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The influence of Multi-Step Sequential Decay on Isoscaling and Fragment Isospin Distribution in GEMINI Simulation *

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Extensive calculations on isoscaling behavior with the sequential-decay model GEMINI are performed for the mediate-heavy nuclei in the mass range $A = 110$ and at excitation energies of up to 3 MeV per nucleon. Isoscaling can still be observed after entire-step decays are considered for the light products as in the only first-step decay process case. Comparison between the products after the first-step decay and the ones after entire-step decay demonstrates that multi-step secondary sequential decay strongly influences the isoscaling parameters α, β as well as the fragment isospin distribution. After entire-step decays, the isoscaling parameters α and β are decreased and the fragment isospin distribution can better reproduce the isospin distribution shape as the experimental data.

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The equation of state (EOS) of isospin asymmetric nuclear matter is a longstanding problem in both nuclear physics and astrophysics and has received much attention in the past years. The development of radioactive beam facilities around the world during recent decades makes it possible to experimentally study the properties of nuclear matter or finite nuclei under the extreme conditions of large isospin asymmetry in terrestrial laboratories. There has been a surge of research activities on this problem. One of main goals of the isospin physics is to determine the isospin dependence of the in-medium nuclear effective interactions and the EOS of isospin asymmetric nuclear matter or finite nuclei, particularly its isospin-dependent term, i.e., the density dependence of the nuclear symmetry energy. Knowledge of nuclear symmetry energy is essential for understanding not only many problems in nuclear physics, such as the dynamics of heavy-ion collisions induced by radioactive beams and the structure of exotic nuclei, but also a number of important issues in astrophysics, such as the supernova simulation and neutron star models, which require inputs of the nuclear EOS at extreme values of density and asymmetry.[1,2] Recently impressive progress has been made experimentally and theoretically, a couple of reviews on isospin physics with heavy-ion reactions can be found in literature.[3−5]

Heavy-ion collision provides a unique laboratory to extract symmetry energy for both sub-normal densities and supra-normal densities. In the region of sub-normal densities, one of the sensitive observables to the symmetry energy is the fragment isotopic composition investigated via the isoscaling approach.[6−25] Isoscaling law means that the ratio of isotope yields $R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z)$, from two similar reactions, denoted as reactions 1 and 2, which are different only in their isospin asymmetries, is found to exhibit an exponential relationship as a function of the neutron number N and proton number Z,[6] i.e.

$$R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} = C\exp(\alpha N + \beta Z), \qquad (1)$$

where $Y_2(N,Z)$ and $Y_1(N,Z)$ are the fragment yields from the neutron-rich and the neutron-deficient reaction, respectively, C is an overall normalization factor, α and β are the fitted parameters.

Ideally, primary fragments should be detected right after emission in order to extract information about the collisions and Eq. (2) is derived based on the primary reaction products bypassing secondary decays. However, the detected experimental data are for cold products after the secondary decays from hot products. Isoscaling has also been reasonably reproduced in the sequential decay codes.[21,26] However there are still arguments on the sequential decay effect on isoscaling, some models show that the effect from sequential decays on isoscaling is negligible, but some efforts show that sequential decay affects on the isoscaling parameters.[27−30]

The GEMINI model[31] was widely used to simulate the hot equilibrium source de-excitation, or as an "afterburner" code to analyze the hot fragments

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decay after dynamical simulation.[32−41] In our previous study, isoscaling has been investigated by the GEMINI,[21] but only the first-step sequential decay was simulated there. In this Letter, we simulate the entirely decayed fragments from excited sources, comparing with the only first-decay fragments from the same source and analyze the multi-step decay effect on the isoscaling and isospin distribution fragments.

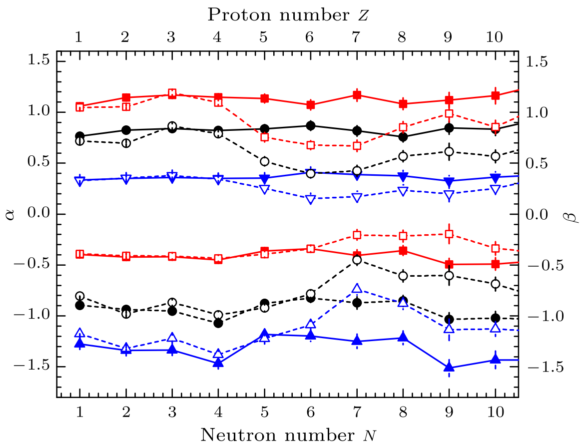

Fig. 1. Comparisons of isoscaling parameters α (positive values) and β (negative values) as versus the fragment proton number Z or neutron number N from source pairs of $Z_s = 50$ at excitation energies $E_{ex}/A = 2.4$ MeV. All the solid symbols represent the results for only the first-step secondary decay products and the open symbols for entire-step secondary decay products. $Y_{A_s=105}/Y_{A_s=100}$ (squares), $Y_{A_s=110}/Y_{A_s=100}$ (circles), $Y_{A_s=115}/Y_{A_s=100}$ (up-triangles).

The detailed description of the GEMINI code can be found in Ref. [21,31], the same configuration and parameters of the GEMINI code are adopted similarly to Ref. [21]. Several pairs of equilibrated sources are considered at various initial excitation energies $E_{ex} = 1.0$, 1.4, 2.0, 2.4, 3.0 MeV/nucleon. We select source pairs with the same proton number Z_s but different mass number A_s to systematically study the isoscaling behavior, to avoid possible effects of different magnitudes of Coulomb interaction on isotopic distributions. The equilibrated source pairs are chosen in different mass regions and system isospin asymmetries N/Z, source pairs are $Z_s = 50$ with $A_s = 100$, 105, 110 and 115, respectively. Following literature the index "2" denotes the neutron-rich system as widely used in convention and index "1" denotes the neutron-deficient system. In our previous work,[21] the statistical decay stops after one particle emitted from the source, called the "first-step" decay in this study, which is a simple picture. The decay procedure can be expressed definitely and clearly. In that case, isoscaling has been confirmed for the first-step decay products in detail and the reasonability of extracting symmetry energy coefficient $C_{\rm sym}$ from the simulation results via experimental analysis technique has been demonstrated. However, the first-step decay is not a real case, experiments measure the final products after multi-step decays until no fragments produced or gamma rays emit, which is called the "entire-step" decay in this study.

Isoscaling is analyzed from the emitted light fragments in the above two cases, namely first-step decay only and entire-step decay chains for all the simulated systems. As an example shown in Fig. 1 the comparison of the isoscaling parameters α and β is plotted as functions of emitted light fragment proton number Z and neutron number N, between the first-step decay and entire-step decay fragments for the source pairs of $Z_s = 50$. As we can see from Fig. 1, the isoscaling parameters α (β) are independent of proton (neutron) number Z (N) of fragments for the first-step case. However, they display considerable fluctuations for the entire-step decay chains at larger Z or N, which indicates that larger fragments suffer a stronger decay effect. In general, isoscaling can be still observed after entire-step decay chains are considered, but the values of α and β extracted from isotopic yield ratios of the final emitted light fragments show discrepancy. Average α and β values over fragments Z and N are used in the following to discuss the overall property.

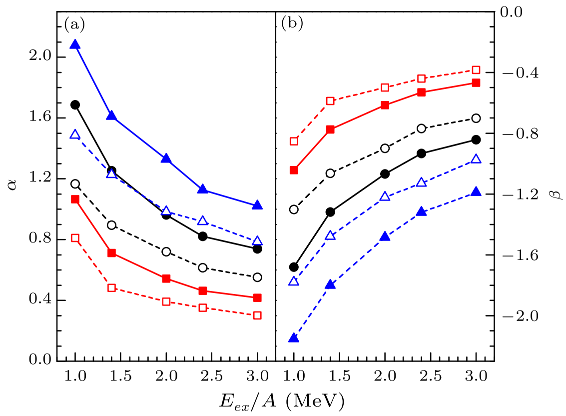

Fig. 2. Comparisons of isoscaling parameters α (a) and β (b) as a function of the source excitation energy from source pairs of $Z_s = 50$. Symbols are the same as Fig. 1.

In Fig. 2 we show the comparison of isoscaling parameters α and β as a function of excitation energy of sources from different source pairs. If the entire-step decay chains are taken into account, which are depicted by the open symbols in Fig. 2, α and $|\beta|$ values show significant decrease. This reduction is about 20% in average, consistent with the result in Refs. [26,28] for the $C_{\rm sym} \approx 25$ MeV case, but the excitation energy dependent trend of α and β does not change.

Isospin evolution and distribution are critical issues in the reactions involved by isospin asymmetry nuclei. It is difficult to measure the isospin evolution. The only data that can be obtained from experiment is the isospin distribution of the final fragments, thus comparing the isospin evolution or distribution in theory or model simulation with experimental data plays an important role in the isospin study. Symmetry energy coefficient $C_{\rm sym}$ in EOS is connected with isoscaling parameters α by the equation

$$\alpha = \frac{4C_{\rm sym}}{T}\Big[\Big(\frac{Z}{A}\Big)^2_{s1} - \Big(\frac{Z}{A}\Big)^2_{s2}\Big] \equiv \frac{4C_{\rm sym}}{T}\Delta\Big(\frac{Z}{A}\Big)^2_{s}, \quad (2)$$

where Z_{s1}, Z_{s2} and A_{s1}, A_{s2} are the charge and mass numbers of the sources from the two systems and T is their temperature. This relation has also been evidenced in other model frameworks.[7–21,24]

We have noticed that isoscaling parameters α and β are modified by the multi-step sequential decay, consequently the symmetry energy coefficient $C_{\rm sym}$ will be distorted if Eq. (2) is straightly used. In the following, we discuss the influence of secondary sequential decay on isospin evolution and distribution.

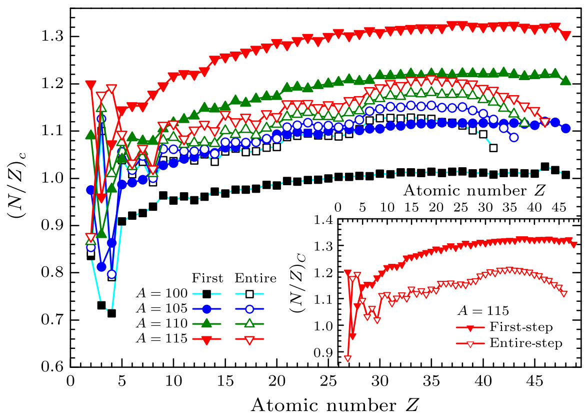

Fig. 3. Comparisons of fragment isospin distributions $(N/Z)_c$ after first-step decay (solid symbols) and entire step decay chains (open symbols) from sources with different isospin asymmetries as a function of fragment atomic number Z. In the calculation, the initial excitation energy E_{ex}/A is 3 MeV and the sources are $Z_s = 50$, $A_s = 100$ (squares), 105 (circles), 110 (up-triangles) and 115 (down-triangles).

Isospin equilibration rate is not very clear yet so far, GEMINI can give us the information of isospin evolution step by step since GEMINI can provide the fragment information in each decay step. We study the fragment isospin distributions in the above-mentioned first-step decay and in the entire-step decay case, respectively, to simplify the process. In Fig. 3 the fragment isospin distributions are plotted as a function of fragment atomic number Z, with different isospin sources. These sources are $Z_s = 50$, $A_s = 100$, 105, 110 and 115, respectively, the corresponding initial source isospin $N/Z = 1.0$, 1.1, 1.2, 1.3, respectively. Fragment isospin distributions after the first-step decay only are plotted by solid symbols, fragments after the entire-step decay case are open symbols. Fragment isospin $(N/Z)_c$ which is defined as the center of isotope distribution here is calculated by fitting the isotope distribution with a single Gaussian function. The inset shows the individual plot for the $A_s = 115$ source so that we can clearly see the multi-step decay effect on the isospin distribution. For both the first-step decay and entire-step decay, $(N/Z)_c$ as a function of fragments Z exhibit the similar trend.

After first-step decay, heavy fragments close to the source are residues of the sequential decay, their isospin is close to the isospin of the source values. When the fragments become far away from the source, their isospin decreases, becoming more proton-rich than the source and the residues except for the lightest fragments such as $Z = 1$ and $Z = 2$. One can find from Fig. 3 that isospin of fragment $Z = 2$ jumps suddenly, in all the four different source simulations, which mainly stems from the special abundance of α-particles. In the inset of Fig. 3, isospin distribution of fragments for the source $Z_s = 50$ and $A_s = 115$ is plotted for the two decay cases, changes of isospin distribution of fragments are obvious after the entire-step decay case and there exits a jump of lightest fragment, too. After the first-step decay, isospin of fragments aligns following the source isospin. There are a large isospin for all fragments if isospin of source has a large value.

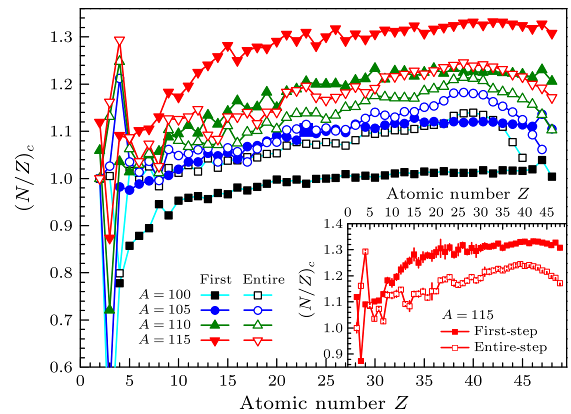

Fig. 4. The same as Fig. 3 but with initial excitation energy $E_{ex}/A = 1.4$ MeV.

After entire-step decays, residual and emitted fragments from different isospin sources seem to approach almost together, i.e. isospin of fragments reaches the stable line or the evaporation attractor line,[42] but still keep slight memory of the source isospin. One possible reason is as follows. At the beginning stage of the decay of hot nuclei with rich excess of neutrons, when the source becomes cooled by the emission of neutrons and/or neutron-rich light fragments, it is also neutralized simultaneously. Thus till its intermediate stage or end of life, the N/Z ratio deviates from its original phase, approaching to the stability line. Isospin of the highest residues is proton-richer than the middle heavy fragments and while for the emitted light charged fragments, such as $Z = 3$, 4, 5, one bump of isospin appears in this region. This bump was observed in the multifragmentation,[26] indicating that neutron-richer light charged fragments are emitted from residues which finally become neutron-poorer than the middle heavy fragments.

In Fig. 4 we plot the simulation results as in Fig. 3, but with initial excitation energy $E_{ex}/A = 1.4\,\mathrm{MeV}$. After entire-step decays, the isospin difference of final fragments among different sources is larger than the case with $E_{ex}/A = 3\,\mathrm{MeV}$. When a higher-excited system becomes cooled, more neutron contents could be emitted. In this regard, it is understandable that the fragment N/Z content exhibits quite difference with varying the initial excitation energy.

In summary, even though the isoscaling method could provide a useful method to study the isospin degree of freedom in nuclear reactions induced by asymmetry nuclei and then to constrain the symmetry energy term in nuclear equation of state at sub-saturate energy, it is under the assumption that secondary decay effect of the hot fragments can be neglected. In many previous experiments, researchers have verified the existence of isoscaling in different reaction mechanisms and studied the dependence of symmetry energy coefficient $C_{\rm sym}$ on isoscaling parameters via theoretical or model simulations. However, as we known, secondary decays of hot fragments are important steps during later stage evolution of nuclear reaction. Up to date systematical studies on isoscaling have not been completely consistent with each other on symmetry energy coefficient $C_{\rm sym}$ without considering secondary decay of hot fragments.

Considering that the statistical sequential decay model GEMINI has been widely used in the nuclear collisions as an "afterburner" process, we use this code to simulate the excited sources with different isospin and excitation energies, to investigate the systematic rules in sequential decay, by dividing the decay into the first-step decay and the entire-step decay cases. Our simulation shows that isoscaling parameters α and β are suppressed by the multi-step sequential decays in comparison with only considering the first-step decay, even though its dependence on isospin asymmetry of the source and excitation energy (temperature) are similar. The decreasing of isoscaling parameters due to multi-step sequential decays will finally distort the symmetry energy coefficient extraction from experiment. Therefore caution is needed when we try to extract the symmetry energy coefficient via the final cold products.

The isospin evolutions of the fragments are also presented for the first-step and entire-step decays. After the decays, the isospin of the fragments tend to the β-stability line. For light fragments with $Z = 3, 4, 5$, the trend of isospin distribution is consistent with the experimental data. By measuring the fragment isospin distribution decaying from different temperature systems, we can obtain important information of isospin evolution.

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