Exploring the symmetry energy with isospin effects in heavy-ion collisions

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Physics motivations

Heavy-ion collisions can be considered the only terrestrial means to explore the nuclear equation of state (EOS) under laboratory controlled conditions. Indeed, during an energetic impact between two heavy ions, nuclear matter evolves through density and temperature states that can otherwise be encountered only in astrophysical environments like supernovae explosions and neutron stars.

The nuclear equation of state (EOS) at zero-temperature can be expressed as

$$E(\rho,\delta)/A = E(\rho,\delta=0)/A + C_{Sym}(\rho)\cdot\delta^2 \qquad (1)$$

where $\rho = \rho_n + \rho_p$ and $\delta = (\rho_n - \rho_p)/\rho$ are the total density (neutron + proton) and the isospin asymmetry, respectively. In the case of symmetric nuclear matter (δ=0) the equation of state has been very extensively explored and constraints on its stiffness have been established [1]. However, the equation of state for asymmetric nuclear matter ($\delta \neq 0$) is still largely unknown. More in particular, several experimental and theoretical studies are devoted to the search for the density dependence of the symmetry energy term, contained in the function $C_{Sym}(\rho)$ in Eq. (1) [2-8]. These efforts are further stimulated by the fact that $C_{Sym}(\rho)$ determines several properties of the inner crust of neutron stars as well as the features of exotic nuclear systems, like neutron halos, where regions of very neutron-rich nuclear matter at low density exist [10]. As

Eq. (1) suggests, the symmetry energy term in the EOS depends of the square of the isospin asymmetry, δ. In this respect, the symmetry energy can be best investigated with nuclear collisions between target and projectile combinations leading to the formation of nuclear systems very asymmetric in neutron and proton numbers. The recent availability of accelerator facilities capable of producing both stable and radioactive beams over a wide range of N/Z asymmetries has stimulated further experimental programs devoted to exploring the asymmetric nuclear EOS.

The density dependence on the symmetry energy is expected to affect several observables that can be measured in heavy-ion collisions [2-5,8,11]. Among these, the isotopic composition of clusters produced in the decay of excited nuclear systems has been extensively studied [4-7,11]. The ratios, $R_{12}(N,Z)= Y_1(N,Z)/Y_2(N,Z)$, between the yields of a given fragment (N,Z) measured in two reactions, 1 and 2, differing by the N/Z of the total system (target + projectile), have been shown to satisfy a very intriguing scaling behavior, $R_{12}(N,Z)=C\exp(\alpha N+\beta Z)$ [4]. This phenomenon has been termed "isoscaling" and its characteristic parameters have been found to be sensitive to the density dependence of the symmetry energy $C_{sym}(\rho)$ in Eq. (1) [4,7,11].

In the case of nuclear matter at saturation density and zero-temperature, $C_{sym}(\rho_0)$, has been extensively studied and can be obtained by fitting all known nuclear binding energies with the liquid-drop mass formula which contains a symmetry energy term [12]:

$$E_{sym}(N,Z)=c(A)\frac{(N-Z)^2}{N+Z} \tag{2}$$

The coefficient c(A) is commonly described as the sum $c(A)=c_V+c_S A^{-1/3}$ [13,14]. c_V is a volume term, not dependent on mass number A and therefore directly related to the symmetry energy in infinite nuclear matter at saturation density. The surface term, $c_S A^{-1/3}$, takes into account the effects of the finiteness of nuclei. Typical values for these coefficients of c_V=-27.3 MeV and c_S=-23.7 MeV, can be found in the literature [12]. In order to understand the nuclear equation of state for asymmetric nuclear matter, one needs to investigate the symmetry energy also at low densities, $C_{sym}(\rho<\rho_0)$. One way to do this is to study isotopic effects in multifragmentation phenomena observed in central heavy-ion collisions at intermediate energies [4,8,9,11]. Indeed, in these reactions complex fragments are expected to be formed at sub-saturation densities (ρ~0.1-$0.5\rho_0$) and finite temperatures (T=3-5 MeV). However, the symmetry energy extracted from this systems could be very different from the symmetry energy of infinite nuclear matter. Finite size (surface) effects are known to be important at saturation densities where they reduce the value of the symmetry energy in the case of infinite nuclear matter. What happens at subsaturation density? One of the basic questions to face is the following: *Is the surface contribution to the symmetry energy still relevant at the subsaturation densities? Can the symmetry energy deduced in multifragmentation be used as a good estimate of the symmetry energy in infinite nuclear matter?*

This important question has been recently addressed by the authors of Ref. [8] who have studied AMD (Antisymmetrized Molecular Dynamics) simulations of central ^{40}Ca+^{40}Ca, ^{48}Ca+^{48}Ca, ^{60}Ca+^{60}Ca and ^{46}Fe+^{46}F collisions at E/A=35 MeV [8]. In the context of their model calculations they conclude that the symmetry energy extracted from multifragmentation data shows a negligible surface effect. This finding suggests that the isospin properties of infinite nuclear matter can be directly obtained from studies of isotopic distributions measured in nuclear reactions at intermediate energies. In order to reach this conclusion, the authors of Ref. [8] construct a global isotopic distribution, K(N,Z), by combining together all the yields of fragments (N,Z) obtained in the 4 studied reaction systems. Fig. 1 shows the obtained distribution of the function K(N,Z) as a function of A=N+Z and for all isotopes Z=3-18. The open and filled squares correspond to odd- and even-Z nuclei, respectively. The K(N,Z) distributions for each Z-value, are well fitted by a quadratic function

$$K(N,Z)=\eta(Z)+\xi(Z)N+\zeta(Z)\frac{(N-Z)^2}{N+Z} \tag{3}$$

where $\eta(Z)$, $\xi(Z)$ and $\zeta(Z)$ are the fitting parameters. The obtained parameter $\zeta(Z)$ of the quadratic term in (N-Z) is associated by the authors to the symmetry energy c(A) in Eq. (2) through the relation $\zeta(Z)=c(A)/T$, where T is the temperature of the system. The obtained values of $\zeta(Z)=c(A)/T$ for

each Z are plotted in Fig. 2 as a function of Z. It is observed that $\zeta(Z)$ has almost no dependence on the charge Z (Z > 4). The lines in Fig. 2 show the expected $\zeta(Z)$ values that one would obtain for different values, $k = -c_S / c_V$, of the ratio between the surface and the volume contributions to the symmetry energy. The thick solid line refers to the surface-to-volume ratio corresponding to ground state nuclei, k=1.44. The thin solid and the dashed lines show $\zeta(Z)$ values for k=0.5 and k=0, respectively. The AMD predictions of constant $\zeta(Z)$ values with increasing Z indicate that the contributions of the surface to the symmetry energy are strongly reduced in multifragmentation events. Based on these findings, the authors or Ref. [8] conclude that, at the low density freeze-out stage, the surface term does not contribute strongly to the symmetry energy. Therefore, the symmetry energy, c(A), at finite temperature and subsaturation densities that one can extract from fragment isotopic distributions correspond to the volume term of the symmetry energy in infinite nuclear matter.
The important conclusion of Ref. [8] is based on the observation that the fit parameter $\zeta(Z)$ does not depend on Z as it is predicted by AMD calculations. This result requires experimental confirmation.

Proposed experiment

We propose to explore the presence of surface effects in the symmetry energy by measuring a wide range of isotopic distributions in ^{40}Ca+^{40}Ca, ^{40}Ca+^{48}Ca, ^{48}Ca+^{40}Ca and ^{48}Ca+^{48}Ca reactions at E/A=35 MeV. Our goal consists of obtaining an experimental verification of the results predicted by AMD calculations in Fig. 2. We plan to measure isotope production cross sections over a wide range of Z and N. With these cross sections, we can study the isotopic distributions with the analysis technique suggested in Ref. [8] in order to extract the Z-dependence of the fit parameter $\zeta(Z)$. The details of this Z-dependence will allow us to estimate the relative contributions of the surface and volume terms to the symmetry energy at finite temperature and at saturation and subsaturation density. This study will therefore also permit us to estimate how negligible the effects of the surface on the symmetry energy are, as it is predicted by the calculations shown on Ref. [8]. We will compare the experimental data to predictions of microscopic calculations containing explicitly the density dependence of the symmetry energy (AMD, BNV, etc.). Possible distortions induced by secondary decays on the primary isotopic distributions will need to be estimated with the aid of statistical model decay calculations [11].
The use of a magnetic spectrometer allows one to measure a very wide range of isotopic distributions. Indeed, these detectors are characterized by isotopic resolution which much higher than in any other kind of detector systems. For example, Fig. 3 is extracted from Ref. [6] and shows the isoscaling observables obtained by the ratio between the yields of fragments (N,Z) measured in ^{86}Kr+^{58}Ni and ^{86}Kr+^{64}Ni reactions at E/A=25 MeV. The yields are measured with the MARS magnetic spectrometer at Texas A&M University. Fig. 3 shows clearly the isotope resolving power of magnetic spectrometers.
In view of the above considerations, we would like to perform the experiment using the VAMOS spectrometer coupled to the Indra 4π array (see Fig. 4 and the next section for experimental details). We want to study both peripheral and central collisions. The use of both VAMOS and Indra will allow a good impact parameter determination and the use of calorimetry techniques to estimate excitation energies and temperatures in these reactions. In the case of peripheral collisions we will measure the isotope production cross sections for PLFs produced by deep inelastic mechanism at lower excitation energy. The extraction of the $\zeta(Z)$ parameter for each element Z will provide information about the surface effects in the symmetry energy at finite temperature and at densities close to the saturation density. The acceptance of the VAMOS spectrometer will allow to measure also isotopic distributions produced in more central collisions. In these more violent events, higher excitation energies are involved and we expect to approach the multifragmentation regime where a study of the isotopic distributions will provide access to $\zeta(Z)$ and the symmetry energy at somewhat sub-saturation densities.

Experimental set-up

We would like to take advantage of the coupling of INDRA and VAMOS spectrometer to perform this experiment (Fig. 4). The coupling will be set for experiment E494S on spring 2006. VAMOS will be used to detect the mass and atomic number of projectile like fragments (PLF) and possible heavy residue produced in incomplete fusion reactions. In this configuration, the angular acceptance of VAMOS is limited to θ=±4°. However it is possible to use three different angular positions of the spectrometer to cover an angular range up to θ=20°. INDRA will be used to detect, in coincidence with VAMOS, the light charged particles and intermediate mass fragments in the whole solid angle between θ=7° and θ=176° (Only the three first rings of INDRA will be removed to allow the setting of the entrance of the first VAMOS quadrupole). The INDRA detector allows charge and isotope identification up to Be and only charge identification for heavier fragments. To achieve a good mass resolution up to Z = 8-10, we will replace the 300μm thick silicon detectors of Ring 6 and 7 by 150μm thick to lower energy thresholds for mass identification and to permit the use of larger gains on the electronics. We will make the same modification in two modules at Rings 4, 5, 8 and 9 (reaching a maximum angle of about θ=45°). These modifications will allow us to obtain limited but valuable information on an extended range of isotopes.

The INDRA-VAMOS coupling will permit for the first time the measurement of the cross section of isotopic distribution for the whole charge produced in the ^{40,48}Ca+^{40,48}Ca reactions at E/A=35 MeV in the full angular range from 0° to 45°.

Beam requests

In order to perform the required analysis, we need to collect enough statistics for central collisions ($b/b_{red}<0.3$) where the reaction cross section is smaller. In previous experiments with INDRA abount 30000 central collisions events were typically collected during 1.5-2 UT under the following conditions: Xe ion beam intensities of 4-5x10^{7}pps with an incident energy E/A=32 MeV bombarding a 350μg/cm^2 thick Sn target. The proposed study requires an increase of statistic by a factor of 3 to detect a total of about 3500 oxygen fragments in the Indra modified modules. So, our demand for beam time is 5 UT per reaction, assuming a beam intensity of about 4-5x10^7 pps, which is the maximum that can be accepted by INDRA. This amount of beam time will also allow to perform a $B\rho$ scanning of the momentum distributions of the isotopes detected by VAMOS in order to better measure their production cross sections. Considering the four reaction systems that we want to study, our total beam time request consists of 24UT (5UT per reaction + 4UT for VAMOS and Indra tuning).

We would like to run the experiment with ^{40,48}Ca beams because very CPU intensive AMD theoretical calculations are already available for these reaction systems. However, if the availability of ^{48}Ca beams will present some difficulties, we would like to perform the experiment using ^{78}Kr and ^{86}Kr beams at E/A=35 MeV on ^{58}Ni and ^{64}Ni targets.

We also need 6 UT of light ion beam (around carbon) at E/A = 95 MeV to calibrate the INDRA detector. We will use, as usual, the secondary cocktail beam produced in SISSI and selected in Bρ with the alpha spectrometer to provide several calibration points. This calibration will be used also for the E494S accepted experiment.

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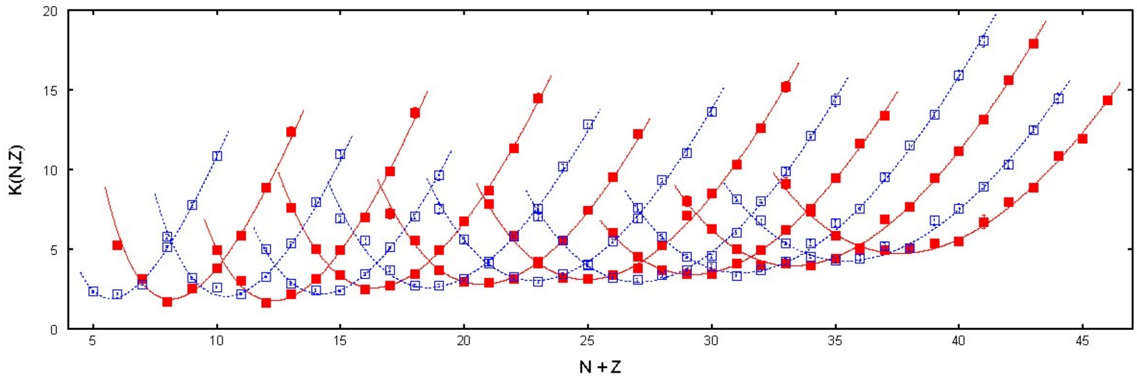

Fig. 1 The values of $K(N,Z)$ for $3 \leq Z \leq 18$ are shown by symbols for the abscissa of $N+Z$. The values are obtained by combining the results of ^{40}Ca + ^{40}Ca, ^{48}Ca + ^{48}Ca, ^{60}Ca + ^{60}Ca and ^{46}Fe + ^{46}Fe simulations. The error bars show the statistical uncertainty due to the finite number of events. The curve for each Z was obtained by fitting $K(N,Z)$ using Eq. (7).

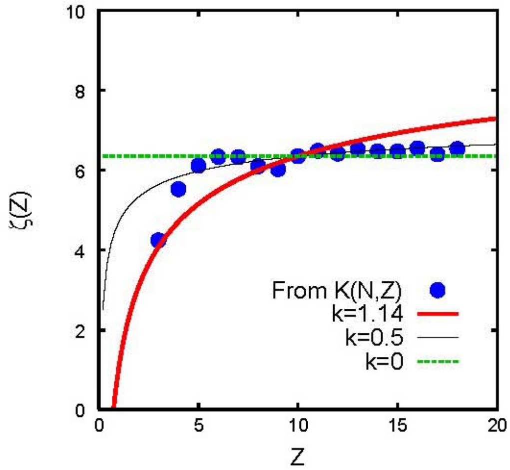

Fig. 2. The solid points are the extracted values of the coefficients $\zeta(Z)$ of Eq. (7) using the combined fragment yields of four systems shown in Fig. 2. The thick solid curve, the thin sold curve and the dashed line show functions $\zeta(Z) \propto 1 - k(2Z)^{-1/3}$ normalized at $Z = 10$ for $k = 1.14$, 0.5 and 0, respectively.

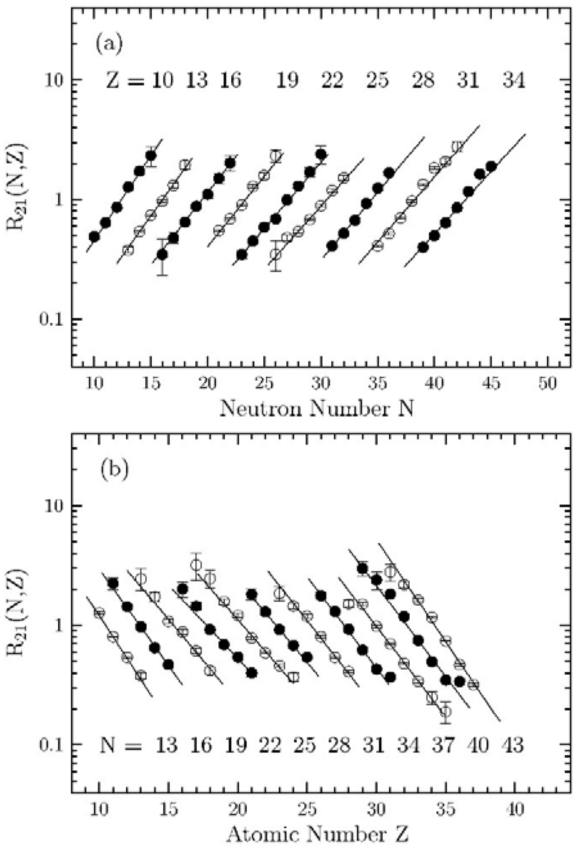

Fig. 3 Yield ratios $R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z)$ of projectile residues from the reactions of ^{86}Kr (25 MeV/nucleon) with ^{64,58}Ni (a) with respect to N for the Z's indicated, and (b) with respect to Z for the N's indicated. The data are given by alternating filled and open circles, whereas the lines are exponential fits (see text).

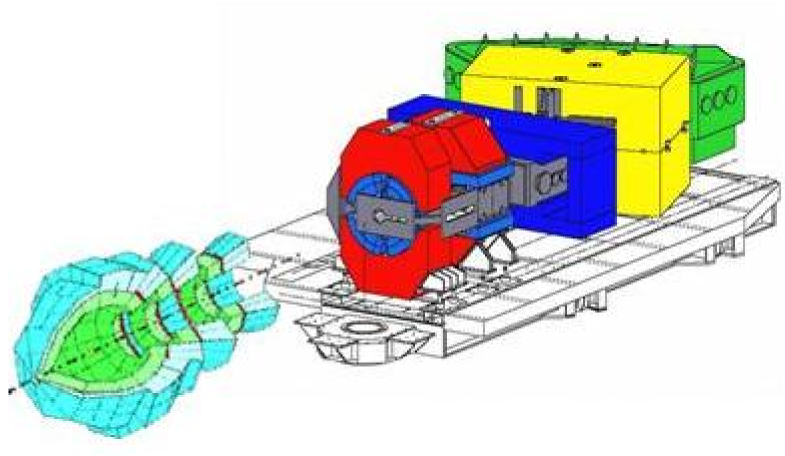

Fig. 4. Drawing of the coupling of the Indra array to the VAMOS spectrometer for the experiment E494S.