Isotope analysis in central heavy ion collisions at intermediate energies

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Abstract. Symmetry energy is a key quantity in the study of the equation of state of asymmetric nuclear matter. Heavy ion collisions at low and intermediate energies, performed at Laboratori Nazionali di Legnaro and Laboratori Nazionali del Sud, can be used to extract information on the symmetry energy coefficient $C_{sym}$, which is currently poorly known but relevant both for astrophysics and for structure of exotic nuclei.

PACS. 25.70.-z Low and intermediate energy heavy-ion reactions – 25.70.Pq Multifragment emission and correlations

Heavy-ion collisions can be considered an excellent tool to explore the nuclear equation of state (EOS) of nuclear matter in laboratory controlled conditions. With the availability of radioactive beam facilities, the isospin is being extensively explored. One of the goals of these studies is to provide a better knowledge of the symmetry term of the EOS. In particular, stable and radioactive beams over a wide range of $N/Z$ asymmetries allow to explore the asymmetric nuclear EOS and the density dependence of the symmetry energy.

Symmetry energy and its density dependence determine several properties of neutron stars as well as features (binding energy and rms radii) of exotic nuclear systems as neutron halo nuclei.

In statistical and dynamical models, the isotopic composition of fragments emitted in multi-fragmentation phenomena, in central heavy-ion collisions at intermediate energies, are sensitive to the density dependence of the symmetry term and therefore it can provide information on symmetry energy at low density. Indeed, in these reactions complex fragments are expected to be formed at low densities ($\rho \sim 0.1 - 0.5\rho_0$) and temperatures $T=3$-5 MeV. The study of the production yields of isotopically resolved nuclear particles and fragments can complete the knowledge of the EOS, as a function of $N/Z$, and is essential in searching for a possible occurrence of critical phenomena associated to fluctuations in the proton concentration of asymmetric nuclear matter. In the grand canonical model, the ratio of the primary fragment yield (for a given isotope emitted in two different reactions differing only in $N/Z$ ratio) depends exponentially on the neutron and proton number, the so-called isoscaling [[1]], by the relation:

$$R_{21} = \frac{Y_1(N, Z)}{Y_2(N, Z)} = C_{sym} \left(\frac{\alpha N + \beta Z}{A_2}\right)$$

where $Y_1$ and $Y_2$ are the yield of a given isotope respectively in the neutron rich and neutron deficient system, $C$ is an overall constant and $\alpha$ and $\beta$ are the isoscaling parameters. It turns out that [[2]] the isoscaling parameter $\alpha$ is almost independent on the secondary de-excitation of the primary fragments inducing to use it as a robust observable to extract information on the symmetry energy. Indeed, different statistical and dynamical models [[3]] relate $\alpha$ to the symmetry energy coefficient $C_{sym}$ via

$$\alpha = \frac{4C_{sym}}{T} \left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$

where $T$, $Z$ and $A$ are the temperature, charge and mass of the fragmenting system. In this way an estimate of the symmetry energy coefficient can be obtained whenever the isoscaling is observed and the temperature and the $Z/A$ ratio for the fragmenting systems are determined.

We present here two different sets of data collected with 4 $\pi$ detectors at Laboratori Nazionali del Sud (LNS)
and Laboratori Nazionali di Legnaro (LNL). In particular $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{125}\text{Sn}+^{58}\text{Ni}$ reactions at 35 AMeV incident energy were studied by using the 688 Si-CsI telescopes of the forward part ($1^\circ \leq \theta_{lab} \leq 30^\circ$) of CHIMERA multi-detector at LNS, in the framework of the REVERSE experiment. The most central collisions were selected by means of a multidimensional analysis of the experimental observables. A detailed analysis of the yields of the detected isotopes of light fragments ($3 \leq Z \leq 8$) provided information on breakup temperatures of the emitting sources, by means of the double isotope ratio thermometers, which resulted $\sim 4$ MeV. Isoscaling has been observed for fragments ($1 \leq Z \leq 8$), with $\alpha$ equal to 0.44. In Fig. 1 the scaled ratio

$$S(N_f) = R_{21} \exp(-\beta Z) = C \exp(\alpha N)$$

is plotted as a function of fragment neutron number. For the Sn+Ni reactions at 35 AMeV an estimate of the symmetry energy coefficient can be obtained considering the Z/A ratio suggested by SMM (Statistical Multifragmentation Model), which was used only to reconstruct (back-tracing) the characteristics of the sources formed in central collisions. A $C_{sym}$ close to 12 MeV has been evaluated, in agreement with similar estimates demonstrating that $C_{sym}$ for hot light nuclei in multifragmentation decreases with the excitation energies from 25 MeV for very peripheral collisions to 15 MeV or lower for central collisions. Isotope analysis has been performed also for fragments produced in central and semi-central collisions at lower incident energy. Beams of $^{32}\text{S}$ were accelerated at 14.5 AMeV on $^{58}\text{Ni}$ and $^{64}\text{Ni}$ targets at LNL. The reaction products were detected with the forward GARFIELD chamber coupled to the Ring Counter (RCo), a forward-angle apparatus specially designed for small polar angles. The very good mass resolution of the RCo Si-CsI telescopes and the good coverage of the phase space of the whole apparatus enable us to carry out accurate thermodynamics of excited systems with different N/Z at low energies where the hot composite systems is expected to enter the liquid-gas coexistence. Central collisions were selected imposing the presence of at least three fragments in Garfield and RCo apparatus and a flat distribution of the $\cos(\theta_{flow})$, corresponding to $\theta_{flow} \geq 60^\circ$. Events characterized by $\theta_{flow} \leq 30^\circ$ and a total fragment multiplicity greater or equal 3 were provisionally labelled as semi-central. A deeper analysis on these latter events is in progress in order to evaluate possible contaminations of semi-central events from residues coming from deep-inelastic collisions. The detected isotopes of light fragments (1 < Z < 8) have been used to extract double isotope ratio temperature of the formed sources, resulting respectively equal to 3.5 and 3.2 MeV. The isoscaling analysis has been performed and the scaled ratio is displayed in Fig. 1 for both reactions. The parameter $\alpha$ is influenced both by the difference in (N/Z) of the two systems used to construct $R_{21}$ and by the excitation energy of the fragmenting system. The S+Ni central collisions show a slope lower than the S+Ni semi-central reactions, in so far as increasing the excitation energy the $\alpha$ parameter decreases. Moreover, the S+Ni central collisions exhibit an $\alpha$ parameter very close to the Sn+Ni central collisions one. This is due to the larger difference in the N/Z ratio of the two systems used to construct $R_{21}$ for the Sn+Ni reaction, inducing a reduction of the $\alpha$ parameter.

In order to extract the symmetry energy for these reactions an estimate of the Z/A ratio of the fragmenting systems is necessary. To this end a comparison of experimental quantities with dynamical and statistical model has been undertaken. As a preliminary attempt one can estimate the Z/A ratio in the hypothesis that it does not change from the entrance channel value. In this case one obtains $C_{sym} = 12$ MeV for central collisions and $C_{sym} = 14$ MeV for semi-central collisions, respectively. Even if this evaluation sensitively depends on the Z/A of the sources, which has to be refined by model predictions, the trend of $C_{sym}$ is consistent with other studies that reveal a $C_{sym}$ closer to the standard value (25 MeV for normal nuclei at saturation density) at lower excitation energies ($E^*/A \sim 2$ MeV), decreasing monotonically as the excitation energy $E^*/A$ grows up to 5-8 MeV.

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