Photodisintegration of N=Z light nuclei below Pion-threshold

Rajesh Beniwal[1*], Bhupesh Khyalia[1], Ranjeet dalal[1],
[1]Guru Jambheshwar University of Science and Technology, Hisar - 125001, INDIA
. * email: rajubeniwal666@gmail.com

Introduction

The photo-disintegration of nuclei using photons of energy (Eγ) between 10 to 140 MeV has been an important tool to investigate the NN correlations and structure. In GDR region for Eγ between 10-40 MeV, the nuclear photo-disintegration takes place mainly through (γ, N) channel and is considered due to the collective vibrations of protons with respect to neutrons, either globally or on a local scale. Above 40MeV, the (γ, np) channel dominates for which Levinger [1] in 1951 formulated a phenomenological quasi-deuteron model (QDM) assuming that neutrons and protons are forming quasideuteron like structures inside nuclei. The resulting model, clearly at odds with the shell model, has been quite successful in explaining the interaction of energetic photons with nuclei. The $\sigma(\gamma, np)$ in QDM region for nucleus ${}^{A}_{Z}X$ is given by [1];

$$\sigma_{\gamma,np} = L\,\frac{NZ}{A}\,\sigma_d \qquad (1)$$

Where L is Levinger constant and σ_d is photo-disintegration cross-section for free deuteron.

The presence of quasideuterons or spatially correlated neutron-proton structures (or np SRCs) inside nuclei has been confirmed by pion interaction with nuclei where pion absorption take place mainly through 2N absorption mechanism. The dominance of np SRCs has been confirmed using energetic e^-/p collisions with nuclei in Jefferson Lab and BNL [2].

Since the neutron (n) and proton (p) are two different type of fermion, they would be occupying the similar orbitals in N=Z nuclei leading to stronger NN interaction between such n & p. There will be additional interaction between these n-p pairs due to the negative charge density in neutrons near surface and positive charge distribution in protons. Moreover, pairing of these n-p pairs would leads to quasi-alpha type structures inside different orbitals. In present work, we have assumed that incoming energetic photons would either interact with one of such np pair/quasi-deuteron leading to (γ, np) process or it would interact with quasi-alpha structures leading to (γ, N) process. The quasi-deuteron breakup cross-section is computed using well known ED and MD contributions [3] for free deuteron but suitably scaling the n-p separation energy and size parameters. Since ED contribution for (γ, np) process dominates, we have neglected the MD contribution here. The $\sigma(\gamma, N)$ calculation for ^{4}He and quasi-alpha structures is carried out using Gunn and Irving [4] approach for ^{4}He. After understanding the effect of the size parameters on the shape and magnitude of photodisintegration cross-section, we have calculated total σ_{tot} by adding both of these contributions.

In Gunn and Irving approach, neglecting Coulomb interaction of outgoing proton, we have $\sigma_{(\gamma,n)} \cong \sigma_{(\gamma,p)}$. Hence, $\sigma(\gamma, N) = \sigma(\gamma, n) + \sigma(\gamma, p) \cong 2 \times \sigma(\gamma, n)$. The photo-disintegration cross-section assuming exponential wavefunction for ^{4}He is;

$$\sigma_{\gamma,p} = \frac{7\times 4^{11}\pi}{3^9\sqrt{2}}\, e^2\, M^{\frac{5}{2}} \frac{\mu_\alpha^7}{\mu_T^{14}}\, k E^{\frac{3}{2}}\, z^{20}\, \{f(z)\}^2 \qquad (2)$$

Where z and f(z) are defined by;

$$\frac{1}{z^2} = \frac{2ME}{3{\mu_T}^2} + \frac{4{\mu_\alpha}^2}{3{\mu_T}^2} - 1$$

$$f(z) = \frac{735 + 346z^2}{8} + \frac{21}{1+z^2} + \frac{2}{(1+z^2)^2} - \frac{3\cot^{-1} z}{8z}(1155z^4 + 630z^2 + 35)$$

with S_n = Neutron separation energy, μ_α = Size of the alpha particle and μ_T= Size of the remaining tritium, after ejection of neutron from ^{4}He.

The $\sigma(\gamma, np)$ contribution for quasi-deuteron structures is calculated using [3];

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

The σ_{tot} is calculated by combining the contributions of $\sigma(\gamma, np)$ due to quasi-deuterons and $\sigma(\gamma, N)$ due to quasi-alpha contribution.

Results:

For ^{4}He, the σ_{tot} vs E_γ plot is shown in Figure 1 for different values the alpha size parameter, $(1/\mu_\alpha)$ while keeping the Tritium size parameter $(1/\mu_T)$ fixed at 5.5×10^{-13}. It can be seen that the $1/\mu_\alpha=1.7\times10^{-13}$ gives the cross-section values and their trend quite similar to the experimental data [5] as compared to other $1/\mu_\alpha$ values considered.

The ^{12}C nuclei is considered as made up of 6 quasi-deuterons and 3 quasi-alpha structures formed by their pairing. In QD region (40 < E > 150), the main contribution to the photo disintegration cross section is due to the quasi-deuteron contribution while below this range, we have dominant contribution from (γ, N) channel from quasi-alpha structures. Photo disintegration cross section for ^{12}C is calculated by using eq. 2 and 3 in which we have taken the appropriate separation energy for ^{12}C. It can be seen that initial GDR peak in σ_{tot} vs photon energy for ^{12}C (figure 2) is not reproduced by using

$1/\mu_d = 1.7\times10^{-13}$, while slightly larger value of 2.0×10^{-13}, keeping $1/\mu_T$ value fixed as 5.5×10^{-13}, can reproduced the experimental values [6] in this region. Moreover, the calculated cross-section values in QD region agree well with the measured values.

Similarly, the photodisintegration cross section of ^{40}Ca is calculated by assuming quasi-deuteron structure inside nuclei by using appropriate S_n/S_p energy. We found that the alpha size parameter ($1/\mu_\alpha = 2.3\times10^{-13}$) gives results similar to the experimental [6] one (figure 3).

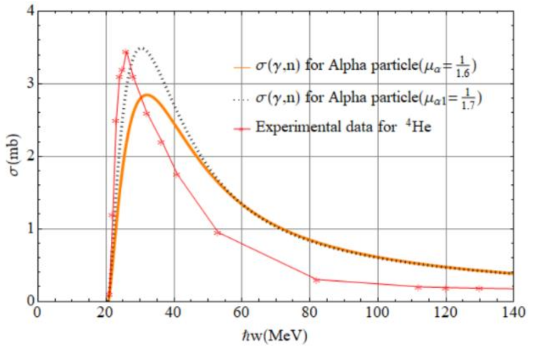

Fig. 1 Photo disintegration cross section vs σ_{tot} curve for ^4He using exponential wave function

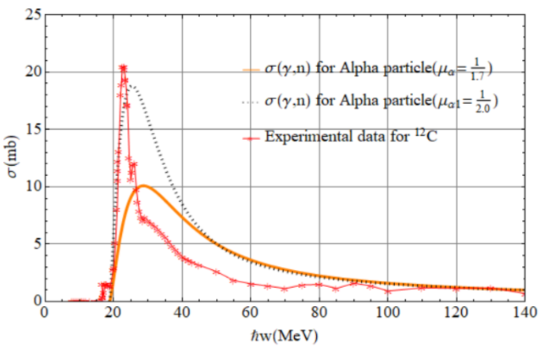

Fig. 2 Photo disintegration cross section vs σ_{tot} curve for ^{12}C

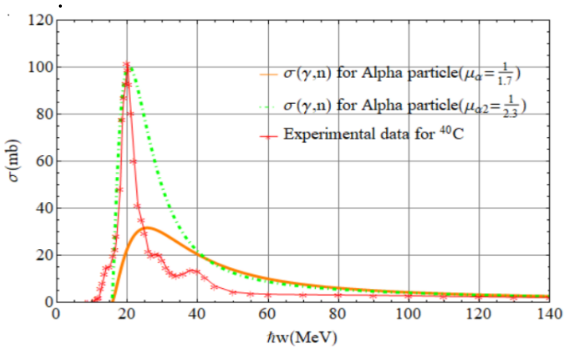

Fig. 3 Photo disintegration cross section curve vs σ_{tot} for ^{40}Ca

Summary

An empirical model is constructed for N=Z nuclei in which tightly bound np quasideuterons are considered as building block of nuclei. The photo-disintegration cross section of these nuclei is the sum of photo-disintegration due the quasideuterons and quasi-α structures formed by paired quasideuterons. The photo-disintegration of quasi-deuterons are calculated by using the well-established formulae for free-deuteron with appropriate neutron-proton separation energy and size parameter. On the other hand, the photo-disintegration of quasi-α structure is inferred from Gunn-Irving formulation for free ^4He. Interestingly, the (γ,N) process for the cluster degree of freedom results in the prominent peak structure in GDR region. Thereafter, the contribution of cluster degree of freedom decreases sharply with Eγ and quasi-deuteron photo-disintegration becomes the major contributor for $E\gamma \geq 50$MeV. The present approach illuminates the microscopic origin of quasi-deuteron formulae of Levinger and indicates that the peak structure in GDR region may be arising from the underlying quasi-α structures inside nuclei. The current photo-disintegration formalism will be extended for the mid- and heavy-mass nuclei by inclusion of three-body SRSCs.

References

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