Model independent approach to photodisintegration of ^7Li at the range of energies of interest to BBN

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Abstract

One of the elements that was synthesized primordially in the standard Big Bang Nucleosynthesis is Lithium. Lithium, being fragile gets easily destroyed at relatively low temperatures in the mixing process between stellar surface and hot internal layers. So that, at the end of the stellar lifetime the lithium content is believed to be depleted. Series of experimental measurements on lithium isotopes were carried out at High Intensity Gamma Ray Source (HIGS) at Duke Free Electron Laser Laboratory. More recently experiments [1]-[2] were performed , to measure the differential cross section of the photo-neutron reaction channel in photodisintegration of ^7Li, where the progeny nuclei is in the ground state as well as in excited states . The purpose of present contribution is to study the reaction channel $^7Li+\gamma\rightarrow{}^6Li+n$ using linearly polarized photons . The model independent irreducible tensor formalism [4]-[6] will be used to study the differential cross section of the reaction. We study the angular dependence of differential cross section by expressing differential cross section in terms of legendre polynomials. In view of the several theoretical and ongoing experimental studies, a detailed theoretical study of the spin structure of the amplitudes in $^7Li+\gamma\rightarrow{}^6Li+n$ and their expansion in terms of 'electric' and 'magnetic' amplitudes is needed to analyze the measurements of spin observables as well as differential cross section, which leads to a better understanding of the problem at astrophysical energies.

Introduction

The study of photodisintegration of lithium is important in the field of astrophysics especially to study Big Bang Nucleosynthesis and in the field of nuclear physics especially to understand the nuclear dynamics . The primordial nucleosynthesis [7]-[9], cosmic microwave background radiation [10]and Hubble expansion [11], provides an important test of Big Bang Cosmology, which has entered the precision era [12] . As the Universe cools from an astounding $10^{32}k$ to approximately 10^9k in the first three minutes, four light nuclei namely ^2H,^3H,^4He and ^7Li are produced in significant amounts which depend on the primordial baryon density Ω_B.The observational data and prediction for primordial abundances of D and ^4He are in good agreement; however primordial ^7Li is overestimated by a factor of 3. This is known as cosmological lithium problem [13]. A new solution to the cosmological lithium problem was suggested [13]and it was found that there is an excellent agreement for D, ^4He and ^7Li predicted and observed primordial abundances for the range of values $1.069 \le q \le 1.082$. WMAP measurements infer that the ^7Li abundance factor is two or three times larger than that inferred by low metallicity halo stars. To solve this problem several methods were introduced, one such is CMSSM (constrained minimal super symmetric standard model) coupled to gravity [14]. It is observed by several studies [15]-[16] that, it is difficult to find the solutions to the problems of ^6Li and ^7Li abundance.

Theoretical Studies

- The mirror radiative capture cross section reaction of $^7Li(n,\gamma)^6Li$ and $^7Li(\gamma,p)^7Be$ has been analyzed by Gammow shell model[3].
- Potential cluster approach described $^7Li(\gamma,n)^6Li$ process where ^7Li nucleus with M1 and E1 transitions are allowed-total and differential cross sections are calculated [19].
- There are several other theoretical studies on lithium has been carried out using effective field theory. [20].

Experimental Studies

- The experimental group at the Duke Free Electron Laser Laboratory have carried out series of measurements on the light nuclei using High Intensity Gamma Ray Source (HIGS) [1]-[2]. The absolute cross section has been studied for various photon energy between 10 to 35 MeV [1]. They have also studied the cross sectional dependence on the polar angle. The experimental group [2] have carried out an analysis of ^7Li data in the reaction channels in which the progeny nucleus is not found in its ground state. This study was carried out at photon energies 12, 13 and 15 MeV. We may quote "We hope that these cross sections along with our previously reported $^7Li(\gamma,n_0)$ cross section will provide a base for further theoretical study of ^7Li photodisintegration."
- An experiment has been carried out at National Superconducting Cyclotron Laboratory (Michigan State University) determined the $^7Li(n,\gamma)$cross section via columb dissociation of ^8Li[17].
- Triangle Universities Nuclear Laboratory Nuclear Data Evaluation Project continues the series of reviews summarizing experimental information on the properties of the light nuclei with mass numbers A= 5,6,7, giving detailed description of ^4He,^3H,^6Li and ^7Li reaction channels[18].

The purpose of present contribution is to study beam analyzing powers in $^7Li+\gamma\rightarrow{}^6Li+n$ reaction, with linearly polarised photons using model independent irreducible tensor approach [4]–[6].

Theoretical Formalism

The model independent formalism [4]-[6] makes use of irreducible tensor approach which helps to make predictions on spin observables and also the differential cross section. We choose z-x plane as the reaction frame. We represent the photon polarization following Rose [21] through $u_\mu = -\mu\mathcal{E}_\mu, \mu = \pm 1$. Following [21] and using same notations, the reaction matrix $T(\mu)$ which is proportional to the on energy shell transition matrix, is given by

$$T(\mu)=\sum_{s=\frac{1}{2}}^{\frac{3}{2}}\sum_{s-\frac{3}{2}}^{s+\frac{3}{2}}(S^\lambda(s,s_i)\ .\ \mathbb{N}^\lambda(s,\mu)) \tag{1}$$

In the above equation, the irreducible tensor operators $S^\lambda_\nu(s,s_i)$ of rank λ connects initial spin state of ^7Li with the final spin state of neutron and ^6Li. $\mathbb{N}^\lambda_q$ represent the irreducible tensor amplitudes of rank λ which are expressed in terms of multipole amplitudes. These irreducible tensor amplitudes are given by

$$\mathbb{N}^\lambda_q(s,\mu)=\mathcal{N}^\lambda_q(s)G^j_{ls;L}C(l,L,\lambda;m_l,-\mu,q)Y_{lm_l}(\theta,\phi) \tag{2}$$

Where

$$\mathcal{N}^\lambda_q(s)=\frac{4\pi\sqrt{2\pi}}{2}\sum_{L=1}^{\infty}\sum_{l=1}^{\infty}\sum_{j=l-s}^{l+s}i^{l-L}(-1)^{j-l+s}[L][j]^2[s]^{-1}W(L\frac{3}{2}ls;j\lambda) \tag{3}$$

And

$$G^j_{ls;L}=[\pi^-M^j_{ls;L}+\pi^+E^j_{ls;L}] \tag{4}$$

The orbital angular momentum is represented by l and total angular momentum of the photon represented by L. We have used the short hand notation $[L]$ to represent $\sqrt{2L+1}$ and the conserved total angular momentum of the reaction is represented by j. $G^j_{ls;L}$ is the partial wave multipole amplitude which depends only on c.m. energy E.

$$\pi^\pm=\frac{1}{2}(1\pm(-1)^{L-l}) \tag{5}$$

assume either of the values 0,1 such that, if $\pi^+=1$ implies $\pi^-=0$ and vice versa. The $G^j_{ls;L}$ denotes electric 2^L -pole amplitudes, if $\pi^+=1$ and magnetic 2^L -pole amplitudes, if $\pi^-=1$. The differential cross section with polarized photon is given by

$$\frac{d\sigma}{d\Omega}=\sum_\mu(\mathbb{N}^\lambda(\mu)\rho\mathbb{N}^{\dagger\lambda}(\mu')) \tag{6}$$

Where

$$\mathbb{N}^{\dagger\lambda}_\nu(\mu)=(-1)^q\mathbb{N}^{*\lambda}_{-q}(\mu) \tag{7}$$

Using standard racah algebra and partial wave analysis the differential cross section for linearly polarized photons can be expressed in terms of associated Legendre polynomial. That is,

$$\frac{d\sigma}{d\Omega}=\sum_l\sum_{m_l=-l}^{l}B_lm_lY_lm_l(\theta,\phi) \tag{8}$$

Where

$$Y_lm_l(\theta,\phi)=\sqrt{\frac{4\pi}{2l+1}}P^{m_l}_l(cos\theta)e^{im_l\phi} \tag{9}$$

We can determine B_lm_l empirically. In the above equation B_lm_l is given by

$$\begin{aligned}B_lm_l=\frac{1}{6}\sum(2s+1)(-1)^{l'+l''+L}[\lambda]^{\frac{3}{2}}[l][l'']C(l,l',l'';0,0,0)C(L,l'',L';-\mu,m_{l''},-\mu')\\ W(LlL'l';\lambda,l'')\mathbb{N}^\lambda_\nu(s,\mu)\mathbb{N}^{\lambda^*}_\nu(s,\mu')\end{aligned} \tag{10}$$

In terms of limited number of partial wave multipole amplitudes the differential cross section can be expressed as

$$\begin{aligned}\frac{d\sigma}{d\Omega}=\pi^2[aP^0_0(cos\theta)+bP^0_1(cos\theta)+cP^0_2(cos\theta)+dP^0_3(cos\theta)+eP^2_2(cos\theta)cos2\phi+\\ gP^2_4(cos\theta)cos2\phi]\end{aligned} \tag{11}$$

Results and Discussion

We have presented theoretical analysis on photodisintegration of lithium in the reaction channel $^7Li+\gamma\rightarrow{}^6Li+n$. In equation 11, $P^{m_l}_l cos\theta$ is the associated legendre function and a,b,c,.. are their coefficients. These coefficients can be extracted from experimental measurements.

The role of multipole amplitudes in the reaction $^7Li+\gamma\rightarrow{}^6Li+n$ can be understood by studying differential cross section in detail. In view of ongoing theoretical and experimental studies we hope that model independent analysis of beam analyzing powers $^7Li+\gamma\rightarrow{}^6Li+n$ would lead to better understanding of problem. Further work on spin observable is in progress.

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