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Research Article

A Systematic Review on (p,α) Cross Section Data at the Energy of 17.9 MeV

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Abstract: Nuclear cross section data are needed in various applications such as radiation therapy, astrophysics, radioisotope production, fusion and fission. The systematics play a very important role in determining cross sections on neutron- and proton-induced reactions at incoming energies of which there are no experimental values. So, empirical systematics have been extensively used at present in the studies on cross section calculations. In this paper, we proposed empirical cross section formulas considering Q–value dependence on (p,α) reactions at proton energy of 17.9 MeV. The present formulas including Coulomb and odd-even effects are based on the statistical theory. In addition, these formulas are a modification to the Levkovskii's original asymmetry parameter formulas for neutron induced reactions and the Tel et al.'s empirical formulas for proton reactions. Fitting parameters of formulas were determined by least-squares fitting to experimental excitation function data. It is seen that new empirical formulas give good fits with (p,α) experimental cross section values in the literature at 17.9 MeV.

***Key words*:** Statistical theory, Cross section, Empirical systematic, (p,α) nuclear reaction, Asymmetry parameter, Odd-even effects.

17.9 MeV'lik Enerjide (p,α) Tesir Kesiti Verileri üzerine Sistematik Bir İnceleme

Öz: Radyasyon tedavisi, astrofizik, radyoizotop üretimi, füzyon ve fisyon gibi çeşitli uygulamalarda nükleer tesir kesiti verilerine ihtiyaç duyulmaktadır. Sistematikler, deneysel değeri olmayan gelme enerjilerde nötron ve protonla oluşturulan reaksiyon tesir kesitlerinin belirlenmesinde önemli bir rol oynamaktadır. Bu yüzden, ampirik sistematikler günümüzde tesir kesiti hesaplamaları üzerine çalışmalarda yaygın olarak kullanılmaktadır. Bu çalışmada, 17.9 MeV'lik proton enerjisinde (p,α) reaksiyonları üzerine Q-değeri bağımlılığını göz önünde bulundurarak ampirik tesir kesiti formülleri önerdik. Coulomb ve tek-çift etkileri dahil eden mevcut formüller istatistiksel teoriye dayanmaktadır. Ek olarak, bu formüller, Levkovskii'nin nötron kaynaklı reaksiyonlar için orijinal asimetri parametre formüllerinin ve Tel ve arkadaşlarının proton kaynaklı reaksiyonlar için ampirik formüllerinin bir modifikasyonudur. Formüllerin fit parametreleri deneysel uyarılma fonksiyonu verilerinin en küçük kareler fit işlemi tarafından belirlendi. Yeni ampirik formüllerin, 17.9 MeV'de literatürdeki (p,α) deneysel tesir kesiti değerleri ile iyi uyum sağladığı görülmektedir.

***Anahtar kelimeler*:** İstatistiksel teori, Tesir kesiti, Ampirik sistematik, (p,α) nükleer reaksiyonu, Asimetri parametresi, Tek-çift etkiler.

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1. Introduction

Nuclear data for excitation functions are needed in many applications which non-energy related studies are radiation therapy, medical radioisotope production, astrophysics, etc. and also energy related studies are accelerator driven systems (ADS) and fusion/fission reactor systems, etc. [1-8]. In addition, they play a fundamental role in reaction theory. The nuclear cross sections can be obtained both from experimental measurements and theoretical calculations. Obtaining systematics at different projectile energies is an important part of studies concerned with the cross section calculations on various reaction channels. Thereby, empirical systematics have been widely used at present for nuclear cross section predictions [7,9-11]. Particularly, the systematics play an important role in determining excitation functions at incoming energies of which there are no experimental cross section. There are many empirical systematics in predicting the neutron induced reaction cross sections of whereas there are very few for proton reactions in literature. Further investigations on various target nuclei at different incident energies are required for performing complete description of the proton-induced reactions [8,12,13]. Data on the excitation function of proton-induced reactions are needed to understand the nature of nuclear interaction and structure. Furthermore, the reactions with the intermediate proton energies have been used for the production of radioisotopes which are needed in medicine, industry and technology. And also, the nuclear reactions with high proton energies are required for the high energetic proton induced fission reactions and neutron spallation source [14-16]. The gas production in fusion reactor structures can be induced as a result of various proton, neutron and alpha-induced reactions above a certain critical threshold energy. So, such reactions at nuclear fusion applications can make up notable changes in physical properties of structural materials. Obtaining excitation function data on gas production is very important in fusion technology, particularly in the prediction of nuclear heating, nuclear conversion ratios and radiation damage [3]. Since the measured cross section values are generally limited in terms of the incident particle energy, model calculations and empirical systematics are essential to provide the insight how the proton-induced reactions evolve along the proton-nucleus interaction.

In previous papers [9,10,17], the empirical formulas with the directly reaction Q–value dependence of excitation function data of (n, 2n), (n, t) and (n, d) reactions were reported for the incident energies ∼14-15 MeV. Here, new empirical cross section formulas using the same relation have been suggested for (p,α) reactions. These empirical formulas include the coulomb effects for estimating (p,α) cross sections at incoming energies about 17.9 MeV.

2. Material and Method

2.1 Empirical systematics

Obtaining the unavailable experimental cross section values could be carried out by the nuclear simulation codes based on the consistent nuclear models. Nuclear codes may predict the various data of all reaction channels such as angular distribution, excitation functions, energies and differential cross sections. On the other hand, it is difficult to input and adjust many nuclear parameters such as gamma-branching, exciton numbers, level densities, giant dipole resonance parameters, binding energies, spins and optical potential of the residual and target nuclides to fit all the experimental data. As a result, it is very important to develop empirical systematics to obtain the cross sections [18]. The aim of this work is to investigate empirical systematics for (p,α) cross section estimations at incoming energy of 17.9 MeV. Empirical cross section systematics ignore an important role of pre-compound process of nuclear reactions on particle emission at the medium and heavy mass nuclides. These systematics are based on the evaporation model, and they have the exponential dependence of cross sections on neutron and proton numbers in target nuclide. However, the semi-empirical formulas use the analytical expressions in predicting the particle emissions in the frame of the evaporation and pre-compound exciton models. Empirical and semi-empirical formulas in literature were mostly proposed by modifying the original formula of Levkovskii [19]. Levkovskii's formula for nuclear cross section predictions on (n,p) reactions at 14 MeV projectile energies was given as following

$$\sigma_{n,p} \approx \sigma_n exp\left[-33\left(\frac{N-Z}{A}\right)\right] \tag{1}$$

In Equation 1, $\sigma_n = \pi r_0^2 \left(A^{1/3}+1\right)^2$; $r_0 = 1.2 * 10^{-13}$ cm. According to [19], the proton emission probabilities for a given nucleus are found to increase with increasing the relative proton number. Thereby, empirical expression in calculating cross sections for nuclear reactions with fast incident neutrons is approximately written as following,

$$\sigma_{n,x} = C\sigma_{ne} exp[as] \tag{2}$$

where, the term "$s = (N-Z)/A$" corresponds to the asymmetry parameter, "x" is the particle produced, the coefficients "a" and "C" calculated from least squares method are the fitting parameters, the term "σ_{ne}" is neutron non-elastic cross section. Semi-empirical equations for the predictions of cross section of the (p,n) reactions at proton energies of 7.5, 12.4 and 24.8 MeV were recently obtained by Broeders and Konobeyev [16]. Their equations are based on the expressions of which are obtained using the semi-empirical mass formula, exciton model and evaporation model. Additionally, the semi-empirical equations of (p,α), (p,np) and (p,nα) reactions were also obtained for projectile energies of 17.9 and 28.5 MeV in another study of Broeders and Konobeyev [20]. The following equation for calculating (p,α) cross section at 17.9 MeV was proposed by Broeders and Konobeyev [21].

$$\sigma = \sigma_{non}\left[A^{-1/3}(\alpha_1 X_1 + \alpha_2) + exp\left\{A^{1/2}\left(\alpha_3 X_2^2 + \alpha_4 X_3 + \alpha_5 + \alpha_6 f_{sh,p}\right)\right\}\right] \tag{3}$$

The parameters α_i, X_1, X_2 and X_3 can be found in Ref. [20]. The empirical function $f_{sh,p}$ has the shell and pairing effects.

The empirical formulas taking into account Coulomb and pairing effects by Tel et al. [15] were derived for (p, np) reaction at 22.3 MeV, (p, α) reaction at 17.9 MeV and (p, nα) reaction at 24.8 and 28.5 MeV. Their empirical formulas in calculating cross sections on the nuclear reactions of induced by protons were given as following,

$$\sigma(p,x) = CZ^2\left(A^{1/3}+1\right) exp[as] \tag{4}$$

The coefficients "C" and "a" obtained from least squares method are the fitting parameters [15]. Besides, the asymmetry term and Coulomb effects were investigated for performing complete description of (d,n) and (d,2n) cross sections [11,12]. In this framework we obtained (p,α) empirical cross section formulas by considering the original formula of Levkovskii on the calculations of cross section for (p,α) nuclear reactions at 17.9 MeV. We researched the Coulomb and odd-even effects on (p,α) nuclear reactions. The present formula considers the Q–value of nuclear reactions instead of the widely used asymmetry parameter.

3. Results

This paper suggests new empirical equations of which can be used in the cross section predictions of (p,α) nuclear reactions at proton energy of 17.9 MeV. The empirical formulas were proposed by considering the Coulomb effects. Namely, the influence of the Coulomb force between the charged particles of target nuclide and the projectile proton particle can be given by the proton Coulomb effect cross section for nuclear reactions of incident proton particles. Based upon the studies of [11,12,15], we assumed that the empirical equation for (p,α) cross sections is approximately written as following,

$$V_{Coul} \approx \frac{Z^2}{R} \approx \frac{Z^2}{\left(A^{1/3}+1\right)}$$

$$\sigma_{Coul} \approx \frac{Z^2}{\left(A^{1/3}+1\right)}$$

$$\sigma(p,\alpha) = \beta_1 \sigma_{Coul} exp[\beta_2 s] \qquad (5)$$

where the term σ_{Coul} denotes the proton Coulomb effect cross section. β_1 and β_2 calculated from least squares method are the fitting parameters. The parameter values in fitting of Eq. (5) to the experimental data are presented in Table 1. For fitting process, we used 26 experimental cross section values of different target nuclei taken from the paper of [20]. Here, it was used the experimental cross sections for the target nuclei that are changed by the mass number A = 46–197, neutron number N = 24–118 and atomic number Z = 22–79. Figure 1 presents the Q-value dependences on the mass number of the target nuclides for the (p,α) cross sections. From Figure 1, the Q-values for the considered (p,α) nuclear reactions increase with increasing the mass number of the target nuclides. The literature experimental data of (p,α) cross sections are fitted using the least squares method via Eq. (5), and the systematics are given in Figures. 2-4. In Figure 2 we have presented a fitting procedure for all target nuclides used in the present study. The empirical formulas can be investigated by evaluating the 'chi-square' (χ^2). The chi-square statistic is the measure of goodness of fit that is the ratio of sum of square of differences between measured and calculated data to the calculation [21,22]. The χ^2 value for this systematic is equal to 28.43. Moreover, a good fitting is achieved for (p,α) cross sections including the odd-even effects. The systematics of the (p,α) cross sections for even Z–even N and even Z–odd N nuclei are given in Figure 3 and Figure 4, respectively. The χ^2 values calculated for even–even and even–odd nuclei are equal to 14.79 and 37.83, respectively. It is shown that the χ^2 values for the cross sections estimated using new empirical systematic show the smaller values for even–even nuclei. The ratios of the $\sigma(p,\alpha)_{exp.}$ to the $\sigma(p,\alpha)_{syst.}$ for target nuclides used in the present study are plotted against reaction Q-values in Figure 5. The predictions of empirical formula for even–even nuclei give better agreement with experiment data than does other two empirical formulas.

4. Conclusion and Comment

In the present paper, new empirical formulas have been proposed to systematise (p,α) cross sections at 17.9 MeV. It is seen that cross section results estimated by our empirical formulas at 17.9 MeV projectile energy are in good agreement with the literature values of (p,α) nuclear reactions. In addition to, the cross sections of (p,α) nuclear reaction are strongly dependent on the Q-values. Particularly, the empirical formula obtained for even–even nuclei has a good fitting with low chi-square value of χ^2 =14.79. Furthermore, a very good calculation of experimental cross sections values of (p,α) nuclear reactions was obtained by taking into account the Coulomb effects. Thereby, the present empirical formulas will be useful for future theoretical and experimental researches of proton-induced reactions cross section.

Table 1. the fitting parameters and chi-square values for the present empirical systematics

Sets	β_1	β_2	χ^2
All nuclei	0.408	-0.453	28.43
even –even nuclei	0.444	-0.361	14.79
even–odd nuclei	0.434	-0.583	37.83

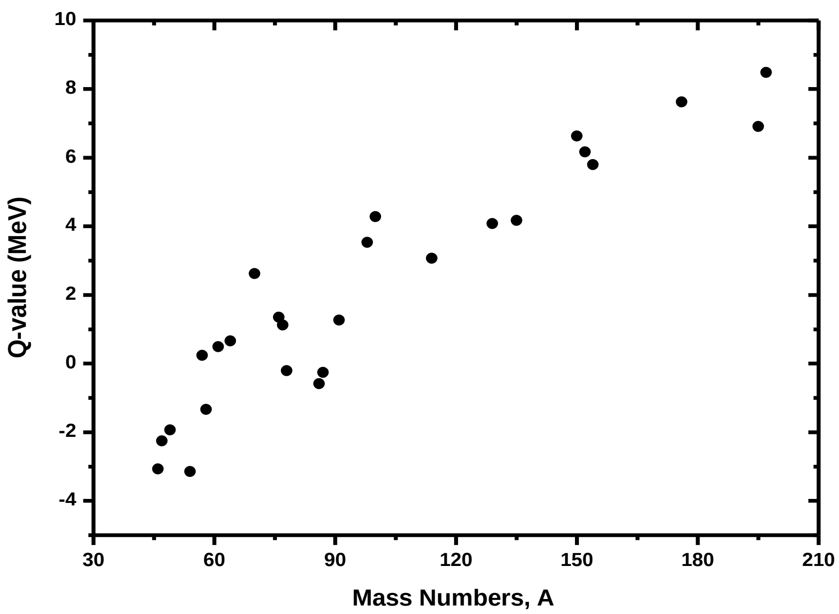

Figure 1. Q-values for ($A = 46{\sim}197$) target nuclides used in the present study.

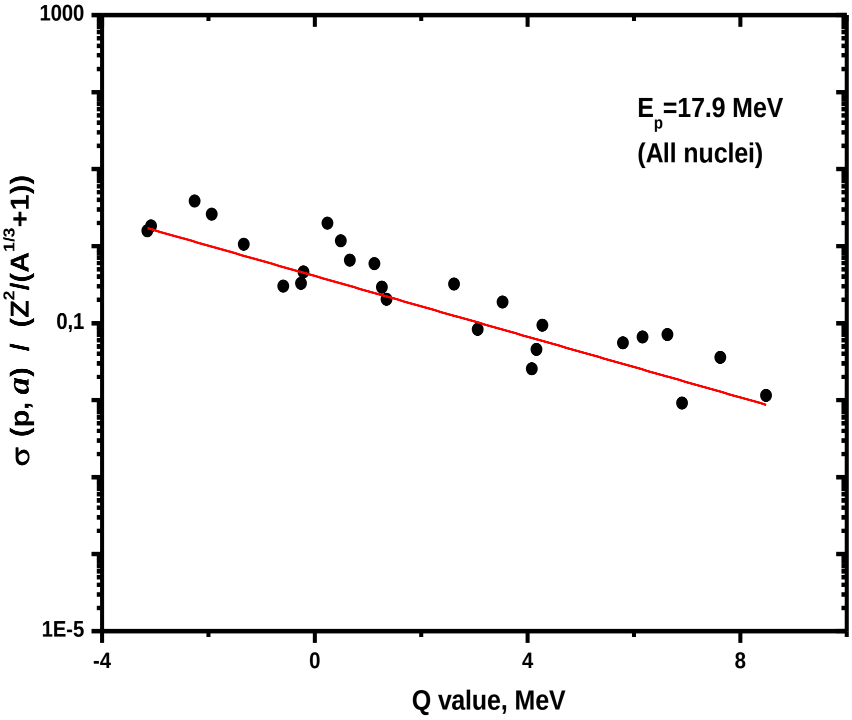

Figure 2. (p,α) cross section systematics including Coulomb effect for all target nuclides ($46 \leq A \leq 197$) used in this study.

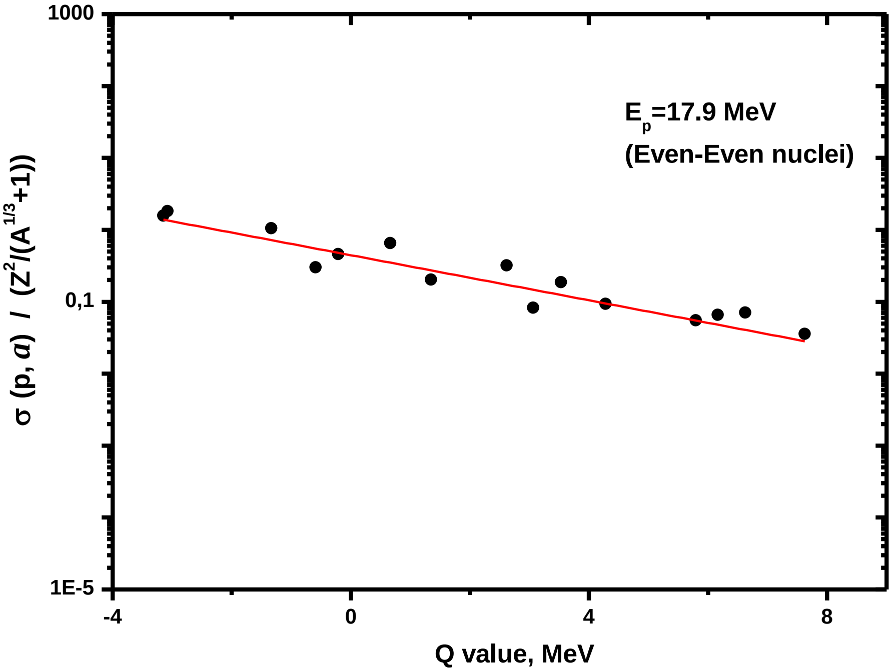

Figure 3. (p,α) cross section systematics including Coulomb effect for even-even target nuclides ($46 \leq A \leq 176$) used in this study.

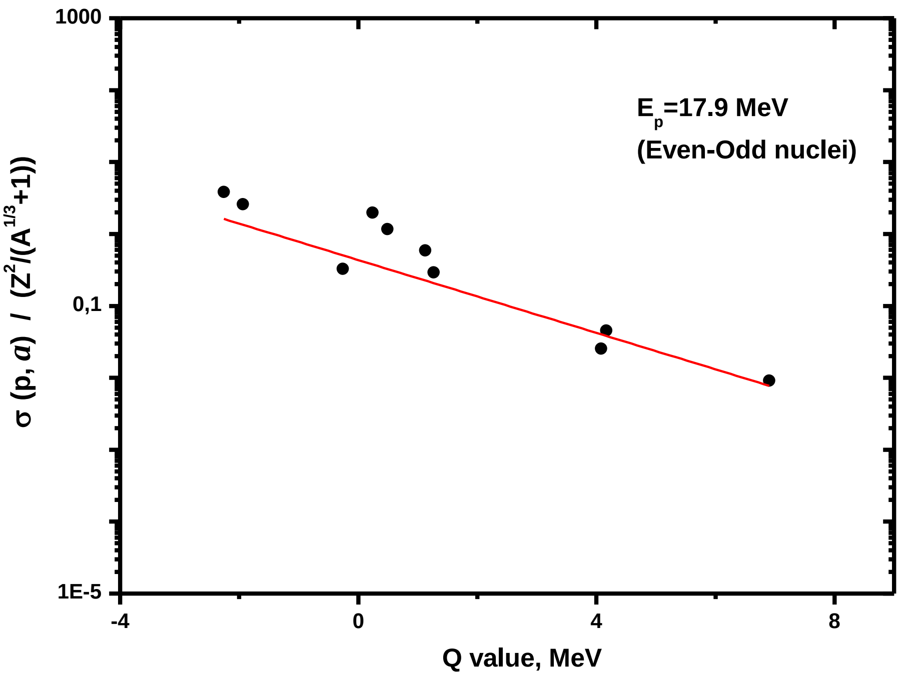

Figure 4. (p,α) cross section systematics including Coulomb effect for even- odd target nuclides ($47 \leq A \leq 195$) used in this study.

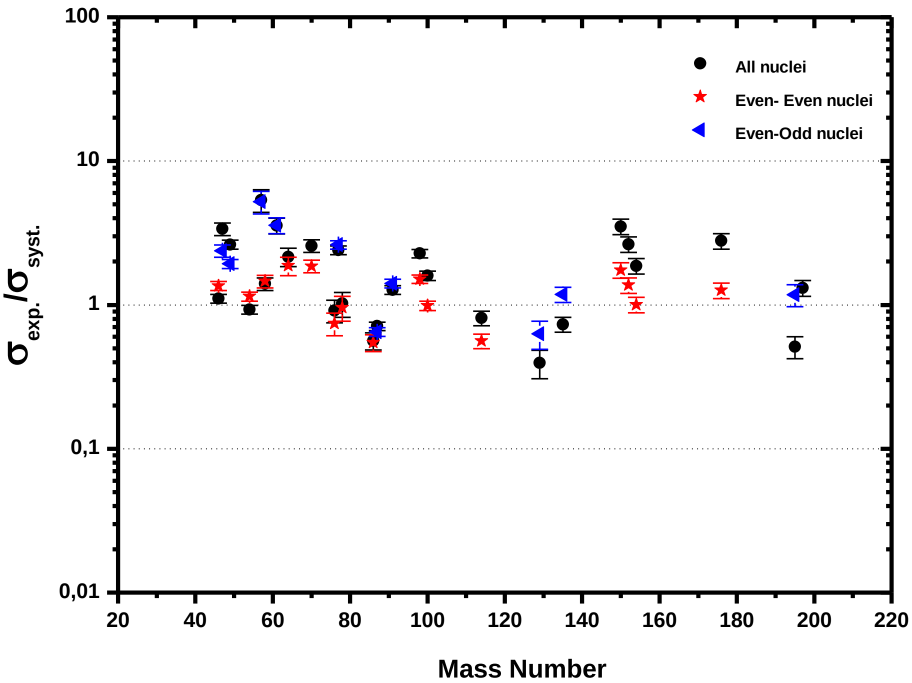

Figure 5. A comparison for the (p,α) cross sections on empirical formulas obtained using the present systematic given in Eq. 5.

Author Statement

Mustafa Yiğit: Investigation, Data Curation, Formal Analysis, Methodology, Review and Editing, Supervision, Advice
Hüseyin Dönmez: Investigation, Original Draft Writing, Validation, Observation

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As the authors of this study, we declare that we do not have any support and thank you statement.

Conflict of Interest

As the authors of this study, we declare that we do not have any conflict-of-interest statement.

Ethics Committee Approval and Informed Consent

As the authors of this study, we declare that we do not have any ethics committee approval and/or informed consent statement.

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