Isospin effects and sensitive observables in the Fermi energy domain

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Abstract

We review recent results obtained for charge asymmetric systems at Fermi energies. Observables sensitive to the isospin dependent part of nuclear interaction are discussed, providing information on the symmetry energy behavior below normal density.

1 Introduction

The behavior of nuclear matter under several conditions of density and temperature is of crucial importance for the understanding of a large variety of phenomena, ranging from the structure of nuclei and their decay modes, up to the life and the properties of massive stars. Different mechanisms involving nuclear processes at fundamental level can be linked by the concept of nuclear Equation of State (EOS). In particular, over the past years, many efforts have been devoted to the investigation of the isovector part of the nuclear interaction, aiming at constraining the density dependence of the symmetry energy \(E_{\text{sym}}\) (Iso-EOS) \([1, 2]\). Transient states of nuclear matter far from normal conditions can be created in heavy ion collisions at Fermi and intermediate energies. Hence reactions with neutron-rich/poor systems and, in perspective, with exotic beams can be seen as a suitable tool to explore this issue. Our strategy to constrain the nuclear interaction is to implement effective density functionals into transport codes, devoted to
simulate the collisional dynamics (here we follow the Stochastic Mean Field (SMF) approach \[3\]). Then predictions can be compared to experimental data for specific reaction mechanisms, and related observables, particularly sensitive to isospin effects. We will focus on collisions at Fermi energies, where one essentially explores the low-density behavior of \(E_{\text{sym}}\). We will test an asy-soft parametrization, with an almost flat behavior below \(\rho_0\), or an asy-stiff behavior, with a faster decrease at lower densities \[4\].

2 Isospin diffusion in semi-peripheral reactions

We consider semi-peripheral reactions between two nuclei (denoted by H and L) having different N/Z and we investigate the diffusion of the initial isospin gradient. This process involves nucleon exchange through the low density neck region and hence it is sensitive to the low density behavior of \(E_{\text{sym}} \[5, 6, 7\]. Within a first order approximation of the transport dynamics, the relaxation of a given observable \(x\) towards its equilibrium value can be expressed as: 

\[ x_{P,T}(t) - x^{eq} = (x_{P,T} - x^{eq}) e^{-t/\tau}, \]

where \(x_{P,T}\) is the \(x\) value for the projectile (P) or the target (T) before the diffusion takes place, \(x^{eq} = (x^P + x^T)/2\) is the full equilibrium value, \(t\) is the elapsed time and \(\tau\) is the relaxation time, that depends on the mechanism under study. The degree of isospin equilibration reached in the collision can be inferred by looking at isospin dependent observables in the exit channel, such as the asymmetry \(\beta\) of projectile-like (PLF) and target-like (TLF) fragments. It is rather convenient to construct the so-called imbalance ratio \[5\]:

\[ R_{P,T} = (x_{P,T} - x^{eq})/|x_{P,T} - x^{eq}| \]  

Clearly, this observable measures the difference between the actual asymmetry of PLF (or TLF) and the full equilibrium value, normalized to the initial distance (i.e. to the conditions before the diffusion process has started). In the calculations the latter can be evaluated by looking at the asymmetries of PLF (or TLF), as obtained in the symmetric reactions HH and LL (where diffusion does not take place), after fast particle emission is over. Within our approximation, the imbalance ratio simply reads: \(R_{P,T} = \pm e^{-t/\tau}\). According to this expression, the observable \(R_{P,T}\) is actually independent of the initial asymmetry distance between the reaction partners and isolates the effects of the isodiffusion mechanism, whose strength is determined by the relaxation time \(\tau\), related to the symmetry energy. However the degree of equilibration reached in the reaction crucially depends also on the contact time \(t\), i.e. on the reaction centrality. To pin down the information on
$E_{\text{sym}}$ we study the correlations between isospin equilibration and the kinetic energy loss, that is adopted as a centrality selector \cite{8, 6}. The simple arguments developed above are confirmed by the simulations of $^{124}$Sn (H) + $^{112}$Sn (L) collisions at 35 and 50 MeV/u, that have been carried out employing the SMF treatment with momentum dependent (MD) and momentum independent (MI) interactions \cite{6}. In fig.1 we report the correlation between

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Imbalance ratios as a function of relative energy loss. Upper panel: separately for stiff (solid) and soft (dashed) Iso-EOS, and for two parametrizations of the isoscalar part of the interaction: MD (circles and squares) and MI (diamonds and triangles), in the projectile region (full symbols) and the target region (open symbols). Lower panel: quadratic fit to all points for the stiff (solid), resp. soft (dashed) Iso-EOS.}
\end{figure}

$R_{P,T}$ and the total kinetic energy loss, normalized to the total energy available in the center of mass $E_{\text{cm}}$, for the full set of calculations performed. On the bottom part of the figure one can see that all the points essentially follow a given line, depending only on the symmetry energy parametrization adopted. A larger equilibration (smaller $R$) is observed in the asy-soft case, corresponding to the larger value of $E_{\text{sym}}$ at low density. We mention that, according to its definition, the imbalance ratio does not change if one considers as observable $x$, instead of the asymmetry of PLF and TLF, other observables that are linearly correlated to it and more accessible from the experimental point of view, such as isoscaling coefficients, ratios of production of light isobars \cite{9} or isotopic content of light particle emission \cite{10}.

An experimental study of isospin diffusion as a function of the dissipated kinetic energy has been recently performed by the Indra collaboration \cite{10}. Two systems, with the same projectile, $^{58}$Ni, and two different targets ($^{58}$Ni and $^{197}$Au), at incident energies of 52 MeV/u and 74 MeV/u have been considered, with the aim to study isospin diffusion between Ni and Au nuclei. An isospin-dependent variable, correlated to the PLF asymmetry, is constructed from the isotopically identified light particles emitted from the
PLF, namely their average isotopic content, \((N/Z)_{CP}\). The analysis of this observable in terms of imbalance ratios is not possible for this set of reactions. Hence, in fig. 2 we plot directly the results of the SMF simulations concerning the variable \((N/Z)_{CP}\) (lines), calculated after de-exciting the hot primary PLF’s with the help of the SIMON code \(^{11}\). One can notice (see top-left panel) that isospin diffusion effects are larger in asy-soft case (full line), as expected. For the symmetric Ni + Ni system, isospin effects are only due to pre-equilibrium emission. Concerning the experimental data, open points show the values obtained forward in the nucleon-nucleon (NN) frame. In this case mid-rapidity particles and those coming from the PLF de-excitation are mixed up. The close points in fig.2 are related to the values of \((N/Z)_{CP}\) forward in the PLF frame. They are more representative of the isotopic content of the particles emitted from the PLF and can be compared with the results of the simulations. When looking globally at the results for the four cases treated here, the agreement is better when the asy-stiff EOS is used. However for Ni+Au at 52 MeV/u, where isospin transport effects are dominant, the close points lie in between the simulated results with the two iso-EOS. To conclude, this analysis points to a symmetry energy behavior in between the two adopted parametrizations, in agreement with other recent estimates \(^{12, 13}\).

3 Isospin dynamics in neck fragmentation

It is now quite well established that the largest part of the reaction cross section for dissipative collisions at Fermi energies goes through the Neck Fragmentation channel, with intermediate mass fragments (IMF) directly produced in the interacting zone in semiperipheral collisions on very short time scales \(^{14}\). It is possible to predict interesting isospin transport effects for this fragmentation mechanism since clusters are formed still in a dilute asymmetric matter but always in contact with the regions of the projectile-like and target-like remnants almost at normal densities. In presence of density gradients the isospin transport is mainly ruled by drift coefficients and so we expect a larger neutron flow to the neck clusters for a stiffer symmetry energy around saturation \(^{11}\). This is shown in fig.3 (left), where the asymmetry of the neck region is plotted for the two Iso-EOS choices, compared to the PLF-TLF asymmetry, for Sn + Sn reactions at 50 MeV/u, \(b = 6\) fm. In order to build observables less affected by secondary decay effects, in fig.3 (right) we consider the ratio of the asymmetries of the IMF’s to those of the residues for stiff and soft iso-EOS. This quantity can be
Figure 2: Isospin ratio of complex particles for Ni quasi-projectile vs dissipated kinetic energy, for the two reactions and the two energies. Circles correspond to the experimental data, open for data forward of the N-N velocity, full for data forward in the PLF frame. Dotted lines are for asy-soft calculations and full lines for asy-stiff. Adapted from ref. [10].

estimated on the basis of simple energy balance considerations. Starting from a residue of mass $A_{res}$ and a neck of mass $A_{IMF}$ we assume that the mass $A$ participating in the isospin exchange is approximately equal to the mass of the neck, while it is small relative to the mass of the residue. This will lead to the asymmetry $(\beta + \Delta \beta)$ of the neck, and to a total asymmetry $\beta_{res} = [\beta(A_{res} - A) + (\beta - \Delta \beta)A]/A_{res} = \beta - \Delta \beta A/A_{res}$ of the residue, with $\Delta \beta$ to be determined by minimization of the symmetry energy. The corresponding variation of the symmetry energy is equal (apart from a constant) to:

$$\Delta E_{sym} = A_{res}E_{sym}(\rho_R)(\beta - \Delta \beta A/A_{res})^2 + AE_{sym}(\rho_I)(\beta + \Delta \beta)^2;$$

(2)

where $\rho_R$ and $\rho_I$ are the densities of the residue and neck regions, respectively. The minimum of the variation of $\Delta E_{sym}$ yields

$$\frac{\beta_{IMF}}{\beta_{res}} = \frac{E_{sym}(\rho_R)}{E_{sym}(\rho_I)}$$

(3)

From this simple argument the ratio between the IMF and residue asymmetries should depend only on symmetry energy properties and, in particular,
on the difference of the symmetry energy between the residue and the neck regions, as appropriate for isospin migration. It should also be larger than one, more so for the asy-stiff than for the asy-soft EOS. It is seen indeed in fig.3, that this ratio is nicely dependent on the iso-EOS only (being larger in the asy-stiff case) and not on the system considered. If final asymmetries were affected in the same way by secondary evaporation in the case of neck and PLF fragments, then one could directly compare the results of fig.3 (right) to data. However, due to the different size and temperature of the neck region with respect to PLF or TLF sources, de-excitation effects should be carefully checked with the help of suitable decay codes.

4 Conclusions

We have reviewed some aspects of the phenomenology associated with nuclear reactions at Fermi energies, from which new hints are emerging to constrain the EOS of asymmetric matter below normal density. A considerable amount of work has already been done in this domain. We note also recent confirmations from structure data, see for instance the study of monopole resonances in Sn-isotopes [15]. In the near future, thanks to the availability of both stable and rare isotope beams, more selective analyses, also based on new exclusive observables, are expected to provide further stringent constraints.
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