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ORIGINAL RESEARCH

A Study on the New Empirical Cross Section Formulae for (γ, p) Reactions at 20 ± 1 MeV Incident Energy

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Abstract

In this study, we have investigated theoretical cross sections of (γ, p) reactions at 20 ± 1 MeV for the photon incident energy and then we have obtained two new empirical formulae for $40 \leq A \leq 108$ and for the even Z-even N target nuclei including new fitting parameters. These new empirical formulae depending on the asymmetry parameters (s = (N − Z)/A) were determined by using the least squares approximation fitting method to the available experimental cross section data taken from EXFOR. The results have been compared with the experimental data and found to be well in agreement.

Keywords EXFOR · Empirical formula · Cross-section · (γ · P) reaction

Introduction

The primary step in nuclear reactor technology is nuclear reactions for necessary to production of energy. Photonuclear reactions are used with an increasing to understand of nuclear reactions in the fusion and fusion-fission hybrid reactors. High-energy photons emitted by a radioisotope will be generated via nuclear reactions in reactors and then subsequently interact with the materials and during the plasma shot. During the fusion plasma shot, de-confined run-away electrons can interact with the first wall of the reactor and produce high energy photons in a fusion reactor [1]. The (γ, n) (γ, p), (γ, 2n), (γ, 3n) reaction channels occur with high energy photons. The most dominant reaction is (γ,n) which has a lower threshold than multi-neutron emission, but the Coulomb barrier needs to be take into account for charged particle emission. Such reactions need to be better known in order to obtain more accurate nuclear transport calculations. Nuclear reactors (fusion-fission) require a complete dataset of neutron and photon induced reactions [1]. Nuclear reaction models and empirical for cross-section calculations therefore play an important role in the evaluation of cross sections because of the limited experimental data in literature.

Photon is used for many interaction reactions which is required to advanced nuclear system such as production of energy, medical applications, archaeological [2], environmental studies [3], and others. Especially, there are many applications for photon induced reactions to be improved reactor technology. Kaplan et al. [4] investigated Al, Si, Cr and Fe isotopes to develop reactor material technologies evolving for many years in the search of obtaining safe, clean and efficient energy production. High-energy photon is used to be performed these researches. Some nuclear reactions can be occurred during these applications. Some nuclear databases such as EXFOR [5] and the JENDL, TENDL, JEFF, and ENDF evaluated nuclear data libraries from EXFOR [5] are available for photon induced reactions. It is also important the influence of photons on material irradiation in photo-proton reaction cross-section applications. For this purpose, a new data file called PADF (the Proton Activation Data File) has been created by Koning et al. [6] and Broeders and Konobeyev [7] at various energy intervals to respond to intermediate proton energies in nuclear data.

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In this study, we have developed the new empirical cross-section formula for the (γ, p) reactions cross sections around 20 MeV photon incident energy in the framework of 40 ≤ A≤108 target nuclei. The experimental data have been obtained from EXFOR data library and literature.

Empirical Cross Section Formulae for Particle Induced Reactions in Literature

Nuclear reaction systematics, theoretical models, empirical and semi-empirical cross sections formulae have been worked and suggested by a lot of authors (such as Levkovskii [8], Ait-Tahar [9], Kumabe and Fukuda [10], Ikeda et al. [11], Belgaid and Asghar [12], Aydin et al. [13, 14], Tel et al. [15–17], and Belgaid et al. [18]). These developed formulae depend on atomic properties of the target nucleus such as mass number (A), neutron number (N) and proton number (Z) of the target [10]. Moreover, isotopic, isotonic and odd–even properties of nuclei have also been observed in cross section data and so these are attributable to the asymmetry parameter (s = (N − Z)/A).

Photonuclear reactions are known as emission of nucleon from target material via interaction with high energy photons. The nuclear binding energies per nucleon are above 6 MeV for many nuclei. Therefore, photons must be having threshold energy above the binding energy to release of nucleons. Photonuclear reactions are very important for fusion reactions. In these reactions, three specific mechanisms depending on photon energy can be mainly given as giant dipole resonance (GDR), quasi-deuteron (QD) production and intra nuclear cascade [1, 19]. GDR mechanism is followed the photons below 30 MeV. Photons with oscillating electrical field are used for transfer of energy to the nucleus which induces oscillations among nucleons inside the nucleus [19]. QD effect occurs above the 30 MeV and it is valid up to 140 MeV. Over the 140 MeV, threshold energy pion production is achieved [20].

In this study, we suggested an empirical (γ, p) reaction cross section formula based on the asymmetry parameters (s = (N − Z)/A) and the photon non-elastic interaction as,

$$\sigma(\gamma,p) = \sigma_{\gamma non}\exp[as] \tag{1}$$

where $\sigma_{\gamma non} = \pi r_0^2 A^{2/3} \approx CA^{2/3}$ is the photon non-elastic cross section and a and C are fitting parameters defined from last square method for different reactions [15–17]. We determined fitting parameter of empirical formula to all target nuclei at around 20 MeV incident photon energy for (γ, p) reactions. These data were then divided into two groups by using classification of target nuclei as even–even as shown in Table 1. In Table 1, second column gives newly produced two empirical cross section formulae for (γ, p) reaction at 20 ± 1 MeV for the photon incident energy. Mass region with 40 ≤ A ≤ 108 and with the even Z-even N is given in third column. Values of the correlation coefficients of R^2 are given in last section. When the results from this classification are compared, the formulae give slightly higher definition for even Z- even N nuclides. These two formulae are given in Table 1.

Therefore, the (γ, p) with even Z-even N nuclei reaction formula have an improvement than the empirical cross section formula with no nuclei pairing effect including no selection of experimental data. Due to the pairing effect of the target nuclei, the new empirical formula has better fitting for photon induced reaction and thus can be used reactions. In Table 1, newly developed empirical cross section formula may also be useful for theoretically calculations for difficult and the limited experimental data.

Results and Discussion

A lot of the researches [4, 13, 16–18] on cross sections showed that Q-value strong depends on (N-Z)/A asymmetry parameter. In this present study, we assumed that it may be same correlation for the (γ, p) reaction cross–sections. Firstly, excitation function shape was analyzed and then taken maximum cross-section values of experimental data from EXFOR at 20 ± 1 MeV photon energy.

We used the number of 12 experimental reaction cross section data for different nuclei obtained from EXFOR library for fitting procedure. These nuclei are chanced by mass number between 40 and 108. As can be seen in Fig. 1, cross section values are depend up on the target nuclei and decrease with the increasing mass number (A) of the target nuclei between A = 40 to 108. In Fig. 2, we found that

Table 1 The new empirical cross section formulae for (γ, p) reaction for target nuclei with 40 ≤ A≤108 and with the even Z-even N at 20 ± 1 MeV

Number	Formula (mb)	Mass region	R^2
(1)	$\sigma(\gamma, p) = 6.53(A^{2/3}) \exp[-23.734\, s]$	$40 \le A \le 108$	0.508
(2)	$\sigma(\gamma, p) = 7.43(A^{2/3}) \exp[-27.623\, s]$	even-Z, even-N	0.577

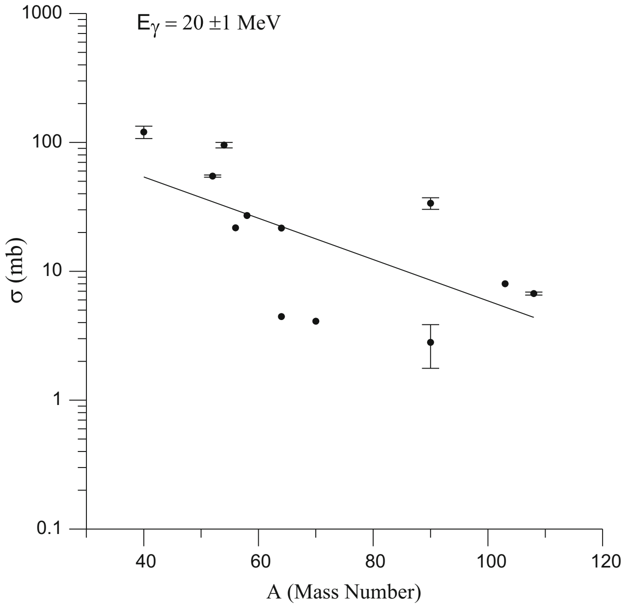

Fig. 1 Mass number (A) versus cross section dependence. Experimental data were taken from EXFOR

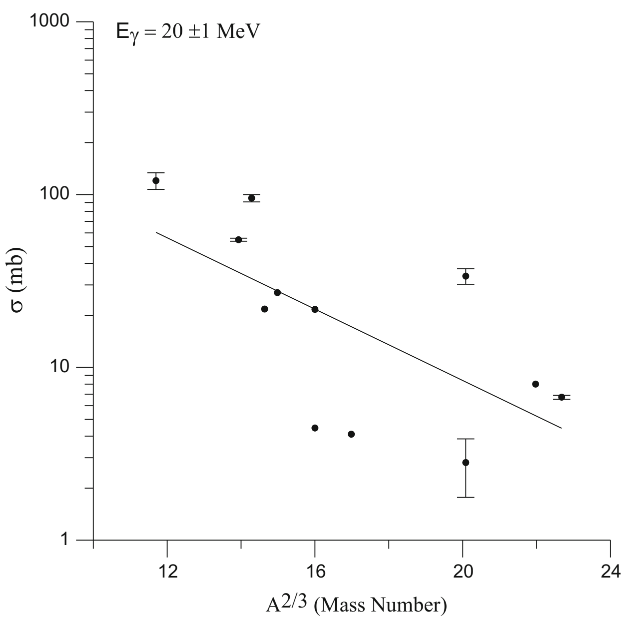

Fig. 2 Mass number ($A^{2/3}$) versus cross section dependence. Experimental data were taken from EXFOR

experimental cross section values depend on the target nuclei mass number-$A^{2/3}$. The depending on $A^{2/3}$can be thought to be a surface term effects of the target nuclei. It can be seen that the (γ, p) reaction cross section data exhibit a trend line behavior in Figs. 1, 2 for mass number-A. As seen from these figures, the trend line decrease from heavier mass number to lighter mass number.

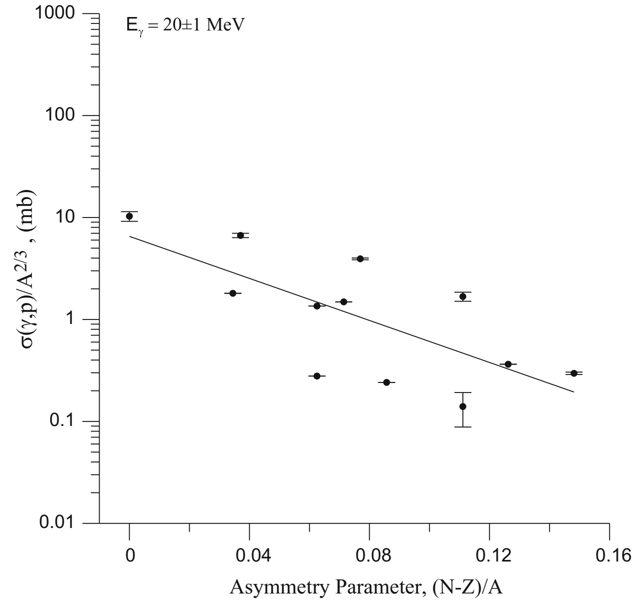

Fig. 3 Experimental data were fitted with Eq. (1). Obtained formula is shown in Table 2. Experimental (γ, p) reactions (in mb) at 20 ± 1 MeV for all target nuclei were taken from EXFOR

Figure 3 shows plotting the asymmetry parameters versus $\sigma(\gamma, p)/A^{2/3}$. The asymmetry parameter values are changed from 0 to 0.15 as seen from Fig. 3. It can also be seen that asymmetry parameters increase with mass number-A of target nuclei from light to heavier. In Fig. 3, the (γ, p) reaction cross sections data also exhibit similar trend line behavior as in Figs. 1, 2. The dependencies of the plotted parameters on each other were examined and the correlation coefficients of R^2 were obtained to be 0.406, 0.428, and 0.508 for Figs. 1, 2, 3, respectively. It was clearly seen that the correlation coefficient in Fig. 3 is better than those of others.

In Fig. 4, we determined even–even groups by the classification of target nuclei. We then plotted the even Z-even N target nuclei (γ, p) reaction cross sections because of pairing effect of target nuclei. The correlation coefficient of 0.577 in Fig. 4 was seen better than those of others.

Figure 5 shows the ratios of the (γ, p) experimental cross sections to the empirical formulae obtained formulae given Table 1 for this study. The calculated empirical data are concentrated around the 1 and scattered between 0.6 and 1.06. It can be seen that both the experimental data and theoretical data from the calculated empirical formulae are reasonably in accordance between each other. Comparison between the experimental and theoretical cross sections are given in Table 2. In Table 2, first and second columns give our empirical cross section data for (γ, p) reaction at 20 ± 1 MeV for the photon incident energy for target nuclei with $40 \leq A \leq 108$ (Formula 1) and with the even

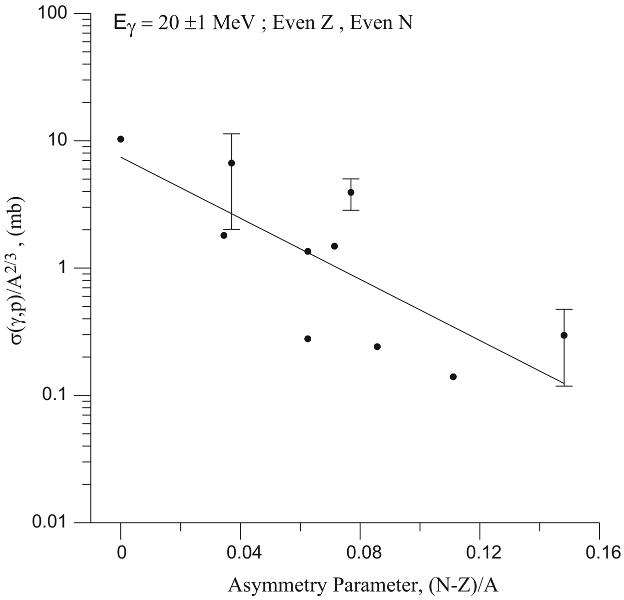

Fig. 4 Experimental data were fitted with Eq. (1). Obtained formula is shown in Table 2. Experimental (γ, p) reactions (in mb) at 20 ± 1 MeV for for even-Z, even-N nuclei were taken from EXFOR

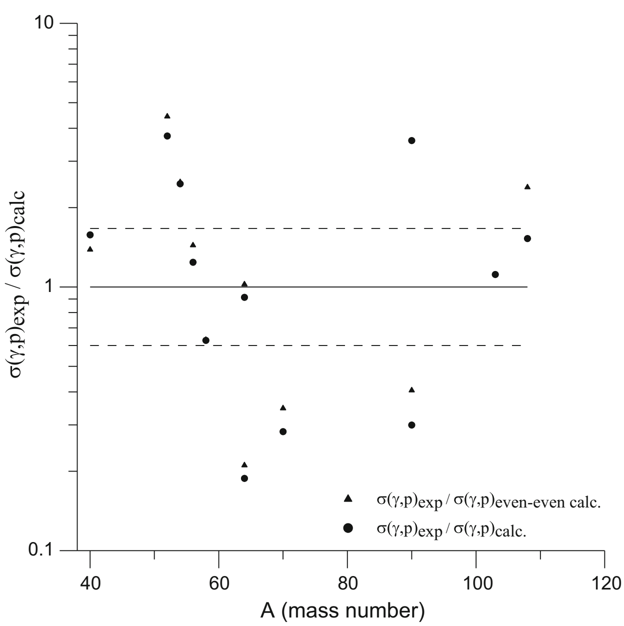

Fig. 5 Ratios of the (γ, p) experimental cross sections to the cross sections calculated with empirical formulae developed in this work

Z-even N (Formula 2) using Table 1, respectively. Third column is the experimental data from the EXFOR.

Summary and Conclusions

In this work, we investigated the (γ, p) reaction cross section data at 20 ± 1 MeV photon energy and then developed two new formulae. These formulae have been tested for 12 nuclei with 40 ≤ A ≤ 108. We suggested empirical formulas including the new coefficients found by fitting two parameters for photon induced reactions. We obtained two new empirical formulae including new correlation coefficients.

We briefly summarized the conclusions as;

- The (γ, p) reaction experimental cross section values depend on asymmetry parameter of the target nuclei
- The (γ, p) reaction experimental cross section values depend on surface term $A^{2/3}$ effect of the target nuclei
- The (γ, p) reaction cross sections at 20 ± 1 MeV decrease by the increasing of the asymmetry parameter.
- The best correlation coefficient for (γ, p) cross sections were obtained by considering the pairing correction.

Table 2 The empirical cross sections (in unit mb) for (γ, p) reaction for target nuclei with 40 ≤ A ≤ 108 and with the even Z-even N at 20 ± 1 MeV obtained formulae given Table 1 and the experimental data from the EXFOR

Target	Formula (1)	Formula (2)	Experimental
Ca-40	76.375	86.901	120.40 ± 13.2 [21]
Cr-52	14.656	12.364	54.79 ± 1.09 [22]
Fe-54	38.733	38.159	95.34 ± 4.66 [23]
Fe-56	17.543	15.120	21.76 ± 0.0 [24]
Ni-60	43.161	42.947	27.07 ± 0.0 [24]
Zn-64	23.703	21.150	4.46 ± 0.0 [25]
Ge-70	14.503	11.824	4.10 ± 0.0 [26]
Zr-90	9.385	6.932	33.72 ± 3.46 [27]
Zr-90	9.385	6.932	2.81 ± 1.04 [27]
Rh-103	7.175	–	8.00 ± 8 [28]
Pd-108	4.400	2.814	6.72 ± 0.17 [29]

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