case of BUU calculation without high-momentum tail is somewhat lower than the experimental data. From Fig. 2, it is seen that the electromagnetic probe (*i.e.* the hard photon production) constrains the high-momentum cutoff parameter to be $\lambda \leq 2$. Combining the constraints from hadronic probe π^+ production (shown in Fig. 1) and that from electromagnetic probe(shown in Fig. 2), we can conservatively conclude that the value of the high-momentum cutoff parameter λ in nuclei is less than 2.5 and the overlap-area is $\lambda \leq 2$.

Constraints on the high-momentum cutoff parameter λ in nuclei have implications in the studies of nuclear force at short distance, in the construction of nuclear transport model of heavy-ion collisions at intermediate energies, in the studies of equation of state of dense nuclear matter and the nuclear symmetry energy at suprasaturation densities or in the study of the physics in neutron stars, *etc*.

Reference

[1] G. C. Yong, Phys. Lett. B, 765(2017)104.

* Foundation item: National Natural Science Foundation of China (11375239, 11435014)

1 - 6 Cross-checking the Symmetry Energy at High Densities*

Yong Gaochan

By considering both the effects of the nucleon-nucleon short-range correlations and the isospin-dependent in-medium inelastic baryon-baryon scattering cross section in the transport model, two unrelated Au + Au experimental measurements at 400 MeV/u beam energy are simultaneously analyzed, a mildly soft symmetry energy at supra-saturation densities is obtained[1].

In our transport model, by considering the effects of the nucleon-nucleon short-range correlations on the kinetic symmetry energy, a new density-dependent symmetry energy is recent obtained. Fig. 1 shows the density-dependent symmetry energy with different x parameters.

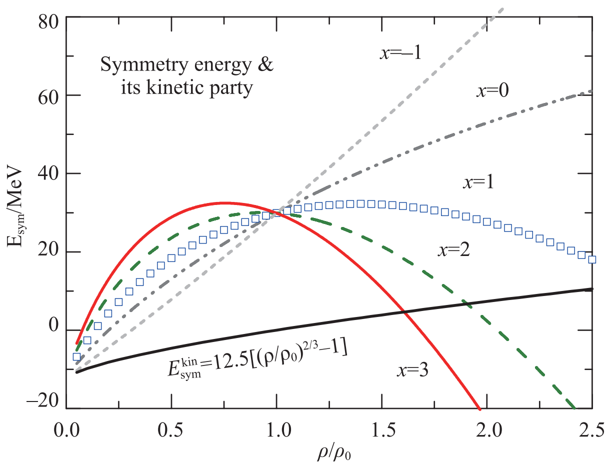

Fig. 1 (color online) Kinetic symmetry energy and density-dependent symmetry energy with different x parameters.

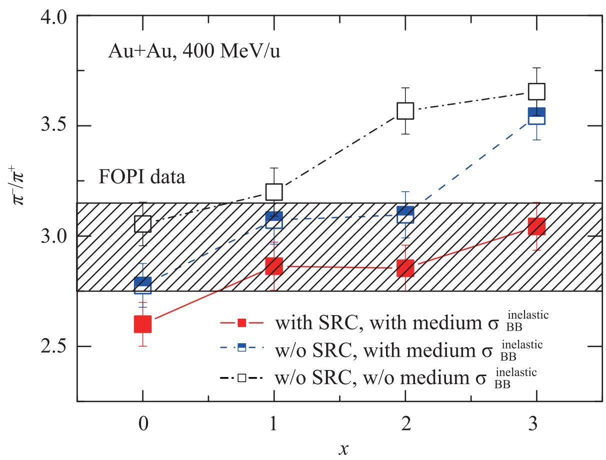

Fig. 2 (color online) π^-/π^+ ratio in Au+Au reaction at 400 MeV/u with different symmetry energies. Also shown are the effects of the SRC of nucleon-nucleon and the in-medium inelastic cross section on the π^-/π^+ ratio with same x parameters.

Fig. 2 shows the π^-/π^+ ratio predicted by our IBUU model with different symmetry energies. Because softer symmetry energy causes more neutron-rich dense matter and π^-'s are mainly from neutron-neutron collision whereas π^+'s are mainly from proton-proton collision, it is not surprising that one sees larger π^-/π^+ ratio with softer symmetry energy. To see the effects of the nucleon-nucleon SRC and the reduction of the in-medium inelastic baryon-baryon scattering cross section, with same x parameters, we made calculations by turning off the SRC and by reducting of the in-medium inelastic baryon-baryon scattering cross section, respectively. From Fig. 2, we can see that both of them affect the value of π^-/π^+ ratio evidently. Both the SRC of nucleon-nucleon and the reduction of the in-medium inelastic baryon-baryon scattering cross section decrease the value of π^-/π^+ ratio. Proton-proton collision is also affected by the Coulomb interaction, so π^+ production, which is mainly from proton-proton collision, is relatively less affected by the in-medium inelastic baryon-baryon scattering cross section.

Shown in Fig. 3 are the predicted elliptic flow ratios of neutron and proton $V_2^{\rm n}/V_2^{\rm p}$ with different symmetry energies as well as experimental data. Since stiffer symmetry energy/symmetry potential causes relatively more neutrons to be emitted in the direction perpendicular to the reaction plane, one sees larger values of elliptic flow ratios of neutron and proton $V_2^{\rm n}/V_2^{\rm p}$ with stiffer symmetry energies. With the nucleon-nucleon SRC in the transport model, the $V_2^{\rm n}/V_2^{\rm p}$ ratios are larger than that without the SRC. This is because the SRC of nucleon-nucleon cause neutron and proton to be correlated together, the value of $V_2^{\rm n}/V_2^{\rm p}$ ratio trends to unity. Owing to the competing effects of the SRC and the symmetry energy, for $x = 0$ case, the effects of symmetry energy on the trend of the ratio of $V_2^{\rm n}/V_2^{\rm p}$ with the SRC changes compared with that without the SRC. On the whole, the sensitivity of the observable $V_2^{\rm n}/V_2^{\rm p}$ to the symmetry enegy at FOPI-LAND experimental conditions and geometry is smaller than that of the FOPI π^-/π^+ ratio. Fig. 3 indicates the FOPI-LAND elliptic flow experimental data does not favor very soft symmetry energy ($x = 2$, 3).

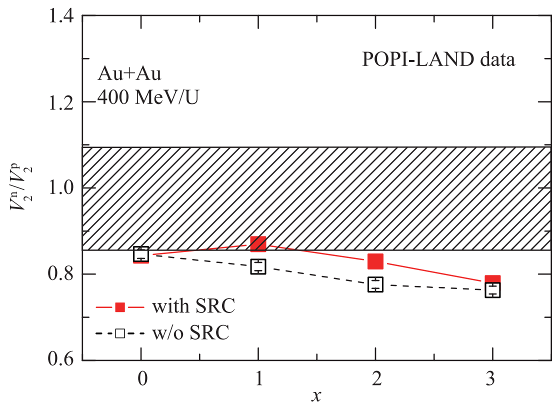

Fig. 3 (color online) The ratio of elliptic flow $V_2^{\rm n}/V_2^{\rm p}$. The effects of the SRC of nucleon-nucleon on the $V_2^{\rm n}/V_2^{\rm p}$ with same x parameters are also shown.

Combining the studies of nucleon elliptic flow and previous π^-/π^+ ratio, one may roughly obtain the symmetry energy stiffness parameter $x = 1$. It in fact corresponds a mildly soft density-dependent symmetry energy at supra-saturation densities. While the specific density region of the present constraints on the nuclear symmetry energy needs to be further studied.

Reference

[1] G. C. Yong, Phys. Rev. C, 93(2016)044610.

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1 - 7 Hollow Nuclear Matter*

Yong Gaochan

It is generally considered that an atomic nucleus is always compact. Based on the isospin-dependent Boltzmann nuclear transport model, here I show that large block nuclear matter or excited nuclear matter may both be hollow. Existence of hollow nuclear matter may have many implications in nuclear physics, astrophysics and some practical applications[1].

Fig. 1 shows the time evolution of the contour density distribution of the atomic nucleus $^{197}_{79}$Au in $X-Y$ plane with the Boltzmann nuclear transport model. The given average excitation energy (an average energy per nucleon increased relative nuclear ground state) is 5 MeV per nucleon. It is seen that as time increases a bubble steadily appears in the compact light atomic nucleus $^{197}_{79}$Au. Because the surface tension is relatively strong for relatively light atomic nucleus, to form bubble configuration in compact nucleus, one has to give excitation energy for relatively light atomic nucleus.

Shown in Fig. 2 is the $^{197}_{79}$Au + $^{197}_{79}$Au head-on collision at incident beam energy of 35 MeV/u. One can see that internally hollow nuclear matter is formed in the nucleus-nucleus collisions as time increases. And inner halo in the bubble of nuclear matter is also seen.

Internally hollow nuclear matter may have many implications in nuclear physics, astrophysics such as the physics of neutron stars, and some practical applications. Existence of internally hollow atomic nucleus may promote the developments of quantum many-body theory and nuclear theory. Increased radius of the hollow atomic nucleus may cause inner electrons of some atoms to be absorbed easily by inner nucleons. And the existence of internally hollow nuclear matter may hint the hollow configuration of neutron stars. Internally hollow superheavy or excited atomic nuclei may affect the hyperfine configuration of atomic spectrum, which is widely used in a lot of fields.