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Probing the neutron-skin thickness by photon production from reactions induced by intermediate-energy protons

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The photon from neutron-proton bremsstrahlung in p+Pb reactions is examined as a potential probe of the neutron-skin thickness in different centralities and at different proton incident energies. It is shown that the best choice of reaction environment is about 140 MeV for the incident proton and the 95%–100% centrality for the reaction system since the incident proton mainly interacts with neutrons inside the skin of the target and thus leads to different photon production to a maximal extent. Moreover, considering two main uncertainties from both photon production probability and nucleon-nucleon cross section in the reaction, I propose to use the ratio of photon production from two reactions to measure the neutron-skin thickness because of its cancellation effects on these uncertainties simultaneously, but preserved about 13%–15% sensitivities on the varied neutron-skin thickness from 0.1 to 0.3 fm within the current experimental uncertainty range of the neutron-skin size in ^{208}Pb.

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The neutron-skin of nuclei is a fundamental physical quantity in nuclear physics, and has received considerable attention due to its importance in determining the structure of neutron-rich nuclei in nuclear physics and the property of neutron-rich matter in astrophysics. To determine the neutron-skin thickness of nuclei, one should know the proton density distribution and neutron density distribution, and then determine the corresponding neutron-skin thickness by calculating the root-mean-square (rms) radius difference between proton and neutron. Presently, the proton rms radius can be determined precisely, typically with an error of 0.02 fm or better for many nuclei [1–3]; the neutron rms radius is much less well known although many efforts have been devoted to probing the neutron density distribution by theoretical and experimental methods such as the nucleon elastic scattering [4–7], the inelastic excitation of the giant dipole and spin-dipole resonances [8,9], the pygmy dipole resonance [10,11], and experiments in exotic atoms [12–17]. This is because almost all of these probes are hadronic ones and need model assumptions to deal with the strong force introducing possible systematic uncertainties even if some of them reach small errors [18]. In this situation, the parity radius experiment (PREX-I) at the Jefferson Laboratory (JLab) [19] has been performed to measure the neutron-skin thickness of ^{208}Pb using parity violating e-Pb scattering, the measured value of $0.33^{+0.16}_{-0.18}$ fm in ^{208}Pb obviously differs from previous value of 0.11 ± 0.06 fm of ^{208}Pb from π^+-Pb scattering [20] albeit largely overlapping with each other within error bars. However, the obtained results from PREX-I experiment suffer from large uncertainties although the PREX-I experiment aims to a model-independent measurement of the neutron-skin thickness of ^{208}Pb. It is interesting, however, to note that the neutron-skin for ^{208}Pb as thick as $0.33 + 0.16$ fm reported by the PREX-I experiment cannot be ruled out within a relativistic mean-field model [21]. This situation stimulated the JLab to plan to remeasure the neutron-skin thickness of ^{208}Pb and ^{48}Ca, i.e., the PREX-II experiment and the calcium radius experiment, which are expected to provide more accurate neutron-skin thickness for ^{208}Pb and ^{48}Ca [22]. While waiting the experimental data, theoretical efforts on this problem are required to indicate what are the sensitive probes of the neutron-skin thickness especially those of nonhadronic ones.

Similar to electrons, photons interact with nucleons only electromagnetically, and they escape almost freely from the nuclear environment once produced. In fact, photon production in heavy-ion reactions has been extensively studied in experiment and theory [23–25]. For example, the hard photon from neutron-proton bremsstrahlung is employed to probe the nuclear caloric curve [26], the dynamics of nucleon-nucleon interactions [27–29], the time-evolution of the reaction process before nuclear break-up [30] as well as the space-time extent of the photon emitting sources [31]; and the soft photon from giant dipole resonances in heavy-ion reactions is used to study the symmetry potential term of the nucleon-nucleon interactions [32]. A natural question is whether the photon can be used as a potential sensitive probe of the neutron-skin thickness in nuclear reactions. Before answering this question, let us first initialize the ^{208}Pb target with different density distribution corresponding to two different neutron-skin sizes of $S = 0.10$ and 0.30 fm within the current experimental uncertainty range of the neutron-skin size of ^{208}Pb, which are predicted by Hartree-Fock calculations based on the MSL model [33,34]. Different values of neutron-skin thickness can be obtained by changing only the value of L in the MSL0 force [34] while keeping all the other macroscopic quantities the same. Shown in Fig. 1 are the density profiles corresponding to the neutron-skin thickness of 0.1 and 0.3 fm for ^{208}Pb target [35,36], the proton distributions are almost identical, while the neutrons distribute differently in the two cases considered.

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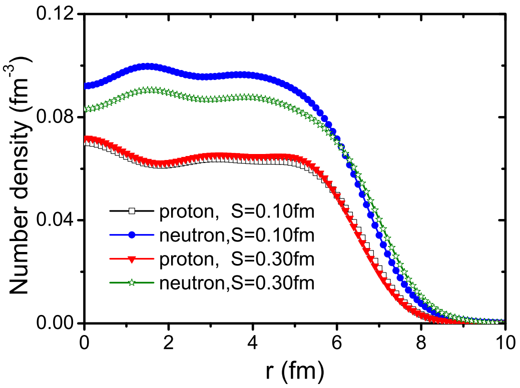

FIG. 1. (Color online) The neutron and proton density profiles for ^{208}Pb target with the neutron-skin thickness of 0.1 and 0.3 fm.

To answer the question mentioned above, one has to confront two main uncertainty factors because they can significantly influence the photon production in our reaction model IBUU [37]. One is the in-medium nucleon-nucleon cross section defined as

$$\sigma_{\text{med}}^{NN} = \sigma_{\text{free}}^{NN}\left(\frac{\mu_{NN}^{*}}{\mu_{NN}}\right)^{2}, \tag{1}$$

where the μ_{NN}^{*} and μ_{NN} are the in-medium and free-space reduced nucleon-nucleon mass. The scaling factor $(\frac{\mu_{NN}^{*}}{\mu_{NN}})^{2}$ reduces significantly the relative cross sections of nucleon-nucleon collisions due to the momentum dependence of the nuclear interactions [38]. Another is the photon production probability, since this probability is very small, i.e., just one photon producing roughly in 1000 nucleon-nucleon collisions. Therefore, photon production in dynamical calculations of nuclear reactions at intermediate energy is usually treated in a perturbative manner [23,25]. In this approach, one calculates the photon production as a probability at each proton-neutron collision and then sums over all such collisions over the entire history of the reaction [39,40]. Two kinds of probability formulas are commonly used to predict the photon production in nuclear reactions. One is based on the semiclassical hard sphere collision model [23,25], its definition is

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

where ε_{γ} is the 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. Another is based on the one-boson exchange model involving more quantum mechanical effects [41] as follows:

$$p_{\gamma}^{b} \equiv \frac{dN}{d\varepsilon_{\gamma}} = 2.1 \times 10^{-6} \times \frac{(1-y^2)^{\alpha}}{y}, \tag{3}$$

where $y = \varepsilon_{\gamma}/E_{\text{max}}$, $\alpha = 0.7319 - 0.5898\beta_i$, and E_{max} is the energy available in the center of mass of the colliding proton-neutron pairs.

Now let us check the sensitivities of photon production from neutron-proton bremsstrahlung on the neutron-skin thickness in the p+Pb reaction. Shown in Fig. 2 is the time evolution of photon multiplicity with different energies (upper panel) and total photon multiplicity (lower panel) in the p+Pb reaction with 95%–100% centrality and at the proton incident energy of 140 MeV within the neutron-skin thickness of 0.1 and 0.3 fm. Here, the centrality is defined as the percent of impact parameter over the size of the reaction system. First, it can be seen from the upper panel of Fig. 2 that the photon multiplicity is decreasing with increasing photon energy, and thus the production of a photon with energy beyond about 50 MeV can be ignored in the intermediate energy p+Pb reaction. Second, the photon multiplicity with the thicker neutron-skin is larger than that with the thinner neutron-skin especially for those of lower energy photon; this is because the larger neutron densities inside the thicker neutron-skin get these neutrons with higher probability to repeatedly collide with incident proton and thus leads to higher photon production, especially for emitting lower energy photon. However, considering that photon production is insufficiently large after all, I thus check the sensitivity of total photon multiplicity with an energy from about 10 to 50 MeV on the neutron-skin thickness. It can be seen from the lower panel of Fig. 2 that the total photon multiplicity is also sensitive to the neutron-skin thickness, and shows about 15% relative sensitivity. Nevertheless, is 140 MeV the best proton incident energy for probing the neutron-skin thickness using photon production in the p+Pb reaction, and whether the 95%–100% centrality is the best choice for the reaction system? Shown in Figs. 3 and 4 are the total photon multiplicity and corresponding relative sensitivity on the neutron-skin thickness in different centralities but with the given proton incident energy of 140 MeV, and in different proton incident energies but the given centrality of 95%–100%, respectively, within the neutron-skin thickness of 0.10 and 0.30 fm. It can be seen that the best choice of reaction environment is about 140 MeV for the incident proton and the 95%–100% centrality for the reaction system since the incident proton mainly interacts with the neutron

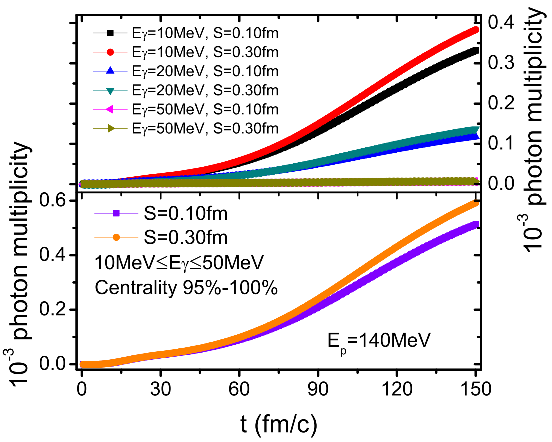

FIG. 2. (Color online) The time evolution of photon multiplicity with different energies (upper panel) and total photon multiplicity (lower panel) in the p+Pb reaction with 95%–100% centrality at the proton incident energy of 140 MeV within the neutron-skin thickness of 0.1 and 0.3 fm. The probability formula p_{γ}^{b} and in-medium nucleon-nucleon cross section are used.

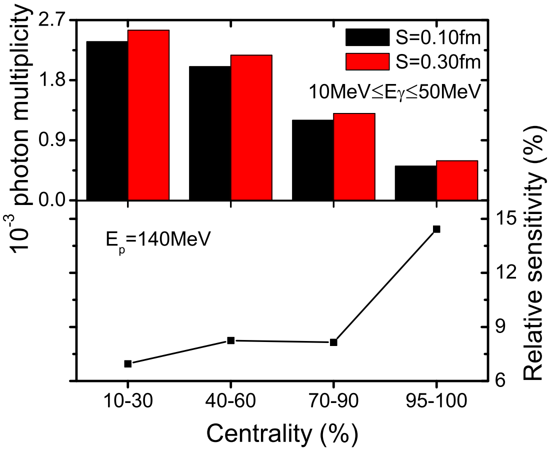

FIG. 3. (Color online) Total photon multiplicity and the corresponding relative sensitivity on the neutron-skin thickness in different centralities but with the given proton incident energy of 140 MeV within the neutron-skin thickness of 0.10 and 0.30 fm. The probability formula p_γ^b and in-medium nucleon-nucleon cross section are used.

inside the skin of the target and thus leads to a different photon production to maximal extent. Certainly, with the incident proton energy increasing the higher photon production may be reachable, but the produced π^0 mesons can also produce photons and thus bring in a more complicated physics process. Therefore, I employ the proton incident energy of 140 MeV and the centrality of 95%–100% as the best reaction environment in probing the neutron-skin thickness using the photon production.

However, the influence of two main uncertainties from both nucleon-nucleon cross section and photon production probability may change the effects of the neutron-skin thickness on the total photon multiplicity. Shown in Figs. 5 and 6 are the time evolution of total photon multiplicity with different nucleon-nucleon cross section, and with different photon production probability, respectively, within the neutron-skin thickness of 0.10 and 0.30 fm. First, the total photon multiplicity with free-space nucleon-nucleon cross section is higher than that with in-medium nucleon-nucleon cross section because the scaling factor $(\frac{\mu_{NN}^*}{\mu_{NN}})^2$ reduces significantly the relative cross sections of nucleon-nucleon collisions [38]. Second, the total photon multiplicity with probability formula p_γ^a is higher than that with probability formula p_γ^b similar to the results reported in previous Refs. [39–41]. It is fortunate to see that the sensitivity of total photon multiplicity on the neutron-skin thickness is not changed no matter how the nucleon-nucleon cross section and/or photon production probability change. However, the influence of these uncertainties on photon production is much more than the effects from the neutron-skin thickness. This will significantly prevent one from extracting useful information about the neutron-skin thickness from photon production. How to cancel out the influence of these uncertainties on photon production is the main task I shall discuss in the following.

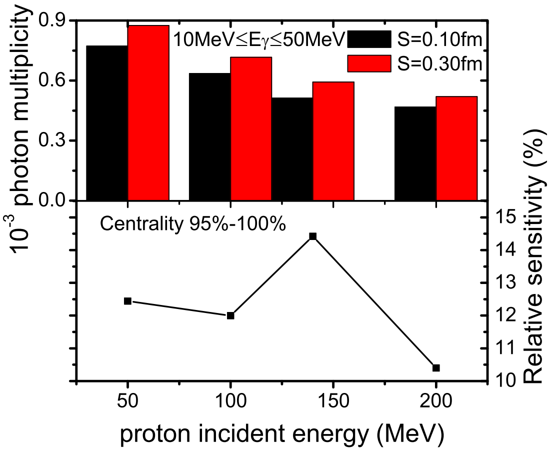

FIG. 4. (Color online) Total photon multiplicity and the corresponding relative sensitivity on the neutron-skin thickness in different proton incident energies but the given centrality of 95%–100% within the neutron-skin thickness of 0.10 and 0.30 fm. The probability formula p_γ^b and in-medium nucleon-nucleon cross section are used.

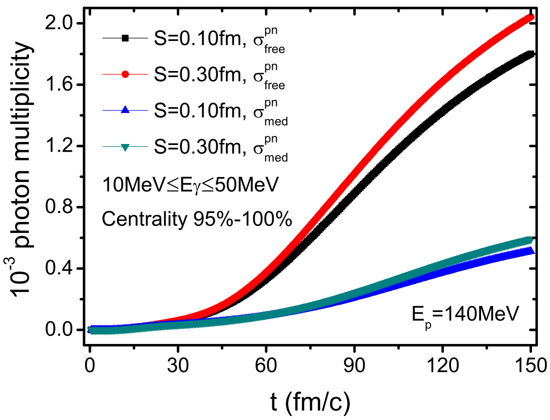

FIG. 5. (Color online) The time evolution of total photon multiplicity with free-space and in-medium nucleon-nucleon cross section in the proton incident energy of 140 MeV and the centrality of 95%–100% within the probability formula p_γ^b and neutron-skin thickness of 0.10 and 0.30 fm.

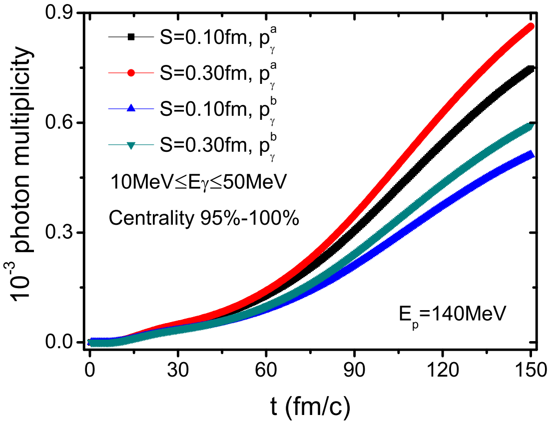

FIG. 6. (Color online) The time evolution of total photon multiplicity with probability formulas p_γ^a and p_γ^b in the proton incident energy of 140 MeV and the centrality of 95%–100% within the in-medium nucleon-nucleon cross section and neutron-skin thickness of 0.10 and 0.30 fm.

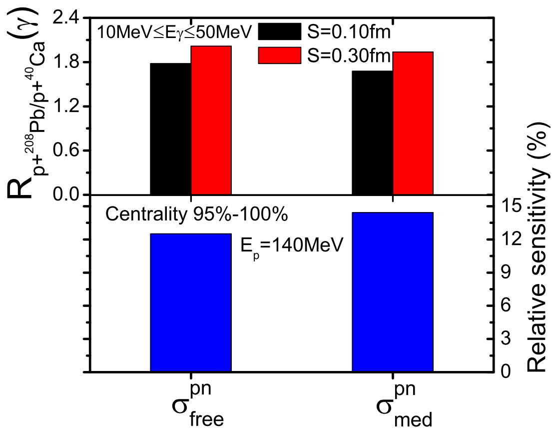

FIG. 7. (Color online) The ratio of photon multiplicity from two reactions and the corresponding relative sensitivity on the neutron-skin thickness with free-space and in-medium nucleon-nucleon cross section within the probability formula p^b_γ and neutron-skin thickness of 0.10 and 0.30 fm.

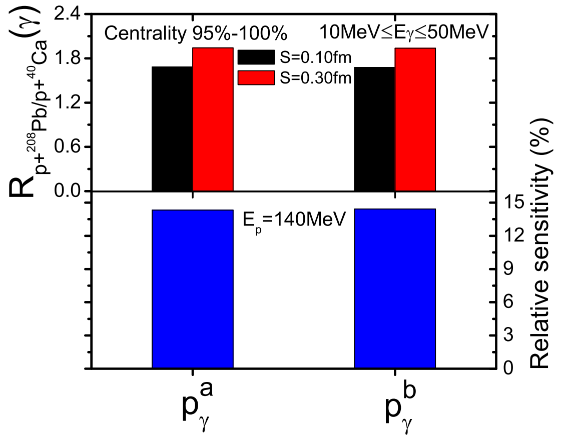

FIG. 8. (Color online) The ratio of photon multiplicity from two reactions and the corresponding relative sensitivity on the neutron-skin thickness with different photon production probability within the in-medium nucleon-nucleon cross section and neutron-skin thickness of 0.10 and 0.30 fm.

To reduce these uncertainties, I propose to use the ratio of photon production from two reactions to probe the neutron-skin thickness, its definition is

$$R_{p+^{208}\mathrm{Pb}/p+^{40}\mathrm{Ca}}(\gamma) \equiv \frac{N_\gamma(p + {}^{208}\mathrm{Pb})}{N_\gamma(p + {}^{40}\mathrm{Ca})}. \quad (4)$$

In the above equation, the $p+^{40}$Ca reaction with the centrality of 0–100 % is used as a referential reaction to cancel out the uncertainties from both nucleon-nucleon cross section and/or photon production probability. This is because the photon production is mainly determined by the proton-neutron colliding number; the proton-neutron collisions inside the ^{208}Pb target can be canceled out by the proton-neutron collisions inside the ^{40}Ca, naturally the difference of the photon production from the incident proton interacting with neutrons inside the skin of ^{208}Pb can be shown to a maximal extent. In fact, the ratio from two reactions which is usually used in experiments searching for minute but interesting effects, can reduce maximally not only the systematic errors but also some 'unwanted' effects [39,40]. Shown in Figs. 7 and 8 are the ratio of the photon multiplicity from two reactions and the corresponding relative sensitivity on the neutron-skin thickness with different nucleon-nucleon cross sections, and different photon production probability, respectively, within the neutron-skin thickness of 0.10 and 0.30 fm. It can be found that the ratio of photon multiplicity from two reactions can almost completely cancel out the uncertainties from nucleon-nucleon cross section and photon production probability, respectively, but can keep about 13%–15% sensitivity on the neutron-skin thickness.

Finally, it is necessary to check whether the ratio of photon multiplicity from two reactions can simultaneously cancel out these uncertainties from both nucleon-nucleon cross section and photon production probability since the uncertainties from the nucleon-nucleon cross section and photon production probability exist simultaneously in the p+Pb reaction. Shown in Fig. 9 are the ratio of photon multiplicity from two reactions and the corresponding relative sensitivity on the neutron-skin thickness with two kinds of settings in the p+Pb reaction, i.e., free-space cross section with photon production probability formula p^b_γ and in-medium nucleon-nucleon cross section with photon production probability formula p^a_γ. It is clear to see that this ratio can almost completely cancel out these uncertainties from both nucleon-nucleon cross section and photon production probability simultaneously, but can preserve about 13%–15% sensitivity on the neutron-skin thickness within the neutron-skin thicknesses of 0.10 and 0.30 fm. On the other hand, considering the experimental technology limitation of sorting events according to the centrality criteria, the similar plot with Fig. 9 but with 90%–100% centrality is shown in Fig. 10. It can be found that this ratio is also sensitive to the neutron-skin thickness and shows about 10%–15% sensitivities, but is independent approximately of

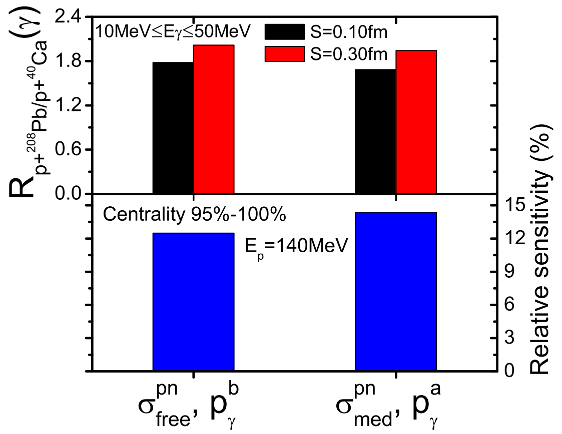

FIG. 9. (Color online) The ratio of photon multiplicity from two reactions and the corresponding relative sensitivity on the neutron-skin thickness with two kinds of setting in the p+Pb reaction, i.e., free-space cross section with photon production probability formula p^b_γ and in-medium cross section with photon production probability formula p^a_γ within the neutron-skin thickness of 0.10 and 0.30 fm.

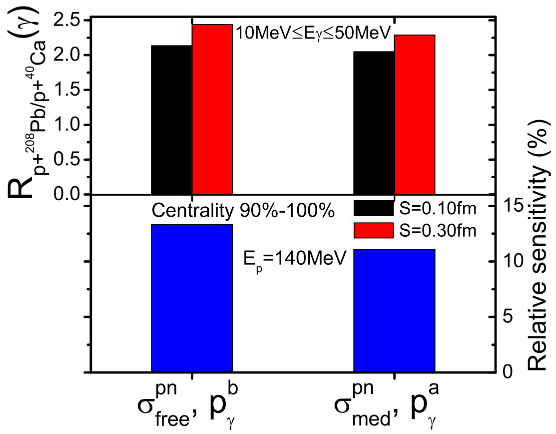

FIG. 10. (Color online) Same as Fig. 9 but with a centrality of 90%–100%.

the nucleon-nucleon cross section and photon production probability.

In summary, I have carried out an investigation about the feasibility of probing the neutron-skin thickness by photon production from neutron-proton bremsstrahlung in intermediate energy proton-induced reactions. Within the current experimental uncertainty range of the neutron-skin size of ^{208}Pb, the p+Pb reaction is performed in different centralities and at different proton incident energies within a transport model. It is shown that the energy of about 140 MeV for the incident proton and about 95%–100% centrality for the reaction system are the best reaction environment to probe the neutron-skin thickness using photon production. While the sensitivity of photon production on the neutron-skin thickness is much smaller than those due to possible uncertainties from both nucleon-nucleon cross section and photon production probability, the ratio of photon production from two reactions can almost completely cancel out the influence of these uncertainties simultaneously but can preserve about 13%–15% sensitivity on the neutron-skin thickness. Compared to other probes involved in nucleon elastic and/or inelastic scattering, the photon once produced can escape almost freely from the strong force environment, it is thus a potential sensitive probe of the neutron-skin thickness in intermediate energy proton-induced reaction.

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