Nuclear Engineering and Technology 55 (2023) 4026–4031

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

A study on (n, α) reaction cross sections using a new empirical systematic

Sema Küçüksucu [a], Mustafa Yiğit [b,*]

[a] Department of Physics, Faculty of Science, University of Zagreb, Bijenicka c. 32, Zagreb, 10000, Croatia
[b] Department of Physics, Faculty of Arts and Science, Aksaray University, Aksaray, 68100, Turkiye

ARTICLE INFO

Keywords:
Cross section
Empirical formula
Neutron induced reactions

ABSTRACT

In this article, we report a new empirical formula for quick calculation of cross sections of (n, α) reactions with 14–15 MeV neutrons. Cross sections are analysed in terms of the compound nucleus model. A systematic trend for 14–15 MeV neutrons is found in the variation of (n, α) reaction cross sections with the parameters $(N - Z + 1)$, $(E_n + Q)^{0.5}$ and N/Z. The empirical relation between the cross sections and these parameters has been obtained, which give fairly good fits with the experimental data. We have also investigated the odd-even effects on (n, α) cross sections considering binding energy systematic of the shell model. The present formula is very useful in predicting of the (n, α) cross sections, where the measurements are not available as well as in testing new experimental data.

1. Introduction

Nuclear reaction cross section data are essential ingredients in a wide range of applications, including the fission/fusion systems, accelerator driven systems, medical radionuclide production, radiation therapy, astrophysics, [1–7]. Cross section data for individual isotopes at particular incident energies for a given reaction can be measured experimentally, or else they are predicted by various nuclear model-based calculations and empirical/semi-empirical systematics. An experiment usually provides a single cross section value at a particular incident energy or at most, cross section behaviour at a rather limited energy region. Thereby, a very large number of experiments are required to obtain sufficient cross section data. Performing such a large number of nuclear reaction experiments is a very costly task, especially when we consider that experimental data are not available in some energy ranges. Therefore, it is very popular today to resort the theoretical calculations and the systematics in the cross section behaviour of nuclei with similar characteristics, especially in term of obtaining data quickly and being less costly [8–13]. The reliable nuclear models and computer programs are needed for theoretical calculations. The incident neutrons with 14–15 MeV energies are enough to excite the nucleus for nuclear reactions such as $(n, 2n)$, (n, α), (n, p), (n, t) and (n, d). At this energy range, the reaction cross section data and particle emission spectra are very important in understanding the basic nucleon-nucleus interaction, the binding energy systematics, refined reaction models and nuclear structure [14,15]. Actually, although extensive researches on cross sections of neutron-induced reactions continue, there is still lack of data in some reaction channels. For example, experimental studies on cross section of (n, α) reactions induced by neutrons at energies of 14–15 MeV are quite limited. In addition, some existing experimental results contradict each other. In fact, there is large discrepancy among some experimental values by a factor more than 2. Therefore, experimental values by theoretical analyses should be tested and further experiments should be guided [16,17]. The (n, α) reactions may contribute a large fraction of the gas production on the reactor materials and components. As a result, (n, α) cross section calculations at these incident energies play a fundamental role for the design and optimisation of fusion power reactors, including the evaluation and verification of their nuclear performance. In recent years, much theoretical effort has focused on the study of data evaluations using empirical formulas for the cross sections of (n, α) nuclear reactions [18–20]. Cross section systematics of neutron-induced reactions are mostly based on the asymmetry parameter $(S{=}(N - Z)/A)$. However, various systematics have also been established depending on nuclear parameters such as $(2Z - 1)/A$, $(N - Z + 1)/A$, $(Z - 1)/A^{1/3}$, $A^{1/2}$ and the reaction threshold energy E_{th} and the reaction $Q -$ value. Furthermore, accurate definitions of cross sections using the systematics can also be obtained by considering shell and pairing effects. In this study, a new empirical formula based on statistical theory will be developed for (n, α) reactions with 14–15 MeV neutrons (see Table 1).

* Corresponding author.
E-mail addresses: semak@phy.hr (S. Küçüksucu), mustafayigit@aksaray.edu.tr (M. Yiğit).

https://doi.org/10.1016/j.net.2023.07.017
Received 6 June 2023; Received in revised form 11 July 2023; Accepted 15 July 2023
Available online 23 July 2023
1738-5733/

Table 1
Comparison among the fitting processes made by using Eq. (8) under four different assumptions in this study.

Assumption	Mass Region	Fitting parameters	χ^2	F/N
first	$13 \le A \le 208$ (All nuclei)	$a = 3.95E10$; $b = -20.18$	7.88	0.37
second	$13 \le A \le 144 (N/Z \le 1.40)$	$a = 8.53E10$; $b = -20.88$	6.15	0.32
	$133 \le A \le 208 (N/Z \ge 1.41)$	$a = 3.66E10$; $b = -20.01$		
third	$16 \le A \le 208$ (Even-A)	$a = 2.56E10$; $b = -19.69$	4.28	0.25
	$13 \le A \le 205$ (Odd-A)	$a = 1.59E10$; $b = -19.62$		
fourth	$16 \le A \le 150$ ($N/Z \le 1.42$ Even-A)	$a = 4.39E10$; $b = -20.19$	1.46	0.16
	$138 \le A \le 208$ ($N/Z \ge 1.43$ Even-A)	$a = 7.99E9$; $b = -18.74$		
	$13 \le A \le 115$ ($N/Z \le 1.35$ Odd-A)	$a = 1.75E11$; $b = -21.67$		
	$133 \le A \le 205$ ($N/Z \ge 1.41$ Odd-A)	$a = 4.83E15$; $b = -28.11$		

2. Empirical formulas for neutron-induced reaction cross sections

It has long been known that neutron-induced reaction cross sections vary rather smoothly with the atomic number (Z), neutron number (N) and mass number (A) of target nucleus. Therefore, the systematics are mostly based on various nuclear parameters such as $(N-Z)/A$, $(2Z-1)/A$, $(N-Z+1)/A$, $(Z-1)/A^{1/3}$ and $A^{1/2}$. The effects attributable to these parameters as well as to the shell and pairing effects on the cross section data have been also observed [21–24]. Vogt et al. [25] has demonstrated that single- and two-nucleon separation energies can be parametrized by a simple empirical systematics using the ratio N/Z. According to Vogt et al. [25], all single- and two-nucleon separation energies have a N/Zdependence. The underlying physical reason of the N/Z dependence is that separation energies of isotonic and isotopic nuclei of a given parity type (even-even, odd-even, even-odd or odd-odd) follow linear systematics within each shell region if plotted against Z and N, respectively [25,26]. It is known that the reaction cross sections are very sensitive to the separation energies. Therefore, the target neutron to proton ratio N/Z is one of the parameters that affect the formation and decay of compound nuclei into different exit channels. Several studies have shown that the ratio N/Z is an effective factor influenced considerably the reaction dynamics and the fragment production of the heavy-ion reactions [27,28]. We demonstrate the ratio N/Z dependence for the (n, α) cross sections in this study.

The empirical cross section systematics of (n, α) reactions induced by 14–15 MeV neutrons in literature were proposed using the evaporation model in the framework of the statistical theory to nuclear reactions. The empirical cross sections of nuclear reactions produced by fast neutrons can be approximately described by the following formula

$$\sigma(n,x) = C\sigma_{ne} exp[as] \quad (1)$$

here the a and C denote the fitting parameters. The term s is asymmetry parameter and is equal to $(N-Z)/A$. The exponential expression in Equation (1) has a strong asymmetry parameter dependence and it represents the escape of the compound nucleus products of nuclear reaction. The term σ_{ne} represents the neutron non-elastic cross section. It shows the non-elastic interaction between the projectile with target. It is given as follows

$$\sigma_{ne} = \pi r_0^2 (A^{1/3}+1)^2 \quad (2)$$

here the term r_0 corresponds to the nuclear radius constant. Equation (1) is the most widely used systematic for cross section predictions of nuclear reactions with 14 MeV energy. This equation represents the Levkovskii formula [29–36] which is obtained from the statistical model and a semi-empirical mass equation. Levkovskii's empirical formula has been used in many articles for different reaction channels and incident particles. Lu and Fink [37] demonstrated the applicability of the constant nuclear temperature approximation in the cross section calculations of statistical model of $(n, 2n)$, (n, p) and (n, α) reactions of neutrons with 14.4 MeV energy on medium-Z target nuclei. According to Lu and Fink [37], the exponential dependence of asymmetry parameter on cross sections in Levkovskii's empirical formula may be obtained from the statistical model with a constant temperature level density formula and a semi-empirical mass formula. Bansal and Mohindra [38] obtained the

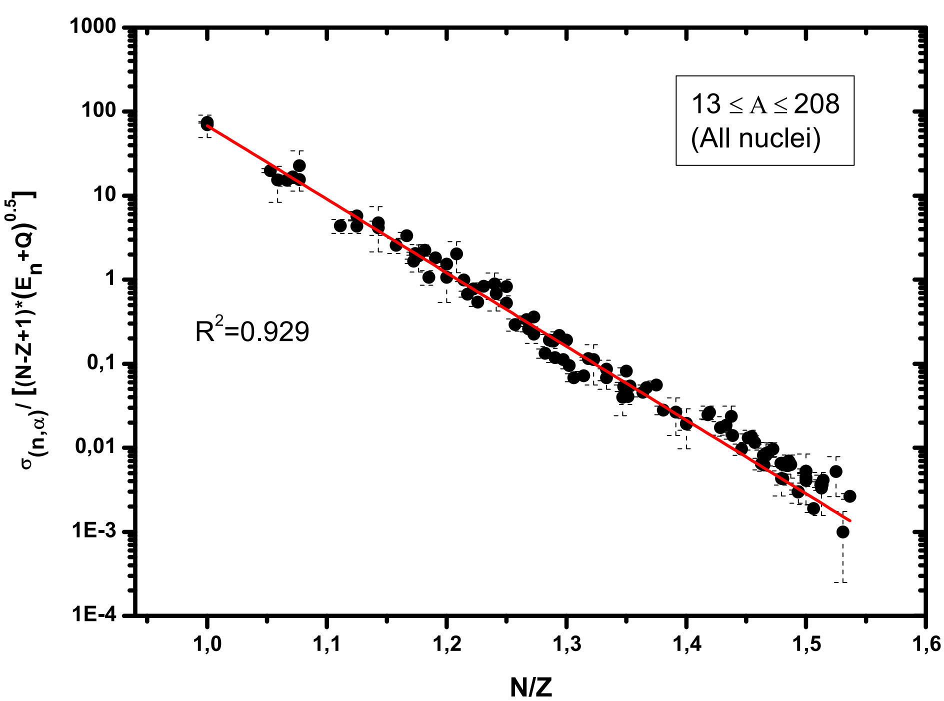

Fig. 1. Fitting with first assumption of the (n, α) cross sections for all target nuclei $13 \le A \le 208$ at 14–15 MeV energy.

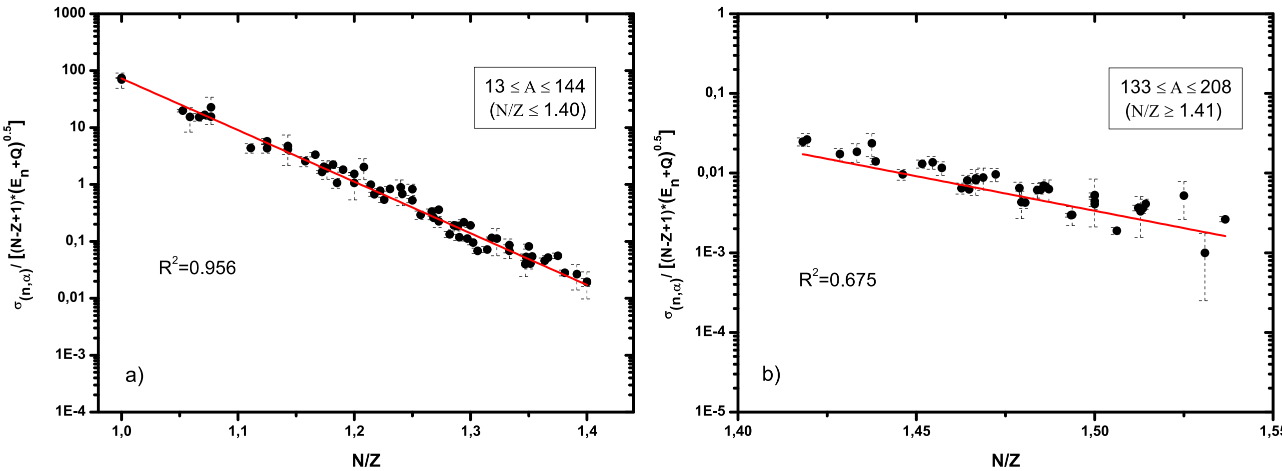

Fig. 2. Fitting for the second assumption of the (n, α) cross sections at 14–15 MeV energy. (a) for target nuclei with $N/Z \leq 1.4$ and $13 \leq A \leq 144$. (b) for target nuclei with $N/Z \geq 1.41$ and $133 \leq A \leq 208$.

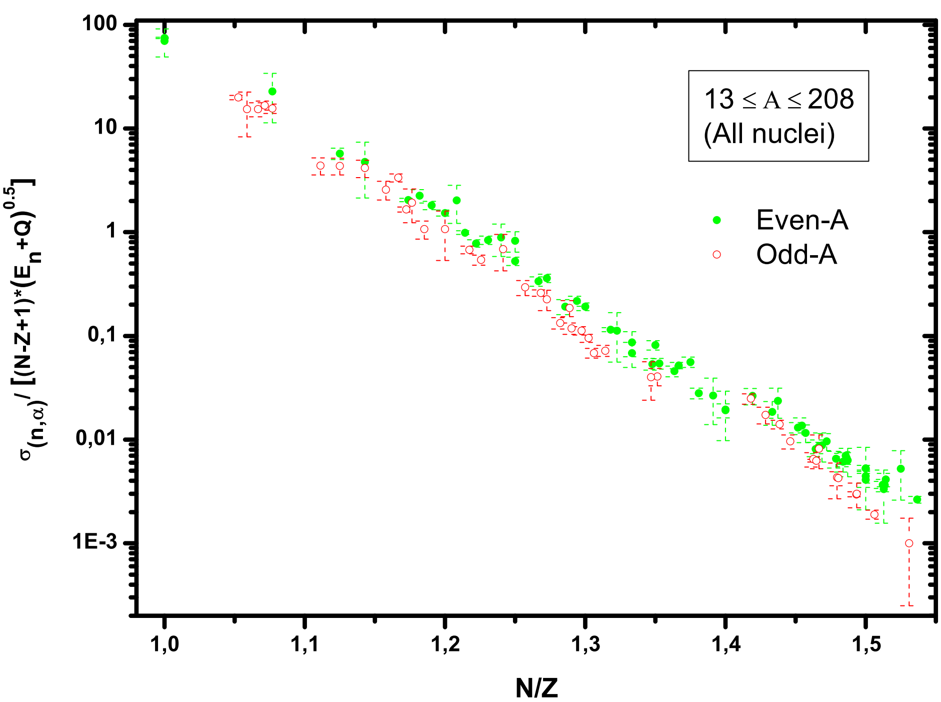

Fig. 3. Comparison of cross section of odd-*A* and even-*A* target nuclei of (n, α) cross sections at 14–15 MeV energy.

empirical formulas for cross sections of (n, t), (n, d) and $(n,{}^3He)$ reactions at neutron energies around 14 MeV. They observed the shell effects at magic nucleon numbers for the (n, t), (n, d) and $(n,{}^3He)$ cross sections. A semi empirical formula with six parameters on the basis of analytical expressions for the evaluation of the proton spectrum using evaporation and pre-equilibrium exciton models is derived by Konobeyev and Korovin [39] for the predictions of cross section of (n, p) reactions at 14.5 MeV energy. Belgaid and Asghar [40] proposed a semi empirical systematic in evaluating the (n, α) cross section values for 120 nuclei with $39 \leq A \leq 209$ at 14.5 MeV energy. Their systematic is based on the evaporation model and uses the Droplet model of Myers and Swiatecki for the reaction energy $Q(n, \alpha)$. An empirical formula on (n, α) reaction cross sections at the 14.5 MeV neutron energy is proposed by Atasoy et al. [41] using the cross sections for 40 nuclides in the mass region of $A = 9$ to 42. Their formula is derived by fitting the experimental cross sections as a function of the parameters $(N - Z)$ and $(14.5 - E_{th})^{1/3}$. Here, the terms E_{th} and $(N - Z)$ are the reaction threshold energy and the neutron excess of target nucleus, respectively. Their empirical equation was given as follows

$$\sigma_{n,\alpha} = ae^{-b(N-Z)}(14.5 - E_{th})^{1/3} \tag{3}$$

here the fitting parameters a and b were determined by least-squares fitting as follows:

$$\begin{aligned} a &= 65.034; \quad b = 0.34 \quad for \quad 0 < (N - Z) \leq 8 \\ a &= 12.1; \quad b = 0.089 \quad for \quad 9 \leq (N - Z) \leq 43 \end{aligned} \tag{4}$$

Fuga [42] derived an empirical formula for predictions of (n, α) cross sections on target nuclei with $19 \leq A \leq 238$ at 14.5 MeV energy. This formula based on mass number A, asymmetry parameter $(N - Z)/A$ and the parameter $(14.5 - E_{th})^{1/3}$ can be given as below

$$\sigma_{n,\alpha} = 18A^{1/2}(14.5 - E_{th})^{1/3}exp^{-30(N-Z)/A} \tag{5}$$

For the cross sections of (n, α) reactions with 14 MeV neutrons, the

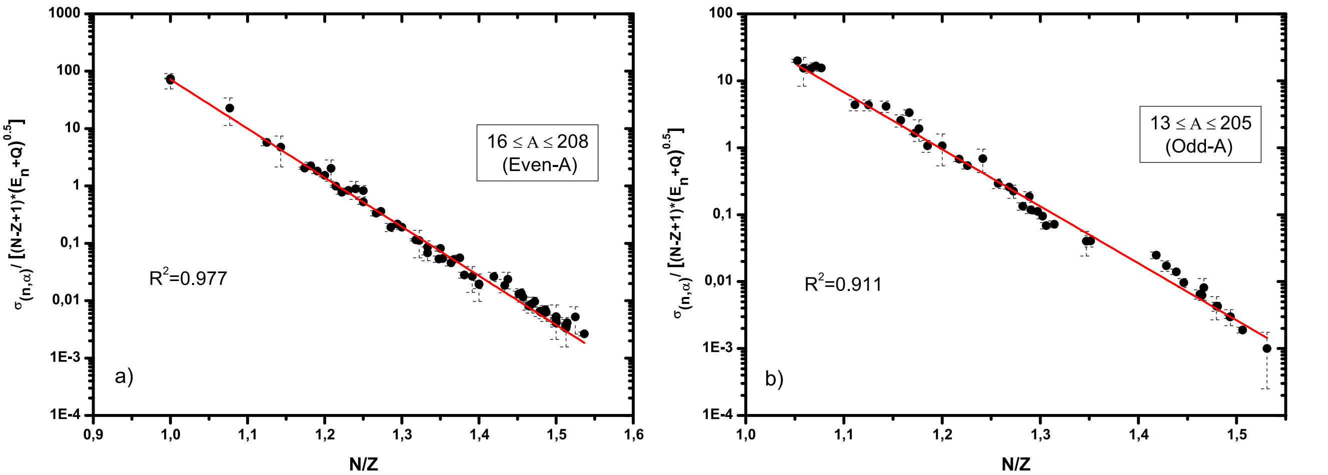

Fig. 4. Fitting for the third assumption of the (n, α) cross sections at 14–15 MeV energy. (a) for even-A target nuclei with 16≤ $A \leq 208$. (b) for odd A target nuclei with 13≤ $A \leq 205$.

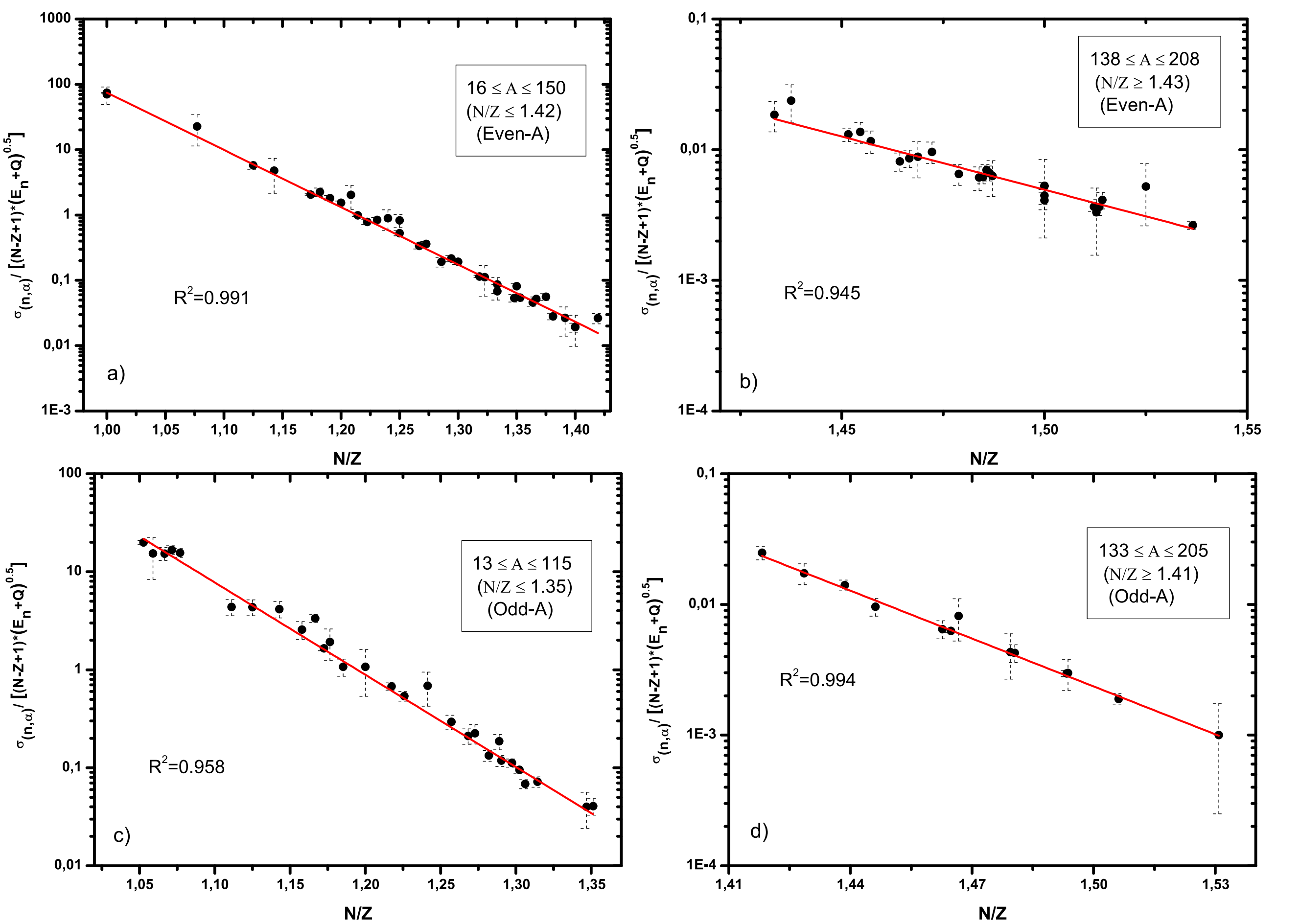

Fig. 5. Fitting for the fourth assumption of (n, α) the cross sections at 14–15 MeV energy. (a) for even-A target nuclei with $N/Z \leq 1.42$ and $16 \leq A \leq 150$. (b) for even-A target nuclei with $N/Z \geq 1.43$ and $138 \leq A \leq 208$. (c) for odd-A target nuclei with $N/Z \leq 1.35$ and $13 \leq A \leq 115$. (d) for odd-A target nuclei with $N/Z \geq 1.41$ and $133 \leq A \leq 205$.

empirical systematic proposed by Kumabe and Fukuda [43] modifying Levkovskii's formula can be given as follows

$$\sigma_{n,\alpha} = aA^b exp[-c(N-Z)/A] \quad (6)$$

here the a, b and c are fitting parameters which are determined by least-squares fitting to experimental cross sections. Their empirical formulas were derived separately in three ranges of mass number $30 \leq A \leq 60$, $61 \leq A \leq 105$ and $106 \leq A \leq 140$. The fitting parameters a, b and c were determined separately for each of the above three mass regions. Empirical formulas which are based on the statistical model for calculating the cross sections of (n, α) reactions at 14.5 MeV energy were proposed by Habbani and Osman [44] as follows:

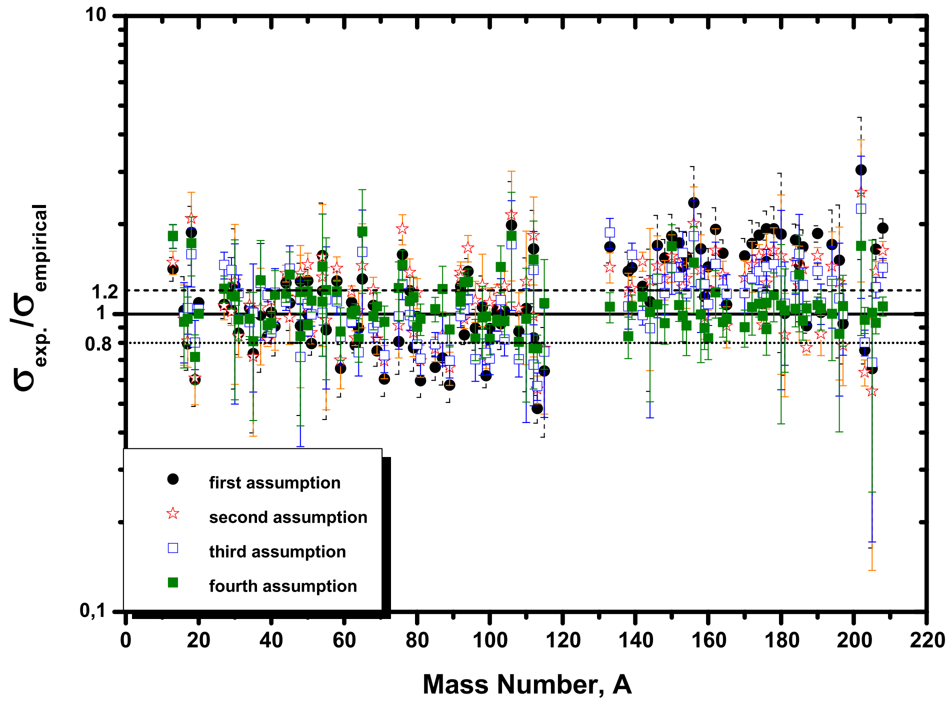

Fig. 6. Comparison of (*n*, *α*) cross sections predicted from four assumptions in the present work with experimental data at 14–15 MeV energy.

$$\begin{aligned}\sigma_{n,\alpha} &= 3.6(A^{1/3}+1)^2 exp[-25(N-Z-3)/A] \\ &\quad 26 \le A \le 238; \quad even-A \\ \sigma_{n,\alpha} &= 35(A^{1/3}+1)^2 exp[-37.714(N-Z)/A] \\ &\quad 27 \le A \le 209; \quad odd-A\end{aligned} \tag{7}$$

Theirs formulas explicitly take into consideration the odd-even effects and Q-value dependence.

3. Results and discussion

Most of the experimental studies on the cross sections of (*n*, *α*) nuclear reactions are in the energy range of 14–15 MeV. So, the cross section calculations in this energy range have an important place in nuclear reaction physics. In this work, a new empirical systematic based on the nuclear parameters $(N - Z + 1)$, $(E_n + Q)^{0.5}$ and N/Z for cross sections of (*n*, *α*) reactions in energy range of 14–15 MeV has been obtained by taking into account the compound nucleus model. This systematic contains the exponential dependence on N/Z for (*n*, *α*) cross sections. Here, we propose that a good fit for predicting the (*n*, *α*) reaction cross sections at 14–15 MeV is carried out by the following systematic:

$$\sigma_{n,\alpha} = a(N-Z+1)^*(E_n+Q)^{0.5} exp(b^*N/Z) \tag{8}$$

here, *a* and *b* are the fitting parameters.

The experimental cross section data taken from Ref. [45] in the 14–15 MeV energy range are used for obtaining a new empirical formula in the present work. The fitting parameters were determined on 103 experimental data in a wide range of target nuclei with mass number $A = 13$ to 208 and atomic number $Z = 6$ to 82. The fitting process has been carried out by using Eq. (8) under four different assumptions of the mass regions, N/Z parameter values, and even-odd nuclei character. Nine pairs of the (*a*, *b*) fitting parameters for four different assumptions are given in Table I. Table I also presents the χ^2 and F/N values for the comparison of the present assumptions. The obtained systematics under four assumptions are shown in Figs. 1–5, where $\sigma_{n,\alpha}/[(N-Z+1)^*(E_n+Q)^{0.5}]$ is plotted versus the neutron to proton ratio N/Z for all target nuclei. A striking correlation between these two parameters can be seen at Figs. 1–5 along with the values *R*-squared. The cross sections of (*n*, *α*) reactions at 14–15 MeV appear to decrease exponentially with increasing the neutron to proton ratio N/Z. Thereby, a strong exponential dependence on the N/Z was observed in calculating the (*n*, *α*) reaction cross sections. The first assumption was obtained for 103 experimental data with the mass numbers of $A = 13$–208, and was presented in Fig. 1. As can be seen in Fig. 1, a relatively acceptable fit is found for the (*n*, *α*) reaction channel at 14–15 MeV energy. The χ^2 and F/N values corresponding to the description of experimental values from the first assumption are equal to 7.88 and 0.37, respectively. The quality of fits was tried in order to improve using different approaches. In this context, the second assumption considered in this work, is the one, which relates the low and high values of the ratio N/Z. When the determination of such a limitation for the ratio N/Z, the agreement is much improved, as seen in Fig. 2 and in Table I. The χ^2 and F/N values for the second assumption are equal to 6.15 and 0.32, respectively. On the other hand, the odd-even effects were observed in the cross sections of (*n*, *α*) reaction at 14–15 MeV energy. Fig. 3 presents the dependence of the cross sections on the rate N/Z for even-*A* and odd-*A* nuclei at 14–15 MeV energy. As can be seen in Fig. 3, the curve of even-*A* nuclei is located above that of odd-nuclei. Thus, the fitting procedure for the third assumption was carried out by taking into account the effects of even-*A* and odd-*A* nuclei based on the rate N/Z, as seen in Fig. 4 The χ^2 and F/N values for this assumption are equal to 4.28 and 0.25, respectively. Finally, the possibility that the fits could be improved by taking into account the both the magnitude of ratio N/Z and the odd-even effects was examined. A good fit for obtaining the fourth assumption is given in Fig. 5. The values χ^2 and F/N calculated from this assumption are equal to 1.46 and 0.16, respectively. As a result, the fitting of experimental data made by taking into account the magnitude of ratio N/Z and the odd-even effects did reduce χ^2 and F/N considerably. In addition, the fourth assumption shows generally a better *R*-squared as compared to the others shown in Figs. 1–5. The ratio of the experimental data to the calculated results for the target nuclei used in this work is shown in Fig. 6. The predictions of final assumption give better agreement with experiment data than other three assumptions obtained from this work. The ratios of the fourth assumption are in the region of 0.71–1.89.

4. Conclusion

In this paper, a new empirical formula has been derived to systematise the cross section data of (n, α) reactions at 14–15 MeV. The present formula leads to a significantly low values of χ^2 and F/N and, so it gives a good agreement with the results of available experimental measurements of (n, α) reactions at 14–15 MeV. The (n, α) cross sections are found to be strongly dependent on the neutron to proton ratio N/Z in the exponential term of the empirical systematics. As a result, it has been shown that N/Z is a good parameter to describe the variation of (n, α) cross sections. Additionally, we point out that the dependency of odd-even effects on (n, α) cross sections is very clear. Therefore, a good fitting for (n, α) reaction cross section data is obtained from the empirical formula under fourth assumption taking into account the magnitude of ratio N/Z and the odd-even effects. It can also be stated that the presence of extended experimental data in the range of $N =$ 7–126 in the present study causes an increase in the goodness of fit, as well as a comparative analysis of various results. As a result, this formula can be considered to provide a very useful practical tool for predicting the cross sections of (n, α) reactions with 14–15 MeV energy.

Acknowledgements

This work is supported by the QuantiXLie Centre of Excellence, a project co-financed by the Croatian Government and European Union through the European Regional Development Fund, the Competitiveness and Cohesion Operational Programme (KK.01.1.1.01.0004). S.K. acknowledges support from the Scientific and Technological Research Council of Turkey (TUBITAK) through the International Doctoral Research Fellowship Programme 2214A, 2020/1, Grant No. 1059B142000254.

References

[1] S. Küçüksucu, M. Yiğit, N. Paar, Universe 8 (2022) 25.
[2] N. Paar, G. Co, E. Khan, D. Vretenar, Phys. Rev. C 80 (2009), 055801.
[3] A. Sharma, A. Gandhi, A. Kumar, Phys. Rev. C 105 (2022), 014624.
[4] S.F. Hosseini, M. Sadeghi, M.R. Aboudzadeh, M. Mohseni, Appl. Radiat. Isot. 118 (2016) 361.
[5] S.F. Hosseini, M. Sadeghi, M.R. Aboudzadeh, Appl. Radiat. Isot. 127 (2017) 116.
[6] Z. Karimi, M. Sadeghi, N. Mataji-Kojouri, Appl. Radiat. Isot. 137 (2018) 56.
[7] F. Soltani, A. Bahrami Samani, M. Sadeghi, S. Shirvani, K. Yavari, J. Radioanal. Nucl. Chem. 303 (2014) 385.
[8] A. Trkov, Nucl. Eng. Technol. 37 (2005) 11.
[9] H. Özdoğan, Y. Ali Üncü, M. Şekerci, A. Kaplan, Appl. Radiat. Isot. 199 (2023), 110922.
[10] H. Özdoğan, M. Şekerci, A. Kaplan, Mod. Phys. Lett. 34 (2019), 1950044, https://doi.org/10.1142/S0217732319500445.
[11] M. Şekerci, H. Özdoğan, A. Kaplan, Appl. Radiat. Isot. 186 (2022), 110255.
[12] H. Özdoğan, Y.A. Üncü, M. Şekerci, A. Kaplan, Mod. Phys. Lett. 36 (2021), 2150168, https://doi.org/10.1142/S0217732321501686.
[13] H. Özdoğan, Y. Üncü, M. Şekerci, A. Kaplan, Appl. Radiat. Isot. 184 (2022), 110162.
[14] E. Tel, A. Aydin, G. Tanir, Phys. Rev. C 75 (2007), 034614.
[15] M. Yiğit, Appl. Radiat. Isot. 135 (2018) 115.
[16] J. Luo, F. Tuo, F. Zhou, X. Kong, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 266 (2008) 4862.
[17] M. Yiğit, A. Kara, Nucl. Eng. Technol. 49 (2017) 996.
[18] T. Bitam, M. Belgaid, Nucl. Phys. 991 (2019), 121614.
[19] A. Hingu, S. Parashari, S.K. Singh, B. Soni, S. Mukherjee, Radiat. Phys. Chem. 188 (2021), 109634.
[20] H.M. Abdullah, A.H. Ahmed, Appl. Radiat. Isot. 189 (2022), 110396.
[21] E. Tel, B. Şarer, S. Okuducu, A. Aydın, G. Tanır, J. Phys. G Nucl. Part. Phys. 29 (2003) 2169.
[22] M. Yiğit, Int. J. Mod. Phys. E 29 (8) (2020), 2050062.
[23] M. Yiğit, Int. J. Mod. Phys. E 29 (2) (2020), 20050005.
[24] M. Yiğit, Appl. Radiat. Isot. 176 (2021), 109894.
[25] K. Vogt, T. Hartmann, A. Zilges, Phys. Lett. B 517 (2001) 255.
[26] N. Zeldes, T. Dumitrescu, H.K. öhler, Nucl. Phys. 399 (1983) 11.
[27] M. Kaur, B. Singh, S. Kaur, R.K. Gupta, Phys. Rev. C 99 (2019), 014614.
[28] T.A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia, Phys. Rev. C 83 (2011), 054615.
[29] V. Levkovskii, J. Exp. Theor. Phys. 45 (1964) 305.
[30] M. Yiğit, Appl. Radiat. Isot. 190 (2022), 110488.
[31] E. Tel, A. Bülbül, M. Yiğit, Hakkı Sarpün, Y. Kavun, Appl. Radiat. Isot. 192 (2023), 110613.
[32] M. Yiğit, Appl. Radiat. Isot. 128 (2017) 307.
[33] M. Yiğit, E. Tel, J. Fusion Energy 35 (2016) 585.
[34] M. Yiğit, Appl. Radiat. Isot. 105 (2015) 15.
[35] M. Yiğit, E. Tel, Kerntechnik 79 (2014) 488.
[36] M. Yiğit, E. Tel, Nucl. Eng. Des. 280 (2014) 37.
[37] W. deh Lu, R.W. Fink, Phys. Rev. C 4 (1971) 1173.
[38] S. Bansal, R.K. Mohindra, Indian J. Phys. 69A (3) (1995) 361.
[39] A. Konobeyev, Y. Korovin, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 103 (1995) 15.
[40] M. Belgaid, M. Asghar, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 149 (1999) 383.
[41] H. Atasoy, S. Dökmen, Y. Özbir, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 61 (1991) 251.
[42] P. Fuga, Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 368 (1996) 559.
[43] I. Kumabe, K. Fukuda, J. Nucl. Sci. Technol. 24 (1987) 839.
[44] F. Habbani, K.T. Osman, Appl. Radiat. Isot. 54 (2001) 283.
[45] N. Otuka, E. Dupont, V. Semkova, B. Pritychenko, A. Blokhin, M. Aikawa, S. Babykina, M. Bossant, G. Chen, S. Dunaeva, R. Forrest, T. Fukahori, N. Furutachi, S. Ganesan, Z. Ge, O. Gritzay, M. Herman, S. Hlavač, K. Katō, B. Lalremruata, Y. Lee, A. Makinaga, K. Matsumoto, M. Mikhaylyukova, G. Pikulina, V. Pronyaev, A. Saxena, O. Schwerer, S. Simakov, N. Soppera, R. Suzuki, S. Takács, X. Tao, S. Taova, F.T. árk ányi, V. Varlamov, J. Wang, S. Yang, V. Zerkin, Y. Zhuang, Nucl. Data Sheets 120 (2014) 272.