Probing the symmetry potential with neutron-proton bremsstrahlung in heavy-ion collisions*

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Abstract: In the framework of the isospin-dependent quantum molecular dynamics transport model (QMD), the effects of symmetry potential on the collision number and the neutron-proton bremsstrahlung photon in the reactions of ^{40}Ca+^{40}Ca, ^{124}Sn+^{124}Sn, ^{40}Ca+^{64}Zn, ^{40}Ca+^{124}Sn at different incident beam energies are studied. It is found that the collision number shows moderate sensitivity to the stiffness of the symmetry potential and the number of hard photons calculated with stiff symmetry potential is obviously smaller than that with soft symmetry potential. Thus, the neutron-proton bremsstrahlung photons produced in heavy-ion collisions may be a useful probe for the high-density behavior of the nuclear symmetry potential.

Key words: symmetry potential, neutron-proton bremsstrahlung, heavy-ion collisions, quantum molecular dynamics model

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1 Introduction

The study of the isospin degree of freedom of nuclear reaction has been a fascinating subject and has attracted much attention for quite some time [1–6]. One of the most fundamental problems in nuclear physics is the isospin dependence of nuclear equation of state (EoS) (i.e. the symmetry energy), which is extremely important for understanding not only the structure of radioactive nuclei but also the evolution of many astrophysical objects, such as neutron stars, supernova explosions, etc. [7–14].

In theoretical study of the symmetry energy with transport models, one of the the most important inputs is the symmetry potential. Unfortunately, there are large uncertainties in the form of the symmetry potential in the high density region. To constrain the high density behavior of the symmetry potential, it is crucial to find out the experimental observables that are sensitive to the density dependence of the nuclear symmetry potential. Much progress has been achieved and a number of useful probes are proposed, such as the free n/p [15], the isospin fractionation [16, 17], the neutron-proton correlation function [18], the isospin diffusion [19], the transverse differential flow [20], the proton differential elliptic flow [21, 22], the π^-/π^+ ratio [1, 23, 24] and the production of hard photons [25].

Among the above-mentioned observables, the hard photon as a probe is particularly significant because it is produced by a weak interaction. On the other hand, the neutron-proton bremsstrahlung photo produced in heavy-ion collisions has been studied for a long tome. The TAPS collaboration carried out a series of comprehensive measurements at various detailed properties, such as energy spectra, angular distributions, total photon multiplicities di-photon correlation function, etc. at beam energies between about 10 and 200 MeV/u. The bremsstrahlung photon has been used as a tool to study the nuclear caloric curve, the dynamics of nucleon-nucleon interactions, and the time-evolution of the reaction process before nuclear break-up. It is concluded that the neutron-proton (n-p) bremsstrahlung in the early stage of the reaction is the main source of high energy γ rays [26–29]. The photon production probability has been investigated with the Boltzmann-Uehling-Uhlenbeck (BUU) model [25]. Based on the equation used to calculate the number of photons, we propose a new approach to calculate it with the IQMD model.

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Within the framework of IQMD model, this paper studies the effects of the symmetry potential on n-p collision number and the photon production probability. It is proved that the information about the symmetry potential would be extracted from the photon production in intermediate-energy reaction especially in heavy-ion collision system.

2 The theoretical model

The photon production probability is so small that only one out of roughly a thousand nucleon-nucleon collisions produces a photon. An approach could be used in dynamical calculations of the photon production at intermediate energies, where one calculates the photon production as a probability in each proton-neutron collision and then sums over all such collisions over the entire history of the reaction. There are several methods to calculate the photon production, such as the elementary probability for neutron-proton bremsstrahlung photon ($\mathrm{pn}\rightarrow\mathrm{pn}\gamma$) by using the neutral scalar σ meson exchange model in the nucleon-nucleon center-of-mass system [30], the semiclassical bremsstrahlung method for the $\mathrm{pn}\rightarrow\mathrm{pn}\gamma$ probability [31] and so on. Here we use Equation [32]:

$$\frac{\mathrm{d}^2p_\gamma}{\mathrm{d}\Omega\mathrm{d}E}=1.67\times10^{-7}\frac{(1-y^2)^\alpha}{y}. \tag{1}$$

Photons are assumed to be emitted isotropically in the nucleon-nucleon center-of-mass frame, therefore the photon probability is averaged over the solid angle of 4π. By integrating Eq. (1) over the photon emission angle, one obtains the single differential probability by [25]:

$$p_\gamma=\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}=\int_{\mathrm{o}}^{4\pi}\frac{\mathrm{d}^2p_\gamma}{\mathrm{d}\Omega\mathrm{d}E}\mathrm{d}\Omega=2.1\times10^{-6}\frac{(1-x^2)^\alpha}{x}, \tag{2}$$

where $\alpha=0.7319-0.5898\beta$, $x=E_\gamma/E_{\max}$, $\beta=v/c$, v is the initial velocity of the proton in the proton-neutron center of mass frame, $E_{\max}$ is the energy available in the center of mass of the colliding proton-neutron pairs, and they are calculated by

$$\begin{cases}\dfrac{v}{c}=\dfrac{p}{m},\\ E_{\max}=2\times(m-m_0),\end{cases} \tag{3}$$

where p is the momentum of the proton in the center of mass of the colliding proton-neutron pairs, m is the mass of proton of motion state, $c=1$ in natural system of coordinates.

The symmetry potential used in the transport model is:

$$\begin{cases}U_1^{\mathrm{sym}}=32\times\dfrac{\rho}{\rho_0}\times\dfrac{\rho_\mathrm{n}-\rho_\mathrm{p}}{\rho}\tau_z,\\ U_2^{\mathrm{sym}}=32\times\left(\dfrac{\rho}{\rho_0}\right)^2\times\left[\dfrac{\rho_\mathrm{n}-\rho_\mathrm{p}}{\rho}\tau_z+\dfrac{1}{2}\left(\dfrac{\rho_\mathrm{n}-\rho_\mathrm{p}}{\rho}\right)^2\right],\\ U_3^{\mathrm{sym}}=32\times\sqrt{\dfrac{\rho}{\rho_0}}\times\left[\dfrac{\rho_\mathrm{n}-\rho_\mathrm{p}}{\rho}\tau_z-\dfrac{1}{4}\left(\dfrac{\rho_\mathrm{n}-\rho_\mathrm{p}}{\rho}\right)^2\right],\end{cases} \tag{4}$$

where ρ and ρ_0 are the nuclear density and its normal value. ρ_n and ρ_p represent the neutron and proton densities. $\tau_z=1$ for neutron and $\tau_z=-1$ for proton.

3 Results and discussions

Figure 1 denotes the symmetry potential changing with the relative density. The solid line, dash line and dash dot line represent the results by using U_1^{sym}, U_2^{sym} and U_3^{sym}, respectively, with the relative neutron excess ($(\rho_\mathrm{n}-\rho_\mathrm{p})/\rho=0.4$). It is noticed that the absolute value of symmetry potential increases with the increase of relative density. The incompressibility coefficients for U_1^{sym}, U_2^{sym} and U_3^{sym} are -27 MeV, 322 MeV and -70 MeV,

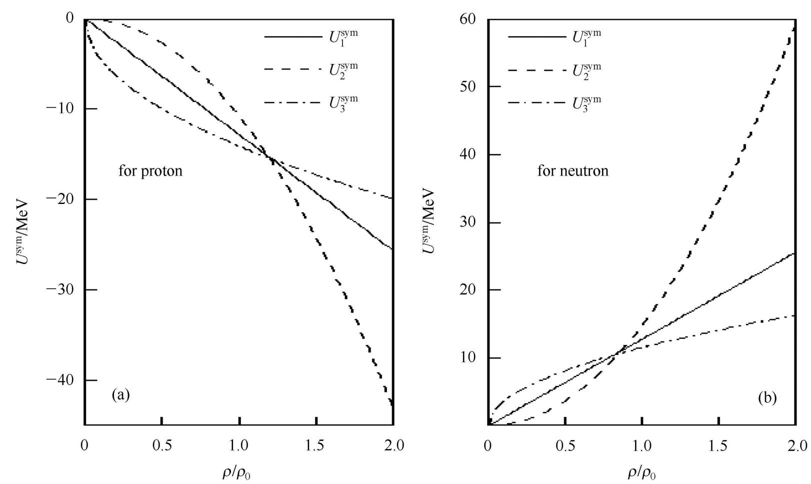

Fig. 1. The density dependence of symmetry potential for proton and neutron.

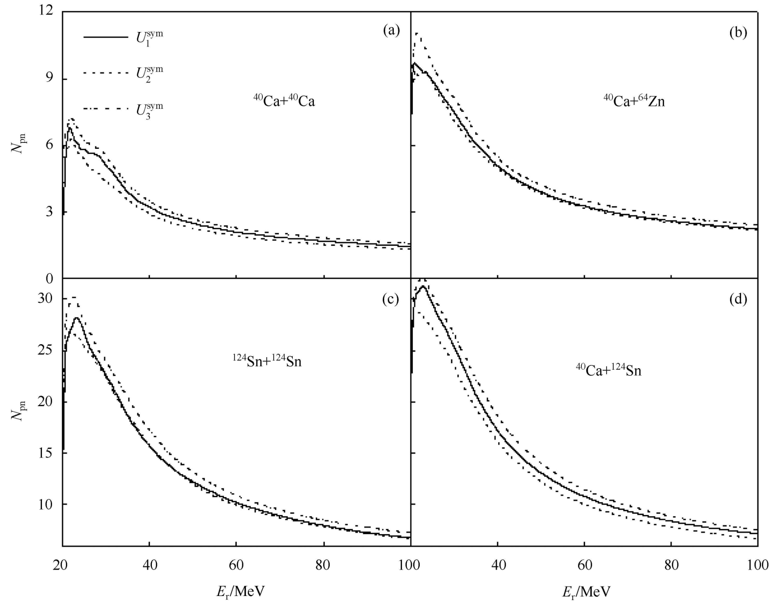

Fig. 2. The collision number of n-p varying with reaction energy when the impact parameter b=1 fm.

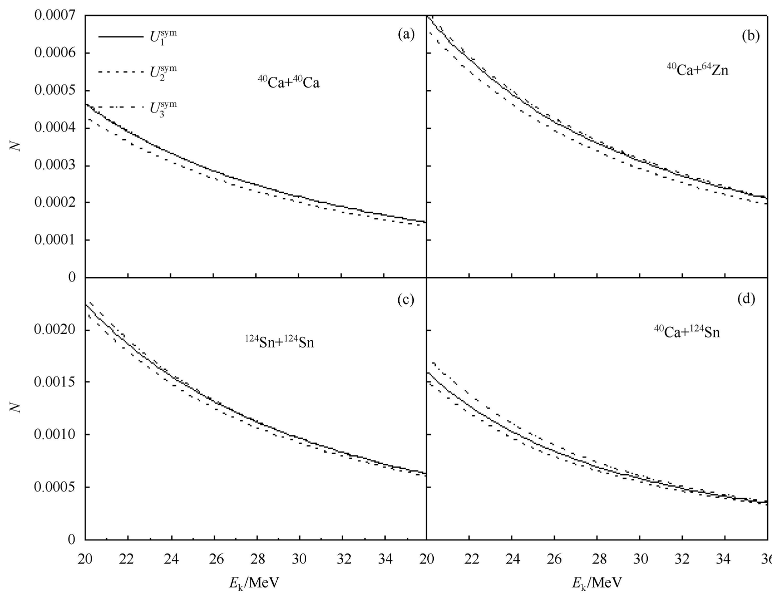

Fig. 3. The kinetic energy dependence of the photon number.

respectively. From Fig. 1, we can easily conclude that the absolute value of symmetry potential with larger incompressibility coefficient is smaller than the others under the saturation density. However, it is larger than others above saturation density.

Figure 2 shows the reaction energy (E_{r}) dependence of collision number of n-p for symmetric collision systems and asymmetric collision systems at an incident energy of 100 MeV/u. The three curves correspond to the same symmetry potential as in Fig. 1. From Fig. 2, it can be seen that both in the symmetric collision system and the asymmetric system, there are differences between the n-p collision numbers for different symmetry potentials with the same reaction energy. It is clearly shown that the results for U_3^{sym} are always larger than the others, while the results for U_2^{sym} are always smaller than the others, which illustrates that the n-p collision number calculated is large for soft U^{sym} and small for stiff U^{sym}. This phenomenon denotes that the softer U^{sym} makes the collision reaction more violent at the reaction energy that we have investigated.

Figure 3 denotes the kinetic energy dependence of the photon number with three symmetry potentials for the same collision systems at 100 MeV/u, which results from

Eq. (6). It can be seen that the symmetry potential with smaller impressibility coefficient leads to higher photon production. There are two reasons for this: firstly, the n-p collision number, which is closely related to photon production, is large for soft $U^{\rm sym}$ and small for stiff $U^{\rm sym}$; secondly, the collision reaction with soft $U^{\rm sym}$ rather than stiff $U^{\rm sym}$ leads to more nucleon-nucleon collision reactions. It is seen that the difference between the results of different symmetry potential is small; however, the difference would be big on experiment where there are a lot of the events of collision.

So we would take the energy dependence of the photon number as a probe for symmetry potential.

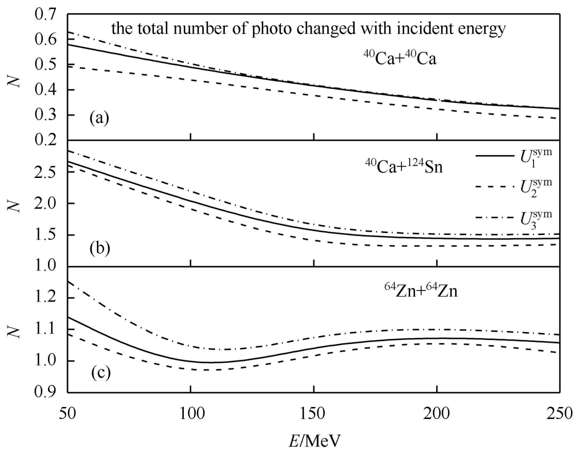

Fig. 4. The relationship between the total photon number and the incident energy.

Figure 4 shows the total photon number varying with the incident energy for the three collision systems. It can be seen that the total photon number decreases with the increase of the incident energy, this could be explained by the high incident energy, which leads to small reaction cross section and small collision number. We notice that there is a great effect of the symmetry potential on photon production, especially for the heavy systems. In more detail, soft symmetry potential leads to a large total photon number, which can be explained by the softer symmetry potential, which leads to a larger collision number. For the collision system of ^{40}Ca+^{40}Ca, the effect of the symmetry potential on photon production can be easily seen at low incident energies, while it is small at the most incident energies that we have investigated. However, the effect of the $U^{\rm sym}$ can be noticed at all of the incident energies that we have investigated for the other collision systems. We could get the idea that useful information about the symmetry potential can be extracted from the photon production in heavy-ion reactions, especially in heavy collision systems.

4 Summary

In summary, in the framework of the isospin-dependent quantum molecular dynamics (IQMD) model, we have carried out an exploratory study of the effect of the symmetry potential on the collision numbers and the production of photons in the reactions of ^{40}Ca+^{40}Ca, ^{124}Sn+^{124}Sn, ^{40}Ca+^{64}Zn, ^{40}Ca+^{124}Sn. It is found that the collision number calculated with soft symmetry potential is higher than that with stiff symmetry potential. As a result, the bremsstrahlung photon also shows obvious sensitivity to the stiffness of the symmetry potential, which is consistent with earlier studies based on IBUU04. Thus, the neutron-proton bremsstrahlung photons produced in heavy-ion collisions may be a useful probe for the high-density behavior of the nuclear symmetry potential. It is suggested that the detection of the low energy photon would get more information of the symmetry potential in experiment.

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