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Quasideuteron mechanism and the photodisintegration of ^{4}He at intermediate energies*

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The ^{4}He$(\gamma, p)^3$H and ^{4}He$(\gamma, n)^3$He reactions from $E_\gamma \gtrsim 60$ MeV to $E_\gamma \lesssim 170$ MeV are considered, along with the ^{4}He(γ, pnd) reaction from threshold up to intermediate energies. The absorption of photons in the intermediate energy range up to pion threshold is expected to occur predominantly via the quasideuteron mechanism as is indicated from the reaction ^{4}He(γ, pnd). For the (γ, pnd) amplitude, the breakup of ^{4}He into a deuteron and quasideuteron is calculated using a ^{4}He Gaussian ground-state wave function fitted to the form factor, a quasideuteron S-wave scattered state, and a deuteron effective range wave function. The photobreakup of the quasideuteron can be expressed in terms of the amplitude for the photobreakup of the deuteron as shown by Levinger. The photoamplitude for the (γ, pnd) reaction is used to obtain the photoamplitude for the (γ, n) and (γ, p) reactions. The contribution to the (γ,p) and (γ, n) reactions from the quasideuteron mechanism is calculated as a rescattering of a nucleon-deuteron pair to form a triton. For both nucleon-triton reactions, this yields angular distributions with forward peaking in agreement with the forward asymmetry obtained experimentally. The cross section at intermediate energy appears to be dominated by the quasideuteron effect. Finally, the alternative quasideuteron calculation using nucleon-nucleon short-range correlations is shown to be equivalent to the present quasideuteron calculation.

[NUCLEAR REACTIONS ^{4}He(γ, pnd), ^{4}He(γ,p), ^{4}He(γ,n); calculated $\sigma(E_\gamma)$, $d\sigma/d\Omega_N$ (E_γ=60–170 MeV), quasideuteron mechanism.]

I. INTRODUCTION

The photon-nucleon interaction can be used as a probe in the study of nuclear structure. Furthermore, photodisintegration of light nuclei provides a means for studying the relative importance of various reaction mechanisms involved in the photonuclear process. For photodisintegration at low energies ($E_\gamma < 50$ MeV), the photon can interact with an individual nucleon in the nucleus emitting it directly. Alternatively, the photon can be absorbed by the entire nucleus exciting the nucleus into a metastable state, which subsequently decays into one of the available particle channels. At higher energies, the electromagnetic interaction can probe deeper into the nuclear structure. As discussed by Levinger,[1] at higher energies ($E_\gamma > 75$ MeV) the photon can be absorbed by an n-p pair or quasideuteron. At even higher energies ($E_\gamma > 150$ MeV) other reaction mechanisms such as pion production, photopion reabsorption, and pion-nucleon resonances can dominate the photodisintegration process. In this discussion, we will limit ourselves to the intermediate energy range and discuss primarily the quasideuteron mechanism.

In the quasideuteron mechanism developed by Levinger[1] (see also Ref. 2) for nuclear photodisintegration, an n-p pair in the nucleus absorbs the photon much like the photodisintegration of the deuteron. Since the photodisintegration reaction is predominantly $E1$ as it is for the deuteron, n-n and p-p pairs do not contribute (they have no $E1$ moments). The probability for emission of an n-p pair via the quasideuteron process is then essentially equal to the product of the probability for finding a quasideuteron pair in the ground state of the target nucleus times the cross section for photodisintegration of the quasideuteron. To a first approximation, the quasideuteron model predicts that the angular distribution and photodisintegration cross section for photoprotons or photoneutrons will be the same as that obtained from the deuteron photodisintegration.

Since Levinger's development of the quasideuteron model, much work has been done on photonuclear reactions, experimentally supporting the validity of the quasideuteron model, and theoretically developing the model as a tool to calculate photodisintegration cross sections.[3] Reactions of the type $A(\gamma, np)A-2$ for nuclei ^{16}O, ^{14}N, and ^{12}C have been considered via the quasideuteron mechanism by the introduction of a two-body correlation function $f(r_{ij})$. In these calculations, a pure shell-model wave function is modified to obtain the state of the n-p pair in the target nucleus (Jastrow model[4]), e.g.,

$$\phi_{\text{Jastrow}} = \phi_{\text{IPM}} \prod_{i<j}^{A} f(r_{ij}),$$

where IPM is the independent particle model. By judiciously choosing the shape and parameters of the correlation function, the general features for the photodisintegration cross section for these reactions as well as for the (γ, N) reactions on

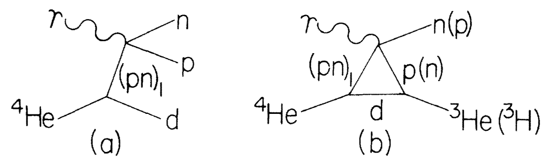

FIG. 1. Diagrammatical representation of the photodisintegration of ^{4}He into (a) pnd and (b) n^3He(p^3H) via the quasideuteron mechanism.

^{16}O, ^{6}Li, and ^{12}C can be reproduced.[3,5]

Early attempts to apply the quasideuteron mechanism to the photodisintegration of ^{4}He met with limited success.[6] Recently, in our preliminary report,[7] we indicated the ability of the quasideuteron mechanism to explain the general features of the ^{4}He (γ, pnd) reaction as well as the ^{4}He$(\gamma,N)T$ reactions above 60 MeV (the ^{4}He$(\gamma,N)T$ reactions below 60 MeV have been considered by other authors[8-11]). (The symbol T stands for either ^{3}H or ^{3}He depending on whether N is a proton or a neutron.) Gari and Hebach[12] have also proposed a quasideuteron type of scheme for calculating photonuclear reactions at intermediate energies. They account for nucleon-nucleon (N-N) interactions by means of mesonic exchanges. They apply their scheme to ^{4}He $(\gamma, N)T$ reactions using the usual shell-model wave functions. The parameters in their calculations can be chosen such that the general features of the ^{4}He$(\gamma, N)T$ reactions for $50 \leq E_\gamma \leq 140$ MeV are reproduced. The calculations presented here differ from Gari and Hebach's and other short-range-correlation (SRC) calculations (see Appendix II) in that we place the emphasis on scattering amplitudes and not on wave functions. By using reaction amplitudes, we have a more direct means of inputting information obtained from other nuclear reactions. Also, the ambiguity of choosing the correlation function and correlation parameter is eliminated.

We present the outline of our quasideuteron calculation in Sec. II. In Sec. III we discuss the results and the comparison with the results of Gari and Hebach. Section IV summarized our results. In Appendix II we show the connection between the present calculation and the usual Jastrow model calculation which considers N-N interaction via short-range correlations.

II. METHOD OF CALCULATION

In order to calculate the amplitudes for the ^{4}He(γ, N) reactions, we consider first the amplitude for the ^{4}He(γ, pnd) reaction. The reaction ^{4}He(γ, pnd) proceeding via the quasideuteron mechanism is represented in Fig. 1(a). The amplitude associated with this diagram is

$$\langle pnd|\mathcal{H}_\gamma|^4\text{He}\rangle = \sum_{(pn)_1} \langle pn|\mathcal{H}_\gamma|(pn)_1\rangle \times \left[\frac{1}{E_{(pn)_1} - \hbar^2 p_{(pn)_1}{}^2/2\mu_{(pn)_1}}\right] \times \langle (pn)_1 d|V|^4\text{He}\rangle, \tag{1}$$

where $\langle (pn)_1 d|V|^4\text{He}\rangle$ is the $(pn)_1 d$-^{4}He vertex function and $\langle pn|\mathcal{H}_\gamma|(pn)_1\rangle$ is the quasideuteron photodisintegration amplitude. This expression can be simplified by combining the propagator and vertex function. It follows from Schrödinger's equation that

$$\frac{\langle (pn)_1|V|^4\text{He}\rangle}{E_{(pn)_1} - \hbar^2 p_{(pn)_1}/2\mu_{(pn)_1}} = \langle (pn)_1 d|^4\text{He}\rangle \tag{2}$$

(see for example Ref. 13), so that

$$\langle pnd|\mathcal{H}_\gamma|^4\text{He}\rangle = \sum_{(pn)_1} \langle pn|\mathcal{H}_\gamma|(pn)_1\rangle\langle (pn)_1 d|^4\text{He}\rangle. \tag{3}$$

$\langle (pn)_1 d|^4\text{He}\rangle$ is the amplitude for the (virtual) breakup of ^{4}He into a deuteron and a quasideuteron $[(pn_1)]$. The summation sign stands for integration over nucleon momenta and summation over nucleon spins.

Because the quasideuteron photodisintegration amplitude $\langle pn|\mathcal{H}_\gamma|(pn)_1\rangle$ appears explicitly in Eqs. (1) and (3), we return to Levinger's original development of the quasideuteron model[1] and use

$$\langle pn|\mathcal{H}_\gamma|(pn)_1\rangle = \langle pn|\mathcal{H}_\gamma|d\rangle f(q)/N_d. \tag{4}$$

The quasideuteron amplitude is now expressed in terms of the deuteron photodisintegration amplitude. $f(q)$ is the S-wave triplet n-p scattering amplitude with q the $(pn)_1$ pair relative momentum, and N_d is the normalization constant for the deuteron wave function in the effective range theory. This gives as a final amplitude for the ^{4}He(γ, pnd) reaction via the quasideuteron mechanism

$$\langle pnd|\mathcal{H}_\gamma|^4\text{He}\rangle = \sum_{(pn)_1} [f(q)/N_d]\langle pn|\mathcal{H}_\gamma|d\rangle \times \langle (pn)_1 d|^4\text{He}\rangle. \tag{5}$$

The ^{4}He$(\gamma, N)T$ reaction via the quasideuteron mechanism is diagrammatically represented in Fig. 1(b). The amplitude associated with this diagram can be written as

$$\begin{aligned}\langle NT|\mathcal{H}_\gamma|^4\text{He}\rangle &= \sum_{N'd,(pn)_1} \langle T|V'|N'd\rangle\left(\frac{1}{E_{N'd} - \hbar^2 p_{N'd}{}^2/2\mu_{N'd}}\right)\langle pn|\mathcal{H}_\gamma|(pn)_1\rangle \frac{1}{E_{(pn)_1} - \hbar^2 p_{(pn)_1}{}^2/2\mu_{(pn)_1}}\langle (pn)_1 d|V|^4\text{He}\rangle \\ &= \sum_{N'd}\langle T|V'|N'd\rangle \frac{1}{E_{N'd} - \hbar^2 p_{N'd}{}^2/2\mu_{N'd}}\langle pnd|\mathcal{H}_\gamma|^4\text{He}\rangle.\end{aligned} \tag{6}$$

The $N'd$ summation represents integration over N' and d momenta and summation over their spins. We notice here that the $^4\text{He}(\gamma, pnd)$ amplitude is contained in the $^4\text{He}(\gamma, N)T$ amplitude for the quasideuteron mechanism. Again, it follows from the Schrödinger equation that

$$\frac{\langle T|V'|N'd\rangle}{E_{N'd}-\hbar^2 p_{N'd}{}^2/2\mu_{N'd}}=\langle T|N'd\rangle. \tag{7}$$

Hence the amplitude for the $^4\text{He}(\gamma, N)T$ reaction can be simplified to yield

$$\langle p^3\text{H}|\mathcal{H}_\gamma|^4\text{He}\rangle=\sum_{nd}\langle^3\text{H}|nd\rangle\langle pnd|\mathcal{H}_\gamma|^4\text{He}\rangle,$$
$$\langle n^3\text{He}|\mathcal{H}_\gamma|^4\text{He}\rangle=\sum_{pd}\langle^3\text{He}|pd\rangle\langle pnd|\mathcal{H}_\gamma|^4\text{He}\rangle. \tag{8}$$

Equations (5) and (8) are the amplitudes used to calculate the respective photodisintegration cross sections via the quasideuteron model.

III. RESULTS AND DISCUSSION

Gorbunov[14] investigated the $^4\text{He}(\gamma, p)^3\text{H}$ and $^4\text{He}(\gamma, n)^3\text{He}$ reactions, making note of the angular distribution of the protons and neutrons for the respective reactions. The photodisintegration cross sections of Gorbunov and most of the other experimental $^4\text{He}(\gamma, N)$ results are in good agreement.[8] (A notable exception is the earlier experiments of Berman and collaborators.[15]) A feature of Gorbunov's data is $\sigma(\gamma, n)\approx\sigma(\gamma, p)$, which is expected from simple $E1$ dominance (assuming charge independence of the N-N interaction). Another feature of the $^4\text{He}(\gamma, N)$ data is the interesting behavior of the asymmetry coefficient β. The asymmetry coefficient β is defined in the earlier work by Gorbunov and Spiridonov[16] and appears explicitly in their expansion for the differential cross section

$$\frac{d\sigma}{d\Omega}=A(\sin^2\theta+\beta\sin^2\theta\cos\theta+\gamma\sin^2\theta\cos^2\theta+\cdots). \tag{9}$$

Above 35 MeV, both (γ, N) reactions exhibit a forward asymmetry. However, electric dipole ($E1$) and electric quadrupole ($E2$) contributions in the long wavelength limit gives $\beta(\gamma, n)=-\frac{1}{5}\beta(\gamma, p)$ (see Appendix I).

By considering the resonance states of ^{4}He, Crone and Werntz[10] accounted for the general behavior and magnitude of $\sigma(\gamma, N)$, and Malcolm and collaborators[11] explained the asymmetry behavior below 60 MeV as a direct consequence of a $J^P=2^+$, $T=0$, ^{4}He resonance state. However, at higher energies away from the resonance, these resonance effects are expected to become negligible.

In order to determine the $^4\text{He}(\gamma, N)^3\text{H}$ photodisintegration cross section due to the quasideuteron mechanism, we first calculated the quasideuteron contribution to the $^4\text{He}(\gamma, pnd)$ reaction. We found that the $^4\text{He}(\gamma, pnd)$ reaction is dominated by the quasideuteron mechanism as was suggested by Gorbunov and Spiridonov.[17] The contribution from photoabsorption by a single nucleon to $\sigma(\gamma, pnd)$ is less than 5%. We have recalculated the photodisintegration cross section for this reaction using Levinger's method and obtained a good fit to the experiment (Fig. 2). Using the $^4\text{He}(\gamma, pnd)$ ampli-

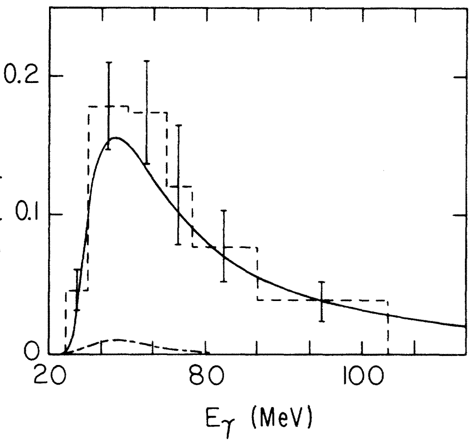

FIG. 2. Comparison of the theoretical results with experimental data for the total cross section for $^4\text{He}(\gamma, pnd)$ as a function of photon energy. ——, quasideuteron contribution; — — — —, direct photon-single nucleon mechanism. The data is from Gorbunov and Spiridonov (Ref. 17).

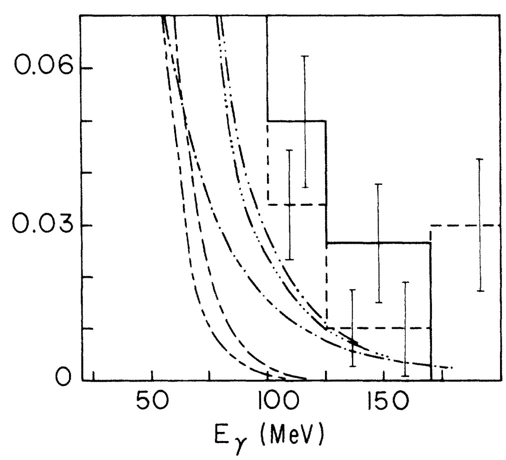

FIG. 3. Comparison of the theoretical results with experimental data for the total cross section for $^4\text{He}(\gamma, n)^3\text{He}$ and $^4\text{He}(\gamma, p)^3\text{H}$: —·–·—, quasideuteron contribution; ————, (γ, n); — — —, (γ, p) direct photon-single nucleon mechanism; —···—, (γ, n); and —··—, (γ, p) from Gari and Hebach (Ref. 12). The dashed and solid histograms are data for (γ, n) and (γ, p), respectively, from Gorbunov (Ref. 14).

tude, we calculated the quasideuteron contribution to the ^{4}He$(\gamma, N)T$ reaction. The cross sections for the ^{4}He$(\gamma, N)T$ reactions given by the single nucleon photoabsorption mechanism and the quasideuteron model are compared (Fig. 3) to obtain the relative importance of each reaction mechanism. It is apparent that for $E_\gamma \gtrsim 100$ MeV the ^{4}He$(\gamma, N)T$ reactions below pion threshold are dominated by the quasideuteron interaction. In this energy range, the asymmetry coefficient obtained from the quasideuteron calculation is in general agreement with the experimental results (Fig. 4).

For photon energies between 50 and 100 MeV both the quasideuteron mechanism and the single nucleon photoabsorption mechanism contribute significantly to the photoreaction process. The calculation in this energy range is rather delicate because detailed knowledge of the ^{4}He ground-state wave function is required for the latter reaction mechanism.

However, we can at least write

$$\begin{aligned} \beta(\gamma, p) &\simeq b + \beta_{qd}(\gamma, p), \\ \beta(\gamma, n) &\simeq -\tfrac{1}{5}\, b + \beta_{qd}(\gamma, n), \end{aligned} \tag{10}$$

where b is determined mainly by the photoabsorption by a single nucleon in the nucleus, and becomes negligible at high energies.

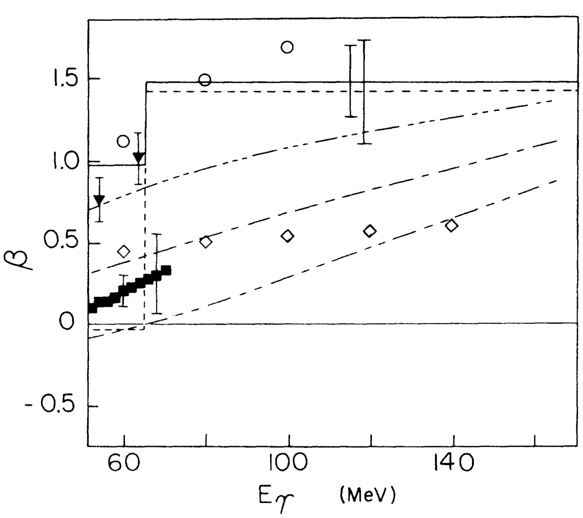

FIG. 4. Comparison of the theoretical results with experimental data for the asymmetry coefficient for ^{4}He$(\gamma, n)^3$He and ^{4}He$(\gamma, p)^3$H. ——–——, quasideuteron contribution using only $E1$ transitions in the photodeuteron amplitude; ——-- ——, (γ, n); ——— --- ——, (γ, p) quasideuteron contribution; ◇, (γ, n); and ○, (γ, p) from Gari and Hebach (Ref. 12). The dashed and solid histograms are (γ, n) and (γ, p) data, respectively, from Gorbunov (Ref. 14): ■, (γ, n) data from Malcolm *et al.* (Ref. 11); ▼, (γ, p) data from Arkatov *et al* [Sov. J. Nucl. Phys. 13, 142 (1971)], see Ref. 8.

Gari and Hebach[12] used the alternative quasideuteron calculation via N-N correlations for the ^{4}He$(\gamma, N)T$ reaction. In addition to the initial and final state N-N correlations (also used in SRC-type quasideuteron calculations), Gari and Hebach include meson exchange terms arising from the consideration of two-body forces. These gauge terms correspond to interactions between the photon and intermediate nucleon states or exchange mesons. Using shell-model wave functions, a Woods-Saxon type single particle potential, an effective potential for the N-N interaction, and $E1$ and $E2$ interactions, they calculate $\sigma(\gamma, N)$ and $\beta(\gamma, N)$. Their results are also shown in Figs. 3 and 4.

The gauge terms which dominate $\sigma(\gamma, N)$ above 60 MeV in Gari and Hebach's calculation depend on the choices for the initial and final state wave functions, the N-N potential and the effective charges in the electric operators. The effective potential for the N-N interaction is chosen for simplicity; the range is fixed and the strength varied to illustrate its effect on the results. They recognize the problem of specifying the effective charges, and claim that it is of minor importance. Our method of calculation differs from Gari and Hebach's in that once we specify the ^{4}He and $(pn)_1$-d wave functions the rest of the amplitude is determined by the actual deuteron photodisintegration amplitude and by the $(N'd)$-T vertex [obtained from an analysis of ^{3}He$(p, 2p)$ and ^{3}He(p, pd) quasifree scattering[18]]. We have no other parameters to adjust or determine. Furthermore, we can check our quasideuteron amplitude directly by looking at that part which corresponds to the ^{4}He(γ, pnd) reaction.

In general, to determine the quasideuteron contribution to the photodisintegration process, one can follow Levinger's method of expressing the quasideuteron process in terms of the photodisintegration of a real deuteron, or one can account for N-N interactions via N-N correlations. The latter calculation depends strongly on the choice of the correlation function and its parameters, while the former depends on the deuteron photodisintegration amplitude off the energy shell. We followed Levinger's development of the quasideuteron calculation which allows us to check the on-the-energy-shell part of the calculation by considering the ^{4}He(γ, pnd) reaction. This method also reduces the number of free parameters. However, in spite of the different methods of calculation, we note that at photon energies where the contribution from the interaction of the photon with a single nucleon becomes negligible ($E_\gamma \gtrsim 120$ MeV), Gari and Hebach's calculations for $\sigma(\gamma, N)$ approaches our result. The asymmetry coefficients from both methods of calculation also show similar trends for $\beta(\gamma, n)$ and $\beta(\gamma, p)$ (Fig. 4).

In summary our results are the following. The cross section for the ^{4}He(γ, pnd) reaction is calculated via the quasideuteron mechanism and found to be in general agreement with experiment. We use the ^{4}He(γ, pnd) amplitude to calculate the ^{4}He$(\gamma, N)T$ cross section. The quasideuteron contribution to $\sigma(\gamma, N)$, which is determined mainly by the $E1$ term of the deuteron photodisintegration amplitude, strongly dominates the high energy N-T photodisintegration. The asymmetry coefficient is more sensitive to the $E2$ term of the deuteron photodisintegration process. In fact, this $E2$ term gives rise to the differences between $\beta_{qd}(\gamma, n)$ and $\beta_{qd}(\gamma, p)$. Our results for the photodisintegration cross section and the asymmetry coefficients for the reactions ^{4}He$(\gamma, p)^3$H and ^{4}He$(\gamma, n)^3$He are in general agreement with the experimental values and the theoretical values of Gari and Hebach[12] calculated using the alternative nucleon pair correlation approach.

IV. CONCLUSION

The main conclusions of the previous section are as follows:

(1) The photodisintegration cross section for the ^{4}He$(\gamma, N)T$ reactions above 60 MeV (below pion threshold) is a consequence of the quasideuteron mechanism in addition to the single nucleon absorption mechanism.

(2) The forward asymmetry of the ^{4}He$(\gamma, N)T$ reactions in the intermediate energy region can be understood in terms of the quasideuteron mechanism.

(3) The quasideuteron mechanism dominates the ^{4}He(γ, pnd) reaction and can explain the general features of the photodisintegration cross section $\sigma(\gamma, pnd)$.

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APPENDIX I: WAVE FUNCTIONS AND AMPLITUDES

To simplify our calculations we chose a wave function which was separable in Jacobi coordinates, but still consistent with the general behavior of the ^{4}He form factor. We used Gaussian ground-state wave functions for the spatial parts of the ^{4}He and triton wave functions:

$$\begin{aligned}\phi_{^4\mathrm{He}} &= N_0 \exp\left[-\sum_{k<j=1}^{4}(\vec{r}_k-\vec{r}_j)^2 a_0\right],\\ \phi_T &= N_T \exp\left[-\sum_{k<j=1}^{3}(\vec{r}_k-\vec{r}_j)^2 b_0\right],\end{aligned}\tag{11}$$

where N_0 and N_T are normalization factors ($\langle\phi\,|\,\phi\rangle = 1$). a_0 is chosen by fitting $\phi_{^4\mathrm{He}}$ to the ^{4}He form factor[19] ($a_0 = 0.050\ \mathrm{fm}^{-2}$, giving a ^{4}He rms radius of 1.68 fm) and b_0 by fitting ϕ_T to the triton matter radius ($b_0 = 0.063\ \mathrm{fm}^{-2}$). By expressing the wave functions in Jacobi coordinates, the behavior of the nucleon relative to the triton in the ^{4}He ground state ϕ_{N-T} can be separated from $\phi_{^4\mathrm{He}}$. Written explicitly,

$$\phi_{N-T}(r) = (6a_0/\pi)^{3/4}\exp(-3a_0 r^2). \tag{12}$$

For the ^{4}He$(\gamma, N)T$ reactions, the single nucleon photoabsorption mechanism gives for the differential cross section in the $E1$-$E2$ approximation

$$\begin{aligned}\frac{d\sigma}{d\Omega}(\gamma, n) &= \frac{1}{6\pi}\frac{e^2}{\hbar c}\frac{\hbar^2}{m}\frac{k^3}{E_\gamma}N_{fi}^2\sin^2\theta\\ &\quad\times\left|\phi_{N-T}(k)+\tfrac{1}{4}K_\gamma\cos\theta\frac{d\phi_{N-T}(k)}{dk}\right|^2,\\ \frac{d\sigma}{d\Omega}(\gamma, p) &= \frac{1}{6\pi}\frac{e^2}{\hbar c}\frac{\hbar^2}{m}\frac{k^3}{E_\gamma}N_{fi}{}^2\sin^2\theta\\ &\quad\times\left|\phi_{N-T}(k)-\tfrac{4}{5}K_\gamma\cos\theta\frac{d\phi_{N-T}(k)}{dk}\right|^2.\end{aligned}\tag{13}$$

$\vec{K}_\gamma$ is the incident photon momentum, $\vec{k}$ is the N-T relative momentum ($\vec{K}_\gamma\cdot\vec{k} = K_\gamma k\cos\theta$), and N_{fi} is the overlap of the triton wave function ϕ_T with the appropriate part of the ^{4}He wave function. For the corresponding asymmetry coefficients, we have

$$\begin{aligned}\beta_0(\gamma, p) &= -\tfrac{8}{5}K_\gamma\left[d\phi_{N-T}(k)/dk\right]/\phi_{N-T}(k),\\ \beta_0(\gamma, n) &= \tfrac{1}{2}K_\gamma\left[d\phi_{N-T}(k)/dk\right]/\phi_{N-T}(k).\end{aligned}\tag{14}$$

For the quasideuteron mechanism, the deuteron and quasideuteron wave functions are taken from the theory of effective range:

$$\begin{aligned}\phi_d &= N_d\exp(-\alpha r)/r\\ N_d &= [2\alpha/4\pi(1-\alpha r_0)]^{1/2},\\ \phi_{(pn)_1} &= \exp(i\vec{q}\cdot\vec{r}) + f(q)\exp(iqr)/r,\\ f(q) &= 1/(-\alpha - iq),\end{aligned}\tag{15}$$

where $\vec{q}$ is the n-p pair relative momentum. For the ^{4}He(γ, pnd) cross section we obtain

$$\sigma(\gamma, pnd)_{(pn)_1} = \frac{2\pi}{\hbar c}\left[\alpha^2 \frac{6\eta^2}{a_0^2}(2\pi/a_0)^{1/2}\right]$$
$$\times \int\int \frac{d^3p_0}{(2\pi)^3}\frac{d^3k}{(2\pi)^3}\exp(-p_d^2/8a_0)|M_d|^2$$
$$\times \delta(E_\gamma - (B_{npd} + E_p + E_n + E_d)). \tag{16}$$

$\vec{p}_0 = \vec{p}_p - \vec{p}_n$ is the n-p relative momentum, $\vec{k}_1 = \frac{1}{2}[\vec{p}_d - (\vec{p}_n + \vec{p}_p)]$ is the d-pn relative momentum, B_{pnd} is the pnd binding energy (26.07 MeV), and

$$\eta = 1 - (\alpha^2\pi/8a_0)^{1/2}\exp(\alpha^2/8a_0)\operatorname{erfc}[(\alpha^2/8a_0)^{1/2}].$$

M_d is the deuteron photodisintegration amplitude without the spin part.

Our calculation for the quasideuteron amplitude utilizes the off-the-energy-shell part of M_d. This necessitates an analytic form for $\langle pn_1|\mathcal{H}_\gamma|d\rangle$. The most complete treatment of the deuteron photodisintegration is Partovi's calculation using relativistic phenomenological theory.[20] The effective range theory fits the deuteron photodisintegration cross section up to $E_\gamma \simeq 100$ MeV, but is unsatisfactory in the region of the nucleon isobar. However, we are mainly interested in the low energy behavior of the deuteron photoamplitude and will neglect meson effects.

Neglecting spin components, we have in $E1$-$E2$ approximation

$$\langle pn|\mathcal{H}_\gamma|d\rangle = \langle \exp(i\vec{p}_0\cdot\vec{r})| - \frac{e\hbar}{m}(2\pi/E_\gamma)^{1/2}(\vec{\epsilon}_\gamma\cdot\vec{p})$$
$$\times(1 + \tfrac{1}{2}i\vec{K}\cdot\vec{r})|\phi_d\rangle$$
$$= -\frac{e\hbar^2}{m}(2\pi/E_\gamma)^{1/2}N_d\, 4\pi\frac{(\vec{\epsilon}_\gamma\cdot\vec{p}_0)}{p_0^2+\alpha^2}$$
$$\times\left(1 + \frac{\vec{p}_0\cdot\vec{K}_\gamma}{p_0^2+\alpha^2}\right), \tag{17}$$

where $\vec{\epsilon}_\gamma$ is the photon polarization unit vector. With increasing energy, the effective range overestimates the $E2$ contribution. To reduce the $E2$ contribution, we multiply the quadrupole term by a factor of $1/[(E_\gamma/255\text{ MeV})^2+1]$ (This form has been chosen for its simplicity with the parameter chosen to fit the data). Hence we use

$$M_d = \frac{-e\hbar^2}{m}(2\pi/E_\gamma)^{1/2}N_d\,4\pi\frac{(\vec{\epsilon}_\gamma\cdot\vec{p}_0)}{p_0^2+\alpha^2}\left[1 + \frac{\vec{p}_0\cdot\vec{K}}{(p_0^2+\alpha^2)}\times\frac{1}{(E_\gamma/255\text{ MeV})^2+1}\right]. \tag{18}$$

For the ^{4}He$(\gamma, N)T$ differential cross section, we obtain

$$\frac{d\sigma(\gamma,N)_{(pn)_1}}{d\Omega} = \frac{2\pi}{\hbar c}\frac{m}{\hbar^2}\frac{k_{N-T}}{(2\pi)^3}|g_{T,N'-d}|^2\frac{\alpha^2 27\eta^2}{a_0^2}(2\pi/a_0)^{1/2}\left[\int\frac{d^3p_1}{(2\pi)^3}\frac{M_d\exp(-p_d^2/16a_0)}{B_{N'd}+p_1^2/2\mu_{N'd}}\right]^2 \tag{19}$$

where $B_{N'd}$ is the $N'd$ binding energy ($B_{nd} = 6.257$ MeV and $B_{pd} = 5.493$ MeV) and $\vec{p}_1$ is the N'-d relative momentum. The vertex constant $g_{^3\text{He},p-d}$ is obtained from the analysis of $(p, 2p)$ and (p, pd) quasifree scattering on ^{3}He[18] ($g_{^3\text{He},p-d} = 138$ MeV fm$^{3/2}$). The vertex $g_{^3\text{H},n-d}$ is taken to be the same. $\vec{k}_{N-T}$ is the N-T relative momentum. The integral can be expanded in terms of $\cos\theta_{NT}$:

$$\int\frac{d^3p_1}{(2\pi)^3}\frac{M_d\exp(-P_d^2/16a_0)}{B_{N'd}+p_1^2/2\mu_{N'd}} = (\vec{\epsilon}_\gamma\cdot\vec{p}_{N-T})(F_0 + F_1\cos\theta_{N-T} + F_2\cos^2\theta_{N-T} + \cdots), \tag{20}$$

giving as the asymmetry coefficient

$$\beta_{(pn)_1}(\gamma, N) = 2F_1/F_0. \tag{21}$$

APPENDIX II: AMPLITUDE AND CORRELATION METHODS FOR THE QUASIDEUTERON MECHANISM

An alternative method of calculating the effect of photoabsorption by a nucleon pair is to extend the independent particle model (IPM) by including Jastrow-type N-N short-range correlations (SRC). With a judicious choice for the correlation function, we can show that our method is essentially equivalent. Calculations following the SRC method[3,5] generally begin with a pure shell-model wave function $|A\rangle$ which is modified by a two-body correlation function $f_c(r_{kl})$ to include a correlated nucleon pair in the ground state of the target nucleus

$$|\tilde{A}\rangle = \prod_{k<l} f(r_{kl})|A\rangle.$$

For the photointeraction Hamiltonian $\mathcal{H}_\gamma = \mathcal{H}_\gamma(1) + \mathcal{H}_\gamma(2) + \cdots + \mathcal{H}_\gamma(A)$, the transition matrix element is

$$\langle\tilde{f}|\mathcal{H}_\gamma|\tilde{A}\rangle = \langle f|\prod_{k'<l'}\bar{f}_c(r_{k'l'})\mathcal{H}_\gamma\prod_{k<l}f_c(r_{kl})|A\rangle; \tag{22}$$

$\bar{f}_c$ denotes the final state correlations. The effective interaction Hamiltonian $\mathcal{H}_{\gamma\text{eff}}$ is expanded in a series of k-body operators using $f_c(r_{kl}) = 1 - g(r_{kl})$:

$$\mathcal{H}_{\gamma\text{eff}} = \prod_{k'<l'}\bar{f}_c(r_{k'l'})\mathcal{H}_\gamma\prod_{k<l}f_c(r_{kl})$$
$$= \mathcal{H}_\gamma - \sum_{k,l}\bar{g}(r_{kl})\mathcal{H}_\gamma(l) + \mathcal{H}_\gamma(l)g(r_{kl}) + \cdots. \tag{23}$$

The first term gives rise to the usual uncorrelated transition matrix element representing the single nucleon-photoabsorption mechanism. The second term corresponds to the two-particle process from which the quasideuteron mechanism arises; furthermore, only (k, l) corresponding to n-p pairs are considered. These SRC calculations appear to be strongly sensitive to the shape and parameters chosen to describe the two-body correlation function. Using the best fit to the data below pion threshold, the parameters can be chosen to reproduce the general features of the cross sections for the (γ, pn) reactions on ^{16}O, ^{14}N, and ^{12}C[3], and the (γ, N) reactions on ^{16}O, ^{6}Li, and ^{12}C[5]. The Jastrow model SRC method is essentially equivalent to the method presented here in determining the quasideuteron contribution to the photoprocess. By judiciously choosing $f_c(r_{kl})$, we can transform the term representing the two-particle process in the SRC calculations

$$M^{\rm SRC}=\langle f|\sum_{k,l}\mathcal{H}_\gamma(l)g(r_{kl})|A\rangle \tag{24}$$

into the transition matrix element used in the present calculation. [For simplicity, $g(r_{kl})$ is assumed to commute with $\mathcal{H}_\gamma(l)$ and constant numerical factors will be neglected.]

Designating particles (1, 2) as protons and (3, 4) as neutrons for ^{4}He, $M^{\rm SRC}$ is explicitly

$$M^{\rm SRC}=\langle f|\mathcal{H}_\gamma(1)[g(r_{13})+g(r_{14})] + \mathcal{H}_\gamma(2)[g(r_{23})+g(r_{24})]|^4\mathrm{He}\rangle. \tag{25}$$

Because $|f\rangle$ and $|^4\mathrm{He}\rangle$ are antisymmetric in the pairs (1, 2) and (3, 4), we need only consider the one term

$$M^{\rm SRC}=\langle f|\mathcal{H}_\gamma(1)g(r_{13})|^4\mathrm{He}\rangle. \tag{26}$$

We choose $g(r)$ to be of the form $\exp(-\xi r)/\xi r$ with Fourier transform $w(q)$:

$$\begin{aligned} g(r) &= \sum_q \exp(-i\vec{q}\cdot\vec{r})w(q), \\ w(q) &= N_\xi/(q^2+\xi^2) = |h(q)|^2, \end{aligned} \tag{27}$$

where N_ξ is a constant and summation over q represents integration over momentum $\vec{q}$. Using $h(q)=(N_\xi)^{1/2}/(-q-i\xi)$, we obtain

$$\begin{aligned} M^{\rm SRC} &= \sum_{q_{13}}\langle f|\mathcal{H}_\gamma(1)h(q_{13})\exp(-i\vec{q}_{13}\cdot\vec{r}_{13})h^*(q_{13})|^4\mathrm{He}\rangle \\ &= \sum_{q_{13},B}\langle f|\mathcal{H}_\gamma(1)h(q_{13})|B\rangle \\ &\qquad\times\langle B|h^*(q_{13})\exp(-i\vec{q}_{13}\cdot\vec{r}_{13})|^4\mathrm{He}\rangle, \end{aligned} \tag{28}$$

where we have inserted a complete set of states $\sum_B|B\rangle\langle B|$ in $M^{\rm SRC}$. The factor $\exp(i\vec{q}_{13}\cdot\vec{r}_{13})$ can be considered as a plane wave representing the relative motion of an n-p pair with relative momentum $\vec{q}_{13}$. The effect of $h(q_{13})$ in the matrix element is to pick out $|B\rangle$ states consisting of the correlated pair (1, 3) and the remaining nucleons (2, 4) (i.e., $|B\rangle=|(13)(24)\rangle$). Letting

$$\begin{aligned} h(q_{13})\exp(i\vec{q}_{13}\cdot\vec{r}_{13})|(13)\rangle &= |h(q_{13})\exp(i\vec{q}_{13}\cdot\vec{r}_{13})(13)\rangle \\ &= |(13)_{qd}\rangle \end{aligned} \tag{29}$$

represent a quasideuteron and approximating the remaining n-p pairs by deuterons, $M^{\rm SRC}$ becomes

$$M^{\rm SRC}=\sum_{q_{13},B}\langle f|\mathcal{H}_\gamma(1)h(q_{13})|(13)_d(24)_d\rangle \times\langle(13)_{qd}(24)_d|^4\mathrm{He}\rangle, \tag{30}$$

where the B summation now represents an integration over the momentum components of state $|B\rangle=|(13)(24)\rangle$, and a summation over the spin components of state $|B\rangle$. For $|f\rangle=|pnd\rangle$, the (2, 4) pair singles out the $|(1)(3)(24)_d\rangle$ contribution to the pnd final state, giving

$$\begin{aligned} \langle f|\mathcal{H}_\gamma(1)h(q_{13})|(13)_d(24)_d\rangle &= \langle(1)(3)(24)_d|\mathcal{H}_\gamma(1)h(q_{13})|(13)_d(24)_d\rangle \\ &= h(q_{13})\langle(1)(3)|\mathcal{H}_\gamma(1)|(13)_d\rangle. \end{aligned} \tag{31}$$

$M_{pnd}^{\rm SRC}$ is then

$$M_{pnd}^{\rm SRC}=\sum_{q_{13},B}\langle h(q_{13})(1)(3)|\mathcal{H}_\gamma(1)|(13)_d\rangle \times\langle(13)_{qd}(24)_d|^4\mathrm{He}\rangle. \tag{32}$$

Recalling that (1, 2) are protons and (3, 4) are neutrons, $M_{pnd}^{\rm SRC}$ can now be written as

$$M_{pnd}^{\rm SRC}=\sum_{q,B}h(q)\langle pn|\mathcal{H}_\gamma|d\rangle\langle(qd)d|^4\mathrm{He}\rangle. \tag{33}$$

If we set $\xi=\alpha$, then $h(q)$ is equal to $f(q)$ up to a constant and $M_{pnd}^{\rm SRC}$ is equivalent to Eq. (5).

For the N-T final state, we introduce another set of complete states $\sum_A|A\rangle\langle A|$ into Eq. (30) and obtain

$$M_{N-T}^{\rm SRC}=\sum_{q_{13},B,A}\langle f|A\rangle\langle A|\mathcal{H}_\gamma(1)h(q_{13})|(13)_d(24)_d\rangle \times\langle(13)_{qd}(24)_d|^4\mathrm{He}\rangle. \tag{34}$$

The presence of $(24)_d$ selects states A with a $(24)_d$ pair. $\mathcal{H}_\gamma(1)$ effectively photodisintegrates the remaining (13) pair. Hence $|A\rangle$ is specified as $|(1)(3)(24)_d\rangle$. Using Eq. (31), $M_{N-T}^{\rm SRC}$ becomes

$$M^{\mathrm{SRC}}_{N-T} = \sum_{q_{13},B,A} \langle f\,|\,(1)(3)(24)_d\rangle\, h(q_{13}) \times \langle (1)(3)\,|\,\mathcal{H}_\gamma(1)\,|\,(13)_d\rangle \times \langle (13)_{qd}(24)_d\,|\,{}^4\mathrm{He}\rangle = \sum_A \langle f\,|\,(1)(3)(24)_d\rangle M^{\mathrm{SRC}}_{pnd}\ , \quad (35)$$

where the A summation represents integration over momentum components and summation over spin components of state $|A\rangle = |(1)(3)(24)_d\rangle$. Using

$$\langle f\,|\,(1)(3)(24)_d\rangle = \langle (N)(N'24)\,|\,(1)(3)(24)_d\rangle = \langle (N'24)\,|\,(N')(24)_d\rangle\ , \quad (36)$$

where one of the nucleons (1 or 3) recombines with the pair (24) to form a triton (^{3}He or ^{3}H, respectively), we obtain

$$M^{\mathrm{SRC}}_{N-T} = \sum_A \langle (N'24)\,|\,(N')(24)_d\rangle M^{\mathrm{SRC}}_{pnd}\ . \quad (37)$$

M^{SRC}_{N-T} can now be written as

$$M^{\mathrm{SRC}}_{N-T} = \sum_A \langle T\,|\,N'd\rangle M^{\mathrm{SRC}}_{pnd}\ , \quad (38)$$

which is equivalent to Eq. (8).

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