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Photonuclear Interaction of N≠Z Light Nuclei Using Few-Nucleon Correlated Structures

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The energetic photons in the quasi-deuteron region are expected to interact with few-nucleon correlated structures and clusters present in light nuclei. Hence, the photonuclear reaction cross-section for light nuclei like ^{6}Li, ^{7}Li, ^{7}Be, ^{12}C, ^{15}N, ^{16}O etc., can be evaluated by summing the cross-sections of their constituent 2N, 3N correlated structures, and α-clusters. After a detailed analysis of the photonuclear processes for deuteron, tritium, ^{3}He, and ^{4}He and assuming that the photonuclear cross-section of quasi-deuterons/quasi-tritium/quasi-^{3}He and α-cluster can be evaluated by scaling the appropriate expressions for their free counterparts, we have obtained the photonuclear reaction cross-sections for light nuclei ^{7}Li, ^{7}Be, and ^{15}N. The (γ,N) contribution from quasi-α structures themselves may account for a significant fraction of the GDR cross-section. The present work proposes a modification of the quasi-deuteron model of Levinger for light nuclei by considering quasi-tritium and quasi-^{3}He structures along with quasi-deuteron structures. Some of the testable predictions for the current approach are also outlined.

Keywords: Nuclear photo-disintegration, Nuclear reaction, Nuclear structure

1 Introduction

Theinteraction of photons with nuclei in the energy range of 40 to 140 MeV is well understood in the quasi-deuteron model (QDM) of Levinger[1] proposed in 1951. It envisages the formation of n-p quasi-deuteron structures whose average separation is less than the average NN separation inside nuclei[1]. The electric dipole interaction (E1) of energetic photons with these short-ranged structures would eject correlated protons and neutrons in the quasi-deuteron region. The predominance of the quasi-deuteron mechanism has been verified by many subsequent experiments[2-6]. Subsequent investigations revealed that the two-nucleon short-ranged structures are essential for understanding the interaction of pions with nuclei[7], sub-threshold production of particles in hadron-nuclei collisions [8] and understanding the energy profile of backscattered hadrons from nuclei[9]. The short-range correlations have been further quantified by recent measurements in BNL, USA and JLab, USA, using proton and electron beams[10-11]. These experimental and theoretical investigations are reviewed in a recent paper by Dalal and Macgregor[12].

Pauli's principle does not restrict the neutron-proton interaction inside nuclei and will be enhanced by their opposite surface charge densities. Due to this, the neutrons and protons occupying similar states in N=Z nuclei will form quasi-deuteron-like structures. Using this argument, an empirical photonuclear reaction model was proposed for N=Z light nuclei[13-14]. In this model, the well-known expressions for electric dipole E1 and magnetic dipole M1 photodisintegration processes for the free deuteron have been used to compute the $\sigma(\gamma, \mathrm{np})$ cross-section values for the quasi-deuterons by suitably scaling the n-p separation energy and effective n-p separation distance. The proposed approach has many advantages; (i) It accounts for $\sigma(\gamma, \mathrm{np})$cross-section values in a coherent manner from its threshold energy to the pion production threshold. (ii) The cross-section thus obtained does not require the Levinger damping factor[15], or Pauli's blocking function[16]. The Levinger damping factor was introduced by Levinger to account for the significantly lower (γ, np) cross-section (compared to QDM predictions) at lower photon energy (E_γ <60 MeV). Similarly, the idea of Pauli's blocking was introduced to account for the mismatch between observed and predicted cross-section values by QDM. (iii) It provides a microscopic origin of the Levinger constant straightforwardly. (iv) Unlike the Levinger model, thequasi-deuteron pairs occupying

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different energy levels can be handled separately in this model. For example, in ^{6}Li, the outer loosely bound n-p quasi-deuteron can be treated differently from n-p quasi-deuterons from core-alpha by using different n-p separation energy values, and the enigmatic double-peak structure in ^{6}Li photonuclear excitation function can be accounted[13-14].

We have extended the above-mentioned photonuclear reaction model for the N≠Z light nuclei inthe present work. For $N = Z$ light nuclei, the contribution of the single-nucleon ejection$(\gamma, n/p)$ process is only a few percent of the overall photonuclear cross-section in the quasi-deuteron region, and gamma interaction is predominantly with 2N quasi-deuteron structures[6,14]. Now, if one neutron is added to such a nucleus, the valence neutron may interact with the outermost quasi-deuteron and would result in the formation of a 3N quasi-tritium structure. An illustrative example of this mechanism is inthe ^{7}Li nucleus, where the additional neutron in ^{6}Li forms a quasi-tritium outside the core-α. The core-α+quasi-tritium approximation of the ^{7}Li nucleus has been verified by theoretical[17]and experimental means [18]. Similarly, an additional proton in ^{6}Li would result in a 3N quasi-^{3}He structure with core-α for^{7}Be. As a reasonable approximation, the photonuclear cross-section in the quasi-deuteron region is insensitive towards the shell structure of nuclei and dependent on the presence of short-ranged 2N (and possibly 3N) structures. Hence, the photonuclear cross-section in this energy region can be estimated by adding the respective cross-section values for the short-ranged structures. In the next section, the photonuclear processes for free deuteron, tritium, and ^{3}He are discussed and compared with the measured value. The expressions thus obtained can be used to infer the photonuclear cross-section for their counterparts inside nuclei, i.e., quasi-deuteron, quasi-tritium, and quasi-^{3}He, using suitable separation energy and scale factors. A brief description of$\sigma(\gamma, N)$ calculation for ^{4}He is also given, which has been used to infer the corresponding cross-section value for quasi-alpha structures inside light nuclei. These results are used to calculate the photonuclear cross-section for light nuclei ^{7}Li, ^{7}Be, and^{15}N.

2 Method and Result

The theoretical framework for the photo-disintegration of free deuteron through the(γ, np) channel is well-established theoretically[19-20]. The electric dipole $\sigma_{\mathrm{ED}}$and approximated magnetic dipoleσ_{MD} contributions for the photonuclear$d(\gamma, np)$ process are given by;

$$\sigma_{\mathrm{ED}} = \frac{8\pi}{3}\frac{e^2}{\hbar c}\lambda^{-2}\left(\frac{k\lambda}{k^2+\lambda^2})\right)^3 \frac{1}{1-\lambda r_{0t}} \times 10^4 \qquad \dots (1)$$

$$\sigma_{\mathrm{MD}} = \frac{2\pi}{3}\frac{e^2}{\hbar c}\left(\frac{\hbar}{Mc}\right)^2 \left(\mu_n - \mu_p\right)^2 \frac{k\lambda(1-\lambda a_s)^2}{(k^2+\lambda^2)(1+k^2 a_s^2)} \qquad \dots (2)$$

where $k = \sqrt{\frac{mc^2 \times (E_\gamma - \mathrm{B.E.})}{(\hbar c)^2}}$, $\lambda = \sqrt{\frac{mc^2 \times \mathrm{B.E.}}{(\hbar c)^2}}$ with B.E. as the binding energy of the deuteron, r_{0t} is the effective range of the triplet state, $\mu_{n,}$ and μ_p are the magnetic moments of the neutron and proton, while a_s is the singlet state scattering length of the deuteron.

Since the quasi-deuteron structures are similar to those of the free deuteron, the $\sigma_{\mathrm{ED}}(\gamma, np)$ and $\sigma_{\mathrm{MD}}(\gamma, np)$ contributions for the quasi-deuteron photo-disintegration will be given by similar expressions, i.e. Eqs. 2 and 3 with appropriate n-p separation energy and effective range/size-parameter $r_{0t.}$ The approximate n-p separation energy of quasi-deuterons inside nuclei can be estimated from binding energy data. The effective range r_{0t} of the quasi-deuteronis related to the size of the n-p system, and its value will reduce with the increase in n-p separation/binding energy. The $\sigma_{\mathrm{ED}}(\gamma, np)$ variation for three representative cases having different n-p separation values is shown in Fig. 1. A cross-section variation can also be obtained for $\sigma_{\mathrm{MD}}(\gamma, np)$[13]. However, it has been observed that $\sigma_{\mathrm{ED}}(\gamma, np)$ is the dominating contributor toward $\sigma(\gamma, np)$ process, and MD contribution can be neglected[14] for most purposes.

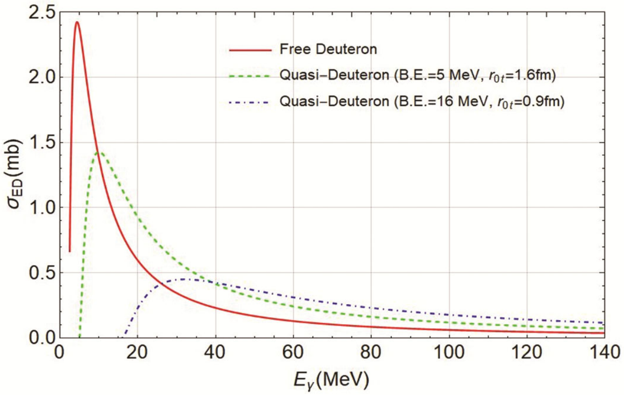

Fig. 1 — The ED contributions to photonuclear cross-section for free deuteron andquasi-deuteron configurations for np separation energy of 5 MeV and 16MeV[13]

The structure of the three-nucleon system tritium and ^{3}He has been the subject of intense study due to its potential to shed light on 3N forces[21]. Again, neglecting shell structure, we are concerned with the possible short-range interaction of nucleons for these nuclei. The probability of NN short-ranged interaction between like nucleons, i.e. neutron-neutron (n-n) and proton-proton (p-p)in nuclei, is only a few per cent of that of neutron-proton (n-p)[6,11-12]. Neglecting long-range pairing interaction between n-n, the proton in ^{3}H is expected to be in a singlet and triplet configurations with two neutrons at a given time[21]. The interacting gamma photon would interact and dissociate either the singlet n-p bond (with the second neutron in a triplet configuration with the proton) or would interact and dissociate thetriplet bond (with the second neutron in a singlet configuration with the proton) in tritium. In the case of gamma photon interaction witha singlet n-p bond in ^{3}H, it would result in the (γ, nd) outcome since the remaining n-p structure is in a triplet configuration, which is equivalent to a free deuteron. In the case of gamma photon interaction with the triplet n-p bond, it will result in a free neutron and n-p structure having a singlet unstable bond, leading to (γ, nnp) outcome. The interaction probability of gamma photon with a single/triplet bond of ^{3}H can be inferred from the free deuteron expressions Eqs. 1 and 2 with the appropriate separation energy (required to break n-p bond) and reduced mass of the separating $n + np$ system, which is equal to 2M/3 (In case of deuteron, reduced mass is M/2). As discussed in our previous work[13], the effective range r_{0t} is dependent on the n-p separation energy. The maximum value of r_{0t} is taken for deuteron (which is the most loosely bound n-p system) while a minimum value of 0.8 fm is taken for ^{4}He (which has a very large n-p separation energy of about 26 MeV). For all other cases, the intermediate r_{0t}value is used. The calculated two-body photonuclear reaction cross-section $\sigma_{^3\mathrm{H}}(\gamma, \mathrm{nd})$ and three-body photonuclear reaction cross-section $\sigma_{^3\mathrm{H}}(\gamma, \mathrm{npn})$for different E_γ values are shown in Fig. 2. Except for slightly different energy thresholds, the cross-section values and trends for two- and three-body photo-disintegration processes are similar. This is in accordance with the measurements[22]. The combined photo-disintegration cross-sectionσ_{tot} for ^{3}H is also plotted in figure 2, along with the experimentally measured values[22-23]. A fairly good agreement between the measured and calculated values has been observed.

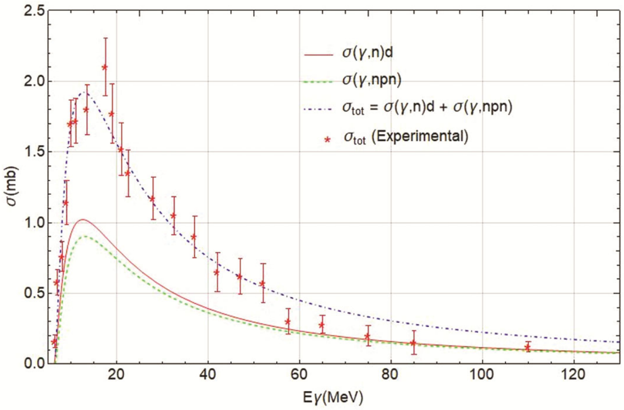

Fig. 2 — The two- and three-body photo-nuclear cross-section vs E_γ plot for ^{3}H

A comparison of total photonuclear cross-section and experimental results[22] is also given in the Fig. 2. The two- and three-body photonuclear cross-section for ^{3}He can be obtained using similar arguments. Except for the small Coulomb correction due to the outgoing proton, the photonuclear cross-section values are expected to be similar to that of ^{3}He. This is in accordance with the measured results[23-24].

The long-range pp and nn pairing interaction, along with strong n-p interaction between n-p occupying similar orbitals, would lead to the formation of spin-0 quasi-α structures in nuclei. The single-nucleon photo-ejection cross-section $\sigma(\gamma, N)$ for quasi-α structures is modelled using calculations of Gunn-Irving[13-14,24] for an α-particle. The Gun-Irving calculation for the $\sigma(\gamma, \mathrm{N})$ process for ^{4}He requires appropriate size parameters for α and residual^{3}H/^{3}He. The systematic comparison of calculated σ(γ, N) values for the ^{4}He nucleus with their measured counterparts led to the estimation of size parameters for ^{4}He and resulting product nuclei ^{3}H/^{3}He[13-14]. The framework, thus developed, has been used for the $\sigma(\gamma, N)$calculations for the quasi-alpha structures inside nuclei as described in our previous work[13-14]. The cross-section for the (γ, n) channel is considered equal to that of the (γ, p) channel by neglecting the small Coulomb effect of the outgoing proton and ^{3}H. At sufficient photon energy, the (γ, n), (γ, p), and (γ,np) channels would be contributing simultaneously, and σ_{tot} for ^{4}He (or quasi-α) is obtained by adding these individual cross-sections[13-14].

The ^{7}Li structure can be approximated by core-α and loosely bound outer quasi-tritium[17-18]. The σ_{tot} for ^{7}Li would be the sum of individual photonuclear cross-sections of quasi-tritium, quasi-α, and possible low-energy contributions from the ^{7}Li(γ,^{3}H)^{4}He channel. The ^{7}Li(γ,^{3}H)^{4}He channel is of astrophysical importance and has been investigated theoretically and experimentally[23,25]. This channel has a peak value between 1.5 to 2.0 mb below Eγ of 20 MeV, which decreases rapidly with Eγowing to the large size parameters of interacting particles. The photonuclear cross-sections for quasi-tritium, quasi-α and their sum, along with experimental values, is depicted in Fig. 3. Except for the discrepancy below Eγ<20MeV (due to the contribution from the ^{7}Li(γ,^{3}H)^{4}He channel, which is not calculated in the present work but can be found in[25]), the calculated and measured values are in fairly good agreement. Similarly, the structure of ^{7}Be can be approximated by a core-α and loosely bound outer ^{3}He. The total photonuclear cross-sectionσ_{tot} for the ^{7}Be nucleus can be evaluated in a similar manner and is expected to be similar to that of ^{7}Li. However, photon interaction with quasi-tritium in ^{7}Li results in (γ,npn) and (γ,nd) channels, while photon interaction with quasi-^{3}He in ^{7}Be will result in (γ,pnp) and (γ,pd) channels with almost equal strength (a possible role of secondary interactions is not considered here). A photonuclear reaction measurement using quasi mono-energetic photonsources using laser Compton backscattering process[26] E_γ<20MeV (below activation energy of photonuclear channels from core-α) could distinguish these outcomes.

A comparison of the total photonuclear cross-section and experimental results[22]is also given in the Fig. 3. Total photonuclear cross-section includes all possible channels as described in the text of the present work and in reference[22].

Similar arguments could estimate the photonuclear cross-section for other lighter nuclei. For example, the structure of ^{15}N can be approximated with three quasi-α structures and quasi-tritium. A detailed discussion about photonuclear cross-section in terms of (γ,N) and (γ,np) channels for these is given in our previous work[14]. A comparison of calculated and measured results is given in Fig. 4. A possible low energy discrepancy may be due to ^{15}N(γ,^{3}H)^{12}C channel, which is not added intoσ_{tot}. Photonuclear measurement for channels (γ,N), (γ,nd) and (γ,^{3}H) using photons of energy E_γ<20MeV could confirm the proposed approach. The experimental and theoretical estimates vary significantly for higher gamma energy values. It appears that the size of quasi-alpha structures inside the^{15}N nucleus is significantly different compared to free alpha, leading to a significant difference in experimental and theoretical values. Such a variation was also observed for the^{12}C nucleus in our earlier work[14]. Further investigation of this behaviour is ongoing.

A comparison of the total photonuclear cross-section and experimental results[22]is also given in the Fig. 4. The total photonuclear cross-section is obtained by combining the contributions of all of the above-mentioned channels.

Apart from the photonuclear response of light nuclei, the present work proposes an important modification to the Levinger Quasi-Deuteron Model (QDM)[1], which predicts that (γ,np) will be the dominant reaction channels for E_γ between 40 and 120 MeV. In neutron/proton rich light nuclei, along with quasi-deuteron structures, quasi-tritium/^{3}He structures are also expected. These 3Nquasi-tritium/^{3}He structures can disintegrate through two-body $(\gamma,\mathrm{nd})/(\gamma,\mathrm{pd})$ and three-body $(\gamma,\mathrm{npn})/(\gamma,\mathrm{pnp})$ reaction channels. Coincidence measurements

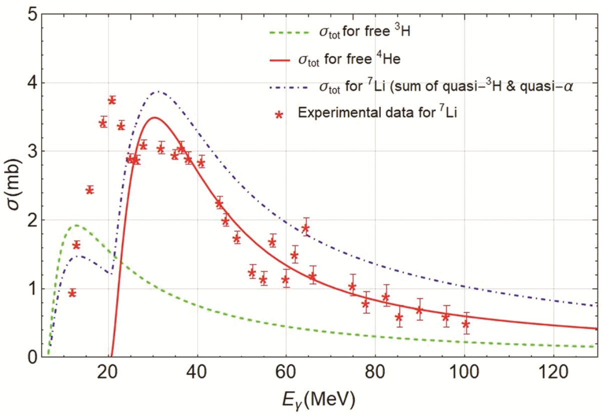

Fig. 3 — The photonuclear cross-section vs E_γ plot for tritium, ^{4}He and^{7}Li (sum of quasi-tritium and core quasi-α)

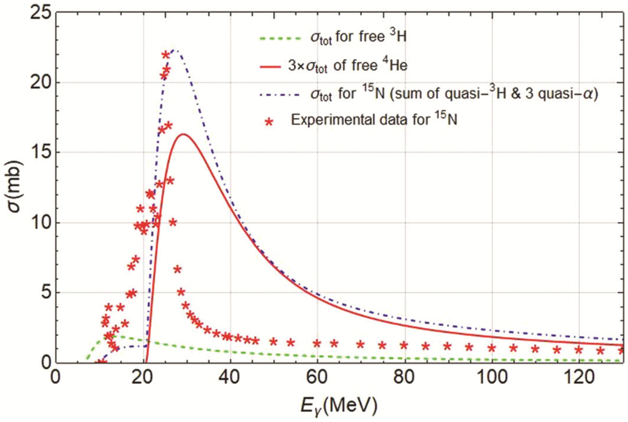

Fig. 4 — The photo-nuclear cross-section vs E_γ plot for tritium, ^{4}He (multiplied by 3) and^{15}N (sum of quasi-^{3}H and three quasi-α)

of kinematically correlated outgoing reaction products on light and mid-mass nuclei targets can decisively verify this prediction. For such nuclei, the photonuclear reaction will lead to enhanced deuteron production (compared to N=Z nuclei). This has been a well-known result for the ^{6}Li/^{7}Li nuclei, but it should be true for other light nuclei too. For heavy nuclei, a strong coulomb barrier, a significant amount of secondary interactions of initial reaction products, and low binding energy of the deuteron (leading to an easy breakup of the outgoing deuteron) would alter the final outcome of the reaction.

3 Summary

Building on our previous work, we have calculated the photonuclear cross-section of some of the light nuclei in terms of underlying quasi-deuteron, quasi-tritium/quasi-^{3}He and quasi-α structures. The present work highlights the importance of a few-nucleon structures in understanding the photonuclear interaction of light nuclei in the quasi-deuteron region. Along with quasi-deuteron structure, 3N quasi-structures should be included for a proper description of photonuclear reactions of light nuclei.Some of the possible experimental tests of the proposed approach are also highlighted. A possible extension of the present approach for heavy ions is currently being developed.

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