Enhanced emissions of hard photons in heavy ion reactions by the particle correlation effect

Zhisong Wang
T. D. Lee Physics Laboratory, Fudan University, Shanghai 200433, China

Yukun Ho*
China Center of Advanced Science and Technology (World Laboratory), P.O. Box 8730, Beijing 100080, China and Physics Department 2, Fudan University, Shanghai 200433, China

Zhengying Pan
T. D. Lee Physics Laboratory, Fudan University, Shanghai 200433, China

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This paper studies the particle correlation effect on hard photon production in heavy ion reactions at intermediate energies. It is indicated that this mechanism is able to increase the high-momentum component in nucleon distribution in phase space, and consequently increase the production of hard photons. A modified version of the Boltzmann-Uehling-Uhlenbeck equation by incorporation of the α-like cluster effect has been developed. As examples, we studied, by using the new model, the photon productions in the reactions of ^{88}Kr on ^{12}C, $^{\mathrm{nat}}$Ag, and ^{197}Au targets, respectively, at the same beam energy $E/A = 44$ MeV. The results show that the incorporation of the cluster effect would lead to an enhancement of hard photon emission, especially at backward angles, and improve the agreement between the predicted and measured data. The mechanism underlying such enhancement has been explored.

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I. INTRODUCTION

During the past ten years, much attention both experimental [1–9] and theoretical [10–19] has been paid to the investigation of high-energy photon emissions in heavy ion reactions at intermediate incident energies. Having the advantage of not being as seriously disturbed by absorption phenomena as hardrons, photons are believed to carry unambiguous information on the reaction dynamics in the early stage of the reaction. By now the most successfully established mechanism for photon emission is the proton-neutron bremsstrahlung in individual nucleon-nucleon (N-N) collisions within the reaction [10]. A wide variety of dynamic models, in which a n-p collision history is available, were employed to predict the photon spectra, such as the nucleon exchange transport model (NET) [11], the Boltzmann master equation model [12,13], the Boltzmann-Uehling-Uhlenbeck model (BUU) [14–17], as well as the quantum molecular dynamics (QMD) model [18,19]. Among those the BUU model has been most extensively used since this model adopts the pseudoparticle technique [20] to simulate the reaction in full phase space, whereas it requires far less computational time than QMD. It has been shown that though BUU calculations may reproduce the main features of the photon production data, there still exist some remarkable discrepancies between the predictions and measurements [7–9,16]. The most pronounced are the underpredictions of the cross sections at the photon energies near the kinematical threshold. The photon production process is sensitive to the nucleon distribution in the momentum space of the composite system. These discrepancies imply that some mechanisms which might lead to generation of high-momentum nucleons were ignored in the conventional BUU version.

In our previous study [21], we explored such a possible mechanism, the particle correlation effect. It was indicated [21] that the incorporation of the possible cluster structure in nuclei and the so-called shuttle collisions may generate a prominent energy boost in the nucleon distribution in phase space. Here a shuttle collision refers to a two-step successive backward-forward particle-particle collision. At first, a nucleon undergoes the first collision with a particle (nucleon or cluster) from the other partner nucleus of the reaction, and then the reflected nucleon goes on to be bombarded by another particle (nucleon or cluster) from the same partner. Here is a simple kinematic calculation to show the energy boost effect. Assuming the first collision takes place between a projectile nucleon of beam velocity v_0 and mass m_0 with a cluster of mass m_1, which is at rest inside the target before the collision. The second collision happens between the reflected nucleon with another incident cluster of mass m_2 and velocity v_0 in the projectile. Then it is easy to verify that the maximum velocity reached by the nucleon after such a shuttle collision is

*Mailing address: Physics Department 2, Fudan University, Shanghai 200433, China.

$$(v)_{\max} = \frac{v_0}{(1+\gamma_1)(1+\gamma_2)}\{(2-2\beta)^{1/2} + [(1+\gamma_1+\gamma_2)^2 + \gamma_2^2 + 2\gamma_2(1+\gamma_1+\gamma_2)\beta]^{1/2}\}, \tag{1}$$

where $\gamma_1 = m_0/m_1$, $\gamma_2 = m_0/m_2$, $\beta = \cos\theta_c$, and θ_c is the scattering angle of the nucleon in the c.m. frame for the first collision. From Eq. (1), one gets the maximum energy reached by the nucleon after the shuttle collision as $E_{\max} = 4E_0/3$ for $\gamma_1 = \gamma_2 = 1$ (in the absence of any cluster effect), where $E_0 = m_0 v_0^2/2$ is the mean incident energy per nucleon; $E_{\max} = 3.84E_0$ for $\gamma_1 = \gamma_2 = 1/4$ (particles 1 and 2 both are α-like clusters); and the value of $E_{\max}$ will reach a limit of $9E_0$ if both the clusters are assumed to be massive enough ($\gamma_1 \to 0$ and $\gamma_2 \to 0$). In Ref. [21], the energy boost effect on nucleon distribution was studied by means of both analytical calculations and BUU simulations. However, Ref. [21] is just a schematic model study aiming at demonstrating the physical essence and major feature of the particle correlation effect. And the important quantal effects such as the mean field, Fermi motion, and Pauli blocking effects were ignored. Thus it is highly desirable to conduct a realistic treatment of the correlation effect in heavy ion (HI) reactions in order to make a comparison with experiments. This is the major object of the present paper. Here we intend to incorporate the particle correlation effect into the complete BUU frame with those quantal effects all presented, and then to examine its impact on hard photon productions in HI reactions.

In Sec. II, we specify our model and modify the conventional BUU program to allow an incorporation of the particle correlation (specifically the α-like clusters) in the BUU frame with all important quantal effects retained. As examples of application, the photon production cross sections in the reactions ^{86}Kr+^{12}C, ^{86}Kr+$^{\rm nat}$Ag, and ^{86}Kr+^{197}Au, all at the same beam energy $E/A = 44$ MeV, are calculated by using the modified BUU version. The predictions are compared with the measured data as well as the conventional BUU calculations, and the results are presented in Sec. III. Section IV is a brief summary.

II. MODEL AND MODIFIED BUU VERSION

The conventional BUU equation describes the temporal evolution of the reduced one-body phase space distribution function $f(\mathbf{r},\mathbf{p},t)$:

$$\frac{\partial f}{\partial t} + \mathbf{v}\nabla_r f - \nabla_r U(\rho)\nabla_p f = -\frac{1}{(2\pi)^6}\int d^3p_2 d^3p_{2'} d\Omega \frac{d\sigma}{d\Omega} v_{12}\{[f f_2(1-f_{1'})(1-f_{2'}) - f_{1'}f_{2'}(1-f)(1-f_2)] \times (2\pi)^3\delta^3(\mathbf{p}_{2'} - \mathbf{p}_{1'} - \mathbf{p}_2 - \mathbf{p})\}. \tag{2}$$

The terms on the left-hand side of the equation are the ingredients of Vlasov-type one-body dynamics where $U(\rho)$ is the density-dependent mean field potential. The right-hand side of the equation is the Uehling-Uhlenbeck collision integral where $d\sigma/d\Omega$ is the N-N collision cross section, and v_{12} is the relative velocity of the colliding nucleons. Obviously, Eq. (2) contains the major quantal effects: the mean field, Fermi motion, and Pauli blocking effects. A problem with Eq. (2) is that the collision integral contains only the average effect of two-nucleon collisions and thus the existing BUU version fails to provide many-body information and does not include any cluster effect. We notice that some recent efforts [22,23] have been made aiming at possible extensions of BUU dynamics to include the fluctuating two-body collisions. Our goal is to develop a model based on the BUU framework but to include the cluster effect in the collision term. The model contains the following major assumptions: (1) Only nucleons and α-like clusters exist in both the target and projectile before the two partners contact with each other. (2) Only N-N type and N-α type collisions are considered. Collisions between two α-like clusters are ignored. (3) The cluster structure would decompose after a N-α collision. It means that a particle which is bombarded by a nucleon in the BUU frame has some probability of being an α-like cluster only if this is the primary collision undergone by the particle. This probability is time dependent and is given in our model by

$$P_\alpha^i = \frac{N_\alpha^i \sigma_{n\alpha}}{N_\alpha^i \sigma_{n\alpha} + N_n^i \sigma_{nn}}. \tag{3}$$

The superscript i specifies the projectile or target identification of the particle. N_α^i and N_n^i are the numbers of α-like clusters and individual nucleons both assumed to be in the unperturbed part of the partner i of the reaction. This part of the system has never been disturbed by a N-N collision or a N-α collision, and it is in the model the only source of α-like clusters. σ_{nn} and $\sigma_{n\alpha}$ in Eq. (2) are the elastic scattering cross sections for the N-N collision and the N-α collision, respectively. It should be noted that, at the beam energies of interest here, $\sigma_{n\alpha} \simeq 4\sigma_{nn}$. And we also note that the total number of unperturbed nucleons (denoted as $N_{\rm sou}$), including both unperturbed individual nucleons and these involved in α-like clusters, satisfies the particle number conservation

$$N_{\rm sou} = N_n + 4N_\alpha. \tag{4}$$

These lead to the simplified form of P_α as

$$P_\alpha^i = \frac{4N_\alpha^i}{N_{\rm sou}^i}. \tag{5}$$

At the beginning of the temporal evolution, $t = 0$, it is assumed that the maximum even part of protons and an equal number of neutrons in each partner nucleus have coupled to form α-like clusters. Thus the initial particle numbers and the probability are as follows

$$\begin{aligned} N_\alpha^i &= \mathrm{int}(P_i/2), \\ N_n^i &= A_i - 4N_\alpha^i, \\ N_{\mathrm{sum}}^i &= A_i, \\ P_\alpha^i &= \frac{\mathrm{int}(P_i/2)}{A_i}, \end{aligned} \tag{6}$$

where A_i and P_i denote the mass number and the proton number of the partner nucleus. In the BUU simulation process of temporal evolution of the composite system, if a N-α collision with the participant α-like cluster from the partner nucleus i takes place in a time interval $t \sim t+\Delta t$, one has the following equations:

$$\begin{aligned} N_\alpha^i(t+\Delta t) &= N_\alpha^i(t) - 1, \\ N_n^i(t+\Delta t) &= N_n^i(t) + 3, \\ N_{\mathrm{sou}}^i(t+\Delta t) &= N_{\mathrm{sou}}^i(t) - 1. \end{aligned} \tag{7}$$

It means that after a cluster being decomposed, three nucleons from the dissolved α-like cluster are added to N_n^i, and only one is excluded out of the unperturbed part. Thus the cluster probability $P_\alpha(t+\Delta t)$ would become smaller than $P_\alpha(t)$. After all the unperturbed nuclear matter involved in the interaction region of the system have been exhausted, the probability for N-a collision becomes zero. Thereafter, the reaction goes on in the normal BUU procedure. Similarly, if a N-N collision takes place with one unperturbed nucleon from the partner nucleus i, we have

$$\begin{aligned} N_\alpha^i(t+\Delta t) &= N_\alpha^i(t), \\ N_n^i(t+\Delta t) &= N_n^i(t) - 1, \\ N_{\mathrm{sou}}^i(t+\Delta t) &= N_{\mathrm{sou}}^i(t) - 1. \end{aligned} \tag{8}$$

It is ready to verify that the total nucleon number is conserved throughout the reaction process.

A collision being N-α or N-N type in nature is determined by a Monte Carlo sampling according to the probability $P_\alpha(t)$. The reflected nucleon in a N-α type collision is assumed to be of isotropic distribution in the N-α c.m. frame. As for the momentum distribution of the assumed α-like clusters in a nucleus, it is assumed that all the α-like clusters, as bosons, coexist on the lowest energy level in the nuclear potential well. Thus these clusters have the same intrinsic energy

$$E_\alpha = \frac{(\pi h)^2}{2m_\alpha(R_i)^2} \tag{9}$$

where m_α denotes the mass of an α-like cluster $m_\alpha \cong 4m_n$, R_i is the width of the nuclear potential well $R_i = 1.124A_i^{1/3}$ fm. The direction of intrinsic motion of the α-like cluster is assumed to be isotropic.

By the above procedure, we obtain the new collision term with the cluster effect incorporated. At intermediate incident energies, in addition to two-body scatterings (N-N and N-α scatterings), the mean field, Pauli blockings as well as Fermi motion also compete to play a role in reaction dynamics. In the present model, a N-α collision or a N-N collision is allowed to occur only if the reflected nucleon states are not Pauli blocked, and the mean field effect is taken into account too. We deal with the mean field and Pauli blocking effects in the conventional BUU fashion [15,16], but based on the modified nucleon distribution in phase space by the cluster effect presented in the new collision term. The initial momentum distribution of nucleons in nuclei is another important ingredient of the present model for it was indicated to have a drastic effect on energetic particle productions [16]. Some pronounced discrepancies between experiments and BUU calculations were even attributed to the absence of the high-momentum tail in the initial distribution [8,14,16]. In the present model, the momenta of test particles are distributed by using the local Fermi relation and a Woods-Saxon well with the radius parameter $r_0 = 1.124$ fm and surface parameter $a_0 = 0.30$ fm. This procedure is similar with that used in Ref. [16].

III. RESULTS AND DISCUSSIONS

As application examples of the above model, we have calculated the hard photon productions in the reactions with the incident nuclei ^{86}Kr impinging on ^{12}C, $^{\mathrm{nat}}$Ag, and ^{197}Au targets, respectively, at the same beam energy $E/A = 44$ MeV. In the calculations, the numbers of test particles per nucleon for the systems with ^{197}Au, $^{\mathrm{nat}}$Ag, and ^{12}C as target are 80, 120, and 160, respectively. We calculate the photon production cross sections at a series of impact parameters, and then integrate over these parameters to obtain the total cross sections. As a couple of nucleons are scheduled, according to the BUU program, to collide, we first calculate the bremsstrahlung from the N-N collision as is done in the conventional BUU program, and then determine the nucleon momenta after this collision according to the procedure mentioned in the last section where the cluster effect is incorporated. The following classical n-p-γ cross section [15] is adopted in calculating the photon productions:

$$\frac{d^2\sigma}{dE_\gamma d\Omega_\gamma} = \sigma_{nn}\frac{\alpha}{4\pi^2}\frac{1}{E_\gamma}\beta^2(\sin^2\theta' + \tfrac{2}{3}), \tag{10}$$

where β is the initial velocity of the proton in the proton-neutron c.m. frame, α is the fine structure constant, and θ' denotes the scattering angle of the proton in the c.m. frame.

In Figs. 1–3, the calculated double differential energy spectra are compared with the experimental data. It can be seen that, by taking the cluster effect into account, remarkably enhanced emissions of photons have been achieved. At higher photon energies ($E_\gamma > 60$ MeV) the predicted slopes of the spectra with the conventional BUU program are too steep to reproduce the shape of the measured data, especially for backward emissions. The presence of the α-like cluster effect could increase the high-energy components of nucleon distribution and, therefore, increase the hard photon productions. These results lead to an improved agreement with the measured data. On the other hand, in the lower photon energy re-

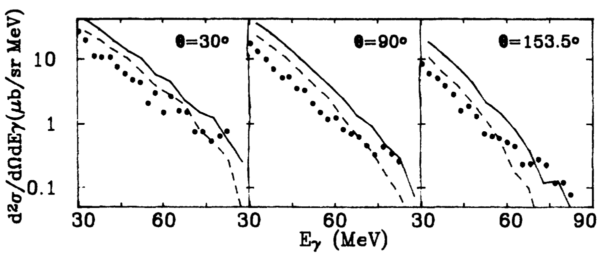

FIG. 1. The photon energy spectra from the reaction $^{86}Kr+^{197}Au$ (44 MeV/nucleon). The full and broken curves are the results of the BUU calculations with and without the α-like cluster effect, respectively. The solid circles represent the experimental data from Ref. [5].

gion, because the conventional BUU calculations without the cluster effect have been already in a good agreement with the measured data, the incorporation of the cluster effect further increases photon cross sections and seems to worsen the overall agreement. However, at higher beam energies, there exist experiments which were underestimated by the conventional BUU calculations over the whole photon energy region detected. The pronounced examples are the reactions $^{12}C+^{12}C$ (84 MeV/nucleon) and N+Zn (75 MeV/nucleon) [8,14,16]. It is expected that the incorporation of the cluster effect will lead to a better agreement in these cases. As for the total photon cross sections, to which the lower energy photons make a major contribution, the conventional BUU model overestimates the data by a factor of 60%, 7%, and 60% for the systems Kr+Au, Kr+Ag, and Kr+C, respectively. The presence of the cluster effect could further increase the results by the factors 57%, 44%, and 14%, respectively. As we know, this is a long-standing problem for BUU treatments [14–16].

In order to show the mechanism underlying the cluster-enhanced photon emissions, the angle-integrated energy spectrum from the system Kr+Au is presented in Fig. 4. The spectrum is divided into two portions: one originates from the primary N-N collisions (denoted as PC), the other comes from the subcascade N-N collisions (denoted as SC). It can be seen from the figure that nearly all the enhancement is attributed to the SC portion. This feature can be well understood, since the enhancement of high-momentum nucleons due to the cluster plus shuttle collision effects appears certainly after the primary col-

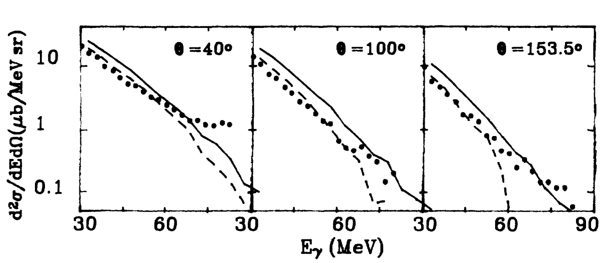

FIG. 2. The same as in Fig. 1, but for the reaction $^{86}Kr+^{nat}Ag$ (44 MeV/nucleon). The experimental data are taken from Ref. [5].

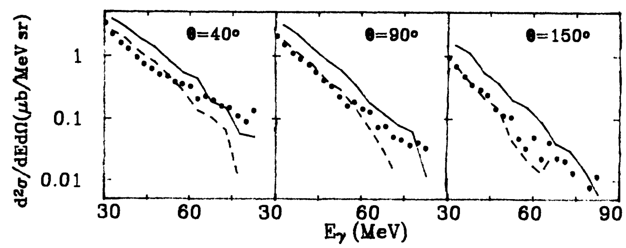

FIG. 3. The same as in Fig. 1, but for the reaction $^{86}Kr+^{12}C$ (44 MeV/nucleon). The experimental data are taken from Ref. [5].

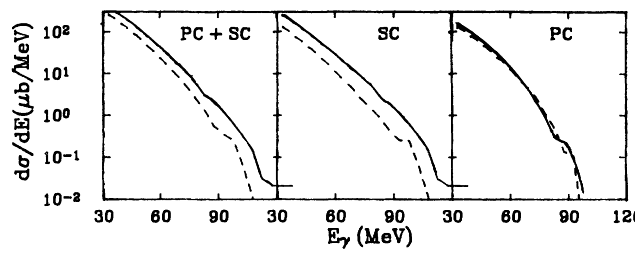

FIG. 4. The angle-integrated energy spectrum for the reaction $^{86}Kr+^{197}Au$ (44 MeV/nucleon). The full and broken curves are the results of the BUU calculations with and without taking the α-like cluster effect into account, respectively.

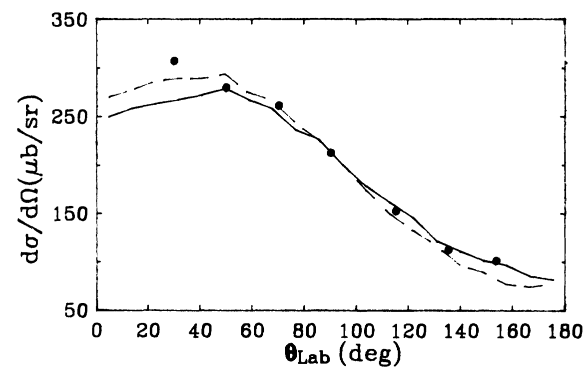

FIG. 5. The angular distribution of hard photons ($E_\gamma \geq 30$ MeV) from the reaction $^{86}Kr+^{197}Au$ (44 MeV/nucleon) in laboratory system. The full and broken curves are the results of the BUU calculations with and without taking the α-like cluster effect into account, respectively. The solid circles represent the experimental data from Ref. [5]. The calculated spectra are normalized to the experimental according to the cross section at $\theta_{\rm lab} = 90°$.

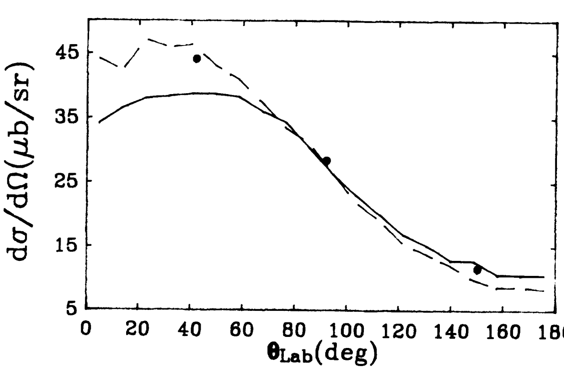

FIG. 6. The same as in Fig. 5, but for the reaction $^{86}Kr+^{12}C$ (44 MeV/nucleon). The experimental data are taken from Ref. [5].

lisions. Also, as an extension of the above analysis it is expected that this effect would become more pronounced for a heavy reaction system than for a light system. This is because the fraction contributed from SC to the photon production for the former case is larger.

In Figs. 5 and 6, the calculated angular distributions of hard photon emissions ($E_\gamma \geq 30$ MeV) from the systems Kr+Au and Kr+C are compared with the measured data. As can be seen that the calculations using the conventional BUU model have well reproduced the shapes of the data but with a little discrepancies at backward angles. The inclusion of the cluster effect could partly remove the discrepancies, but worsens the consistency of the forward peaks. These results may be understood by the following consideration [21]. The cluster plus shuttle collision mechanisms do increase the high-energy nucleon components, but, at the same time, shift the peak of the high-energy components to the backward angles due to the appearance of clusters in shuttle collisions.

IV. SUMMARY

In order to study the particle correlation effect in heavy-ion reactions at Fermi domain, we have modified the conventional BUU model to incorporate the α-like cluster effect in the collision term. In this model all the important quantal effects (mean field, Fermi motion, and Pauli blocking effects) are retained. This new model version has been used to study the particle dynamics and hard photon production in the reactions of ^{86}Kr on ^{12}C, $^{\mathrm{nat}}$Ag and ^{197}Au targets, respectively, at the beam energy $E/A = 44$ MeV. The results show that the incorporation of clusters in the cascade collision process, especially in the shuttle collision mechanism, could lead to enhancements of the higher momentum component in nucleon distribution, and, therefore, of the hard photon production. Those effects could improve the agreement between the predicted and measured data of the hard photon productions.

It is expected that the cluster plus shuttle collision mechanism might also affect the predictions on other subthreshold processes such as pion productions. In fact, it has long been noted that there exist pronounced discrepancies between the conventional BUU calculations and the measured data on those processes, which call for improvement [16]. A possible extension of the present model to study those problems is now in progress.

We also notice that the model presented in this article is still a rather simple one. There might exist other schemes to incorporate the particle correlations into the BUU frame. For example, one might define the cluster structure according to fluctuations in the local nucleon density. These proposals shed light on our future research projects.

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