Isospin transport in heavy-ion reactions reaction around the Fermi energy domain

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One of the most exciting challenges in modern nuclear physics and astrophysics is to understand the behavior of nuclear matter under extreme conditions [1, 2]. Heavy ion reactions in the Fermi energy domain provide a unique opportunity to enrich our knowledge about the nuclear equation of state (EoS). Isospin transport ratio (or isospin imbalance ratio) [3] is directly correlated to the degree of isospin equilibration in heavy ion reactions, which can be defined as,

$$R = \frac{2x_{A_p+A_t} - x_{A_l+A_l} - x_{A_h+A_h}}{x_{A_l+A_l} - x_{A_h+A_h}}. \qquad (1)$$

where, $x_{A_p+A_t}$ is an isospin sensitive observable which can be calculated for each reaction between projectile and target mass number A_p and A_t respectively, corresponding to the same atomic number Z. Two different isotopes are used, and $A_l(A_h)$ denotes the more neutron poor (rich).

The pioneering work by the Michigan group at NSCL clearly identified that the isospin transport ratio is connected to the density dependence of the symmetry energy [4]. However, tighter constraints could not be obtained mainly because of the uncertainty linked to the comparison protocol between nuclear experiments and transport simulations. In particular, the isotopic ratio of the quasi-projectile (QP) remnant, was not directly experimentally measurable with the NSCL detection system. Surrogate variables were therefore employed, such as isoscaling parameters or light cluster isobaric ratios.

The aims of the present work are (a) to investigate whether the isospin transport ratio calculated from two different isospin sensitive observables namely (i) $x = N/Z$ of the quasi-projectile (which gives R_{QP}) and (ii) $x = N/Z$ of the forward emitted free nucleons in the quasi-projectile reference frame (which gives R_{free}) are identical or not and (b) how they are sensitive to symmetry energy at saturation (E_{sym}), it's slope (L_{sym}) and curvature (K_{sym}). In order to do that ^{58}Ni+^{58}Ni, ^{64}Ni+^{64}Ni, ^{58}Ni+^{64}Ni and ^{64}Ni+^{58}Ni reactions have been simulated for a wide range of impact parameter and projectile energy around the Fermi energy domain in the framework of isospin dependent Boltzmann-Uehling-Uhlenbeck transport model (BUU@VECC-McGill) [5, 6] with a metamodelling for the nuclear equation of state [7]. Transport simulations have been performed in the projectile frame with realistic skyrme Sly5 functional [7], and a sensitivity analysis to the different symmetry energy parameters have been examined with

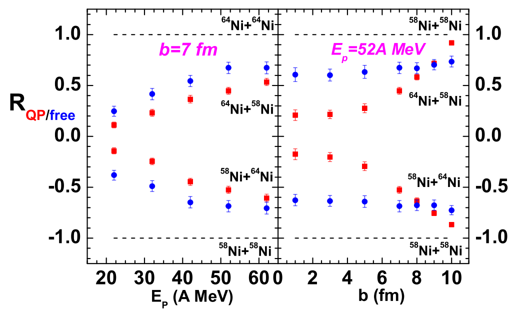

FIG. 1: Projectile energy (left panel) and impact parameter (right panel) dependence of R_{QP} (squares) and R_{free} (circles).

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the available empirical information.

By construction, the isospin transport ratio R defined by Eq. 1 is +1 and -1 for ^{64}Ni+^{64}Ni and ^{58}Ni+^{58}Ni reaction respectively. Fig. 1 represents the entrance channel effect on isospin diffusion from both N/Z of QP as well as that of free nucleons. Left panel shows the beam energy dependence at impact parameter b =7 fm whereas the right panel represents the impact parameter variation at beam energy 52 MeV/nucleon. The results clearly indicate that R_{QP} and R_{free} are different in general. With the increase of centrality of the reaction, participant region increases which enhances the degree of equilibration for isospin asymmetric reactions. Concerning the projectile energy dependence, the increase of absolute value of R for both observables reflects the shorter interaction time, increasing importance of nucleon-nucleon collisions and decreasing influence of the mean field, suggesting the importance of low energy experiments for precise measurements of the EoS properties. Recently, this is also experimentally verified by the first results from the same set of reactions performed by the INDRA-FAZIA collaboration at GANIL [8].

In order to quantify the sensitivity of the isospin transport ratio to the density dependence of symmetry energy, the lowest order isovector parameters E_{sym}, L_{sym} and K_{sym} are tuned independently, i.e. two of

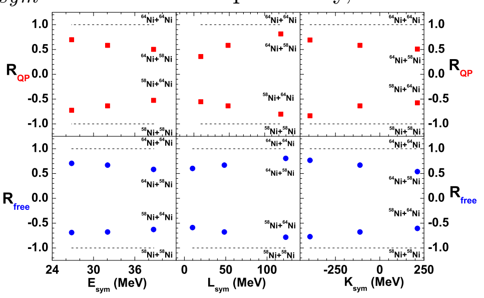

FIG. 2: Sensitivity of R_{QP} (top panels) and R_{free} (bottom panels) with E_{sym} (left panels), L_{sym} (middle panels) and K_{sym} (right panels) for ^{58,64}Ni+^{58,64}Ni reactions at b=7 fm with projectile beam energy 52 MeV/nucleon.

them are kept fixed at the reference of Sly5 EoS, whereas the third one is varied from a minimal to a maximal value compatible with the available empirical information. The results for ^{58,64}Ni+^{58,64}Ni reactions at b=7 fm and 52 MeV/nucleon have been presented in Fig. 2. In the Fermi energy domain, sub-saturation densities are probed and the symmetry energy reduces for lower value of E_{sym} and K_{sym} and higher values of L_{sym}. A lower symmetry energy leads to a decreased isospin transport, and higher absolute values of R. As a consequence, the magnitude of transport ratios increase (decrease) with increasing values of L_{sym} (E_{sym}, K_{sym}, respectively). Both R_{QP} and R_{free} are seen to vary by varying the symmetry energy parameters, but the dependence is much more clear when the QP is considered.

Hence, from this theoretical study, it can be concluded that the isospin transport ratios of the quasi-projectile and free nucleons are different in general and both are sensitive to the symmetry energy at saturation, it's slope and curvature, but the sensitivity is more for quasi-projectile compare to free nucleons. This underlines the importance of using the same observable when isospin diffusion data are compared to transport model prediction.

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