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Isospin effects on the nuclear equation of state at sub-saturation densities

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We investigate nuclear dynamics and the Nuclear Equation of State (NEoS) by a detailed study of heavy-ion collisions at intermediate energies. In particular, we explore the isospin transport phenomena, occurring during the collision between the projectile and target having different neutron-to-proton ratios (N/Z). Two phenomena are investigated: the isospin diffusion and the isospin migration. The former is related to the nucleon exchange process between the projectile and the target, the latter is related to the neutron migration towards the low density region in the neck formed at mid-rapidity. Both provide an important information on the density dependence of the symmetry energy term of the NEoS.

KEYWORDS: Equation of State, Symmetry Energy, Nuclear Reaction Dynamics, Isospin Diffusion/Migration.

1. Introduction

An Equation of State (EoS) is a relation between the intensive properties of a system (pressure, temperature, chemical potentials, . . .) and their extensive conjugate variables (volume, entropy, number of particles, . . .). Thus, an EoS is a link between the macroscopic properties of a system and the underlying microscopic physics, allowing to better apprehend and constrain the interactions and coupling at stake.

The Nuclear Equation of State (NEoS) is defined by the energy per nucleon, as a function of the density ρ, the temperature T and the neutron-to-proton asymmetry (isospin). Significant progress has been made in constraining the NEoS of symmetric matter around saturation density ρ_0 (core density of stable nuclei) [1]. Nonetheless, the description of EoS of asymmetric nuclear matter is still unknown.

One of the most challenging aims of modern nuclear physics is to constrain the density dependence of the nuclear symmetry energy term $\epsilon_{sym}(\rho)$. Indeed, a variety of phenomena are thought to be sensitive to $\epsilon_{sym}(\rho)$, such as binding energies of nuclei [1], neutron-skin width [2], pygmy and giant resonances [3], nucleosynthesis [4], supernova explosion mechanisms [5] or the composition and cooling of neutron stars [6].

In this contribution, we report results obtained on a campain of experiments performed at GANIL, wherethe VAMOS spectrometer was coupled with the 4π INDRA multidetector array. The use of a large acceptance spectrometer such as VAMOS provides unique and unprecedented tools to measure the isotopic and velocity distributions of the residues with high resolution. INDRA is used to estimate the impact parameter and excitation energy by means of the detected charged products emitted in coincidence with the residues. In particular we have investigated two observables related to the density dependence of the symmetry energy: the isospin diffusion and the isospin migration.

2. The isospin transport phenomena

Information on the density dependence of ϵ_{sym} are extracted from nuclear laboratory experiments and astrophysical observations. Heavy-Ion Collisions (HIC), over a large domain of projectile/target isospin with different beam energies, are a unique way to experimentally produce and study very exotic nuclei with a large asymmetry in isospin (N/Z) and high excitation energies, but also submit nuclear matter to various density, pressure, temperature and angular momentum conditions. Comparisons of observables sensitive to ϵ_{sym} between experiments and models allow to better constrain ϵ_{sym}.

Peripheral collisions at intermediate beam energies (from 30 to 100 MeV/A) are of particular interest. Indeed, for such collisions transport models have highlighted a dynamic formation of two hot nuclei kinematically close to the projectile and the target called Quasi-Projectile (QP) and Quasi-Target (QT), but also a neck at sub-saturation density between them. This zone of mid-rapidity is found to be at the origin of the emission of light charges particles ($Z \leq 2$) and intermediate mass fragments ($3 \leq Z \leq 10$), in short-time scales. All of the aforementioned phenomena are found to be sensitive to the symmetry energy density dependence [9].

The exchange of nucleons between two colliding nuclei is called the isospin transport phenomena, which mainly depends of the initial composition of the nuclei, the time of their contact and ϵ_{sym}. Thus, isospin transport is a probe for studying the density dependence of ϵ_{sym}.

Isospin transport can be defined by $\mathbf{j}_n$ and $\mathbf{j}_p$, respectively the neutron and proton currents between the two colliding nuclei, verifying [9]:

$$\mathbf{j}_{n,p} = D^{\rho}_{n,p}\nabla\rho - D^{\delta}_{n,p}\nabla\delta \tag{1}$$

Where $\rho = \rho_n + \rho_p$ is the density of the system, $\delta = (\rho_n - \rho_p)/\rho$ its isospin, $D^{\rho,\delta}_{n,p}$ are the density and isospin neutrons and protons transport coefficients, explicitly defined in [10].

According to Equation 1:

$$\mathbf{j}_n - \mathbf{j}_p = \underbrace{\left(D^{\rho}_{n} - D^{\rho}_{p}\right)\nabla\rho}_{\text{Isospin drift}} - \underbrace{\left(D^{\delta}_{n} - D^{\delta}_{p}\right)\nabla\delta}_{\text{Isospin diffusion}} \tag{2}$$

The first term of Equation 2, called **isospin drift** (or isospin migration) is associated to the density gradient, such as:

$$D^{\rho}_{n} - D^{\rho}_{p} \propto 4\delta\,\frac{\partial\epsilon_{sym}}{\partial\rho} \tag{3}$$

The second term of Equation 2, called **isospin diffusion** is associated to the isospin gradient, such as:

$$D^{\delta}_{n} - D^{\delta}_{p} \propto 4\rho\,\epsilon_{sym} \tag{4}$$

To summarize, during HIC an equilibrium of the N/Z ratio of the colliding nuclei takes place and is governed by the competition between:

- isospin drift (migration) leading to the transfer of neutron to low-density regions, and linked to the derivative (slope) of ϵ_{sym}.
- isospin diffusion leading to the transfer of neutrons from a high N/Z region to a low N/Z one, and linked to the absolute value of ϵ_{sym}.

3. Experimental setup

A campaign of experiments have been performed at GANIL, dedicated to study peripheral to semi-peripheral collisions of ^{40,48}Ca + ^{40,48}Ca at $E/A = 35\ MeV$ beam energy. The setup was constituted by the large-acceptance and high resolution VAMOS magnetic spectrometer [11, 12] and the INDRA multi-detector array [13, 14].

VAMOS was the trigger of the acquisition and covered very forward laboratory angles ($\theta = 2° - 7°$), allowing to measure the charge, mass and velocity of the Projectile-Like Fragment (PLF). The coincident light charged particles were measured by INDRA telescopes covering angles $\theta = 7° - 176°$, allowing to estimate the impact parameter and excitation energy associated to the collisions.

A specific software development of the INDRA-VAMOS coupling has been done within the KaliVeda toolkit [15], so as to ensure the calibration, reduction, normalization and analysis of the data, but also filter the models for comparisons.

A software normalization technique of the data has also been developed, adapted from [12], in order to correct the spectrometer acceptance and overlapping magnetic rigidity settings, inherent to the use of a large acceptance spectrometer. The idea was to apply a weight, on an event-by-event basis, taking into account the spectrometer acceptance, the dead time, the beam intensity and magnetic rigidity recovering among the experimental runs.

4. Isospin diffusion

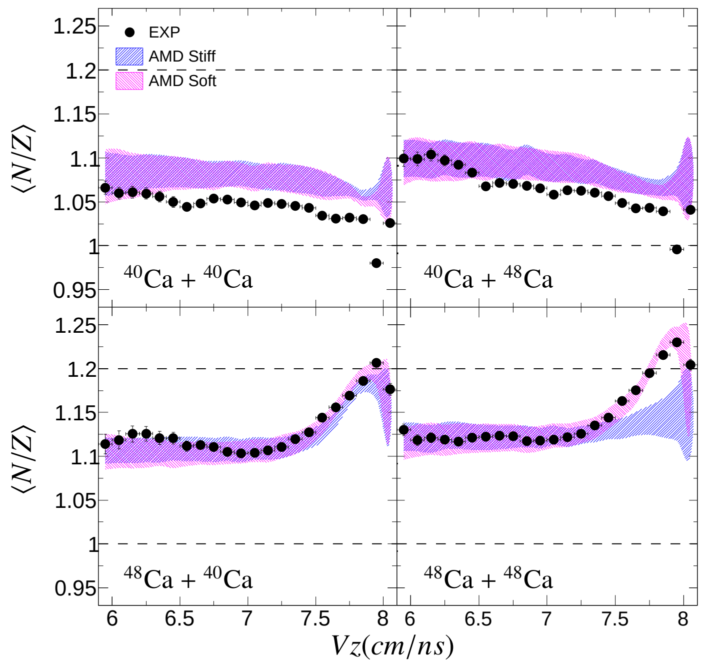

Fig. 1. $\langle N/Z \rangle$ ratio of the residue (PLF) detected in VAMOS as a function of its parallel velocity in the laboratory frame, for the experimental data and the filtered AMD simulations followed by GEMINI++ as after-burner, for ^{40,48}Ca + ^{40,48}Ca collisions at $E/A = 35\ MeV$. The beam velocity corresponds to $V_{beam} \simeq 8\ cm/ns$. The deashed lines corresponds to the total N/Z of the projectile/target system ($N/Z = 1$ for ^{40}Ca + ^{40}Ca and $N/Z = 1.2$ for mixed systems).

As we already mentioned, simultaneous studies from the peripheral to semi-peripheral collisions are a unique experimental way to investigate the isospin transport phenomena. Looking at the evolution of the $\langle N/Z \rangle$ ratio of the PLF as function of the energy dissipation of the collision can give an important information on the isospin diffusion.

Figure 1 shows the $\langle N/Z \rangle$ ratio of the assumed PLF detected in VAMOS as a function of its parallel velocity, for the four system under study. One observes that the systems with the projectile ^{48}Ca (lower panels) produce systematically more n-rich fragments than those with ^{40}Ca (upper panels). For the system having the same projectiles, one observes that the fragment detected with ^{48}Ca targets are systematically more n-rich than those with ^{40}Ca targets. Both observations indicate an effect of the memory of the entrance channel either of the target or projectile side. There is a clear transfer between the two colliding nuclei. Finally, we observe a decrease of the $\langle N/Z \rangle$ ratio with decreasing velocity (*i.e.* increasing dissipation).

In the same figure (Fig. 1) we report the results of the dynamical calculation AMD [16, 17] for two interactions, Gogny and Gogny-AS (soft and stiff, respectively), after decay using statistical model calculation GEMINI++ [18, 19]. The calculation shown in this figure has been filtered, the window acceptance and triggering of VAMOS representing the most restrictive cuts on the events. For the ^{40}Ca projectiles, one observes similarity between the two interactions and both of them overestimate the data, particularly at high velocities (less dissipative collisions). A better agreement is observed at low velocities. For ^{48}Ca projectile, AMD reproduces very well the n-enrichment of the data. Nonetheless, a better reproduction is observed for AMD-Soft than for AMD-Stiff, particularly for the system ^{48}Ca + ^{48}Ca and the more peripheral collisions (Vz close to the beam velocity). This discrepancy may well be due to the fact that the detection is very close to the grazing angle, where huge variations of the reaction kinematics happen.

To summarize this section, AMD seems to reproduce the isospin diffusion observed in our reaction, particularly for n-rich systems. However, it is difficult to distinguish a marked difference between the two interactions, mainly because of the secondary decays. Indeed, by applying systematic studies between the primary/secondary (deexcited) fragments, we have highlighted that the possible differences between the two interactions are blured by the deexcitation.

5. Isospin migration

Our unique experimental setup offers the opportunity to study the second observable sensitive to the density gradient established in Eq. 2. The correlation between the high resolution velocity of the fragment detected in VAMOS spectrometer and the $(\langle N \rangle / \langle Z \rangle)_{CP}$ ratio of the charged particles detected in coincidence in INDRA, allows to probe to the isospin drift at low density.

We defined the average isotopic ratio of Charged Particles (CP) as:

$$(\langle N \rangle / \langle Z \rangle)_{CP} = \sum_{Nevts} \sum_{\nu} N_{\nu} / \sum_{Nevts} \sum_{\nu} Z_{\nu} \tag{5}$$

Where N_ν and Z_ν are respectively the number of neutrons and protons bound in particle ν identified in INDRA telescopes, ν beeing ^{2,3}H, ^{3,4,6}He, ^{6,7,8,9}Li or ^{7,9,10}Be (free protons excluded) [20].

The variable $(\langle N \rangle / \langle Z \rangle)_{CP}$ was computed twice, using two angular ranges in center of mass frame, so as to study isospin drift at mid-velocity. Firstly particles emitted at forward in the center of mass frame were considered ($\theta_{CM} = 7° - 30°$), to depict the QP deexcitation. Secondly particles around mid-rapidity of the reaction were considered ($\theta_{CM} = 67° - 90°$), to depict the neck supposed to be at sub-saturation density.

Figures 2 and 3 represent the experimental and theoretical evolution of the average ratio of the CP detected in INDRA as function of the velocity of the PLF detected in coincidence VAMOS, for the

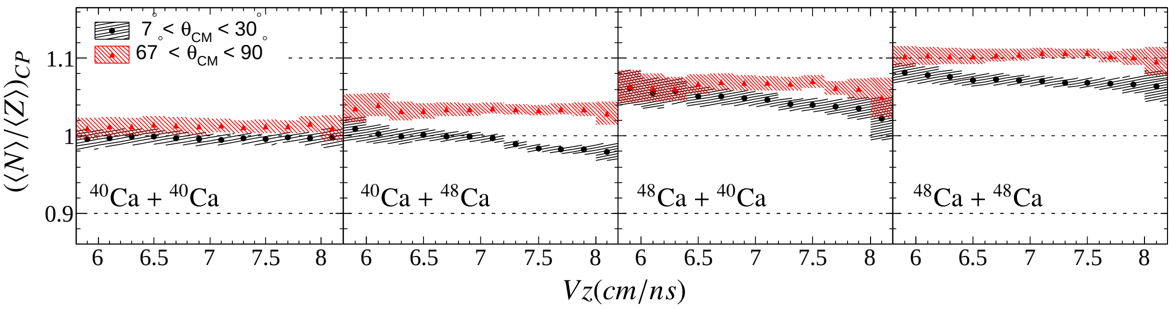

Fig. 2. Experimental isotopic ratios of charged particles detected in INDRA, $(\langle N\rangle/\langle Z\rangle)_{CP}$, at forward angles and mid-rapidity, as a function of the parallel velocity of the fragment detected in coincidence in VAMOS, for ^{40,48}Ca + ^{40,48}Ca collisions at $E/A = 35\ MeV$.

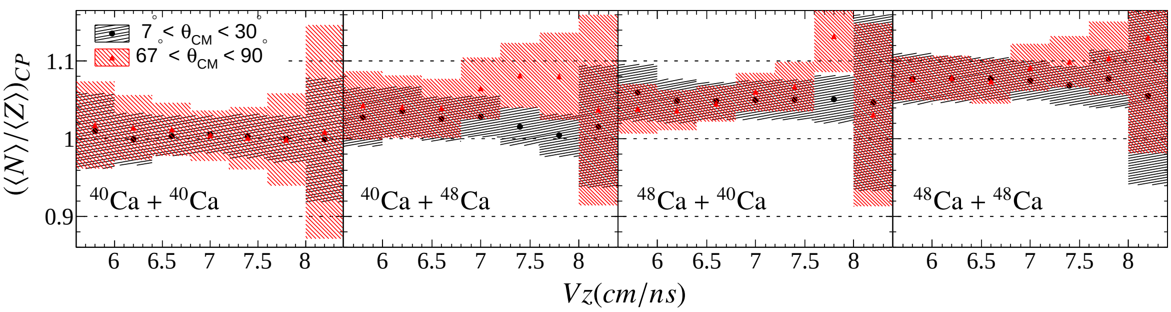

Fig. 3. Same as Fig. 2 but for AMD calculations using Gogny interaction (Soft) followed by statistical model GEMINI++. The calculation is filtered by numerical filter of the apparatuses

two aforementionned angular ranges. Experimentally, we observe that the mid-rapidity show systematically a higher $(\langle N\rangle/\langle Z\rangle)_{CP}$ than the one at the forward angles, whatever the neutron-enrichment of the initial system, and even for the symmetric systems. The above observation suggests that the isotopic ratios reflect the neutron enrichment at the mid-rapidity, which can be interpreted as an isospin migration. This confirms that the density at mid-rapidity is lower than the saturation density ρ_0, thus the neutrons are attracted towards this zone.

The AMD calculation shown in Fig. 3 does not seem to reflect the same tendency. Nevertheless, the error bars are too large to draw any conclusion, even if the trend seems to reproduce the data. Much more statistics are needed to draw a conclusion with simulations.

6. Conclusion

A unique experimental setup, coupling the large acceptance spectrometer VAMOS and the 4π multidetector array INDRA allowed to measure, on an event-by-event basis, the isotopic distribution of PLF residues with the other charged products emitted in coincidence, for peripheral to semi-peripheral collisions over a large domain of projectile/target isospin. Firstly, the isospin diffusion of the PLF has been observed by direct measurement of the PLF residue with VAMOS, without making any reconstruction hypothesis. Secondly, an investigation of the N/Z ratio of particles detected at mid-rapidity with INDRA as a function of the velocity of the PLF suggests isospin migration towards a sub-saturation density region. The data set presented here are a unprecedented probe to measure different isospin sensitive observables in the same reaction. Systematic comparisons with all available transport models would be of particular interest to better constrain the symmetry energy.

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