Analysis of Photoreaction in the Delta Energy Region
by the Quantum Molecular Dynamics Approach

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Abstract

We study the photoreaction in the delta energy region using the QMD approach. The proton and pion cross-sections are calculated and compared with experimental data. Through this work we examine the multistep contributions in the cross-sections and the $\pi$-$\Delta$ dynamics.
I. INTRODUCTION

Δ properties in medium has been investigated both in experiments and in theories. J. Chiba et al. [1] suggested experimentally that the Δ mass becomes lower in nuclear medium than that in the free space. Horikawa et al. [2] gave that the depth of the Δ-potential is about 30 MeV in normal nuclei. On the other hand the recent total photoabsorption experiments [3] showed the broadening of the Δ peak but no shift of the peak-position. These works indicated that Δ properties are modified in nuclear medium, but this medium correction has not been understood definitely.

Experiments with photon in the Δ energy region are expected to have some advantages, compared with other experiments, to get information of Δ properties in medium. First the photon can directly produce Δ in the bulk region since the electromagnetic interaction is weak, while the proton- and pion-induced reactions produce it mainly in the surface region. Second the produced Δ does not have so large momentum because a value of momentum transfer is same as that of energy transfer for photoreaction. In the proton-induced reaction the momentum transfer is much larger than the energy transfer, so that the produced Δ must have a large momentum, and in-medium properties do not strongly affect observables.

The inclusive experimental data of photoabsorption is not sufficient to identify the elementary absorption process uniquely. We need to observe a outgoing nucleon and/or a pion to investigate in-medium Δ properties. In fact TAGX collaboration at INS [4,5] showed in experiments of photoreaction with the $^3,^4$He target that one must observe several outgoing particles coincidentally so as to identify the pure Δ channel. These particles, however, interact with other nucleons before they escape the nucleons and have lost information of the photoabsorption process at the beginning. Thus we have to analyze the multistep collisional processes after the photoabsorption.

Recently we developed a framework of QMD [6] plus statistical decay model (SDM) [7], and applied systematically this QMD + SDM to nucleon- (N-) induced reactions. It was shown [7] that this framework could reproduce quite well the measured double-differential
cross sections of \((N,xN')\) type reactions from 100 MeV to 3 GeV incident energies in a systematic way. In the subsequent papers [8,9], we gave detailed analysis of the pre-equilibrium \((p,xp')\) and \((p,xn)\) reactions in terms of the QMD in the energy region of 100 to 200 MeV. In these analysis, a single set of parameters was used, and no readjustment was attempted.

The reaction process after the initial photoabsorption is almost the same as the pre-equilibrium process of nucleon-induced reactions. It should then be natural to apply the QMD + SDM approach to the analysis of the electron scattering and photoreaction. Of course we have the other methods to calculate the multistep contributions such as the PICA code [10], a Monte-Carlo (MC) model [11] and BUU [12–14]. The PICA does not have a \(\Delta\)-degree of freedom explicitly, and it is not very useful to study the \(\pi-\Delta\) dynamics. The MC calculation is performed only in the momentum-space, and cannot describe the refraction from the mean-field. The BUU approach has succeeded to describe the particle production in the intermediate energy heavy-ion collisions. However this approach can describe only the one-body dynamics, and then it cannot distinguish single nucleons from clusters and cannot calculate coincident observables. Anyway none of these models can treat the nucleon-induced reactions, heavy-ion collisions and photoreactions (electron scattering) in the uniform way. The ability of the uniform description is one of the strongest advantages of the QMD approach.

We then carry out an analysis of photoreactions with the same formula and the same set of parameters as the previous works of the nucleon-induced reactions [7–9]. This enables us to check and improve further the elementary collisional processes included in the QMD approach from another point of view.

In this paper, we focus only on the photoreaction in the energy region above the \(\Delta\) threshold. In the next section, a brief explanation of the QMD plus SDM approach is given. The comparison of the calculation with the experimental data and discussions on the reaction mechanisms are given in section [11]. Summary of this work is given in section [14].
II. BRIEF EXPLANATION OF THE QUANTUM MOLECULAR DYNAMICS

A. Equation of motion

We start from representing each nucleon (denoted by a subscript \(i\)) by a Gaussian wave packet in both the coordinate and momentum spaces. The total wave function is assumed to be a direct product of these wave functions. Thus the one-body distribution function is obtained by the Wigner transformation of the wave function,

\[
f(r, p) = \sum_i f_i(r, p) = \sum_i 8 \cdot \exp \left[ -\frac{(r - R_i)^2}{2L} - \frac{2L(p - P_i)^2}{\hbar^2} \right]
\]

where \(L\) is a parameter representing the spatial spread of a wave packet, \(R_i\) and \(P_i\) corresponding to the centers of a wave packet in the coordinate and momentum spaces, respectively. The equation of motion of \(R_i\) and \(P_i\) is given, on the basis of the time-dependent variational principle, by the Newtonian equation:

\[
\dot{R}_i = \frac{\partial H}{\partial P_i}, \quad \dot{P}_i = -\frac{\partial H}{\partial R_i},
\]

and the stochastic N-N collision term \([7]\). We have adopted the Hamiltonian \(H\) consisting of the relativistic kinetic and mass energies and the Skyrme-type effective N-N interaction \([18]\) plus Coulomb and symmetry energy terms:

\[
H = \sum_i \sqrt{m_i^2 + p_i^2}
\]

\[
+ \frac{1}{2 \rho_0} \sum_i < \rho_i > + \frac{1}{1 + \tau} \rho_0 \sum_i < \rho_i >^\tau
\]

\[
+ \frac{1}{2} \sum_{i,j(\neq i)} \frac{e_i e_j}{|R_i - R_j|} \text{erf} \left( \frac{|R_i - R_j|}{\sqrt{4L}} \right)
\]

\[
+ \frac{C_s}{2 \rho_0} \sum_{i,j(\neq i)} c_i c_j \rho_{ij},
\]

where "erf" denotes the error function, the \(e_i\) is the charge of the \(i\)-th particle, and the \(c_i\) is 1 for proton, -1 for neutron and 0 for other particles. With the definition

\[
\rho_i(r) \equiv \int \frac{dp}{(2\pi \hbar)^3} f_i(r, p)
\]

\[
= (2\pi L)^{-3/2} \exp \left[ -\frac{(r - R_i)^2}{2L} \right].
\]
the other symbols in eq. (3) are given as:

\[ < \rho_i > \equiv \sum_{j \neq i} \rho_{ij} \equiv \sum_{j \neq i} \int d\mathbf{r} \rho_i(\mathbf{r}) \cdot \rho_j(\mathbf{r}) \]

\[ = \sum_{j \neq i} (4\pi L)^{-3/2} \exp \left[ -(\mathbf{R}_i - \mathbf{R}_j)^2 / 4L \right]. \] (5)

The symmetry energy coefficient \( C_s \) is taken to be 25 MeV. The four remaining parameters, the saturation density \( \rho_0 \), Skyrme parameters \( A, B \) and \( \tau \) are chosen to be 0.168 fm\(^{-3}\), \(-124 \) MeV, 70.5 MeV and 4/3, respectively. These values give the binding energy/nucleon of 16 MeV at the saturation density \( \rho_0 \) and the compressibility of 237.7 MeV (soft EOS) for nuclear matter limit. The only arbitrary parameter in QMD, i.e., the width parameter \( L \), is fixed to be 2 fm\(^2\) to give stable ground state of target nuclei in a wide mass range. These values and the details of the other description are just the same as those according to our previous paper [7].

As for the isobar resonances such as \( \Delta \) and \( N^* \), we use the same interactions as nucleons though the symmetry force does not work for them. At each collision process we satisfy the energy conservation by varying slightly an absolute value of relative momentum between colliding two particles.

### B. The initial state of the photoabsorption

The QMD calculation is started at the moment when the photon is absorbed by the target nucleus. As an initial state of the simulation, we have to assume the photoabsorption channels. For 200 - 400 MeV/c incident photon momenta, the one-pion production process is dominant in the photoabsorption. We introduce the following three channels for the photoabsorption, i.e.,

\[ \gamma + N \rightarrow \Delta, \quad (C1) \]
\[ \gamma + N \rightarrow N^*, \quad (C2) \]
\[ \gamma + N \rightarrow N + \pi. \quad (C3) \] (6)
The nuclear resonances $\Delta$ and $N^\ast(1440)$ in the above equations can decay into nucleon and pion according to the decay width and the isospin selection. In addition, the $N^\ast$ can also decay into $\Delta$ and $\pi$ as in our prescription \[1\], which means that the (C2) channel includes implicitly two-pion production process. The channel of the pure $\pi N$-pair production (C3) is adopted only for the charged pion and the isospin symmetry is assumed for the cross section, i.e., $\sigma(\gamma + p) = \sigma(\gamma + n)$.

The cross sections of the above three channels are determined to reproduce the experimental one-pion production data of $\gamma + p \rightarrow N + \pi$ \[15\]-\[16\]. The results are given in Fig. \[4\]. The upper part (a) of Fig. \[4\] denotes the cross-section of $\gamma + p \rightarrow p + \pi^0$ and the lower part (b) denotes that of $\gamma + p \rightarrow n + \pi^+$. The long dashed, dashed and thin solid lines indicate contributions of the $\Delta$ resonance (C1), $N^\ast(1440)$ (C2) and the pure $\pi N$-pair production (Born term) (C3), respectively. For the future discussion, we define the alternative channel (C4) that the all photon is absorbed through the pure $\pi N$-pair with the same amount of the cross-section as the sum of $C1 + C2 + C3$ channels.

In each event, a nucleon which absorbs the photon is selected randomly. The photoabsorption channel is also randomly chosen according to the rate of each cross section. We assume that the angular distribution of the pion emission is isotropic in the center of mass system of the pion and the nucleon.

C. Decomposition into step-wise contribution in multistep reactions

For the later discussion of the multistep reaction, we define here the step number $s$ which indicates the number of collisions responsible for emission of a particle in the QMD calculation as following. First we assign the step number zero to each nucleon in the target nucleus. After a nucleon absorbs the incident photon and becomes a resonance, we set the step number of the resonance to be one. For the case of the pure $\pi N$-pair creation, the step numbers of both $\pi$ and $N$ are one. The rule of the change of the step number for each nucleon is that, if two nucleons $i$ and $j$ having step numbers $s_i$ and $s_j$ make a collision, the
step numbers of both particles are modified to be \( s_i + s_j + 1 \). If a pion \( i \) and nucleon \( j \) becomes a resonance, the step number of the resonance is also \( s_i + s_j + 1 \). When a resonance \( i \) decays into a pion and a nucleon, on the other hand, both the step numbers of the pion and the nucleon are set to be \( s_i \); namely this process does not change the step number. We prohibit successive collisions with the same partner and the collisions between two nucleons with 0-step number. We attach n-step contribution to the \((\gamma, N)\) or \((\gamma, \pi)\) reactions when a nucleon or a pion emitted from the target nucleus has a step number \( n \).

D. Calculation of the Cross-Section

In the simulation, the double-differential cross-section of the emitted particle is calculated as

\[
\frac{d^2\sigma}{dE
d\Omega} = \frac{1}{N_{\text{event}}} \sum_i \sigma_T^\gamma(i)M(E, \Omega, i)
\]

where \( i \) indicates the event number, \( N_{\text{event}} \) is the total number of the events, \( \sigma_T^\gamma(i) \) shows the total photoabsorption cross-section in the \( i \)-th event, and \( M(E, \Omega, i) \) denotes the multiplicity of the particle under interest emitted in the unit energy-angular interval around \( E \) and \( \Omega \) for the \( i \)-th event.

Typically, 400000 events were generated to get a reasonable statistics in the step-wise double-differential cross-section. In the calculation, the parameters have been fixed to the same values as in Ref. [7] without any adjustment.

III. RESULTS AND DISCUSSION

In Fig. 2, we show our results of proton (left-hand-side) and \( \pi^0 \) (right-hand-side) double differential cross sections at \( \theta = 30^\circ, 60^\circ \) and \( 90^\circ \) from \( \gamma(375\text{MeV/c}) + \text{C} \) reaction. The experimental data at \( \theta = 30^\circ \) for proton, which are denoted by the full circles with error bars, are taken from Ref. [17]. In these figures, we decompose the total cross sections into the step-wise contributions. The total results of the QMD+SDM simulation are shown by the
thick lines. In the same figures, we draw the individual contributions from the 1-step process (long-dashed lines), 2-step (dashed lines), 3-step (thin lines) and SDM process (dotted lines), respectively. The contribution from SDM process is shown only for proton.

First we look at the contribution from the 1-step process. The peak of the 1-step process, which is usually called quasi-free (QF) peak, is clearly separated from the multistep contribution in the forward angle ($\theta = 30^\circ$), while it overlaps to other contributions at larger angles, particularly for proton.

For the more detailed analysis of the step-wise contributions, we plot again the the results of the proton cross-section at $\theta = 30^\circ$ from $\gamma(375 MeV/c) + C$ reactions in Fig. 3. The upper column (Fig. 3a) is just the same as that in Fig. 2.

We can see in this figure that the position of the calculated QF peak almost coincides with the experimental peak position, though the absolute value of this peak overestimates the data. This peak comes mainly from the 1-step process, namely from the elementary process of $\gamma + N \rightarrow \pi + N$.

There are two other peaks in our results. The peak in the lower momentum region shows the contribution of SDM, the evaporation from the residual excited nuclei. The higher momentum peak, on the other hand, mainly comes from 2-step process. There is a dip region between this peak and the QF peak, which are not observed experimentally.

In order to understand the meaning of the higher momentum peak, we also decompose contributions to the proton cross-section of the events with zero pion and with one pion at the final state in Fig. 3b. This figure clearly shows that the cross-section around the higher momentum peak comes only from the zero pion events. From this analysis we can easily know that the cross-section around the higher peak comes from the following 2-step process:

$$\gamma + N \rightarrow \Delta,$$

$$\Delta + N \rightarrow N + N.$$  \hfill (8)

This 2-step process is effectively equivalent to the two-nucleons (2N) photoabsorption process.
In Fig. 3, we give also the result (chain-dotted line) of QMD calculation including only the pure $\pi N$ pair as the initial channel (C4 channel mentioned before). It is seen that this result does not show the higher peak of $2N$ photoabsorption any more. Hombach et al. have commented in Ref. [12] that these two channels do not make large difference in $\pi$-productions. At least proton spectra, however, there is important difference between the two initial channels.

In Fig. 4, we show the results of proton energy-spectrum from the photoreaction at the photon-momentum $q = 390\,\text{MeV}/c$ with the target $^{12}\text{C}$ (Fig. 4 (a)) and $^{48}\text{Ti}$ (Fig. 4 (b)). We draw the full results of the QMD+SDM simulation and the individual contributions from the 1-, 2- and 3- step processes as in the previous figures. The experimental data are taken from Ref. [21]. In order to compare each contribution in detail, we plot the results with the logarithmic scale. In this reaction the 1-step and 2-step processes make almost same contributions to the cross section at low proton energy, and the QF peak cannot be seen clearly. Our QMD+SDM results underestimate experimental data around the QF peak and also $2N$-photoabsorption energy regions. The same behavior was seen in the results of PICA for this reaction [21].

In the above two comparisons with the experimental data, it is seen that around the QF peak energy region our calculations overestimate the experimental data at $\theta = 30^\circ$ in Fig. 3, but underestimate at $\theta = 52^\circ$ in Fig. 4. It has been already known from the analysis of the proton-induced reaction [6–9] that the QF contribution strongly depends on the detailed of the elementary process. In this energy region, $q \approx 380\,\text{MeV}/c$, the angular distribution of emitted pion has a sideward peak in the CM system of the $\pi N$-pair [13]. We have not fit the angular distribution of the pion photoproduction cross-section to this experimental data in the elementary process, and this might be the reason for the disagreement near the QF peak.

For the higher momentum region, on the other hand, our results seem to agree with the data and imply that the multistep process, mainly the 2-step process, can explain the data for the photon energy above the pion threshold.
Next we explore the origin of the dip region between the above two momentum region. The experimental analysis [5] with $^3\text{He}$ target indicated that the three-nucleons ($3N$) photoabsorption process also contributes to the final results. The $3N$-photoabsorption process must contribute the proton spectrum around this dip momentum region. We then check the $3N$-photoabsorption process for this experiment.

Of course the semi-classical approach cannot well describe the structure of so small nuclei such as $^3\text{He}$. However a cross-section of each step contribution is almost determined by the geometrical position of nucleon. The interaction range of the two-body collisions is about 1 - 2 fm while the root-mean square radius of $^3\text{He}$ is about 1.8fm. Hence there is no serious trouble to make a rough estimation with the QMD approach.

In Fig. 5 we give a cross-section of two-protons emission from the photoabsorption by $^3\text{He}$ as a function of the undetected neutron momentum. Experimental data is taken from Ref. [5]. In order to separate contributions of the two-protons ($2N(pp)$)-photoabsorption process experimentally [5], they chose the events without pions at the final state and by an experimental trigger that $p \geq 300\text{MeV}/c$ and $\theta = 15^\circ - 165^\circ$ for the two emitted protons. This experimental condition selects the process in which at least two protons are concerned with the photoabsorption. The calculation also follows this condition. In this figure the absolute value is arbitrarily because the normalization of the experimental data has not been determined.

We again decompose the total yield to 0-step (dotted line) and higher step contributions (dashed line) by the step-number of the undetected neutron. In this case, the 0-step process (dotted line) means that the photon is absorbed by the two protons, and that the neutron is a spectator. In the other case of the multistep contributions above 1-step, three nucleons are all related with the photoabsorption process. Though we only treat the sequential binary process, this multistep process is effectively regarded as the $3N$-photoabsorption process, while the 0-step process is the $2N(pp)$-photoabsorption process. In Ref. [5], they also decompose the total yield to the two contributions, one from the spectator neutron for $2N(pp)$ photoabsorption and the other from the emitted neutron for the $3N$-photoabsorption process.
processes. We also plot their decomposition of the $2N(pp)$ process (thin dashed line) and the $3N$ process (long dashed line) in the same figure.

The 0-step contribution appears in the low momentum region as a narrow peak. The peak position of the 0-step process ($2N(pp)$-photoabsorption) is lower than that from the experimental analysis. This peak is sensitive to the momentum distribution of the neutron in the $^3$He, since the neutron is a spectator. The semi-classical approach cannot describe correctly the momentum distribution of nucleons particularly the high momentum component in small nuclei such as $^3$He. This is the reason of this discrepancy.

As for the $3N$-photoabsorption process, we can see that the second peak is much lower than the first peak in our calculation, which disagrees with the experimental result. Namely our simulation does not make so large $3N$-photoabsorption process. The $3N$-photoabsorption process should contribute the cross-section between the QF and the $2N$-photoabsorption processes. The shortage of the $3N$-photoabsorption is the origin of the dip between the QF contribution and the $2N(pp)$ contribution, seen in Fig. 2.

Since both the $2N$- and $3N$-photoabsorption processes make no pion events at the final state, the $\pi$-absorption must play an important role in these absorption processes. Then we can get some information on a reason of the dip by studying the pion photoproduction. In Fig. 6 we show the results of the integrated cross-sections for neutral pion photoproduction in the $^{12}$C, $^{27}$Al and $^{63}$Cu targets, and compare them with the experimental data [22]. The results of full QMD are denoted by the solid lines, while the long-dashed lines indicate the result without $\pi$-absorption. The calculated total cross-sections overestimate the data at the peak energy of the $\Delta$ resonance and decrease faster at lower and higher energies. This behavior is also seen in other calculations [11,12,22]. The overestimate of the calculation becomes larger with increasing mass number $A$.

These results show that the $\pi$-absorption is too small in our approach. In order to examine the effects of the $\pi$-absorption, we make another test calculations by using a fixed pion mean-free path for the $\pi$-absorption process. The pion mean-free path $\lambda$ is estimated to be 5 fm [14]. From the mean-free path we estimate the $\pi$-absorption and the photoproduction
cross-section in the following way.

We factorize the absorption rate \( \exp\left(- \frac{< l >}{\lambda}\right) \) to the results without the \( \pi \)-absorption, where \( < l > \) is a mean distance of pion propagating in nuclear medium. Assuming hard sphere with a radius \( R \) for nucleus, we can estimate \( < l > \) as

\[
< l > = \frac{\int_\Omega dr_1 \int_S dr_2 |r_1 - r_2|}{\int_\Omega dr_1 \int_S dr_2} = \frac{6}{5} R, \tag{9}
\]

where \( \Omega \) and \( S \) indicate the volume and surface integrals in the hard sphere with radius \( R \), respectively. Here the pion is considered to be produced randomly at the position inside the target nucleus, and the \( \Delta \) is not directly taken into account in this estimation.

The results of this test calculation is shown by the dashed lines. They nicely reproduce the experimental result around the \( \Delta \) peak, though it is slightly lower at lower and higher energies. We then need another \( \pi \)-absorption process. It may be a pure \( 2N \pi \)-absorption process which is not taken into account in our approach. This pure \( 2N \pi \)-absorption process is given by the detailed valance of the s-wave pion production. The production rate of this s-wave process is small, but the absorption rate of the \( 2N \) process is not so small \[23\]. This fact suggests us one of the answers of the too small \( 3N \)-photoabsorption process in Fig. 5. If the pion is absorbed by two nucleons, as a result, three nucleons share the photon energy. This is an additional \( 3N \)-photoabsorption process.

However it is not so easy to introduce the pure \( 2N \pi \)-absorption in the actual simulation. We have to treat three body collisions, which is not impossible but difficult in the actual simulation.

Engel et al. \[23\] suggested an easy method of the effective treatment of the \( 2N \pi \)-absorption process by factorizing a density-dependent factor to the cross-section of \( N + \Delta \rightarrow N + N \); later Hombach et al. \[12\] also used the same method in the photoreaction. Here we test this approximate method. In order to estimate this effect in a rough way, we increase this cross section by four times; we call this test simulation “QMD/T1”. We then calculate the total \( \pi^0 \) production cross-sections at the photon momentum \( q = 375 \text{MeV}/c \) as a function of the target mass. The results are shown in Fig. 8. The solid, dashed and broken lines
indicate the results of QMD, QMD/T1, and no absorption, respectively. The full square show experimental data taken from [22]. The QMD/T1 slightly improves the result but still overestimates experimental data.

Furthermore we calculate again the proton and pion momentum-spectra for \(\gamma(375\text{MeV}/c) + C\) reactions in Fig. 4 with QMD/T1. The results are given in Fig. 8 by dashed lines. The QMD/T1 slightly reduces the \(\pi^0\) cross-section overall, and enhances the proton cross-section around 2\(N\)-absorption energy region. However the dip between the QF peak and the 2\(N\)-absorption peak exist in the QMD/T1 calculations. The enlarged \(\sigma_{\Delta N \rightarrow NN}\) mainly enhances the \(\Delta\) absorption process at the second step which contributes the 2\(N\)-photoabsorption part, but it does not contribute higher multisteps such as the 3\(N\)-photoabsorption part.

When a pion propagates in a nucleus, it stays at a pure \(\pi\) state much longer than a \(\Delta\) state because the \(\Delta\) life-time is very short. Then the enlarged \(\sigma_{\Delta N \rightarrow NN}\) does not largely change the \(\pi\)-absorption. One may have an idea that we can increase the \(\pi\)-absorption by enlarging the cross-section of \(\pi N \rightarrow \Delta\) as well as that of \(\Delta N \rightarrow NN\). This approximate method must increase the pion-absorption, but it cannot solve the problem that the enlarged \(\sigma_{\Delta N \rightarrow NN}\) still overestimates the proton cross-section in the 2\(N\)-photoabsorption energy region. Hence the enlargement of \(\sigma_{\Delta N \rightarrow NN}\) and \(\sigma_{\pi N \rightarrow \Delta}\) together cannot explain the experimental results of the proton emission and the pion production at the same time. Thus we need an additional absorption process without a \(\Delta\) state, i.e. the pure 2\(N\)-absorption of pion.

Finally we examine effects of the \(\Delta\)-potential to observables because the photoreactions in the \(\Delta\) energy region are studied for the purpose of the determination of \(\Delta\) properties in nuclear medium. Along this line we calculate positive pion spectra with and without the \(\Delta\)-potential in the \(\gamma(213\text{MeV}/c) + ^{40}\text{Ca}\) reaction. In Fig. 9 we show our results at \(\theta_\pi = 81^\circ, 109^\circ\) and \(141^\circ\); the solid and dashed lines indicate the results with the \(\Delta\)-potential same as nucleon one and those with no \(\Delta\)-potential, respectively. Experimental data are taken from Ref. [23].

From this figure, we see that our results of the pion cross sections are not so largely
different from experimental data though the peak position is slightly shifted to higher energy at $\theta_\pi = 81^\circ$ and $109^\circ$ when the $\Delta$-potential is switched off. In the case of no $\Delta$-potential the QF peaks are further shifted to higher energy, but this difference is not significant; the $\Delta$-potential does not strongly affect the pion spectrum. This result suggests that it is difficult to know in-medium $\Delta$ properties from only simply observing such as a pion spectrum. We should investigate more complicated coincident observables.

IV. SUMMARY

In this paper we have calculated the emitted proton and produced pion cross-sections in the photoreaction within the framework of the QMD approach, and compared them with experimental data. We focus on the examination of applying the QMD approach to the photoreaction, and use rather rough initial photoabsorption in the present analysis. Through this work, however, we can analyze the multistep contribution and check the $\pi$-$\Delta$ dynamics.

As for the proton spectrum, the multistep contributions are not negligibly small even in the forward direction where the contribution from the QF process is dominate. As increasing the emission angle, the multistep contribution becomes larger, and overlaps with the QF contribution. It is found that the high momentum parts in the proton spectrum comes mainly from by the 2-step process without pion, which is effectively identical to the $2N$-photoabsorption process. Thus it is very important to take account of the multistep contribution when comparing a theoretical result with experimental data.

We have examined how the $\Delta$-potential affects the pion spectrum. We cannot find any significant difference between two kinds of results of the inclusive pion spectra with and without the $\Delta$-potential.

The cross-section around QF peak of proton are overestimated at $\theta_p = 30^\circ$ and underestimated at $\theta_p = 52^\circ$. The discrepancy of the cross-section around the QF-peak may be improved by using the realistic angular distribution of $\pi$-production at the initial channels.
In order to include it, we have to introduce the anisotropic decay of \( \Delta \). It is, however, not easy because the spin degree is not involved in our semi-classical approach. We then need to consider a technical extension of our approach such as the p-wave decay of \( \Delta \) given by Engel et al. \[23\].

Furthermore we have the other problems: too large pion-photoproduction and a dip between the QF-peak and the \( 2N \)-absorption peak, which is not observed in the experimental data. These two problems are supposed to be caused by the same reason, i.e. lack of the pure \( 2N \) \( \pi \)-absorption process which does not involve the intermediate \( \Delta \). It is shown that the artificial enhancement of the \( N\Delta \rightarrow NN \) cross-section (QMD/T1 calculation) does not give sufficient absorption of pion. \( ? \) From both results of the proton emission and the pion production, thus, we can conclude that one should treat directly the pure \( 2N \) \( \pi \)-absorption process, i.e. three body collisional process, in the dynamical simulation.

In future we will improve our approach by introducing the pure \( 2N \)-absorption process of pions and more realistic elementary photoabsorption processes of the pion production \[24\] and the quasideutron processes \[26\]. By such improved model, we would like to investigate the proton- and pion-induced reactions as well as the photoreactions simultaneously. Such works will give useful information to extend a simulation for investigation of general reactions.

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FIGURES

FIG. 1. The cross-section of $\gamma + p \rightarrow p + \pi^0$ (a) and $\gamma + p \rightarrow n + \pi^+$ (b) processes. The long dashed, dashed and thin solid lines indicate contributions of the $\Delta$ resonance, $N^*(1440)$ and the Born terms. Experimental data are taken from Refs. [15,16].

FIG. 2. Proton and $\pi^0$ cross-sections at laboratory angle $\theta = 30^\circ$, 60$^\circ$ and 90$^\circ$ for 375 MeV photon + $^{12}$C reactions. The left columns show the proton spectra, and the right ones show the $\pi^0$ spectra. The total (thick solid line), 1-step (dashed line), 2-step (broken line) and 3-step (thin solid line) QMD cross-sections are compared with experimental data [17].

FIG. 3. Proton momentum-spectrum at laboratory angle $\theta = 30^\circ$ for 375 MeV photon + $^{12}$C reaction. The upper figure is the same as the first figure in Fig. 2. In the lower figure the dashed and broken lines indicate contributions from events with zero and one pion at final state. The chain-dotted line shows the total result with all Born initial states.

FIG. 4. Proton energy-spectrum at laboratory angle $\theta = 51^\circ$ for 390 MeV/c photon + $^{12}$C and $^{48}$Ti reactions. Experimental data are taken from Refs. [21].

FIG. 5. Neutron momentum distribution for 280 MeV/c photon + $^3$He reactions. The condition is given in the text. The thick solid line shows the total QMD results, and the dotted and dashed lines denote contributions from 0-step and higher steps, respectively. The experimental data are taken from Ref. [5]. The thin dashed and broken lines indicate $2N(pp)$ and $3N$ processes, respectively, which are given from experimental analysis [5].

FIG. 6. Total $\pi^0$ cross-sections of the targets $^{12}$C, $^{27}$Al and $^{63}$Cu. QMD cross-sections are compared with experimental data [22].

FIG. 7. Target mass-number dependence of the total $\pi^0$ cross-sections at $q = 375$MeV/c. The solid, dashed and broken lines indicate the results of QMD, QMD/T1, and no absorption. The full square show experimental data taken from Ref. [22].
FIG. 8. Proton and $\pi^0$ cross-sections at laboratory angle $\theta = 30^\circ$, 60$^\circ$ and 90$^\circ$ for 375 MeV/c photon + $^{12}$C reactions. The left columns show the proton spectra, and the right ones show the $\pi^0$ spectra. The solid and dashed lines indicate the results by QMD and QMD/T1, respectively.

FIG. 9. $\pi^+$ cross-sections at laboratory angle $\theta = 81^\circ$, 109$^\circ$ and 141$^\circ$ for 213 MeV/c photon + $^{40}$Ca reactions. The solid line shows the QMD results with the $\Delta$ mean-field same as that of nucleons. The dashed line shows the results with the no $\Delta$ mean-field. The experimental data are taken from Ref. [25].
\[ \frac{d^2 \sigma}{dpd\Omega} \text{ (mb/sr/MeV/c)} \]

\( \theta = 30^\circ \)

(a) QMD+SDM
- thick line
- 1-step
- 2-step
- 3-step
- SDM
- EXP

(b) \(N_r=0\)
- thick line
- \(N_r=1\)
- QMD-C4

\[ P \text{ (MeV/c)} \]
\[ q = 390 \text{ MeV/c} \]
\[ \theta = 52^\circ \]

\[ d^2\sigma/dE_d\Omega (\mu b/sr/MeV/c) \]

\( \text{(a)} \)

\[ d^2\sigma/dE_d\Omega (\mu b/sr/MeV/c) \]

\( \text{(b)} \)

- QMD+SDM
- 1-step
- 2-step
- 3-step
- EXP

\[ E_p (\text{MeV}) \]
\[ \frac{d^2\sigma}{d\Omega dT_\pi} (\mu b/\text{MeV/sr}) \]