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Photo-disintegration of N=Z light nuclei using SRC-based approach

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The outcome of any possible nucleosynthesis scenario is strongly affected by the photodisintegration of nuclei through (γ, N) and (γ, np) channels for Eγ > 10 MeV to a few hundred MeV. Though there is a wide range of phenomenological models for the estimation of excitation functions in this energy region, the exact photodisintegration mechanism is not well understood. The shell-model based approaches have not been successful even for the light nuclei of astrophysical importance like ^{6}Li. A simple SRC-based approach is employed to calculate the photo-disintegration of light nuclei in the quasideuteron region. Combining the Gunn-Irving photo-disintegration for α-cluster, the proposed approach is used to calculate the total photo-disintegration cross-sections for Eγ between 10 to 140 MeV for many of the N=Z light nuclei from ^{4}He to ^{40}Ca. Contrary to general perception, the quasideuteron photo-disintegration contribution starts in the GDR region itself and dominates for Eγ > 50 MeV. Along with many interesting new insights, the derivation of the Levinger formula is obtained without any additional assumption. A significant fraction of the photo-disintegration cross-section in GDR region may be accounted by contribution of quasi-α degree of freedom which decreases for higher Eγ. The present work suggests an alternative and viable description of photodisintegration for N=Z nuclei.

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1. Introduction

The photo-disintegration of nuclei using photons of energy (E_γ) between 10 to 140 MeV has been an important tool to investigate the NN correlations as well as nuclear structure. In GDR region for E_γ 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. For individual nucleons moving in a mean-field, as envisaged in the shell model and its variants, the interaction of energetic photons ($E_\gamma > 40$ MeV) should result in the ejection of single nucleons. Instead, careful photo-disintegration measurements observed a preponderance of spatially correlated neutrons and protons in light nuclei where transmission of protons is not suppressed significantly by the Coulomb effect. The angular distribution, cross-section as well as the ratio of ejected protons and neutrons, led Levinger [1] in 1951 to formulate the quasi-deuteron model (QDM) in which neutrons and protons are assumed to be 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 $\sigma(\gamma, np)$ values in QDM region for a nucleus ${}^{A}_{Z}X$ are given by [1];

$$\sigma_{\gamma,np} = L\,\frac{NZ}{A}\,\sigma_d \tag{1}$$

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 and resulting reaction products thereafter [2]. The inclusive and exclusive quasi-elastic reactions (p,p'NN) and (e,e'NN) with high momentum transfer have been investigated at BNL and Jefferson Lab respectively [3].

The dominance of two-body short-ranged spatially correlated n-p structures over n-n and p-p ones is expected since neutrons and protons can occupy similar quantum states in nuclei which may lead to significant overlapping of their wavefunction. Moreover, the positive charge distribution in proton and negative surface charge distribution of neutrons would further enhance the overlapping of neutron-proton wavefunction. Here, we have assumed that the presence of neutrons-protons in various nuclear orbitals is resulting in formation of quasi-deuteron structures. The $\sigma(\gamma, np)$ of these quasi-deuterons is calculated by scaling the n-p separation energy and effective range r_{0t} in well-known photodisintegration expressions for deuteron.

2. Model and results

The approximate np separation energy of quasi-deuterons inside nuclei is estimated from binding energy data. Since the effective range r_{0t} is related to the size of n-p system, its value will reduce for higher n-p separation energy. The r_{0t} value for loosely bound free deuteron system is ~1.75fm. It is assumed that for the maximum n-p separation energy for the quasi-deuterons, the r_{0t} value would be around the distance of minima in NN interaction i.e. about $\sim$ 0.8fm while intermediate values of r_{0t} can be used for the intermediate n-p separation energy values. For example, r_{0t}=1.6fm is used for the loosely bound outer quasi-deuteron in ^{6}Li while r_{0t} value of 0.8fm is used for the quasi-deuterons constituting its core α structure.

The photodisintegration cross-section is well understood for the deuteron [4]. The electric dipole (ED) contribution [4] $\sigma_{ED}(\gamma, np)$ for the deuteron photodisintegration is given by;

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

Where $k = \sqrt{\frac{mc^2\times(E_\gamma - B.E.)}{(\hbar c)^2}}$, $\lambda = \sqrt{\frac{mc^2\times B.E.}{(\hbar c)^2}}$ with B.E. as the binding energy of the deuteron and r_{0t} is the effective range of triplet state.

Apart from an initial sharp peak, the Magnetic Dipole (MD) contribution $\sigma_{MD}(\gamma, np)$ is much smaller than the ED contribution [4] and is ignored in further discussion. The ED contribution to the photo-disintegration cross-section for three representative cases is shown in Figure 1(a). Here, the initial peak in $\sigma_{ED}(\gamma, np)$ decreases progressively with increment in n-p separation energy and does have a much slower decreasing rate for higher E_γ value.

The NN pairing of nucleons together with the above mentioned quasi-deuteron structures in N=Z nuclei would lead to spin zero, four-nucleon quasi-α structures in fully-filled orbitals. For lower E_γ region between 10 to 40 MeV, the quasi-α structure would be the major contributor to the photo-disintegration cross section through (γ, N) channel due to its significantly larger size. The Gunn-Irving model [5] for photodisintegration of ^{4}He nucleus is used for the $\sigma(\gamma, N)$ modelling for the quasi-α degree of freedom. These calculations were carried out by assuming an exponential type wavefunction. For E_γ < 40 MeV, the photo-disintegration contribution of $\sigma(\gamma, n)$ and $\sigma(\gamma, p)$ from quasi-α degree of freedom is significantly higher compared to the quasi-deuterons contributing through (γ, np) process. But, the $\sigma(\gamma, n)$and $\sigma(\gamma, p)$ contributions quickly fade away at higher E_γ resulting in dominance of (γ, np) process for $E_\gamma > 40$ MeV.

The $\sigma(\gamma, N)$ value is dependent on the size parameters μ_α and μ_T [5]. Their value is estimated by systematically comparing the calculated $\sigma_{\gamma,N}$ with the measured one. Such a $\sigma_{\gamma,N}$ plot for different μ_α values is shown in Figure 1(b). The μ_α = 1/1.7 fm^{-1} and μ_T = 1/5.0 fm^{-1} values are finalized. Equal value for $\sigma(\gamma, n)$and $\sigma(\gamma, p)$ is taken by neglecting the small Coulomb effect of the outgoing proton and ^{3}H. The σ_{total} for ^{4}He is plotted in Figure 2(a) which is quite similar to the experimental results [6-7]. The quasideuteron channel contribution (γ, np) starts immediately after it becomes energetically viable. It peaks after 40MeV and skews the α-peak toward higher energy. It dominates for E_γ > 60 MeV. Above 100 MeV, the $\sigma(\gamma, N)$ contribution reduces to few percent of the σ_{total}. Interestingly, the quasi-deuteron contribution agrees well with the prediction of the phenomenological model of Levinger for E_γ > 60 MeV without any additional assumption. Below 60 MeV, the caluclated $\sigma(\gamma, np)$ values differ significantly from the Levinger model and could be used as an experimental test of the present model.

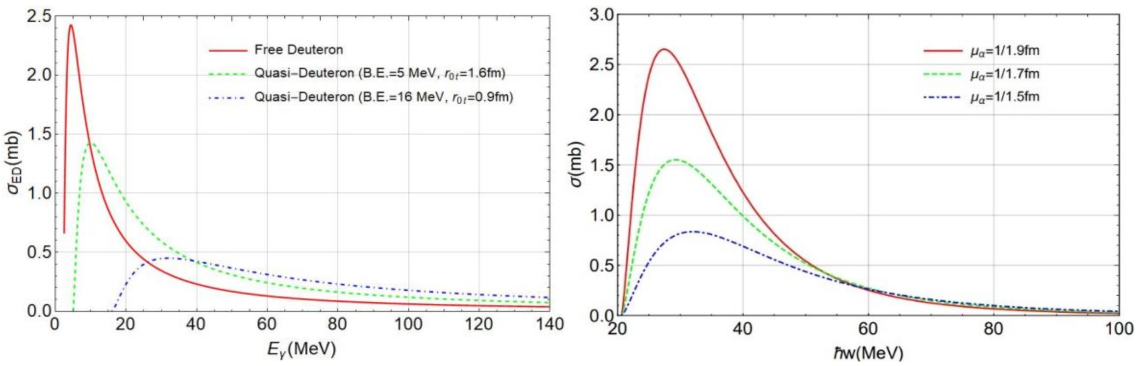

Figure 1 (a) The $\sigma_{ED}(\gamma, np)$ for free deuteron and quasi-deuterons with np separation energy of 5 MeV and 16 MeV. (b) Variation of two-body photo-disintegration $\sigma(\gamma, N)$ for different μ_α values for ^{4}He [5].

The ^{6}Li is approximated with an α-core along with a loosely bound np quasi-deuteron. The σ_{total} of ^{6}Li is the sum of the photodisintegration of quasi-α and loosely bound quasi-deuteron.

For ^{6}Li, the σ_{total} is plotted in Figure 2(b) using two n-p separation values for the outer quasi-deuteron. For each of these cases, there are two distinct peaks, one at lower energy ~ 10 MeV due to outer loosely bound quasideuteron and another at a higher energy at about 25 MeV due to the more tightly bound core alpha. The two-peak structures in σ_{total} vs E_γ plots has been reported in measurements [7-8]. Somewhat higher effective binding energy value for the outer quasi-deuteron is in accordance with the proton scattering experiments where an effective binding energy value of about 5 MeV was reported. Though the two-peak structure in σ_{total} vs E_γ is straightforward for the current model, it has been a challenging task for the ab-initio calculations [9].

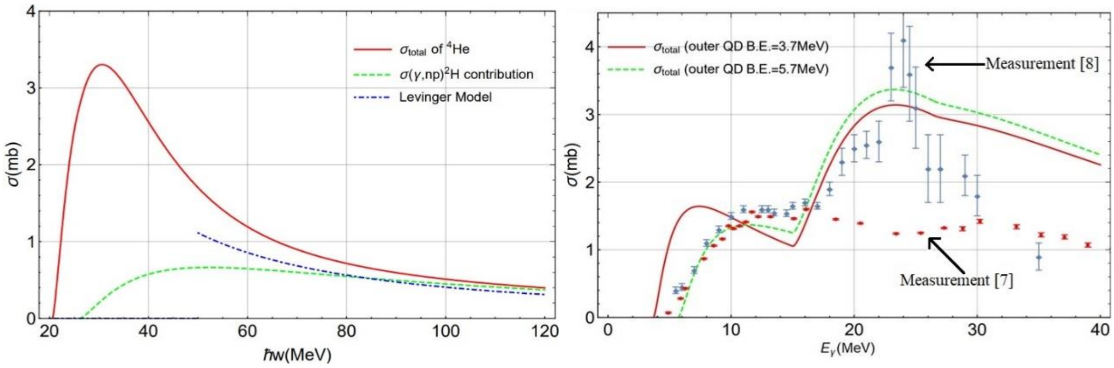

Figure 2 (Left) The σ_{total} vs E_γ plot for ^{4}He. The $\sigma(\gamma, np)$ contribution is shown separately also along with that of Levinger model prediction. (Right) The σ_{total} for the ^{6}Li nucleus for two different effective n-p separation energy values for outer quasi-deuteron along with two sets of measurements [7] & [8].

3. Summary and future outlook

Assuming quasideuteron type structures between neutrons and protons occupying same states in N=Z nuclei, the $\sigma(\gamma, np)$ is calculated from well-known results for free deuteron by appropriately scaling the n-p separation energy and size parameters. The σ_{total} 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-α structures is inferred from Gunn-Irving formulation. The (γ,N) process for the quasi-α degree of freedom results in the prominent peak structure in GDR region which decreases sharply with E_γ and (γ,np) becomes the major contributor for $E_\gamma \geq 50$MeV. The present approach illuminates the microscopic origin of QDM and indicates that the peak structure in GDR region may be arising from the underlying quasi-α structures inside nuclei. The two peak structure of ^{6}Li photo-disintegration can be understood due the contributions from outer loosely bound quasideuteron and due to core-α contributions.

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