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Systematics of (Gamma-N) Reaction with Light Nuclei-Part I

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Abstract—Gamma-Nucleon (γ, N) reactions can provide a wealth of information about nuclear internal structure. Investigation of the photo-nucleon reaction of the types (γ, n) and (γ, np) cross-sections was made in the present paper based the theory of Giant Dipole Resonance (GDR) mechanism. GDR peaks were fitted to obtain the physical quantities related to the well-known Lorentz equation, with results useful in data evaluation of the selected isotopes. The isotopes and reactions selected for the present study are:$Li^6 (\gamma, n) Li^5$, $Li^6 (\gamma, n) Li^5$+$Li^6 (\gamma, np) He^4$, $Li_7 (\gamma, n) Li^6$, $Li^7 (\gamma, n) Li^6$+$Li^7 (\gamma, np) He^5$, $Be^9 (\gamma, n) Be^8$, $B^{10} (\gamma, n) B^9$, $B^{10} (\gamma, n) B^9$+$B^{10} (\gamma, np) Be^8$, $C^{12} (\gamma, n) C^{11}$, $C^{12} (\gamma, n) C^{11}$+$C^{12} (\gamma, np) B^{10}$, $C^{13} (\gamma, n) C^{12}$+$C^{13} (\gamma, np) B^{11}$ and $C^{14} (\gamma, n) C^{13}$+$C^{14} (\gamma, np) B^{12}$ reactions examined with energy range (0-85) MeV. Graphical and numerical comparisons were made. A net result was reached that curve fitting can be safely considered but only for Be^9, B^{10} and $C^{12,13,14}$ isotopes, while other isotopes might not give acceptable results for data fitting.

Keywords—Gamma reactions, Giant Dipole Resonance, Intermediate energy, Nuclear reactions.

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1 Introduction

THE aim of phenomenological studies is to try to explain complicated physical systems using rather simplified mathematical approach. The yield of such studies was always fundamental in the field of nuclear physics, since solving the system's equation is still beyond our reach due to the lack of knowledge about the actual nuclear forces.

Photo-nuclear reactions at intermediate energies characterize many important nuclear features, thus there were many practical applications for these reactions. These applications span from the experimental investigation of the photo-disintegration reactions of the nuclear constituents, to the induced fission reactions [1]. Most significantly, photoneutron nuclear reaction has a unique interest in nuclear waste treatment [2,3,4] and has received special attention. γ-rays reactions has also been the first practical example suggested to explain radiation reaction with the nucleus[5] and is considered as an ideal tool to study the electromagnetic interactions with nuclear matter. Generally, however, the (γ,nucleon) reaction measured from its unique cross-section is explained by two types of reaction models, namely: (a) the low and intermediate excitation energy models described by the Giant Dipole Resonance (GDR) mechanism [6,7] which can be effectively used for energies about 30 MeV, and (b) the high excitation energy models specified by the Quasi-Deuteron (QD) model [8] which is accepted for applications at energies above 150 MeV. Between these energies lays the intermediate range which was examined by other mechanisms, such as the exciton model [9], or other types of models -see Ref.[10] for details. There have been many experimental measurements to calculate photo-nuclear reaction cross-section. Describing the numerous results by a standard form was one of the achievements of the International Atomic Energy Agency (IAEA), where a regular library was put into use [11]. This mission is currently developing rapidly in the course of the data evaluation, which is meant to put the exaggerated reaction data into one standard form evaluated and regularly used in any practical calculation that deal with nuclear data. However, this task was developed further by many attempts to better unify the standard parameters for this special type of nuclear reactions, i.e., the photo-nuclear reactions aside of other types of reactions -for example, see [11-13]. Recent studies of data evaluation made for photo-nuclear reaction mostly focused on heavy isotopes found in nuclear fission process, such as $U^{235,238}$ isotopes, Pu^{239}, and Th^{232} [14]. Earlier studies [15] tried to deal with the entire periodic table which provided basic references for nuclear reaction studies in this field.

The scope of present study deals with photo-nuclear reactions by means of straightforward evaluation of the reaction parameters for light isotopes, using fitting procedure of the experimental results to the well-known Lorentz shape of the reaction cross-section. Results are then compared with experimentally measured parameters.

However, the present treatment shows a relative inadequacy for exact interpretation of data based on theoretical framework, since data fitting was always a method used to correlate data numerically. The examined data were those mainly obtained from online available reaction libraries accessed by JANIS 3.0 program [16], and from the EXFOR library[11]. Details of the examined data and procedure are explained accordingly.

2 Giant Dipole Resonance (GDR)

The reason thought to cause GDR phenomena in different nuclei is that when incident gamma photon (of energy of few tenths of MeV) is absorbed by the nucleus, neutrons and protons will oscillate as individual groups against each other [17]. This oscillation can take two different modes: the isovector and isoscalar modes. Isoscalar mode will correspond to a motion of the center of mass of the entire nucleus, and probably

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will not cause GDR phenomenon. Isovector mode, on the other hand, corresponds to individual oscillation of the nuclear constituents, thus will lead to energy consumption via dipole oscillation and GDR will be observed. This is the Goldhaber-Teller model [18]. Further development of this model was explained for hot (excited) nuclei by means of quantum mechanical model -see Ref. [19].

GDR corresponds to a maxima in the reaction cross-section. This cross-section can be described for spherical nuclei by [15]:

$$\sigma_{DGR}(E_\gamma) = \sigma_E \frac{E_\gamma^2 \Gamma_E^2}{\left(E_\gamma^2 - E_E^2\right)^2 + E_\gamma^2 \Gamma_E^2} \quad (1),$$

and for deformed nuclei as,

$$\sigma_{DGR}(E_\gamma) = \sum_{i=1,2} \sigma_{E,i} \frac{E_\gamma^2 \Gamma_{E,i}^2}{\left(E_\gamma^2 - E_{E,i}^2\right)^2 + E_\gamma^2 \Gamma_{E,i}^2} \quad (2),$$

Eq.(1) is Lorentzian shape and eq.(2) is the sum of two Lorentzians. In these equations, E1,i , $\sigma_{E1,i}$, and $\Gamma_{E1,i}$ are the GDR energy position, peak cross section, and width respectively. The deformed nuclear shapes given in general as [17],

$$R(\theta,\phi) = R_o\left[1 + \sum_{\lambda=2,4,6} \beta_{\lambda_o} Y_{\lambda_o}(\theta,\phi)\right] \quad (3),$$

where $Y_{\lambda o}$ are spherical harmonics and (θ,ϕ) are angular coordinates in the frame of fixed body, R_o is the (spherical) nuclear radius and $\beta_{\lambda o}$ is the deformation parameter. The theory listed above can be assumed proper and fair to describe photoneutron cross-section in the range below 30 MeV, thus it provides enough theoretical bases for comparison with the results of this work. Further details about photoneutron cross-section calculations are found in Refs. [6,7,10, 15, and 17].

3 Data

The data used in this research are listed in Table (1). The reactions were treated according to eq.(1) or (2), as classified by Table (2). The reaction of the type $Li^7(\gamma,n)Li^6$ could not be fitted using either of these equations, so a suggested form:

$$\sigma_{DGR}(E_\gamma) = \sigma_E \frac{E_\gamma^2 \Gamma_E^2}{\left(E_\gamma^e - E_E^2\right)^2 + E_\gamma^2 \Gamma_E^2} \quad (4),$$

was used, where e is a free fitting parameter.

4 Results

The results of the present fitting are listed in Table (3). A comparison with experimental data found in the literature is made in Table (4). The curves are shown in, respectively: Fig. (1) for $Li^6(\gamma,n,p)Li^5$, Fig.(2) for $Li^6(\gamma,n)Li^5$+$Li^6(\gamma,np)He^4$, Fig.(3) for $Li^7(\gamma,n)Li^6$, Fig.(4) for $Li^7(\gamma,n)Li^6$+$Li^7(\gamma,np)He^5$, Fig.(5) for $Be^9(\gamma,n)Be^8$, Fig.(6) $B^{10}(\gamma,n)B^9$, Fig.(7) for $B^{10}(\gamma,n)B^9$+$B^{10}(\gamma,np)Be^8$, Fig.(8) for $C^{12}(\gamma,n)C^{11}$, Fig.(9) for $C^{12}(\gamma,n)C^{11}$+$C^{12}(\gamma,np)B^{10}$, Fig.(10) for $C^{13}(\gamma,n)C^{12}$, Fig.(11) for $C^{13}(\gamma,n)C^{12}$+$C^{13}(\gamma,np)B^{11}$ and Fig.(12) for $C^{14}(\gamma,n)C^{13}$+$C^{14}(\gamma,np)B^{12}$ reactions.

In Fig.s (13) and (14), the curve fitting results of $C^{12}(\gamma,n)C^{11}$ and $C^{12}(\gamma,n)C^{11}$+$C^{12}(\gamma,np)B^{10}$ reactions, respectively, are plotted with unified data showing the two peaks of these reactions.

5 Discussions

It must be mentioned that the present work aimed on fitting available experimental data found in the IAEA standard photonuclear libraries. Therefore curve fitting was made for more than one experimental data set in most cases. Since these sets show some inconsistency amongst themselves some fitting results were appropriately made for the average of sets. Data region illustrated in Fig.(1) were selected during fitting, where some of the experimental points (indicated in the figure) were excluded from the

TABLE(1). EXPERIMENTAL DATA SETS USED IN THIS RESEARCH.

Reaction Type	Number of points	Energy Range (MeV)	Author(s)	Reference J., Vol., p., Yr.
$Li^6(\gamma,n)Li^5$	10	5.43-9.00	L.Green and D.J.Donahue	Phys. Rev. 135,701,1964
	37	5.40-51.90	E.B.Bazhanov, A.P. Komar, and A.V.Kulikov	Zhurnal Eksperimental'noi i Teoret. Fiziki (ZET),46,1479, 1964
	40	4.50-85.00	S.Costa, F.Ferrero, C. Manfredotti, L. Pasqualini and L. Roasio	Nuovo Cimento B,42,382, 1966
	36	7-8.75	S.Karataglidis, D. Zanov, P.D.Harty, and M.N.Thompson	Nucl. Phys. A,501,108,1989
	Tot. 123	4.50-85		
$Li^6(\gamma,n)Li^5$+$Li^6(\gamma,np)He^4$	107	5.68-32.08	B.L.Berman, R.L.Bralett, J.T.Caldwell, R.R.Harvey& S.C.Fultz	Phys. Rev. Lett., 15,727,1965

$Li^7(\gamma,n)Li^6$	8	7.38-10.83	L.Green and D.J. Donahue	Phys. Rev. 135,701,1964
	60	7.05-30.53	R.L.Bralett, B.L.Berman, M.A.Kelly, J.T.Caldwell, and S.C.Fultz	Int. Conf. on Photonucl. Reactions, Pacific Grove (73PACIFI) 1,175, 1973
	1	1.56	M.Fujishiro, K.Okamoto,T.Tsujimoto	Can. J. Phys., 61,1579,1983
	8	1.79-2.19	H.Utsunomiya, & Y.Yonezawa, H.Akimune, T.Yamagata, M.Ohta, M.Fujishiro, H.Toyokawa, H.Ohgaki	Phys. Rev. C 63, 018801,2001
	58	2.11-6.11	H.Utsunomiya, & Y.Yonezawa, H.Akimune, T.Yamagata, M.Ohta, M. Fujishiro, H.Toyokawa, & H.Ohgaki	Evaluated from Phys. Rev. C 63, 018801,2001
$Li^7(\gamma,n)Li^6+Li^7(\gamma,np)He^5$	12	1.68-2.06	K.Sumiyoshi, H.Utsunomiya, S.Goko, and T.Kajino	Nucl.Phys. A,709,467,2002
	6	1.67-2.16	M.Fujishiro, T.Tabata, K.Okamoto, & T.Tsujimoto	Can. J. Phys. 60,1672,1982
	2	1.68-1.85	J.H.Gibbons, R.L. Maclin, J.B.Marion, and H.W. Schmidt	Phys. Rev.114,1319,1959
	3	1.69-1.78	W.John and J.M.Prosser	Phys. Rev. 127,231, 1962
	4	2.61-8.06	R.D.Edge	Nucl.Phys., 2,485,1957
	158	1.67-19.75	A.Goryachev, G.Zalesny &I.V.Pozdnev	Izv. Rossiiskoi Akademii Nauk, Ser.Fiz.(IZV),56, 159,1992 and Bull.Russian Academy of Sciences – Physics (BAS),56, 762,1992
	Tot.264	1.56-19.75		
$B^{10}(\gamma,n)B^9$	4	9.00-10.83	L.Green and D.J.Donahue	Phys. Rev. 135,701,1964
	94	10.52-35.07	U.Kneissl, K.H.Leister, H.O.Neidel, and A.Weller	Nucl. Phys. A, 264,30,1976
$B^{10}(\gamma,n)B^9+B^{10}(\gamma,np)Be^8$	113	8.59-25.26	M.H.Ahsan, S.A.Siddiqui, and H.H.Thies	Nucl. Phys. A, 469,381,1987
	Tot. 207	8.59-35.07		
$C^{12}(\gamma,n)C^{11}$	26	20.17-21.18	W.E.Del Bianco and W.E.Stephens	Phys. Rev.126,709,1962
	80	2.15-26.70	W.A.Lochstet and W.E.Stephens	Phys. Rev.,141,1002,1966
	47	18.7-24.6	J.P.Roalsvig, I.C.Gupta & R.Haslam	Can. J. Phys., 39,643,1961
	25	20.12-21.04	L.O.Cohen and W.E. Stephens	Phys. Rev.Lett.,2,263,1959
	96	20.11-26.69	W.A.Lochstet and W.E.Stephens	Phys. Rev.,141,1002,1966
	9	19-27	L.Katz and A.G.W. Cameron	Can. J. Phys, 29,518,1951
	Tot. 189	2.15-26.7		
$C^{12}(\gamma,n)C^{11}+C^{12}(\gamma,np)B^{10}$	165	18.15-37.35	S.C.Fultz, J.T. Caldwell,B.Berman, R.Bralett and R.Harvey	Phys. Rev. 143,790,1966
	68	19.02-32.06	U.Kneissl,E.A.Koop,G.Kuhl,K.H.Leister, & A.Weller	Nucl. Inst. Meth. Phys. Res., 127,1,1975
	34	18-26.25	E.B.Bazhanov, A.P. Komar,A.V. Kulikov, and V.I.Ogurtsov	Yadernaya Fizika (Yad. Fiz.), 3, 711, 1966
	35	18-51.8	E.B.Bazhanov, & A.P.Komar, A.V.Kulikov,& V.I.Ogurtsov	Yad. Fiz,3,711,1966
	291	18.5-25.6	B.S.Ishkhanov,I.M.Kapitonov I.M.Piskarev, and V.G. Shevchenko	Yad. Fiz.,14,253,1971
	21	18.5-25.6	J.Miller, C.Schuhl, G.Tamas and C.Tzara	Journal de Physique, 27,8,1969
	Tot.594	18-51.8		
$C^{13}(\gamma,n)C^{12}$	162	8.09-19.06	R.E.Pywell, B.L.Berman, P.Kean, M.N.Thompson	Nucl.Phys.A,369,141,1981
	9	6.61-10.83	L.Green and D.J.Donahue	Phys. Rev. 135,701,1964
	Tot. 171	6.61-19.06		
$C^{13}(\gamma,n)C^{12}+C^{13}(\gamma,np)B^{11}$	173	7.59-41.83	J.Jury, B.Berman, D.Faul, P.Meyer, K. Mcneill, and J.G.Woodworth	Phys. Rev.C, 19, 1684, 1979
	89	4.87-25.01	R.Koch and H.H.Thies	Nucl. Phys. A 272, 296, 1976
	Tot.262	4.87-41.83		
$C^{14}(\gamma,n)C^{13}+C^{14}(\gamma,np)B^{12}$	107	8.24-36.20	R.Pywell,B.Berman,J. Woodworth, J. Jury, K.G.Mcneill,& N.T.Thompson	Phys. Rev. C,32,384,1985

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TABLE (2). CLASSIFICATION OF THE FITTED REACTIONS.

Reaction Type	Eq. used in Fitting
$Li^6(\gamma,n)Li^5$	1
$Li^6(\gamma,n)Li^5+Li^6(\gamma,np)He^4$	1
$Li^7(\gamma,n)Li^6$	4
$Li^7(\gamma,n)Li^6+Li^7(\gamma,np)He^5$	1
$Be^9(\gamma,n)Be^8$	1
$B^{10}(\gamma,n)B^9$	1
$B^{10}(\gamma,n)B^9+B^{10}(\gamma,np)Be^8$	1
$C^{12}(\gamma,n)C^{11}$ (Peak No.1)	1
$C^{12}(\gamma,n)C^{11}$ (Peak No.2)	1
$C^{12}(\gamma,n)C^{11}$ (Both Peaks)	2
$C^{12}(\gamma,n)C^{11}+C^{12}(\gamma,np)B^{10}$ Peak No.1	1
$C^{12}(\gamma,n)C^{11}+C^{12}(\gamma,np)B^{10}$ Peak No.2	1
$C^{13}(\gamma,n)C^{12}+C^{13}(\gamma,np)B^{11}$ Peak No.1	1
$C^{13}(\gamma,n)C^{12}+C^{13}(\gamma,np)B^{11}$ Peak No.2	1
$C^{14}(\gamma,n)C^{13}+C^{14}(\gamma,np)B^{12}$	1

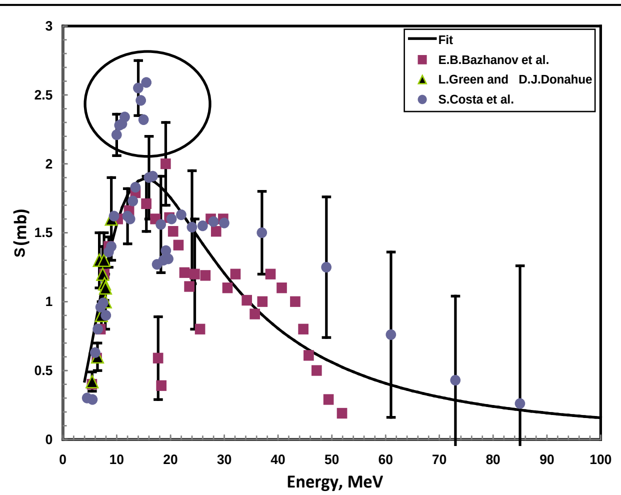

Fig.(1). Curve fitting results for $Li^6(\gamma,n)Li^5$ reaction. Surrounded points were excluded from the fitting.

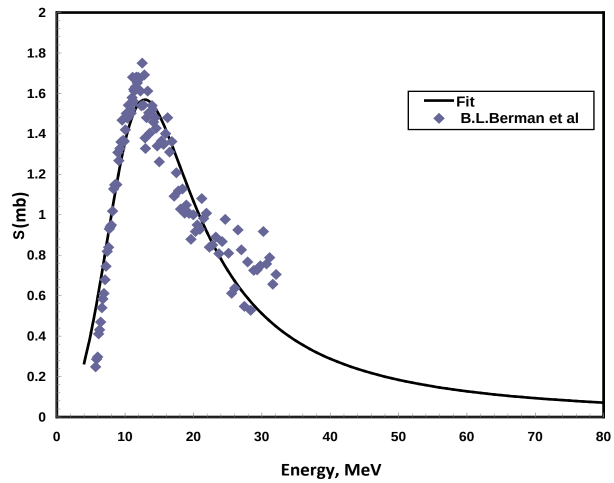

Fig.(2). Curve fitting results for $Li^6(\gamma,n)Li^5 + Li^6(\gamma,np)He^4$ reaction.

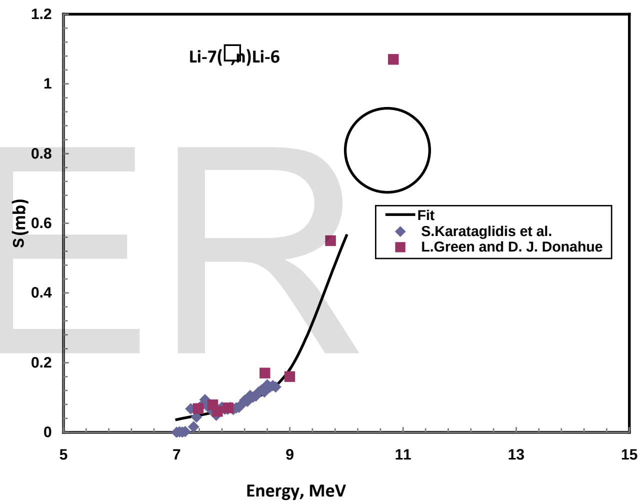

Fig.(3). Curve fitting results for $Li^7(\gamma,n)Li^6$ reaction. Surrounded points were excluded from fitting.

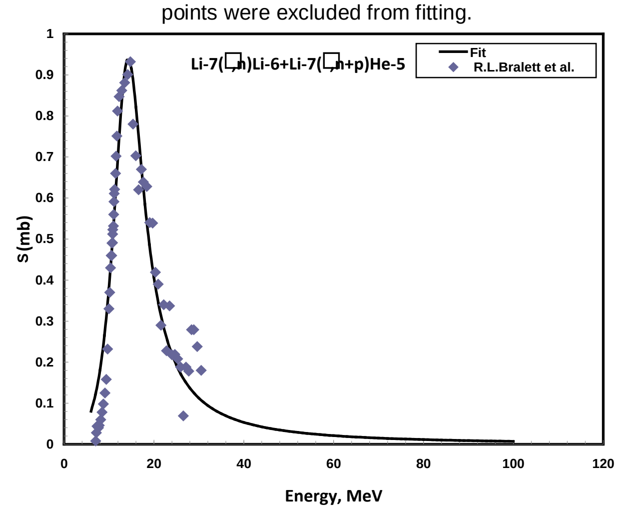

Fig.(4). Curve fitting results for $Li^7(\gamma,n)Li^6 + Li^7(\gamma,np)He^5$ reaction.

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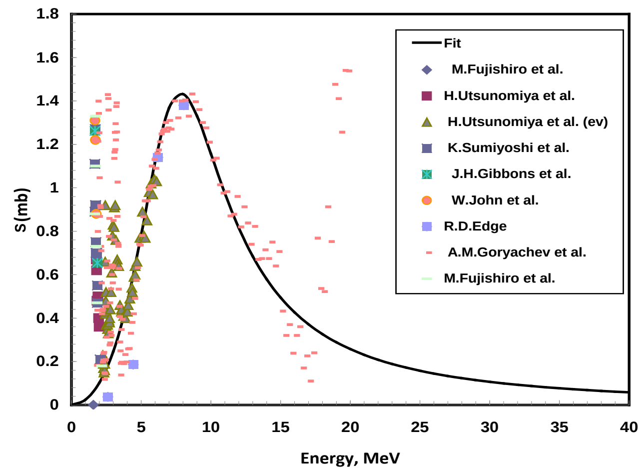

Fig.(5). Curve fitting results for Be^{9} (γ, n) Be^{8} reaction. Fitting range from (2 to 18 MeV).

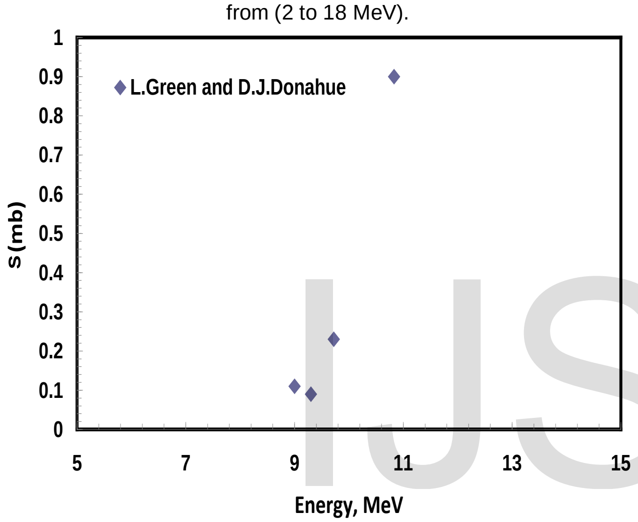

Fig.(6). Experimental results for B^{10} (γ, n) B^{9} reaction. No proper fit was found anywhere.

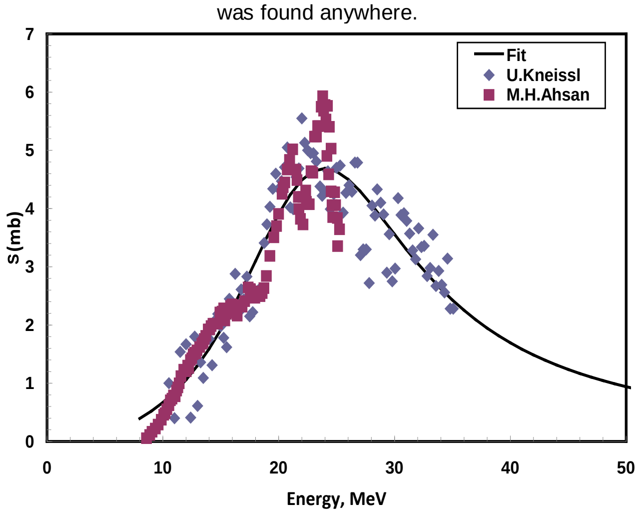

Fig.(7). Curve fitting results for B^{10} (γ, n) B^{9} + B^{10} (γ, np) Be^{8} reaction.

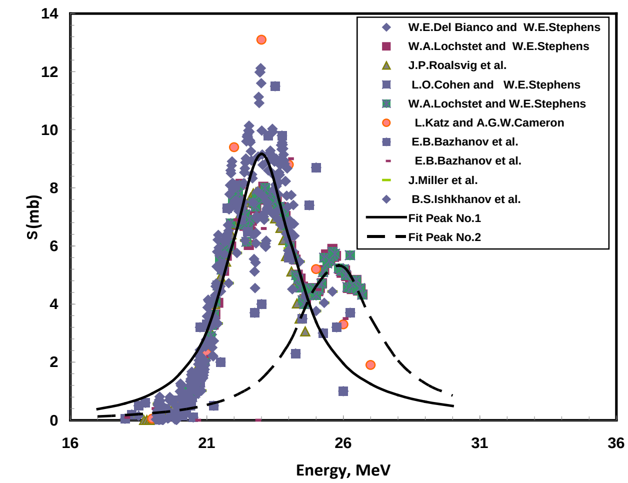

Fig.(8). Curve fitting results for C^{12} (γ, n) C^{11} reaction.

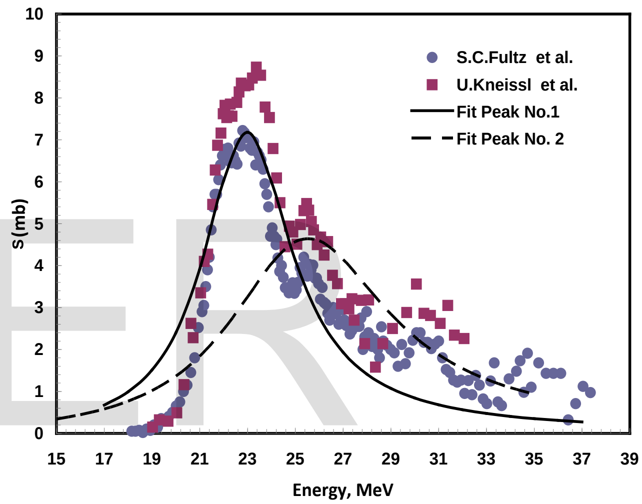

Fig.(9). Curve fitting results for C^{12} (γ, n) C^{11}+C^{12} (γ, np) B^{10} reaction.

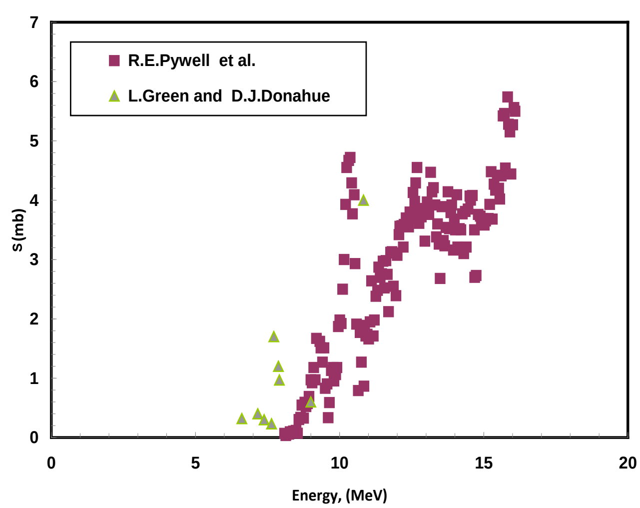

Fig.(10). Experimental results for C^{13} (γ, n) C^{12} reaction. No proper fit was found.

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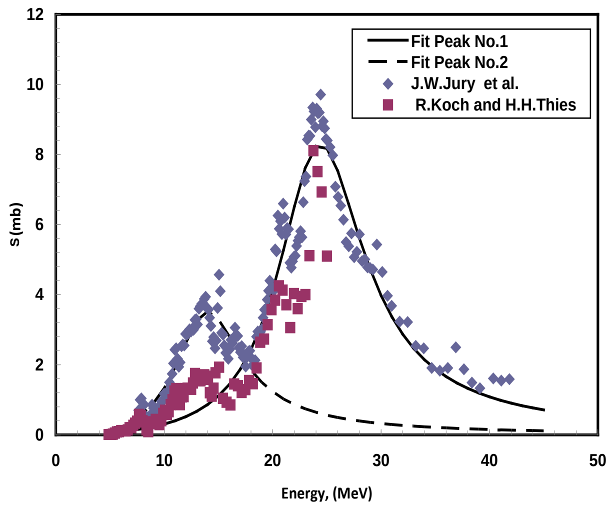

Fig.(11). Curve fitting results for $C^{13}(\gamma,n)$ C^{12} + $C^{13}(\gamma,np)$ B^{11} reaction. Data from Jury et al. were fitted only.

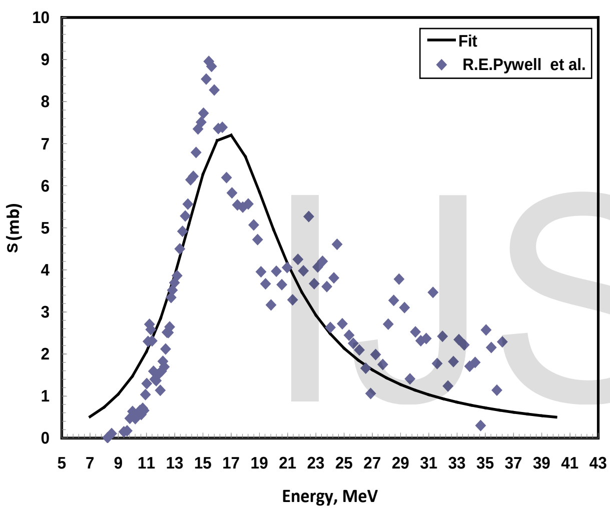

Fig.(12). Curve fitting results for $C^{14}(\gamma,n)$ C^{13} + $C^{14}(\gamma,np)$ B^{12} reaction.

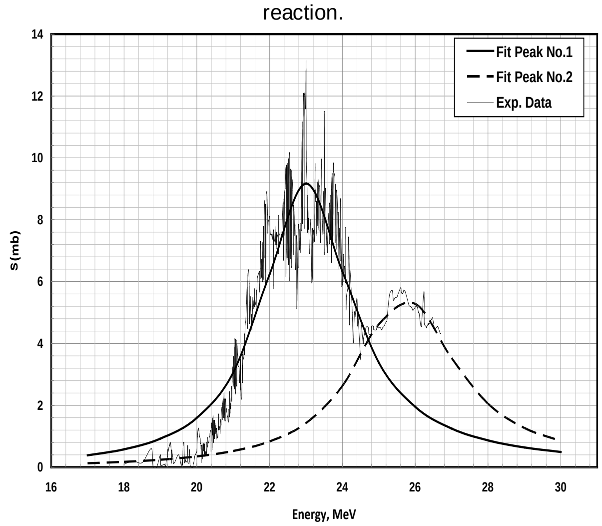

Fig.(13). Curve fitting results of $C^{12}(\gamma,n)$ C^{11} plotted with unified data showing the two peaks.

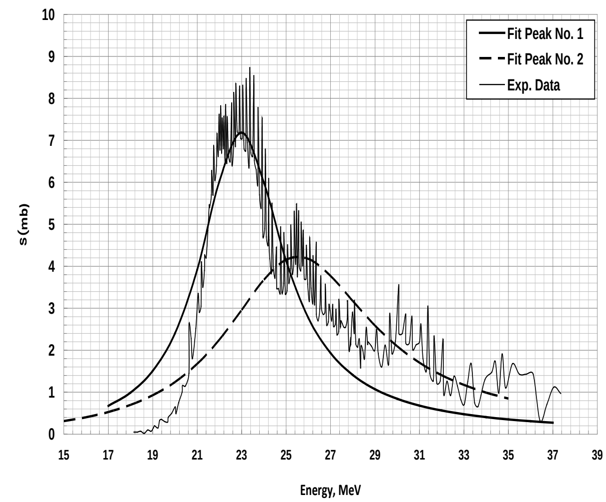

Fig.(14). Curve fitting results $C^{12}(\gamma,n)$ C^{11} + $C^{12}(\gamma,np)$ B^{10} plotted with unified data showing the two peaks.

fitting to achieve the best results. Some of the points of Bazhanov et al. suggest that there are more than one peak in $Li^6(\gamma,n)$ Li^5 reaction, however, the fit assumed only one peak.

Similar remarks are seen for $Li^6(\gamma,n)$ Li^5+$Li^6(\gamma,np)$ He^4 shown in Fig.(2), $Be^9(\gamma,n)$ Be^8 shown in Fig.(5), $B^{10}(\gamma,n)$ B^9+$B^{10}(\gamma,np)$ Be^8 as in Fig.(7), $C^{13}(\gamma,n)$ C^{12} as in Fig.(10) and $C^{14}(\gamma,n)$ C^{13}+$C^{14}(\gamma,np)$ B^{12} in Fig.(14) where some points suggest more than one cross-section maxima. All these reactions were treated assuming only one peak for simplicity, with acceptable fitting results in general. This choice was made in this work based on the fact that more than one peak in the photonuclear cross-section assumes that there is a certain nuclear deformation [17]. Examining the experimental data for the quadrupole moment for Li^6, Be^9, B^{10} showed that these nuclei in their ground states do not possess a detectable quadrupole moment value [22]. Thus only one peak is assumed during data treatment of these nuclei. The experimental data in both Fig.(6) for $B^{10}(\gamma,n)$ B^9 and Fig. (10) for $C^{13}(\gamma,n)$ C^{12} reactions could not be fitted by any equation similar to eq.(1) or (2), or the approximate eq.(4). Thus, these data sets were not treated here. Although the results for $Li^7(\gamma,n)$ Li^6 -Fig.(3)- did not show any peak, it could be fitted. In Fig.(5) the results for $Be^9(\gamma,n)$ Be^8 reaction may also strongly suggest the presence of another peak at energy above 20 MeV. This was not made since the peak at energy 8-10 MeV gave excellent results. The results of $C^{12}(\gamma,n)$ C^{11} shown in Fig.(8) were plotted again in Fig.(13) after unifying experimental data. It can be perfectly seen that there are two distinguished photonuclear peaks at distant energies. Similar remarks are seen for $C^{12}(\gamma,n)$ C^{11}+$C^{12}(\gamma,np)$ B^{10} and for $C^{13}(\gamma,n)$ C^{12}+$C^{13}(\gamma,np)$ B^{11} shown in Fig.s(9,11), respectively. In Fig.(11), data from Jury et al. were fitted only which gave the best results. These results are acceptable since the C^{12} nucleus has experimental quadrupole moment +0.06 mb[22]. Acceptance of the results obtained from these fitting procedures suggests that simple fitting can be efficient for data treatment of these isotopes.

Another comparison of the results is indicated in Table (4). From this table it can be seen that some of the present fitting results encountered percentage error more than 100% which implies their impractical use. However, most these cases with large error actually resulted because the IAEA data were evaluated for all the peaks of the photonuclear reaction, i.e., there were more

TABLE(3). THE RESULTS OF CURVE FITTING.

Reaction	σ_E	Γ	Γ_o	e	Goodness of the Fit
$Li^6(\gamma,n)Li^5$	1.89	29.38	15.33	–	SSE: 8.598 (1), R-square: 0.7073(2)AR: 0.7003 (3), RMSE: 0.3199 (4)
$Li^6(\gamma,n)Li^5$ + $Li^6(\gamma,np)He^4$	1.56	17.00	12.90	–	SSE: 2.168, R-square: 0.8627AR: 0.8601, RMSE: 0.1437
$Li^7(\gamma,n)Li^6$	4.17	0.15	4.99	1.3	SSE: 0.01715, R-square: 0.7613 AR: 0.7424, RMSE: 0.02124
$Li^7(\gamma,n)Li^6$+ $Li^7(\gamma,np)He^5$	0.93	8.56	14.28	–	SSE: 0.4093, R-square: 0.9011 AR: 0.8976, RMSE: 0.08474
$Be^9(\gamma,n)Be^8$	1.43	7.92	7.82	–	SSE: 0.6516, R-square: 0.931 AR: 0.9289, RMSE: 0.09789
$B^{10}(\gamma,n)B^9$	–	–	–	–	None
$B^{10}(\gamma,n)B^9$+ $B^{10}(\gamma,np)Be^8$	4.69	19.31	23.94	–	SSE: 48.27, R-square: 0.8884 AR: 0.8873, RMSE: 0.4864
$C^{12}(\gamma,n)C^{11}$ (Peak No.1)	9.16	2.95	22.99	–	SSE: 625.1, R-square: 0.8694 AR: 0.8688, RMSE: 1.167
$C^{12}(\gamma,n)C^{11}$ (Peak No.2)	5.42	3.42	25.71	–	SSE: 3.475, R-square: 0.6222, AR: 0.6028, RMSE: 0.2985
$C^{12}(\gamma,n)C^{11}$ (Both Peaks)	30.09	3.37	23.11	–	SSE: 921, R-square: 0.808 AR: 0.8072, RMSE: 1.354
$C^{12}(\gamma,n)C^{11}$+ $C^{12}(\gamma,np)B^{10}$ Peak No.1	7.18	4.52	22.97	–	SSE: 267.8, R-square: 0.7618 AR: 0.7597, RMSE: 1.079
$C^{12}(\gamma,n)C^{11}$+ $C^{12}(\gamma,np)B^{10}$ Peak No.2	4.23	8.16	24.53	–	SSE: 74.96, R-square: 0.6861 AR: 0.682, RMSE: 0.6977
$C^{13}(\gamma,n)C^{12}$+ $C^{13}(\gamma,np)B^{11}$ Peak No.1	8.29	9.763	24.41	–	SSE: 55.24, R-square: 0.888 AR: 0.8855, RMSE: 0.7879
$C^{13}(\gamma,n)C^{12}$+ $C^{13}(\gamma,np)B^{11}$ Peak No.2	3.51	7.48	14.00	–	SSE: 11.63, R-square: 0.8776 AR: 0.8746, RMSE: 0.3766
$C^{14}(\gamma,n)C^{13}$+ $C^{14}(\gamma,np)B^{12}$	7.23	8.98	16.67	–	SSE: 145.5, R-square: 0.7125 AR: 0.7069, RMSE: 1.183

(1) SSE: Sum of Square Error. (2)R-square: The coefficient of multiple determination. (3)AR: Adjusted R-square, the degree of freedom adjusted R-square. (4)RMSE: Root Mean Square Error

than one peak resolved experimentally while in this work the assumption was to fit for one peak only. This case is seen specially for $Li^6(\gamma,n)Li^5$+$Li^6(\gamma,np)He^4$and $Li^7(\gamma,n)Li^6$reactions. This strongly suggests that these types of reactions still need further treatment, where the present treatment might not be efficient. On the other hand, however, most of the remaining results were in a good agreement with the IAEA data..

6 CONCLUSIONS

Most photonuclear data found in the IAEA library for the isotopes $Li^{6,7}$, Be^9, B^{10}, and $C^{12,13,14}$ were fitted for the photonuclear reactions (γ,n) and $(\gamma,n)+(\gamma,np)$ for energies around the GDR peaks. Careful yet uncomplicated data fitting was made for these sets of experimental data to obtain the photonuclear data σ,Γ_o,Γ and the results were indicated numerically and graphically. The results showed acceptable match with earlier evaluations. It is concluded that, in general, the simple curve fitting for photonuclear data for the selected isotopes can be safely considered but only for Be^9, B^{10} and $C^{12,13,14}$ isotopes. This is the case for at least the selected reactions (γ,n) and $(\gamma,n)+(\gamma,np)$. Other types of re-actions for the selected isotopes are still needed to be further treated with the same method specially (γ,n) reaction for O and F isotopes in order to complete the KL-shell group, and since there are wide industrial applications regarding these isotopes.

TABLE(4). COMPARISONS OF THE PRESENT RESULTS WITH EXPERIMENTAL AND EVALUATED IAEA PHOTONUCLEAR DATA.

Reaction	σ_o	σ_o [20,21]	Error [a]	Γ	Γ [20,21]	Error	Γ_o	Γ_o [20,21]	Error
$Li^6(\gamma,n)Li^5$	1.892	1.68-2.55	12-25	29.38	11.63-14.0	>100	15.33	11.0-12.0	36-25
$Li^6(\gamma,n)Li^5$+$Li^6(\gamma,np)He^4$	1.569	0.40	>100	17.00	12.00	41	12.90	8.00	50
$Li^7(\gamma,n)Li^6$	4.177 7	0.93	>100	0.159	8.00	>100	4.998	14.75	>100
$Li^7(\gamma,n)Li^6$+$Li^7(\gamma,np)He^5$	0.9394	2.35-4.83	>100	8.562	10.0-13.0	45-38	14.28	17.0-21.0	17-41

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$Be^9(\gamma,n)Be^8$	1.434	2.98	50	7.924	8.00	11	7.823	21.20	>100
$B^{10}(\gamma,n)B^9$	–	–	–	–	–	–	–	–	–
$B^{10}(\gamma,n)B^9+B^{10}(\gamma,np))Be^8$	4.689	5.6-6.8	74-78	19.31	10.0-19.0	90-1	23.94	20.0-24.0	25-1
$C^{12}(\gamma,n)C^{11}$ Peak No.1	9.168	8.1-8.7	12.5-4	2.952	4.0-6.0	25-50	22.99	22.18-23.5	1-5
$C^{12}(\gamma,n)C^{11}$ Peak No.2	5.428	3.3-8.04	60-32	3.429	–	–	25.71	33.0-25.7	21-1
$C^{12}(\gamma,n)C^{11}$ Both Peaks	30.09	–	–	3.373	4.0-6.0	17-45	23.11	–	–
$C^{12}(\gamma,n)C^{11}+C^{12}(\gamma,np)B^{10}$ Peak No.1	7.182	3.5-17.6	>100	4.525	3.2-6.0	40-25	22.97	23.0-41.2	2-50
$C^{12}(\gamma,n)C^{11}+C^{12}(\gamma,np)B^{10}$ Peak No.2	4.229	–	–	8.168	–	–	24.53	–	–
$C^{13}(\gamma,n)C^{12}+C^{13}(\gamma,np)B^{11}$ Peak No.1	8.291	3.0-9.7	>100-14	9.763	7.0-25.0	38-61	24.41	13.8-24.0	84-1
$C^{13}(\gamma,n)C^{12}+C^{13}(\gamma,np)B^{11}$ Peak No.2	3.517	–	–	7.486	–	–	14.00	–	–
$C^{14}(\gamma,n)C^{13}+C^{14}(\gamma,np)B^{12}$	7.239	8.9-9.5	16-23	8.981	5.0-10.0	65-11	16.67	15.0-26.1	2-38

a) Percentage Error (%).

REFERENCES

[1] C.D. Bowman, G.F. Auchampaugh, and S.C. Fultz, "Photo Disintegration Of U^{235}", *Phys. Rev.*, vol. 133, no. 3b, pp. B676-B692, 1964.

[2] F. Sperber, U. Wehman, and U. Strehlen, "Transmutation of Long lived radio nuclides by advanced Converter", Report No. EUR 16605, European Commission on Nuclear Science and Technology, 1995.

[3] L.. Roberts "Radioactive Waste Management", *An.Rev. Nucl. Part.. Sci.*, vol.40, no.1 pp. 79-112, 1990.

[4] L.H. Baetsle, "Application of Partitioning and Transmutation of Radioactive Materials in Radioactive Waste Management", Report Ref. LNS0212001, Nuclear Research Centre of Belgium Sck/Cen, Mol, Belgium, Lectures given at the Workshop on Hybrid Nuclear Systems for Energy Production, Trieste, Italy, Sept. 2001.

[5] N. Bohr and J.A. Wheeler, "The Mechanism of Nuclear Fission", *Phys. Rev.* vol. 56, no.1, pp. 426-450, 1939.

[6] "Handbook for calculations of nuclear reaction data, Reference Input Parameter Library-2 (RIPL-2), Final report of a coordinated research project", Rep. No. IAEA-TECDOC-1506, Vienna, June 2006.

[7] "Handbook on Photonuclear Data for Applications, Cross Sections and Spectra, International Atomic energy Agency formal report", Report No. IAEA-TECDOC-1178, Vienna, March 2000.

[8] I. Rakinyte, E. Dupont, B. Morillon and D. Ridikas; CERN Report Ref. 50021, CERN Libraries, Geneva, 2005.

[9] B. Pritychenko, A.A. Sonzogni, D.F. Winchell, V.V. Zerkin, R. Arcilla, T.W. Burrows, C.L. Dunford, M.W. Herman, V. McLane, P. Obložinsky, Y. Sanborn and J.K. Tuli, "Nuclear reaction and structure data services of the National Nuclear Data Center", *Ann. Nuc. En.* vol.33, no.4, pp. 390-399, 2006.

[10] C. Mahaux, "Intermediate Structure in Nuclear Reaction", *Ann. Rev. Nucl. Sci.*, vol.. 23, pp.193-245, 1973.

[11] IAEA Extended Format Library (EXFOR) ver.2, IAEA, Vienna, 2007.

[12] P. Vertes, "Test Calculations with IAEA Photonuclear Data Library", Vienna, IAEA Formal Report, Rep. No. INDC(HUN)-035, Jan. 2001.

[13] "Handbook for calculations of nuclear reaction data, Reference Input Parameter Library-2 (RIPL-2), Final report of a coordinated research project", Vienna, IAEA Formal Report, Rep. No. IAEA-TECDOC-1506, Jun. 2006.

[14] E. Dupont, I. Rakinyte, A.J. Koning, and D. Ridikas; "The International Conference on Nuclear Data for Science & Technology", DAPNIA-07-50, 2007.

[15] L. Berman and S.C Fultz, "Measurements of the giant dipole resonance with mono-energetic photon", *Rev. Mod. Phys.*, vol. 47, no. 5, pp. 713-748, 1975.

[16] JANIS 3.0 program, OECD Energy Agency, Jun. 2007.

[17] S.M. Wong, "Introductory Nuclear Physics", 2nd Ed., p.207, WILEY-VCH Verlag GmbII & Co. KGaA, Weinheim, Germany, 2004.

[18] J. D. Walecka, "Theoretical Nuclear And Subnuclear Physics", 2nd Ed., p.99, College Press and World Scientific Publishing Co. Pte. Ltd. Singapore, 2004.

[19] T. W. Donnelly; in "Advances in Nuclear Physics: Volume 22", Ch.2: "Aspects of Electromagnetic Nuclear Physics and Electroweak Interactions", p.37, Kluwer Acade-mic Publishers, 2002.

[20] A.V. Varlamov, V.V. Varlamov, D.S. Rudenko, and M.E. Stepanov; "Atlas of Giant Dipole Resonances: Parameters and Graphs of Photonuclear Reaction Cross Sections", IAEA INDC(NDS)-394, Jan. 1999.

[21] "Handbook on Photonuclear Data for Applications Cross-Sections & Spectra: Fin. Rep. Coord. Res. 1996-1999", IAEA-TECDOC-1178, Oct. 2000.

[22] N. Stone, "Table of Nuclear Magnetic Dipole and Electric Quadrupole Moments", Oxford University, 2002.