Two and three nucleon induced photon absorption

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Abstract

We have investigated the mechanisms leading to two and three body photon absorption in nuclei. At photon energies around the pion production threshold we obtain a fraction of three body absorption of less than 10% of the total, contradicting previous theoretical claims that it dominates the absorption process. The strength of the three body channel grows smoothly with the photon energy reaching a maximum of about 60% of the total direct absorption at energies of the photon around 400 MeV.

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I. INTRODUCTION

The subject of how many nucleons are involved in photon absorption in nuclei is bound to follow a similar trend as the same question in pion absorption. This latter topic has attracted much attention experimentally [1] and the findings in medium and heavy nuclei support a picture of pion absorption where the two nucleon mechanism is largely dominant at low pion energies but the three body mechanism becomes more important as the energy increases, reaching a maximum around $T_\pi = 250$ MeV where its strength is about one half of the total absorption rate. The experimental findings follow closely the theoretical predictions of Ref. [2] calculated up to $T_\pi = 400$ MeV. A semiphenomenological evaluation at energies above the $\Delta$ resonance shows the three body absorption playing a smaller role than the two body one [3].

When talking about two and three body absorption one must clarify its meaning. Usually many particles are involved in the process of pion absorption. For instance a pion can undergo quasielastic collisions with other nucleons before it is finally absorbed. On the other hand the nucleons coming from the quasielastic collisions or pion absorption can scatter with other nucleons on their way out. Hence one distinguishes the genuine absorption mechanisms as the one step processes where the pion is absorbed, leaving apart initial state interaction of the pion or final state interaction of the nucleons. In terms of Feynman diagrams for the process it means that genuine absorption diagrams are those where on shell pions and on shell nucleons do not appear in the intermediate lines of the absorption amplitude. Since the particles involved in the diagrams will be off shell, they are short lived and the process is of relatively short range. In this sense it is worth pointing out that the three nucleon absorption mechanisms evaluated in Ref. [4], and which are often quoted in the literature as an example of three body absorption, correspond actually to two step processes of a quasielastic pion collision followed by two body absorption. Similarly the three body exchange currents evaluated in Ref. [5] in the study of the $^3H(e,\gamma)^2H$ reaction also qualify as a $(\gamma, \pi)$ step followed by two body pion absorption, except, obviously,
below pion production threshold. Some genuine three body absorption mechanisms are
diagrammatically depicted there, although they are not evaluated.

Given the fact that the \((\gamma, \pi)\) process at intermediate energies is dominated by the
\(\Delta\) excitation, the analogy with the \((\pi, \pi')\) process is evident around resonance and the
mechanisms for \(\gamma\) and \(\pi\) absorption are related. In this sense the study of photon absorption
in Ref. [6], which uses the same input for the \(\Delta\) self-energy in the medium as Ref. [2],
leads basically to the same proportion of genuine two and three body photon absorption
as in pion absorption. Here again it is worth noting that a considerable fraction of photon
absorption corresponds to two step processes in which a real pion is created in a \((\gamma, \pi)\) step
and the pion is subsequently absorbed by two or three nucleons. This process, which is
called indirect photon absorption and is evaluated in Ref. [7], corresponds, in the case of
pion nuclear reactions, to a \((\pi, \pi')\) step followed by pion absorption, this is, initial state
interaction followed by genuine pion absorption.

Thus, when we talk here about genuine (or direct) photon absorption we refer again to
mechanisms in which real pions or real nucleons are not present in intermediate states in
the absorption amplitude.

In Ref. [8] it was suggested that the whole strength of photon absorption around the pion
production threshold could be due to genuine three nucleon mechanisms in the sense used here.
Comparisons of this model with estimates of two body absorption, based upon the
empirical quasidieutron model, were made in Ref. [9] and reinforced the idea that photon
absorption should be dominated by three body absorption around pion creation threshold.
However, recent microscopical calculations of the two body absorption channels at the same
energy [6] show that the two body mechanisms provide a reasonable reproduction of the
experimental data [10-12].

On the other hand some experimental analyses around the same photon energy in \((\pi, \pi')\)
reactions came to suggest that three body absorption might account indeed for a considerable
fraction of the total absorption rate [13]. Some other data in light nuclei suggest smaller
fractions of three body absorption [14]. The experimental situation is now experiencing a

boom and plenty of data are being analysed, which should shed light on these issues [15].

Meanwhile the idea of Ref. [8] stimulated an interesting work on two nucleon induced \(\Lambda\)
decay [16] which had repercussions on the neutron to proton induced \(\Lambda\) decay ratio, one of the
puzzles in \(\Lambda\) hypernuclear decay [17]. The idea was caught in Ref. [18], improving on several
approximations of Ref. [16], with the result that the two nucleon induced channel represents
about 15\% of the one nucleon induced channel, but still can have large repercussions in the
experimental analysis trying to extract the ratio of \(n\) to \(p\) induced \(\Lambda\) decay. The subsequent
steps given in Refs. [16] and [18] have layed the ground for an accurate evaluation of the
three nucleon mechanism suggested in Ref. [8] for photon absorption and its comparison
with the two nucleon mechanisms studied in [6]. This is the purpose of the present work.
The analogy with the two nucleon and one nucleon induced \(\Lambda\) decay in nuclei is apparent
and we shall closely follow Refs. [16] and [18] in the evaluation of the absorption rates.
The details of the formalism and the approximations used are presented in Sects. II and
III. The results are shown and discussed in Sect. IV. We find that three body absorption
around pion threshold amounts to less than 10\% of the two body channel, while at higher
energies the analysis of Ref. [6] incorporates the three body absorption channel's, via the \(\Delta\)
self-energy, and leads to ratios of three to two body absorption similar to those found for pion
absorption as a function of the available excitation energy. Finally, Sect. V summarizes our
conclusions.

II. FORMALISM FOR \((\gamma, \pi)\), TWO BODY AND THREE BODY ABSORPTION.

The many body approach followed in Refs. [6,7] offers a unified treatment of all the
reaction channels in photon nucleus scattering. At photon energies below 500 MeV those
channels are essentially \((\gamma, \pi)\) and photon absorption by nucleons. The starting point in
Ref. [6] is a model for the elementary \(\gamma N \rightarrow \pi N\) reaction, similar to the one of Ref. [19],
which contains the pion pole, Kroll Ruderman term, nucleon direct and crossed terms and \(\Delta\)
direct and crossed terms. One can obtain photon selfenergy diagrams by folding the terms.
of the $\gamma N \rightarrow \pi N$ amplitude and summing over occupied states. Such terms are depicted in Fig. 1(a). At higher orders in the nuclear density the pion in Fig. 1(a) is allowed to interact with the medium, exciting a $p$ channel for instance, as depicted in Fig. 1(b). Higher order terms in the nuclear density are also considered in Ref. [6]. As an example we show in Fig. 2 terms involving one, two or three occupied nucleons, or equivalently terms linear, quadratic and cubic in the nuclear density approximately.

The total $\gamma$ nuclear reaction cross section (omitting the negligible Compton and coherent $(\gamma, \pi^0)$ channels) is given by [6]

$$
\sigma = \frac{1}{k} \int d^4r \text{Im} \Pi(k, \rho(\vec{r})) ,
$$

where $\Pi(k, \rho)$ is the selfenergy of a photon of momentum $k$ in nuclear matter of density $\rho$. A local density approximation is implicit in Eq. (1) since $\rho$ is substituted by $\rho(\vec{r})$, the local density of the nucleus, and an integral is done over the whole nuclear volume. This approximation was found to be extremely good in Ref. [6], where it was mathematically proved that folding the local selfenergy with any finite range of the interaction leads exactly to the same cross section.

The imaginary part of the photon selfenergy is obtained from the many body diagrams when the set of intermediate states cut by the dotted lines in Figs. 1 and 2 are placed on shell in the intermediate integrations, a procedure which is easily implemented in terms of Cutkosky rules. In Fig. 2 one can see that the cuts of (a), (c) and (d) lead to the $(\gamma, \pi)$ channel, while (b) leads to $2N$ photon absorption and (e) to $3N$ photon absorption.

Let us concentrate in diagram (e) of Fig. 2. The evaluations in Ref. [6] are done omitting the on shell pion in the interaction line (serrated line) closest to the photon in the figure. This is done to obtain the genuine absorption contribution. Assume for a moment that the interaction line corresponds to a pion and the pion is on shell. The process then qualifies as a $(\gamma, \pi)$ step followed by the absorption of the pion by two nucleons, which is what we call indirect photon absorption and is evaluated in Ref. [7]. This latter result looks intuitive but an analytical proof can be found in Ref. [20]. At photon energies where the pion has a kinetic energy of around 100 MeV or more, the propagation of these pions in the nucleus can be done accurately in terms of a Monte Carlo simulation [21] where the real pions move along classical trajectories between collisions or before absorption, with probabilities for these processes calculated with the many body scheme of Ref. [6]. However, if we assume once more one pion exchange in the same interaction line and go down with the photon energy just below pion production threshold, then the OPE exchange corresponds necessarily to an off shell pion and the mechanism has become a genuine three body absorption. This is so since in the photon absorption diagram (just the lower half of diagram (e) below the dotted line) there are no on shell pion or nucleon intermediate lines. The process involves the absorption of the photon by three nucleons and is a one step process.

This latter mechanism is the one considered in Ref. [8], although we have used a different language and motivation in order to put the mechanism in a general framework to the light of the recent findings in photoabsorption. On the other hand, such a contribution for the $\Delta$ excitation pieces in Fig. 2 is also considered in Refs. [2] and [6], but this is irrelevant for photon absorption around pion threshold because, as shown in Fig. 49 of Ref. [6], photon absorption at these energies is practically all given by the non resonant terms, led essentially by the Kroll Ruderman and pion pole terms in the $\gamma N \rightarrow \pi N$ vertex. The three nucleon mechanisms discussed above, but driven by the background terms (non $\Delta$ terms) in the $\gamma N \rightarrow \pi N$ amplitude, were not considered in Ref. [6] and the assumption was made that the proportion of three body to two body absorption would scale, as a function of energy, like the resonant pieces, in which case the three body terms would be negligible at the low photon energies where the non resonant absorption dominates. However, the expected detail of the coming experiments and the existence of published work claiming a dominance of the $3N$ mechanism around pion threshold [8,9] call for a careful evaluation of this mechanism which we conduct in the next section.
III. TWO AND THREE BODY ABSORPTION AROUND PION THRESHOLD.

By following the formalism of Refs. [16] and [18] we would like to evaluate the photon self-energy corresponding to the diagrams of Figs. 1(b) and 3 around pion threshold. The results of Fig. 49 in Ref. [6] indicate that the $\Delta$ led terms account for less than 10% of the direct two body absorption cross section at this energy. Thus, we only consider here the Kroll Ruderman and pion pole terms which are the dominant non resonant terms in the $\gamma N \rightarrow \pi N$ amplitude [6] there. They only contribute for charged pions up to a small contribution in the $\gamma p \rightarrow \pi^0 p$ case which we neglect. We also neglect terms of order $\mu^2/2M$ in the charged pion amplitudes, where $\mu$ and $M$ are the pion and nucleon mass respectively.

All these terms introduce corrections of order $(\mu^2/2M)^2$ in the final result of the photon selfenergy and can thus be disregarded. With these simplifications the Kroll Ruderman and pion pole terms are given by

\begin{equation}
-i\Pi^{KR}_{\gamma N} = \pm e^2 \sqrt{2\alpha \epsilon} \Pi_{\gamma N}^{(k-q)}(k-q)
\end{equation}

\begin{equation}
-i\Pi^{PP}_{\gamma N} = \pm e^2 \sqrt{2\alpha \epsilon} \Pi_{\gamma N}^{(k-q)}\left(\frac{1}{(q-k)^2 - \mu^2}ight) F_{\gamma N}^{(k-q)}
\end{equation}

where $f^2/4\pi = 0.08$, $\epsilon$ is the photon polarization vector (we work in the Coulomb gauge $\epsilon^0 = 0$, $\epsilon^k = 0$) and $F_{\gamma N}^{(k-q)}$ is a monopole form factor with $\Lambda_\pi = 1300$ MeV which we take from Ref. [22]. The $+$ ($-$) sign in Eqs. (2) and (3) stands for the reaction $\gamma p \rightarrow \pi^+ n$ ($\gamma n \rightarrow \pi^- p$).

In spin-isospin saturated nuclear matter, the photon selfenergy for the sum of $\pi^+$ and $\pi^-$ exchange in the diagrams of Figs. 1(b) and 3 is given by

\begin{equation}
-i\Pi(k) = 2 \int \frac{d^4q}{(2\pi)^4} \frac{1}{4} U_N(k-q)[i D_\theta(q)]^2 \left[\sum_{\lambda, \sigma} \sum_{\sigma'} (-it)(-it')\Pi^*_\gamma(q)\right] U_N(k-q)
\end{equation}

where $U_N(k-q)$ is the Lindhard function for ph excitation, $D_\theta(q)$ the pion propagator, $t$ the $\gamma N \rightarrow \pi N$ amplitude and $\Pi^*_\gamma$ the pion selfenergy. We sum over initial and final spins of the nucleons in $|t|^2$ and average over the photon polarization.

In order to obtain $Im\Pi$ we apply the Cutkosky rules [23] adapted to the present case

$$II(k) \rightarrow 2iImII(k)$$

$$U_N(k-q) \rightarrow 2i\theta(k^0 - q^0)ImU_N(k-q)$$

$$II^*_\gamma(q) \rightarrow 2i\theta(q^0)ImII^*_\gamma(q)$$

and we obtain

\begin{equation}
Im\Pi(k) = - \int \frac{d^4q}{(2\pi)^4} \frac{ImU_N(k-q)D_\theta(q)^2}{E_\gamma(k-q)^2 - \mu^2} \sum_{\lambda, \sigma} \sum_{\sigma'} \left[|t|^2 \theta(k^0 - q^0)\theta(q^0)ImII^*_\gamma(q)\right],
\end{equation}

where the sum and average of $|t|^2$ is given by

\begin{equation}
\sum_{\lambda, \sigma} \sum_{\sigma'} |t|^2 = 4e^2 \frac{f_\mu^2}{\mu^2} F_{\gamma N}^{(k-q)} \left(\frac{1}{(q-k)^2 - \mu^2} + \frac{1}{(q-k)^2 - \mu^2}ight)
\end{equation}

The next step requires to consider nuclear polarization effects which proved to be important in Ref. [6]. The RPA diagrams which one considers are those depicted in Fig. 4. We follow here the steps of section 9 of Ref. [6]. On the one hand we must substitute

\begin{equation}
ImII^*_\gamma(q) \rightarrow \frac{ImII^*_\gamma(q)}{|1 - V_\gamma(q)|^2},
\end{equation}

where $V_\gamma(q)$ is the longitudinal part of the ph interaction

$$V_\gamma = \{V_\gamma(q)\delta_{\theta q} + V_T(q)(\delta_{\theta q} - \delta_{\theta q}')\},$$

with

$$V_\gamma(q) = \frac{f_\mu^2}{\mu^2} \left[q^2 F_{\gamma N}^2(q)D_\theta(q) + g'\right]$$

$$V_T(q) = \frac{f_\mu^2}{\mu^2} \left[q^2 F_{\gamma N}^2(q)D_\theta(q)C_\nu + g'\right],$$

$g' = 0.6$, $D_\theta$ the $\rho$ propagator, $C_\nu = 2$ and $F_\sigma$ the monopole $\rho$ form factor with $\Lambda_\rho = 2500$ MeV [18]. Another version using $C_\nu = 3.96$ and $\Lambda_\rho = 1400$ MeV [22] leads basically to the same results. The function $\Pi^*_\gamma$ is related to $\Pi^*_\gamma$ by

\begin{equation}
II^*_\gamma(q) = \frac{f_\mu^2}{\mu^2} q^2 F_{\gamma N}^2(q)\Pi^*_\gamma(q)
\end{equation}
where $\Pi_{\pi}^*(q)$ is the irreducible pion selfenergy in the sense that none of the diagrams it contains consists of two pieces connected by $V_L$. For $\Pi_{\pi}^*$ we consider $\rho h$, $\Delta h$ and $2p2h$ excitation terms:

$$\Pi_{\pi}^*(q) = \Pi_{\pi A}^*(q) + \Pi_{\Delta A}^*(q) + \Pi_{2p2h}^*(q),$$  \hspace{1cm} (11)$$

with

$$\Pi_{\pi A}^*(q) = U_N(q)$$

$$\Pi_{\Delta A}^*(q) = U_{\Delta}(q)$$

$$\Pi_{2p2h}^*(q) = -4\pi \text{Re} C_{\rho}^2 q^2 \left( \frac{f_\pi^2}{\mu^2} \right)^{-1} + i4\pi \text{Im} C_{\rho}^2 q^2 \left[ \text{PH}(\rho, q, \rho) \cdot \text{P} \cdot \text{H}(\rho, q, \rho) \right] \left( \frac{f_\pi^2}{\mu^2} \right)^{-1},$$  \hspace{1cm} (12)$$

where $U_N, U_{\Delta}$ are the ordinary Lindhard functions for $\rho h$ or $\Delta h$ excitation [24] with the normalization of the appendix of Ref. [25]. The function $\text{P} \cdot \text{H}$ takes into account the phase space available for real $2p2h$ excitation with incoming momentum $q^0, \vec{q}$ in nuclear matter at density $\rho$. Explicit expressions for $\text{P} \cdot \text{H}$ can be found in Eqs. (27-31) of Ref. [18] and $\mu^2 = (0.105 + 0.096)\mu^{-2}$.

What one has done in Eq. (12) is to take the empirical input for $\Pi_{2p2h}^*$ from pionic atoms and extend it to off shell situations. This is done by multiplying the off-shell values by the ratio of phase space for $2p2h$, at the appropriate values of $q^0, \vec{q}$ and $\rho$, to the one for the case of pionic atoms, namely $q^0 = \mu, \vec{q} = 0$, and $\rho = 0.75\rho_0$ [26].

On the other hand, Fig. 4 contains also the polarization of the $h$ excitation on the left of the diagram of Fig. 1(b). These corrections must also be implemented in the diagram of Fig. 3. This affects in a different way the three terms in $|t|^2$ of Eq. (7). The first term corresponds to the square of the Kroll Ruderman term while the other two correspond to the square of the pion pole term and the interference of the two terms. The polarization can be taken into account modifying the terms of Eq. (7) as done in section 9 of [6], multiplying the three terms by the factor $P_{\pi, A} = 1, 2, 3$ respectively, where the functions $P_{\pi}$ are given by

$$P_1 = \frac{1}{|1 - V_L(k - q)|^2 (k - q)^2 \left( (1 - \cos^2 \theta) \right)},$$

$$P_2 = \frac{1}{|1 - V_L(k - q)|^2 (k - q)^2 \left( (1 - \cos^2 \theta) \right)},$$

$$P_3 = \frac{1}{|1 - V_L(k - q)|^2 (k - q)^2 \left( (1 - \cos^2 \theta) \right)},$$

where $\theta$ is the angle between $\vec{k}$ and $\vec{q}$.

The difference in the three terms appears because the first term is a mixture of spin longitudinal and transverse parts, while the other two are of pure spin longitudinal nature.

The polarization takes into account long range correlations. One must still correct for the effect of short range correlations and this is done again following the steps of Ref. [6] (appendix D). We use here a simplified version of this latter work which leads practically to the same results and as a consequence we obtain the formula

$$\text{Im}\Pi(k) = -\int \frac{d^4 q}{(2\pi)^4} \text{Im} U_N(k - q) \theta(q^0 - q^0) \theta(\vec{q}) \times \left[ D_0(q)(r_0)(k - q) - D_0(q)(r_0)(F_0(k - q)) \right]^2,$$

$$\frac{f^2}{|1 - V_L(k - q)|^2 \left( (1 - \cos^2 \theta) \right)} \times \sum_{\kappa} \sum_{\gamma} \sum_{\eta} |\gamma| ^2,$$

where $D_0, F_0$ are the same functions $D_0, F_0$ but substituting $\vec{q}$ by $\vec{q}^2 + q^2$ with $q$ $\simeq$ 780 MeV. On the other hand, the sum and average over $|\gamma|$ in Eq. (14) is given by Eq. (7) multiplying each one of the terms in the second member by the corresponding factor $P_1, P_2, P_3$ of Eqs. (13) and omitting the factor $F_0^2(k - q)$, which now appears explicitly in Eq. (14) and is affected by the correlations.

We now split $\Pi_{\pi}^*$ in the numerator of Eq. (14) into the three components of Eq. (11). Below pion threshold we have $\text{Im}\Pi_{\pi A}^* = 0$, and then the contributions proportional to $\text{Im}\Pi_{\pi A}^*$ or to $\text{Im}\Pi_{2p2h}^*$ correspond to photon absorption by two nucleons and three nucleons respectively, since one extra nucleon is implicit in $\text{Im} U_N(k - q)$. As we have commented in former sections the two nucleon contribution is the one considered in Ref. [6] while the three nucleon contribution, obtained from the term proportional to $\text{Im}\Pi_{2p2h}^*$, will be new.

We shall also extrapolate the results of this new channel to energies a bit above pion threshold. Here one must deal also with the pion production channel. In this case, since
\[ \text{Im} \Pi^{\sigma}_{2\Delta} = 0 \text{ when the pion is on shell (no pion absorption by one nucleon), there is no admixture between the pion production mode and the two nucleon absorption channel. However, since Im} \Pi^{\sigma}_{2\Delta} \neq 0 \text{ when the pion can be on shell, the two modes are mixed and a separation must be made. In Ref. [7] this is done with the help of Monte Carlo simulation, by letting a pion be produced according to the probability given by the diagram of Fig. 1(a), then propagate through the nucleus and eventually be absorbed by two nucleons. As we mentioned, this gives rise to the phenomenon of indirect photon absorption. At very low pion energies we can take advantage of the fact that pions are little absorbed to make a simplified, yet realistic, calculation.}

The first step is to add the pionic decay channel of Fig. 1(a) to our results of Eq. (14). This is easily done by means of

\[ \text{Im} \Pi^{\sigma}_{13}(k) = -\int \frac{d^4k}{(2\pi)^4} \text{Im} \mathcal{U}_{N}(k-q)\theta(k^0 - q^0)\theta(q^0)
\]

\[ \times F^2_q(k-q)\text{Im} D_q(q)\sum_{\lambda} \sum_{\mu} \sum_{\eta} \hat{r}^{\lambda\mu\eta}. \]  

(15)

Although the sum of Eq. (15) and (14) seems to consist of a numerator with a \( \delta \) function, from \( \text{Im} D_q(q) \), and a broad peak, from \( [1 - V_\Delta(q)\Pi_{1\Delta}^\sigma(q)]^{-1} \), one can see, by summing analytically the two terms, that there is only a broad peak around the renormalized pion pole with a width related to \( \text{Im} \Pi^{\sigma}_{2\Delta} \). The whole strength corresponds now to a pion in the medium. However, due to the spreading in momentum space of the pion strength, some regions of the spectrum cannot show up as a physical asymptotic pion because they would violate energy and momentum conservation, and they are forced to appear as \( 2\pi \bar{\theta} \) excitations of the pionic mode. In order to evaluate the pion emission rate we take here the same prescription as in Ref. [18] which leads to realistic rates of pion emission in the \( N \) nuclear decay. For this purpose we substitute in Eq. (15)

\[ \text{Im} D_q \rightarrow \text{Im} D_q(q) \simeq -\pi \delta((q^0)^2 - \omega^2(q)) \]

(16)

where \( \omega(q) \) is the modified dispersion relation of the pion in the medium given by the solution of

\[ \omega^2(q) - q^2 - \mu^2 - \Pi_{1\Delta}(\omega(q), q) = 0. \]

(17)

The function \( \Pi_{1\Delta}(\omega(q), q) \)

\[ \Pi_{1\Delta}(q) = \frac{\Pi_{1\Delta}(q)}{1 - \frac{q^2}{m^2} \Pi_{1\Delta}(q)} \]

(18)

is the pion proper self-energy including now all irreducible diagrams not connected by one pion exchange (unlike \( \Pi^\sigma \) which excluded the diagrams connected by the full \( V_\Delta \), i.e. those connected by one pion exchange plus those connected by \( q' \)).

In order to extract the three body absorption contribution in the present case we evaluate the total \( \text{Im} \Pi^{\sigma} \) from Eqs. (14) and (15), subtract the two body absorption contribution obtained from Eq. (14) by keeping only \( \text{Im} \Pi_{1\Delta}(k) \) in the numerator, and then subtract the pionic contribution with the prescription given above. The results are discussed in the next section.

The question of three body absorption at higher energies has an easy answer since we know that at energies 300 MeV < \( E_{\pi} < 500 \) MeV photon absorption is dominated by the \( \Delta \) terms (see again Fig. 1 of Ref. [6]). In pion nucleus scattering the three body absorption has a maximum of about 60% of the total at energies \( \omega_{\pi} \approx 400 \) MeV. Here we should expect the same at photon energies around \( E_{\gamma} = 400 \) MeV the total absorption is \( \Delta \) dominated in about 90%. As a consequence we expect a curve for the ratio of direct two body photon absorption to the total direct absorption pretty much the same as the one given in Fig. 12 (solid line) of Ref. [2].

The \( \Delta \) excitation contribution to the photon selfenergy is given by Eq. (14) of Ref. [6], which we reproduce here for the sake of completeness

\[ \text{Im} \Pi^{\Delta}(k) = -4 \int \frac{dp}{(2\pi)^3} n(p) \times \left\{ \frac{1}{\mu} \right\} \left[ f_1 \right] \left[ \frac{1}{9} \right] \frac{1}{\sqrt{s} - M_\Delta + \frac{1}{2} f(k+p) - \Sigma_\Delta(k+p)} \right\} \]

(19)

where \( f_1 = 0.12 \) is the \( \gamma N \Delta \) coupling constant, \( f \) is the momentum of the nucleon in the Fermi sea, \( k_{cm} \) the photon momentum in the \( \gamma N \) center of mass system, \( \Sigma \) the Pauli
corrected $\Delta$ width and $C_{g}, C_{g2}, C_{g3}$ coefficients of the terms of the imaginary part of the $\Delta$
selfenergy related to the ($\gamma, \pi$) channel, two body and three body absorption respectively.
Analytical parametrizations of these coefficients can be found in Ref. [27].

In Eq. (19) the term proportional to $C_{g2}$ gives the contribution to direct two body absorption and the one proportional to $C_{g3}$ to direct three body absorption when $\Pi^{(3)}(k)$ is
integrated over the nuclear volume as indicated in Eq. (1). The results for the total $\gamma$ cross
section and direct photon absorption can be found in Ref. [6]. In next section we show the
splitting of this cross section in two and three body contributions.

IV. RESULTS AND DISCUSSION.

Our results for direct two and three nucleon photon absorption are shown in Fig. 5 as
a function of the photon energy for two different nuclei, $^{12}\text{C}$ (full line) and $^{208}\text{Pb}$ (dashed line). We observe that the two body absorption results are consistent with those obtained
in Ref. [6]. The three nucleon absorption cross section is very small, of the order of $2-12\%$
of the two nucleon absorption channel in the range $100 \text{ MeV} < E_\gamma < 200 \text{ MeV}$. These
results show that photon absorption around pion threshold is essentially a two body process
(leving apart final state interaction of the nucleons) and strengthens the results obtained in
Refs. [6] and [7].

One can wonder why these results are so much smaller than those obtained in Ref. [8]. For
this purpose let us recall that several approximations were done in Ref. [8] which necessarily
lead to a larger three nucleon absorption rate. On the one hand a constant density $\rho = \rho_0$
was used in Ref. [8], while we use here the local density approximation. Since the three body
absorption terms are of order $\rho^3$, one can see from Eq. (1) that $\sigma_{g3}$/A is proportional
to $\int d^3 \rho_0^2(r)/A = C \rho_0^2$. Using a $\rho$ dependent density we obtain $C = 0.32, 0.36, 0.66$ for $^{12}\text{C}$,
$^{16}\text{O}$ and $^{208}\text{Pb}$ respectively, while $C = 1$ for a sphere of constant density $\rho_0$. On the other
hand a pion selfenergy independent of $q^0$ is also employed in Ref. [8]. This does not provide
the necessary off shell dependence of the selfenergy needed for the present problem. As it was
shown in Ref. [18], neglecting this leads again to an overestimate of the rate. Furthermore,
the nuclear polarization effects discussed here also lead to a reduction as was shown in
Ref. [6]. The apparent good results compared to the data obtained in Ref. [8], using only
the three body absorption channel, are not surprising in view of the previous discussion and the
fact that there was a cut off parameter in Ref. [8] which was adjusted to fit the data.

In Fig. 6 we show the results for the ratio $\sigma_{g2}/\sigma_{g3}$ of three to two body direct photon
absorption in $^{12}\text{C}$ as a function of the photon energy. A very similar ratio is obtained for
heavier nuclei like $^{208}\text{Pb}$.

The curves in Fig. 6 are obtained as follows. The line spanning from $E_\gamma = 100 \text{ MeV}$ to
230 MeV corresponds to a calculation in which only the Kroll Ruderman and pion pole terms
are included in the $\gamma N \rightarrow \pi N$ amplitude. These are the dominant ones for energies around
pion threshold. The line spanning from $E_\gamma = 180 \text{ MeV}$ up to 540 MeV corresponds to photon
absorption led by the $\Delta$ excitation terms alone which are calculated from Eq. (19). These
two curves are dominant at low ($< 150 \text{ MeV}$) and high energies ($> 300 \text{ MeV}$) respectively
and, as we see in the figure, they cross each other around $E_\gamma = 210 \text{ MeV}$ which is also a
transition point for the dominance of the two types of mechanisms. A calculation containing
all terms together would merge the results of Fig. 6 into a continuous curve which would
show up as a smooth interpolation between the two curves around the crossing region. This
is indicated by the dashed line, which is merely a guide to the eye. Hence, the line in Fig. 6
spanning from $E_\gamma = 100 \text{ MeV}$ to 550 MeV gives a fair account of the predictions of the model
of Ref. [6] complemented with the background three body absorption terms introduced in
the present work. We can summarize our findings by saying that two body absorption is
dominant at low energies but from energies $E_\gamma \approx 400 \text{ MeV}$ on the three body contribution
is sizable and comparable, even bigger, than the two body one, as was also found for three
body pion absorption [2].
V. CONCLUSIONS

In view of theoretical claims [8] that photon absorption at energies around pion threshold is dominated by three nucleon absorption and the contradiction with other theoretical claims [6] that it is given by two body absorption, we carried a thorough investigation of the three nucleon channel incorporating all the theoretical ingredients that have proved relevant in recent studies of photon nucleus interaction. The experience gained in the study of one nucleon and two nucleon induced Λ decay [16,18], which is analogous to the present problem, was of much use. The results obtained here give photon absorption rates by three nucleons which are of the order of 10% or less than the two body one around pion threshold and stresses the two body dominance of the photon absorption mechanisms at these energies. The large results obtained in Ref. [8] were traced back to different approximations used there, all of which magnified the relevance of the three body channel. At large photon energies dominated by Λ excitation the situation is different and, analogously to the results obtained in pion absorption, which uses the same input for the Λ selfenergies as the study of photon absorption in Ref. [6], one finds here that the ratio of three body absorption to two body absorption increases smoothly from a few percent at energies around pion threshold up to a ratio close to 1.5 at photon energies around 400 MeV, or equivalently, three body absorption represents there about 60% of the total absorption.

We expect that the coming photon experiments will bring light into this issue much as the experiments in Ref. [1] have brought much light into the question of the number of pions involved in pion absorption.

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REFERENCES

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FIGURES

FIG. 1. (a) Photon self-energy diagram obtained by folding the $\gamma N \rightarrow \pi N$ amplitude. The circle indicates the sum of the terms of this amplitude. (b) Photon self-energy diagram obtained from the one in (a) when the pion is allowed to excite a ph. The cut in the figure (dotted line) corresponds to two-nucleon photon absorption.

FIG. 2. Diagrammatic representation of the $\Delta h$ photonuclear excitation piece, including $\Delta h$ self-energy corrections. The dotted lines indicate the sources of imaginary part of the photon self-energy when the internal lines cut by the dotted line are placed on shell. The cut in (a) accounts for the $(\gamma, \pi)$ channel, the one in (b) for $\gamma$ absorption by two nucleons, the one in (c) for corrections to $(\gamma, \pi)$ when the pion, in the pion exchange included as part of the interaction, is placed on shell. The cut in (d) accounts for 2p2h1$\pi$ excitation. The cut in (e) accounts for $\gamma$-absorption by three nucleons.

FIG. 3. Photon self-energy diagram accounting for the three body absorption discussed in Ref. [8].

FIG. 4. Photon self-energy diagrams, with Kroll Ruderman and pion pole terms in the $\gamma N \rightarrow \pi N$ amplitude, showing the medium polarization through RPA $\phi h$ and $\Delta h$ excitations induced by the pion.

FIG. 5. $\sigma_{ph}/A$ as a function of the photon energy for direct two body and three body absorption. Upper two lines: two body absorption. Lower two lines: three body absorption. Dashed lines are for $^{208}$Pb and full lines for $^{12}$C. Only the Kroll Ruderman and pion pole terms are included in the $\gamma N \rightarrow \pi N$ vertex.

FIG. 6. $\sigma_{3B}/\sigma_{2B}$: Ratio of three to two body direct photon absorption in $^{12}$C as a function of the photon energy. See explanation in the text.
Figure 1

Figure 2

Figure 3

Figure 4