iso-vector channel (see Refs. 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 non-local 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 matter, and the sign of this splitting already is an open and controversial problem (Ref. 3).

Considering separately the local and non-local 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 Ref. 4. The important repulsive non-local 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 very unpleasant feature in the spin channel of the earlier Skyrme forces, the collapse of polarized neutron matter Refs. 5, 6, 7. In correspondence the predictions on isospin effects 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.

We note that the same is predicted from microscopic relativistic Dirac-Brueckner-Hartree-Fock (DBHF) calculations Refs. 8, 9 and in general from the introduction of scalar isovector virtual mesons in Relativistic Mean Field (RMF) approaches Refs. 10, 11. At variance, non-relativistic Brueckner-Hartree-Fock (BHF) calculations are leading to opposite conclusions Refs. 12, 13, 14. However, the comparison between relativistic effective (Dirac) masses and non-relativistic effective masses requires some attention, see the Ch.6 of Ref. 4 and refs. therein. In fact, though the neutron Dirac-mass is below the proton one, in correspondence the non-relativistic Schroedinger-mass splitting can have any sign. Indeed this is just the case of the very recent DBHF analysis of the Tübingen group Refs. 12, 15. 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 sensitive 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 Ref. 16. A decreasing behaviour is observed in the case Ref. 17, while a positive slope is obtained in the opposite case. An important physical consequence of the negative slopes is that the isospin effects on the optical potentials tend to disappear at energies just above 100 MeV (or even change the sign for “old” Skyrme-like forces). Also, 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. 17.

Unfortunately results derived from neutron/proton optical potentials at low energies are not conclusive Refs. 18, 19, 20, since the effects due to 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, due to the crossing discussed before, it is difficult to appreciate differences
between positive or negative slopes.

A positive slope is obtained, for instance, within the phenomenological Dirac Optical Potential (Madland – potential), with different implicit momentum dependences in the self-energies \( \tau = 2 \). This potential has been constructed fitting simultaneously proton and neutron (mostly total cross sections) data for collisions with a wide range of nuclei at energies up to 100 MeV. Recently such Dirac optical potential has been proven to reproduce very well the new neutron scattering data on \(^{208}\text{Pb}\) at 96 MeV \( \tau = 2 \) measured at the Svendberg Laboratory in Uppsala.

More data are needed at higher energies (around/above 100 MeV), to improve the systematics, in order to clearly disentangle between the two trends of the Lane potential and of the effective mass splitting.

We note however that these properties of the interaction will also affect the dynamical evolution of heavy ion collisions. So we can get independent information about it just by looking at some suitable reaction observables. We can expect important effects on transport properties (fast particle emission, collective flows) of the dense and asymmetric \( \text{NM} \) that will be reached in Radioactive Beam collisions at intermediate energies.

Here we will focus on the study of pre-equilibrium emission in neutron-rich central collisions, at 50 and 100 MeV/A. We will see that the energy dependence of the Lane potential for the used integrals of the form:

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

with \( g(\vec{p}, \vec{p}') = (\vec{p} - \vec{p}')^2 \). This choice of the function \( g(\vec{p}, \vec{p}') \) corresponds to a Skyrme-like behaviour and it is suitable for \( \text{BNV} \) simulations. We use a soft equation of state for symmetric nuclear matter (compressibility modulus \( K_{NM}(\rho_0) = 215 \text{MeV} \)). In this frame we can easily adjust the parameters in order to have the same density dependence of the symmetry energy but with two opposite \( n/p \) effective mass splittings, as predicted by the early Skyrme forces \( G \) and the later Skyrme-Lyon parametrizations \( R \). So we can separately study the corresponding dynamical effects, \( R \).

A good way to visualize the physical meaning of the mass splitting is to look at the kinetic energy dependence of the Lane potential \( U_{\text{Lane}} = (U_n - U_p)/2I \). Its slope depends on the value and sign of the mass splitting (see \( R \) 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 difference between neutron and proton masses is \( \sim 10\% \) at normal density), only the sign is opposite. The upper curve well reproduces the Skyrme-Lyon (in particular \( SLy4, SLy7 \)) results, the lower (dashed) the \( GBD, SIII, SKM^* \) ones.

### II. DETAILS OF THE INTERACTION

In order to directly test the influence of the \textit{Schrodinger}-effective mass splitting we will present results from reaction dynamics at intermediate energies analysed in a non-relativistic transport approach, of \( \text{BNV} \) type, see \( G, GBD \). The \( \text{ISO} - \text{MD} \) effective interaction is derived via an asymmetric extension of the \( \text{GBD} \) force \( G, GBD \).

The energy density can be parametrized as follows (see also \( R, G \)):

\[
\varepsilon = \varepsilon_{\text{kin}} + \varepsilon(A', A'') + \varepsilon(B', B'') + \varepsilon(C', C'')
\]

where \( \varepsilon_{\text{kin}} \) is the usual kinetic energy density and

\[
\varepsilon(A', A'') = (A' + A''I^2) \frac{\tau^2}{\rho_0}
\]

\[
\varepsilon(B', B'') = (B' + B''I^2) \left( \frac{\sigma}{\rho_0} \right) \frac{\tau}{\rho}
\]

\[
\varepsilon(C', C'') = C'(\mathcal{I}_{NN} + \mathcal{I}_{PP}) + C''\mathcal{I}_{NP}
\]

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 \( A = N + Z \); the quantity \( \rho_0 \) is the normal density of nuclear matter. The momentum dependence is contained in the \( \mathcal{I}_{\tau \tau'} \) terms, which indicate integrals of the form:

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

FIG. 1: Energy dependence of the Lane potential for the used parametrizations. Small panel: the effective mass splitting, related to the slope of the Lane potential (for a \( I = 0.2 \) asymmetry).

From the figure we can immediately derive the expectation of very different symmetry effects for nucleons around 100 MeV kinetic energy: 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. Besides, 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 in order to clearly see the effect of 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 realistic “ab initio” simulations of collisions at intermediate energies of n-rich systems, in particular $^{132}$Sn + $^{124}$Sn at 50 and 100 AMeV, 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. One of the aims of our work is also to select reaction observables more sensitive to the momentum (non-local 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 nucleon emissions (gas phase) and the corresponding asymmetry. It is shown in Fig. 2 (where $I(t) \equiv (N - Z)/A$) for the 50 AMeV reaction. The solid line gives the initial asymmetry of the total system.

We find an interesting behaviour 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 isospin asymmetry than the *asy-soft* one; later, we can see an inversion of this trend, due to large contributions to the gas phase coming from low density regions [23]; finally, the gas phase is more asymmetric in the *asy-soft* case [24].

This behaviour is mainly due to the local part of the symmetry energy, but for both choices of the density stiffness of the symmetry term we clearly see also the effects of the mass splitting, resulting in a reduced fast neutron emission when $m^*_n > m^*_p$. It is more pronounced during the early stages of the reaction (up to 60 fm/c), when the most energetic particles are emitted [30] 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 order to better isolate the mass splitting effect and to select the corresponding observables, in Figs. 3, 4 we report the N/Z of the “gas” at two different times, $t = 60 fm/c$ (end of the pre-equilibrium emission), and $t = 100 fm/c$ (roughly freeze-out time). We have followed 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 $N/Z = 1.56$).

A general feature of nucleon emission is the isospin distillation (see [28] and refs. therein), which leads to a gas phase with an asymmetry greater than the initial one. We find an interesting behaviour 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 isospin asymmetry than the *asy-soft* one; later, we can see an inversion of this trend, due to large contributions to the gas phase coming from low density regions [23]; finally, the gas phase is more asymmetric in the *asy-soft* case [24].

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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 due to the larger neutron repulsion of the *asy-stiff* choice. The effect is reduced at higher $p_t$’s due to the overall repulsion of the isoscalar momentum dependence.
Finally at freeze out (right panel) the difference is less pronounced, since Isospin Distillation is coming into play during the expansion phase; it is more efficient in the asy-soft choice, \cite{2} and refs. therein.

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 experimental interest, see Fig. 4. As expected the $m_n^* > m_p^*$ sharply reduces the neutron emission at high $p_t$'s. On the other hand, low momentum nucleons show a behaviour which is consistent with Fig. 3, mainly ruled by the local part of the symmetry potential.

We have repeated the analysis at higher energy, 100 AMeV, and the effect appears nicely enhanced, see Fig. 5. The observed differences for nucleons at high $p_t$'s already appear at early times: since these momentum regions are populated mostly during the early stages of the reaction (cfr. \cite{30}), we finally get a permanent signal of a dynamical feature of the interaction. We note a decreasing behaviour of the $N/Z$ content of pre-equilibrium emission versus the transverse momentum, due to a larger neutron attraction, in the $m_n^* > m_p^*$ case, while 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 pre-equilibrium 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 behaviour of the two mass splitting sign. Going to 80 fm/c (new freeze-out time), the differences at small rapidity almost disappear, while the different effects already present at 50 fm/c for large rapidities are kept and are even enhanced. The behaviour 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, especially 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, while it is reduced in the opposite case.

This is fully consistent with the expectations deduced from the Fig. 1 at the end of Sect.II.

Similar results have been obtained in ref. \cite{31} at 400 AMeV in a different Iso-MD model, restricted to the $m_n^* > m_p^*$ choice.

**IV. CONCLUSIONS**

Our aim has been to find an observable effect of the nucleon effective mass splitting, 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
in order 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 behaviour of the $N/Z$ of emitted particles versus rapidity or transverse energy, while the opposite splitting is associated with a flat (or even increasing) trend.

We finally like to remark that this is an observable of experimental interest that can be studied, 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.

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