# 1 - 1 Progress of Theoretical Nuclear Research in 2017 at IMP

Zuo Wei

In 2017, the researchers of Theoretical Physics Group at IMP have carried out their research work on in nuclear physics, heavy ion physics and hadron physics. Some important results have been obtained.

The effect of tensor correlations on the depletion of the nuclear Fermi sea in nuclear matter has been studied within the framework of the extended Brueckner-Hartree-Fock approach[1]. The depletion induced by the isospin $T=0$ interaction is shown to stem almost completely from the 3SD1 tensor channel which turns out to be responsible for most of the depletion, *i.e.*, more than 70 percent of the total depletion.

The inclusive spectra of preequilibrium nucleons produced in low-energy antiproton-nucleus collisions have been investigated within the framework of the Lanzhou quantum molecular dynamics model[2]. The unexpected neutron/proton ratio in comparison to the pion and proton induced reactions is shown to be caused by the isospin effects of pion-nucleon collisions and the density dependence of symmetry energy. Pion production in nucleus-nucleus collisions at intermediate energies has been modeled in the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model[3]. The obtained ratio and yields of $\pi^-$ and $\pi^+$ in Au + Au reaction at 400 MeV/nucleon is shown to reproduce the FOPI data at GSI very well, especially with a soft symmetry energy in the present transport model[4]. The interplay of the nucleon-nucleon short-range correlations (SRCs) and nuclear symmetry energy on the hard-photon spectra in heavy ion collisions has been studied and it is found that over the whole spectra of hard photons, the effects of the SRCs overwhelm those owing to the symmetry energy. The multinucleon transfer reaction has been explored within the dinuclear system model[5], and it is found that the production of heavy neutron-rich nuclei weakly depends on the incident energy.

The neutrino emissivities in beta-stable neutron star matter from the direct Urca (DU) processes and the modified Urca (MU) processes have been calculated by adopting 26 Skyrme interactions[6]. The model-dependence of the neutrino emissivities from the DU processes is found to stem mainly from the model-dependence of the effective mass, while the neutrino emissivities from the MU processes are de-termined by the competition between the effects of the symmetry energy and the effective mass.

In hadron physics, the hidden bottom decays of Zb(10610) and Zb(10650) have been analyzed via final state interaction[7], and the results point out that the final-state interaction plays an important role in interpretation of the branching ratios of the hidden bottom decays of the Z(10650) states.

## References


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# 1 - 2 Isospin Effect on the Fragmentation Reaction Induced by Low-energy Antiprotons*

Feng Zhaoqing

Since the first evidence of antiprotons was found in 1955 at Berkeley in collisions of protons on copper at the energy of 6.2 GeV, the secondary beams of antiprotons were produced at many laboratories, such as CERN, BNL, KEK, *etc.* A more localized energy is deposited in the nucleus with an excitation energy of several hundreds of MeV. The hot nucleus proceeds to the explosive decay via multifragmentation process or the sequential particle evaporation. On the other hand, the collisions of the antiproton and secondary particles with surrounding nucleons lead to the pre-equilibrium particle emissions, which are related to the scattering cross sections of each reaction channels, antiproton-nucleon interaction, particle-nucleon potentials, density profile of target nucleus. The unexpected large neutron yields produced by the stopped antiprotons in nuclei were reported in the low energy antiproton ring (LEAR) experiments[1]. The phenomena has been puzzling physicists several decades. In this work, the preequilibrium nucleon emissions and the neutron/proton (n/p) spectra in antiproton induced nuclear reactions are investigated within the Lanzhou quantum molecular dynamics (LQMD) transport model.

The emission of fast nucleons produced in antiproton induced reactions is significant observable in understanding the energy deposition, antiproton-nucleon and meson-nucleon interactions in nuclear medium. Shown in Fig. 1 is the kinetic energy distributions of neutrons and protons produced in antiproton annihilations on $^{12}$C, $^{\rm nat}$Cu and $^{238}$U at the incident momentum of 200 MeV/$c$ and compared with the available data at the LEAR facility[4]. Overall, the spectra can be nicely understood within the LQMD transport model. The preequilibrium nucleons in the model are constructed with a coalescence approach, in which nucleons at the freeze-out stage in phase space are considered to belong to one cluster with the relative momentum smaller than $P_0$ and with the relative distance smaller than $R_0$ (here $P_0$ = 200 MeV/$c$ and $R_0$ = 3 fm). On the other hand, part of nucleons are from the decay of the primary fragments after the antiproton annihilation, which contribute to the nucleon yields within the kinetic energy below 20 MeV. The nucleon yields are weakly influenced by varying the coalescence parameters. The antiproton-nucleus systems evolve to 500 fm/$c$ for judging the free nucleon formation. It should be noticed that the neutrons are preferable to be emitted in comparison to protons. The energy deposition in antiproton induced reactions is more explosive than the case in Fermi-energy heavy-ion collisions, which leads to the energetic nucleon emission. In the annihilation of an antiproton in a nucleus, pions are the dominant products. For example, the multiplicities of $\pi^-$ and $\pi^+$ on the target of $^{12}$C are 1.5 and 0.6, respectively. On the other hand, the larger elastic scattering cross sections in the $\pi^- n$ reactions (the maximal value being 200 mb at the $\Delta$-resonance energy ($E$ = 0.19 GeV, $p$ = 0.298 GeV/c)) in comparison to the $\pi^- p$ collisions (25 mb at the pion energy of 0.19 GeV), enhance the $\pi^- n$ collision probabilities and are favorable to neutron emissions in the low-energy antiproton induced reactions even on the isospin symmetric target of $^{12}$C. For the neutron-rich target such as $^{238}$U, the difference of neutron and proton yields is more pronounced.

It is interest that the antiproton is mainly annihilated in the density domain of 0.4∼0.8 $\rho_0$. The nucleons are emitted around the densities of 0.08∼0.1 fm$^{-3}$ after interacting with pions[2]. The nucleons from the sub-sequential processes due to the secondary collisions are evaporated from the excited primary fragments with less kinetic energy. Therefore, the n/p ratio with the kinetic energies above 50 MeV directly provides the information of symmetry energy at subsaturation densities. Shown in Fig. 2 is the kinetic energy spectra in antiproton induced reactions on $^{12}$C, $^{\rm nat}$Cu, $^{197}$Au and $^{238}$U with the soft ($\gamma_s$ =0.5) and hard ($\gamma_s$ =2) symmetry energies, respectively. The dashed lines represent the mean n/p values of target nuclei. Calculations are performed at the antiproton momentum of 200 MeV/$c$. I have checked that the spectra are insensitive to the incident energy. It is obvious that the difference of the stiffness of symmetry energy is pronounced in the neutron-rich nuclei. The n/p ratio is enhanced with softening the symmetry energy. Overall, the available data at LEAR[1] are reproduced with the soft symmetry energy.

In summary, the kinetic energy spectra of the n/p ratio produced in the antiproton annihilation in the nucleus have been puzzling for several decades. The structure is quite different with the proton (pion) induced reactions and also with the heavy-ion collisions. The available data from the LEAR facility are nicely explained with the LQMD transport model for the first time. It is found that the $n\pi^-$ scattering and the symmetry energy increase the neutron emission and lead to the enhancement of the n/p ratio, in particular in the domain of kinetic energies below 200 MeV because of the larger $n\pi^-$ collision probability. The soft symmetry energy with the stiffness of $\gamma_s$ =0.5 is constrained from the LEAR data.

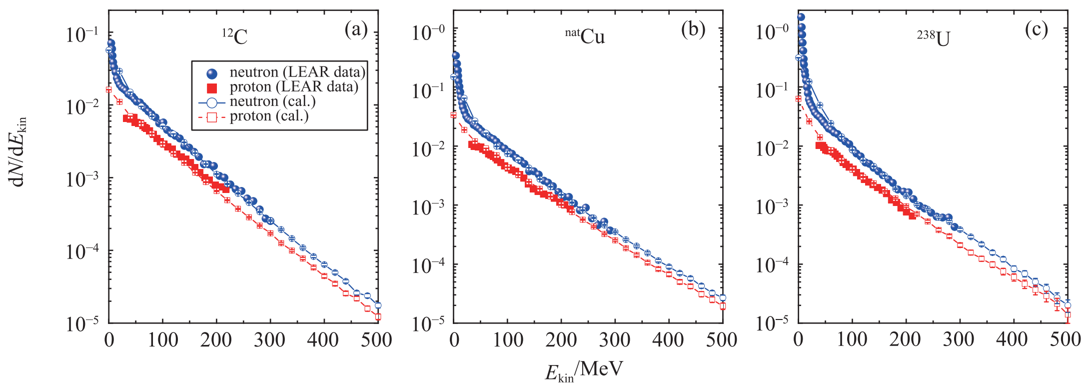


Fig. 1 (color online) Kinetic energy spectra of neutrons and protons produced in antiproton annihilations on carbon, copper and uranium at the incident momentum of 200 MeV/$c$ and compared with the available data at the LEAR facility[1].

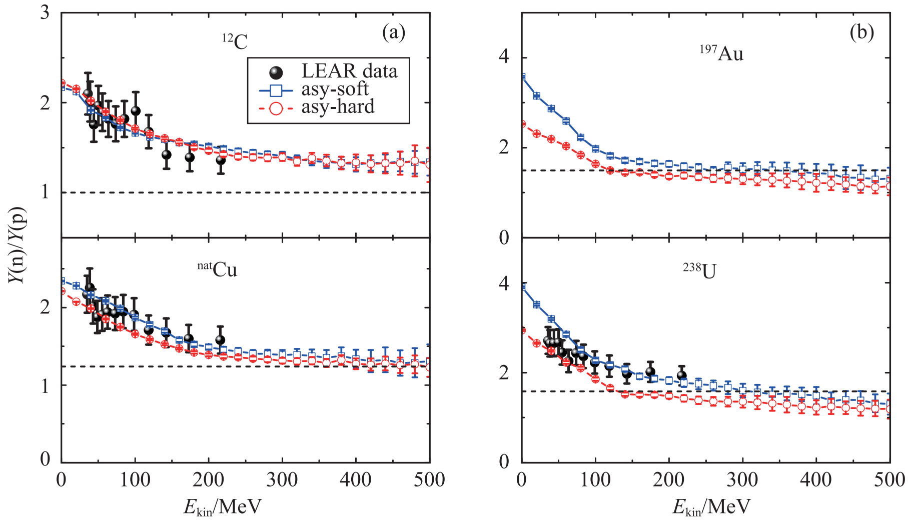


Fig. 2 (color online) The n/p ratios in antiproton induced reactions on $^{12}$C, $^{nat}$Cu, $^{197}$Au and $^{238}$U with different stiffness of symmetry energies and compared with the LEAR data[1].

## References


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# 1 - 3 Modeling Pion Production in Heavy-ion Collisions at Intermediate Energies*


Yong Gaochan


The mechanism concerning to pion production in heavy-ion collisions at intermediate energies has increasing interests recently. We modeled pion production in nucleus-nucleus collisions at intermediate energies in the framework of the Isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model. The effects of nucleon-nucleon short-range correlations in initialization and mean-field potential, isospin-dependent in-medium baryon-baryon elastic and inelastic cross sections and pion in-medium effect are all considered in this model. It is found that the ratio and yields of $\pi^-$and $\pi^+$ in Au+Au reaction at 400 MeV/u reproduce the FOPI/GSI data very well especially with a soft symmetry energy in the present transport model. Predictions on the single and double $\pi^-/\pi^+$ ratio are made for the isotope reaction systems $^{132}$Sn+$^{124}$Sn and $^{108}$Sn+$^{112}$Sn at 300 MeV/u since related experiments are being carried out at RIKEN/Japan[1].

Figure. 1 shows the numbers of charged pions produced with different symmetry energies[1]. It is first seen that both the produced $\pi^-$ and $\pi^+$ by the IBUU model fit the FOPI experimental data quite well. Comparing the produced $\pi^-$ and $\pi^+$ based on the IBUU model, it is seen that sensitivity of the number of the produced $\pi^-$ to the symmetry energy is evidently larger than that of $\pi^+$. This is because the $\pi^-$'s are mainly from neutron-neutron collisions, thus more sensitive to the symmetry energy. It is also seen that for the soft symmetry energy $x = 1$, the produced $\pi^-$ fits the FOPI experimental data very well. With stiffer symmetry energies $x=0,-1$, the model gives smaller $\pi^-$ numbers than the experimental data.

Figure. 2 shows the single ratios of the $\pi^-/\pi^+$ in neutron-rich and neutron-deficient reaction systems $^{132}$Sn+$^{124}$Sn and $^{108}$Sn+$^{112}$Sn at a beam energy of 300 MeV/u[1]. Owing to more neutron-neutron collisions, it is clearly seen that the ratio of $\pi^-/\pi^+$ is higher in neutron-rich reaction system than that in neutron-deficient reaction system. And due to larger asymmetry in neutron-rich reaction system, the effects of the symmetry energy on the $\pi^-/\pi^+$ ratio are evidently larger than that in neutron-deficient reaction system.

To obtain the information on the density-dependent symmetry energy, predictions on single and double pion ratios in isotope Sn reactions in $^{132}$Sn+$^{124}$Sn and $^{108}$Sn+$^{112}$Sn at 300 MeV/u are important for experiments at