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A direct probe of the in-medium *pn* scattering cross section

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ABSTRACT

Hard photon production from neutron–proton bremsstrahlung in intermediate energy heavy-ion reactions is examined as a probe of the in-medium *pn* scattering cross section within a transport model. Uncertainty of photon production probability $pn \to pn\gamma$ is cancelled out by using the ratio of hard photon spectra $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ from two reactions. The in medium *pn* scattering cross section is constrained by using the ratio of hard photon production cross sections of proton-induced reactions $p+{}^{12}\mathrm{C}$ and $p+{}^{2}\mathrm{H}$. A reduction factor $\sigma_{pn}^{medium}/\sigma_{pn}^{free}$ of about 0.5–0.7 around saturation density is obtained by comparing with the existing experimental data.

The in-medium nucleon–nucleon scattering cross section is a fundamental physical quantity in nuclear physics and astrophysics [1–3]. Besides many-body theoretical methods, in fact a lot of literature also reported the studies of the in-medium nucleon–nucleon scattering cross section based on transport models. Because so many uncertainties in the transport model and the complexity in heavy-ion collisions in intermediate energies, till now the in-medium nucleon–nucleon scattering cross section is still an open question although the free nucleon–nucleon scattering cross section is generally considered as a deterministic quantity. One of the hot topics in today's nuclear physics is the Equation of State (EoS) of asymmetric nuclear matter, which is important for understanding many interesting questions in both nuclear physics and astrophysics [1–3]. Among all the uncertainties of probing the symmetry energy [4–8] with heavy-ion collisions, the nucleon–nucleon scattering cross section is considered to be one of the most important factors [4,6,9–11]. Nowadays almost all the probes of nucleon–nucleon scattering cross section are hadronic probes. These probes inevitably suffer from distortions due to the strong interactions in the final state. Ideally one expects more clean ways to study nucleon–nucleon scattering cross section. It is noted that the parity-violating electron scattering has been proposed to measure more precisely the size of the neutron-skin in ^{208}Pb [12]. Similarly to electrons, photons interact with nucleons only electromagnetically. Once produced they escape almost freely from the nuclear environment of nuclear reactions. Following the studies of using hard photon production to probe the symmetry energy [13], in this Letter, based on the Boltzmann–Uehling–Uhlenbeck (BUU) transport model, we report our results of using hard photons from neutron–proton bremsstrahlung in intermediate energy heavy-ion reactions as a direct probe of the in-medium *pn* scattering cross section.

Hard photon production in heavy-ion reactions at beam energies from about 10 to 200 MeV/nucleon had been extensively studied both experimentally and theoretically [14–16]. For instance, the TAPS Collaboration carried out a series of comprehensive measurements at various experimental facilities (GSI, GANIL, KVI) studying in detail the properties of hard photons in a large variety of nucleus–nucleus systems in the range of energies spanning $E_{lab} \approx 20$–200 MeV/nucleon [17]. Theoretically, it was concluded that the neutron–proton bremsstrahlungs in the early stage of the reaction are the main source of high energy γ rays. Further, it was demonstrated clearly that the hard photons can be used to probe the reaction dynamics leading to the formation of dense matter [18–22]. Another favorable factor of using hard photons to probe the *pn* scattering cross section is that effects of the nuclear EoS on the hard photon production was found small [23]. One of the major uncertainties of hard proton studies is the input elementary $pn \to pn\gamma$ probability p_γ which is still rather model dependent [24–28,16]. The recent systematic measurements of the $pn \to pn\gamma$ cross sections with neutron beams up to 700 MeV at Los Alamos and the subsequent state-of-the-art theoretical investigation may help to improve the above situation significantly in the near future [29,30].

Since the photon production probability is so small, i.e., only one photon is produced in roughly a thousand nucleon–nucleon collisions, a perturbative approach has been used in all dynamical calculations of photon production in heavy-ion reactions at

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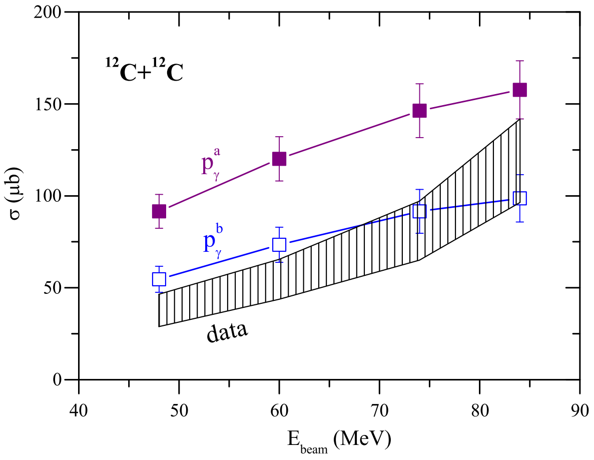

Fig. 1. (Color online.) Beam energy dependence of the inclusive photon production cross sections in $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ collisions. The photon energy is 50 MeV $\leqslant \varepsilon_\gamma <$ 100 MeV. BUU calculations with both p^a_γ and p^b_γ vs experimental data.

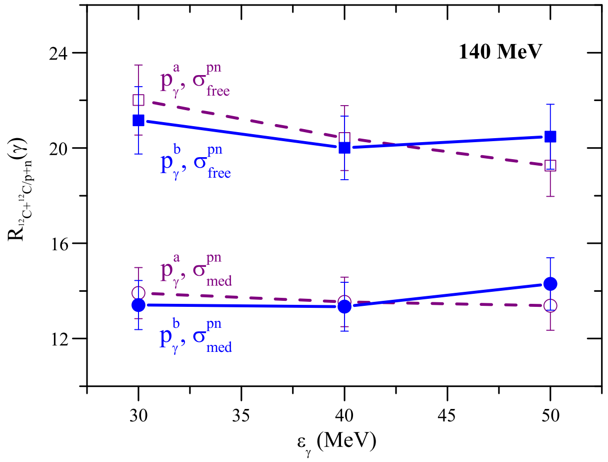

Fig. 2. (Color online.) The ratio of hard photon spectra in the reactions of $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ and $p+n$ at a beam energy of 140 MeV/nucleon with free and in-medium *pn* scattering cross sections using p^a_γ and p^b_γ, respectively.

intermediate energies [14,16]. In this approach, one calculates the photon production as a probability at each proton–neutron collision and then sum over all such collisions over the entire history of the reaction. As discussed in detail earlier in Ref. [16], the cross section for neutron–proton bremsstrahlung in the long-wavelength limit separates into a product of the elastic *pn* scattering cross section and a γ-production probability. The probability is often taken from the semiclassical hard sphere collision model [14–16]. The single differential probability reads

$$p^a_\gamma \equiv \frac{dN}{d\varepsilon_\gamma} = 1.55\times 10^{-3}\times \frac{1}{\varepsilon_\gamma}\left(\beta_i^2+\beta_f^2\right). \tag{1}$$

Where ε_γ is energy of emitting photon, β_i and β_f are the initial and final velocities of the proton in the proton–neutron center of mass frame. We notice that other expressions derived theoretically involving more quantum-mechanical effects exist in the literature, see, e.g., [24–28]. For a comparison we thus also use the prediction of the one boson exchange model by Gan et al. [27]

$$p^b_\gamma \equiv \frac{dN}{d\varepsilon_\gamma} = 2.1\times 10^{-6}\frac{(1-y^2)^\alpha}{y}, \tag{2}$$

where $y=\varepsilon_\gamma/E_{max}$, $\alpha = 0.7319-0.5898\beta_i$, and E_{max} is the energy available in the center of mass of the colliding proton–neutron pairs. As noticed already in Ref. [27,13], the single differential probabilities p^a_γ and p^b_γ from the two models give quite similar but quantitatively different results especially near the kinematic limit where the photon production with p^a_γ is significantly higher than that with p^b_γ. As discussed in the paper of Gan et al. [27], compared with the result using the semiclassical expression, the quantum formula p^b_γ reduces proton production evidently near the kinematic limit. While we are not aiming at reproducing any data in this exploratory work, it is necessary to first gauge the model by comparing with the available data. Shown in Fig. 1 are the BUU calculations with both p^a_γ and p^b_γ and the experimental data for the inclusive cross sections of hard photon production in the reaction $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ [13]. It is seen that both calculations are in reasonable agreements qualitatively with the experimental data, especially at higher beam energies. The agreement is at about the same level as previous calculations by others in the literature [19,21,27]. It is noticed that the uncertainty in the elementary $pn \to pn\gamma$ probability leads to an appreciable effect on the inclusive γ-production in heavy-ion reactions. From Fig. 1, we can clearly see that the quantum formula p^b_γ seems more suitable for describing energetic photon production in intermediate energy heavy-ion reactions. It was noted that for nuclear bremsstrahlung, a strong suppression or coherence of the bremsstrahlung cross section were observed in comparison with predictions of transport models that include bremsstrahlung on the basis of quasi-free nucleon–nucleon collisions [31,32]. In this study, we use the BUU transport model [33] with an isospin-dependent in-medium reduced nucleon–nucleon (NN) cross section [4,6] to treat the in-medium bremsstrahlung semiclassically [34]. The energy and isospin dependent free-space NN cross sections σ^{free}_{NN} are taken from the experimental data. Another important input to the transport model is the momentum- and isospin-dependent single nucleon potential as given in Ref. [35]. The isoscalar part of the single nucleon potential was shown to be in good agreement with that of the variational many-body calculations and the results of the Brueckner–Hartree–Fock approach including three-body forces and the isovector potential is consistent with the experimental Lane potential [36].

Since the energetic photons are produced in *pn* collisions, it is quite obvious that *pp* or *nn* collisions do not influence the production of photons. We can understand this way: (1) The studied hard photon is produced via $pn \to pn\gamma$, so it reflects *pn* scatterings directly. The *nn* or *pp* scatterings may affect *pn* scatterings, and then affect hard photon production. But they are both secondary effects. (2) The increased/decreased *pp* or *nn* cross sections may also increase/decrease the collision number of protons and neutrons, thus may increase/decrease the *pn* collision number. But, on the contrary, the larger/small *pp* or *nn* cross sections may reduce/enlarge the collision number of proton with neutron (or neutron with proton). The secondary effects are thus cancelled out each other. We in fact checked this deduction by BUU calculations and find that the hard photon production is really only sensitive to *pn* cross section, while not sensitive to *pp* or *nn* cross sections.

To reduce uncertainties of the input elementary $pn \to pn\gamma$ probability while using hard photon to probe in-medium *pn* cross section, we provide Fig. 2, the ratio of hard photon spectra in the reactions $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ and $p+n$ at a beam energy of 140 MeV/nucleon. The spectra ratio $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ reads

$$R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma) \equiv \frac{\frac{dN}{d\varepsilon_\gamma}(^{12}\mathrm{C}+{}^{12}\mathrm{C})}{\frac{dN}{d\varepsilon_\gamma}(p+n)}. \tag{3}$$

It is seen that the $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ is quite sensitive to the *pn* scattering cross section while not sensitive to theoretical formu-

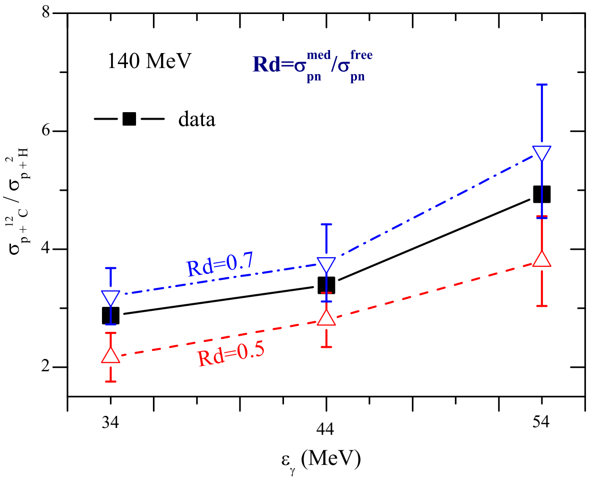

Fig. 3. (Color online.) The ratio of hard photon production cross sections of $p+{}^{12}\mathrm{C}$ and $p+{}^{2}\mathrm{H}$ reactions at a beam energy of 140 MeV/nucleon with different *pn* scattering cross sections. Experimental data are taken from Ref. [21].

las used. This ratio reduces the uncertainties of the theoretical elementary $pn \to pn\gamma$ probability maximally. The change of the *pn* scattering cross section leads to $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ a sensitivity of about 60%. Like in many experiments searching for minute but interesting effects, ratio of observables from two reactions can often reduce not only the systematic errors but also some unwanted effects. At least theoretically, the uncertainty of the γ-production probability gets almost completely cancelled out in the ratio of photon spectra here. From our BUU calculations, the defined quantity $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ does not dependents on the input γ-production probability with a high credibility of 95%. Also in this definition we assume input γ-production probability in matter is the same as that in vacuum since photons interact with hadrons only electromagnetically.

The photon production in ${}^{12}\mathrm{C}+{}^{12}\mathrm{C}$ is determined by *pn* colliding number and the input elementary $pn \to pn\gamma$ probability, the ratio $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ thus only depends on the *pn* colliding number in the reaction ${}^{12}\mathrm{C}+{}^{12}\mathrm{C}$ at certain energies. While the *pn* colliding number in a reaction depends on the *pn* cross section in matter. The spectra ratio $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ is therefore a direct probe of the in-medium *pn* scattering cross section essentially free of the uncertainties associated with both the elementary photon production and the *nn* and *pp* scattering cross sections. Compared with other probes of nucleon–nucleon scattering cross sections, such as nuclear flow and nuclear stopping, hard photon production directly affects the *pn* scattering cross section. Practically, besides cosmic-radiation background, one needs to consider photons from π^0 and fragment decays in the data analysis [37].

While comparing with the experimental data, we find that there are few existing data to use. As a rough comparison, we did simulations of proton induced reactions on ${}^{12}\mathrm{C}$ and ${}^{2}\mathrm{H}$ targets at a beam energy of 140 MeV/nucleon as shown in Fig. 3. Here $\sigma_{p+^{12}\mathrm{C}}/\sigma_{p+^{2}\mathrm{H}}$ reads

$$\sigma_{p+^{12}\mathrm{C}}/\sigma_{p+^{2}\mathrm{H}} = \frac{\int_0^{b_{max}} \frac{dN}{d\varepsilon_\gamma}(p+{}^{12}\mathrm{C})2\pi b\,db}{\int_0^{b_{max}} \frac{dN}{d\varepsilon_\gamma}(p+{}^{2}\mathrm{H})2\pi b\,db}, \tag{4}$$

which in fact is the ratio of $R_{p+^{12}\mathrm{C}/p+^{2}\mathrm{H}}(\gamma)$ with different impact parameters. In the calculations we use simple Fermi-momentum as nucleonic momentum in deuteron and ${}^{12}\mathrm{C}$. And we find that photon production cross section $\sigma_{p+^{2}\mathrm{H}}$ is not sensitive to the distribution of nucleonic momentum in deuteron [38,39,21]. We also assumed there is no medium effect on photon production from $p+{}^{2}\mathrm{H}$. The reference reaction $p+{}^{2}\mathrm{H}$ thus plays roughly the same role as *pn* collision. We define the reduction factor $Rd = \sigma_{pn}^{medium}/\sigma_{pn}^{free}$. From Fig. 3 we can see that the experimental data are roughly within the range of $Rd = 0.5$ and 0.7 settings of our model. This reduction scale is somewhat larger than the Brueckner approach calculations [40–42]. Experimentally, heavy-ion collisions with $N \sim Z$ nuclei (to cancel the effect of symmetry energy) of symmetric system and $p+n$ collision are more suitable to give constraints on the in-medium *pn* scattering cross section by using hard photon production.

In conclusions, we did an exploratory study about effect of the *pn* scattering cross section on the production of hard photons from intermediate energy heavy-ion reactions using a perturbative approach within the BUU transport model. The ratio of hard photon spectra $R_{^{12}\mathrm{C}+^{12}\mathrm{C}/p+n}(\gamma)$ is not only approximately independent of the uncertainties of *nn*, *pp* cross sections and the theoretical elementary $pn \to pn\gamma$ probability, but also quite sensitive to the *pn* scattering cross section. Compared with other probes of nucleon–nucleon scattering cross sections, hard photons are completely free of final state strong interactions, directly reflect the magnitude *pn* scattering cross section and are quite sensitive to the *pn* scattering cross section. Through comparing with existing experimental data, we obtain a reduction factor $\sigma_{pn}^{medium}/\sigma_{pn}^{free}$ of about 0.5–0.7 around saturation density. Heavy-ion collisions with $N \sim Z$ nuclei of symmetric system and $p+n$ collision are needed to further constrain the in-medium *pn* scattering cross section at different densities and nucleonic momenta.

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