1 - 4 Isospin Dynamics on Neck Fragmentation in Isotopic Nuclear Reactions*

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Heavy-ion collisions at the Fermi energies (10~100 AMeV) attract much attention on several topical issues in nuclear physics, *i.e.*, spinodal multifragmentation, liquid-gas phase transition, properties of highly excited nuclei, symmetry energy in the domain of subnormal densities, *etc.* The isospin dynamics in the Fermi-energy heavy-ion collisions is related to several interesting topics, *e.g.*, in-medium nucleon-nucleon cross sections, cluster formation, isotopic distribution, the symmetry energy in dilute nuclear matter, *etc.* Much progress has been made in constraining the density dependence of symmetry energy in the domain of sub-saturation densities both in theories and in experiments. Different mechanisms can coexist and are correlated in heavy-ion collisions at the Fermi energies, such as projectile or target fragmentation, neck emission, preequilibrium emission of light clusters (complex particles), fission of heavy fragments, multifragmentation, *etc*, in which the isospin dependent nucleon-nucleon potential dominates the dynamical processes. The time scales from the dynamical and pre-equilibrium emissions to the statistical decay of excited systems at equilibrium and the isospin effect in neck fragmentation were investigated experimentally[1]. Transport models are needed to understand the mechanisms correlated with the emission time and the dependence on incident energy, collision centrality and reaction systems.

The neck dynamics in Fermi-energy heavy-ion collisions, to probe the nuclear symmetry energy in the domain of sub-saturation density, is investigated within an isospin dependent transport model. The single and double ratios of neutron/proton from free nucleons and light clusters (complex particles) in the isotopic reactions are analyzed systematically. Isospin effects of particles produced from the neck fragmentations are explored. It is found that the ratios of the energetic isospin particles strongly depend on the stiffness of nuclear symmetry energy and the effects increase with softening the symmetry energy, which would be a nice probe for extracting the symmetry energy below the normal density experimentally. A flat structure appears at the tail spectra from the double ratio distributions. The neutron to proton ratio of light intermediate mass fragments (IMFs) with charged number $Z \leq 8$ is related to the density dependence of symmetry energy with less sensitivity in comparison to the isospin ratios of nucleons and light particles[2].

The dynamics of preequilibrium nucleons and light fragments produced in heavy-ion collisions is influenced by the mean-field potentials. To extract the sub-saturation density information of nuclear symmetry energy, one needs to produce the observables formed in the low-density domain. Particles produced from the neck fragmentations in heavy-ion collisions could be probes of the low-density phase diagram, which are constrained within the midrapidities ($|y/y_{\mathrm{proj}}| < 0.3$) in semicentral nuclear collisions. Shown in Fig. 1 are the kinetic energy spectra of neutron/proton ratios from the yields of free nucleons and "gas-phase" nucleons (nucleons, hydrogen and helium isotopes) from the neck fragmentations in the ^{112}Sn+^{58}Ni and ^{124}Sn+^{64}Ni reactions at a beam energy of 35 MeV/u with the different symmetry energies. One can see that the ratios decrease with the kinetic energy. After a turning point around the Fermi energy (36 MeV), the value is enhanced. The structure of the spectra is determined by the competition of Coulomb interaction between charged particles and symmetry potential, which enhance the proton and neutron yields, respectively. The symmetry energy effect is pronounced and close to 50% because of the longer isospin relaxation time in Fermi-energy heavy-ion collisions.

Besides the fast nucleons being probes of symmetry energy in the dilute matter, the neutron to proton ratio of light intermediate mass fragments (IMFs) could be sensitive to the stiffness of symmetry energy because of the isospin migration from the neck fragmentation. The light IMFs ($Z \leq 10$) are measured by the CHIMERA detector at the INFN-LNS Superconducting Cyclotron of Catania (Italy), and emitted preferentially towards the midrapidity domain on a short timescale within 50 fm/c, which can not be entirely described through the decay of the excited projectile-like (PLF) and target-like (TLF) fragments. We constrained the particles emitted from the neck fragmentation within the rapidity range of $|y/y_{\mathrm{proj}}| < 0.3$. Shown in Fig. 2 is the average neutron to proton ratio of light IMFs in the isotopic reactions of ^{112}Sn+^{58}Ni, ^{124}Sn+^{64}Ni, ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn. The isospin effect is pronounced for the light isotopes, *i.e.*, lithium, beryllium and boron. The soft symmetry energy leads to larger n/p ratio of light IMFs.

In summary, within the LQMD transport model we have investigated the neck dynamics in Fermi-energy heavy-ion collisions, in which the single and double ratios of neutron to proton yields from free nucleons and light clusters

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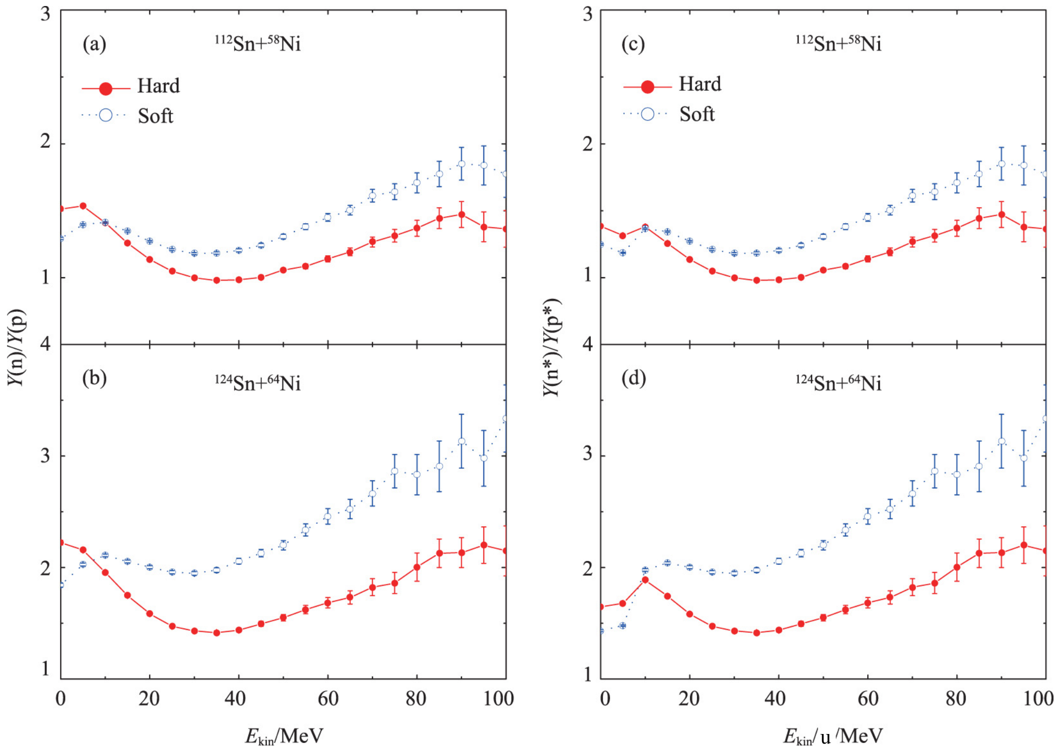

Fig. 1 (color online) Kinetic energy spectra of neutron/proton ratios from the yields of free nucleons and "gas-phase" nucleons (nucleons, hydrogen and helium isotopes) from neck fragmentations in the ^{112}Sn+^{58}Ni and ^{124}Sn+^{64}Ni reactions at the fermi energy of 35 MeV/u within the collision centralities of 6~8 fm.

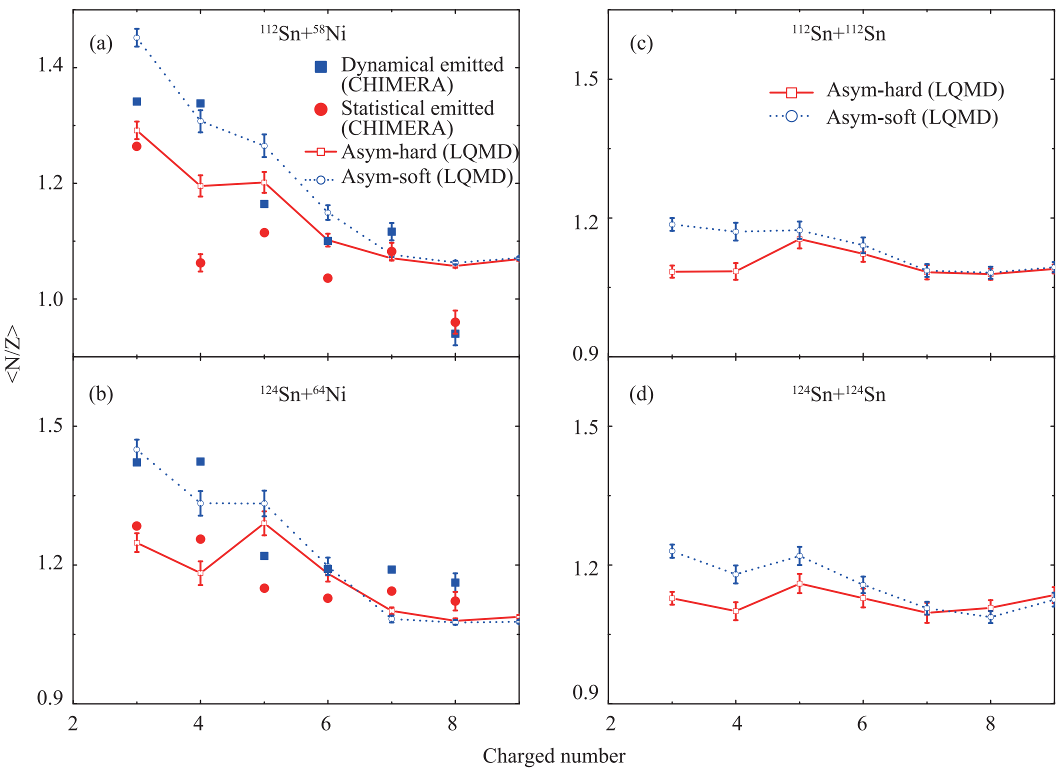

Fig. 2 (color online) The average neutron to proton ratio of IMFs emitted within the rapidity range of $|y/y_{\rm proj}|$ <0.3 as a function of charged number with the different symmetry energies. The data from CHIMERA detector[1] are shown for comparison.

as well as the neutron to proton ratio of light IMFs are particularly concentrated. The secondary decay of the primary fragments formed in heavy-ion collisions increases the IMF production. The light IMFs from the neck fragmentation are emitted preferentially towards the midrapidity domain on a short timescale in comparison to PLFs and TLFs. The isospin ratios depend on the stiffness of symmetry energy and the effects increase with softening the symmetry energy, in particular in neutron-rich nuclear reactions.

References

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1 - 5 Constraining Nucleon High Momentum in Nuclei*

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Recent studies at Jefferson Lab show that there are a certain proportion of nucleons in nuclei have momenta greater than the so-called nuclear Fermi momentum p_F. Based on the transport model of nucleus-nucleus collisions at intermediate energies, nucleon high momentum caused by the neutron-proton short-range correlations in nuclei is constrained by comparing with π and photon experimental data. The high momentum cutoff value $p_{max} \leq 2p_F$ is obtained[1].

Fig. 1 shows π^+ production as a function of high-momentum cutoff parameter λ ($= p_{max}/p_F$, *i.e.*, the ratio of the maximal nucleon momentum over the nuclear Fermi momentum) of colliding nuclei in the Au + Au collisions at 0.4 and 1 GeV/u incident beam energies, respectively. One can clearly see that as the high-momentum cutoff parameter λ increases, more π^+'s are produced. Larger high-momentum cutoff parameter λ causes larger nucleon average kinetic energy, especially proton average kinetic energy, thus the average center-of-mass energy of proton-proton collision also becomes larger. As a consequence more π^+'s are produced in nucleus-nucleus collision. This is the reason why one sees in the upper panel of Fig. 1 more π^+'s are produced with larger high-momentum cutoff parameter λ. As incident beam energy increases, the initial motion of nucleons in nuclei becomes less important in nucleus-nucleus collisions. We thus see, in the lower panel of Fig. 1, at 1 GeV/u incident beam energy, π^+ production is less sensitive to the high-momentum cutoff parameter λ (At 0.4 GeV/u, the sensitivity of π^+ production to λ is about 10 times larger than that of π^+ at 1 GeV/u). Fig. 1 indicates $\lambda \leq 2$ is favored by the FOPI data.

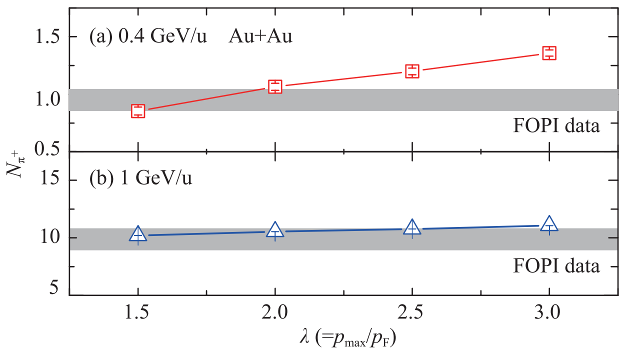

Fig. 1 (color online) The number of produced π^+ meson as a function of high-momentum cutoff parameter λ in the Au + Au collisions at, respectively, 0.4 and 1 GeV/u beam energies.

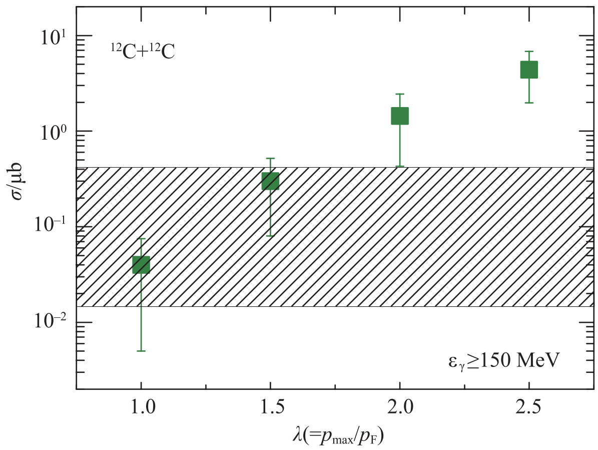

Fig. 2 (color online) Inclusive photon production cross sections ($\varepsilon_\gamma \geq 150$ MeV) in $^{12}C+^{12}C$ collisions at the beam energy of 60 MeV/u. The symbols stand for BUU calculations with, respectively, $\lambda = 1$ (*i.e.*, without high-momentum tail), 1.5, 2, 2.5. The shadow region denotes experimental data.

Fig. 2 compares the theoretical inclusive hard photon production cross sections in $^{12}C+^{12}C$ collisions and the experimental data. Since the hadronic probe π^+ production constrained the high-momentum cutoff parameter λ between 1.5 ~ 2.5, we use $\lambda = 1.5$, 2, 2.5 for the BUU calculations with the high-momentum tail. As comparison, we also calculated the case without high-momentum tail ($\lambda = 1$). From Fig. 2, it is seen that the cross section of the hard photon production in heavy-ion collisions is very sensitive to the high-momentum in of nuclei. The BUU calculations with $\lambda = 2$ and 2.5 are larger than the experimental hard photon production cross section. And the