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ORIGINAL RESEARCH

The Comparison of (n,p), (n,α), (n,2n) and (α,n) Reaction Cross-Sections for ^{7}Li and ^{9}Be Target Nuclei

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Abstract The knowledge of the cross-section is important especially for the fusion and fission reactor technology. In the absence of experimental data or in the difficulty of measuring data, theoretical predictions of nuclear cross-section data are needed to be improved using model calculations or semi-empirical formulas and to be compared with model and formulas to obtain sensitive approaches. In this work, for ^{7}Li and ^{9}Be target nuclei used as blanket materials in fusion reactors, (n,p), (n,α), (n,2n) and (α,n) reaction cross-section data have been evaluated by using some available empirical and semi-empirical cross-section formulas. The (n,p), (n,α), (n,2n) and (α,n) reaction cross-section formulas developed for medium and heavy mass nuclei by some scientist in literature are applied to ^{7}Li and ^{9}Be light nuclei and then results obtained from any systematics are compared with each other and the existing experimental data.

Keywords Reaction cross-section · ^{7}Li · ^{9}Be · Fusion blanket materials · EXFOR library

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Introduction

The knowledge of nuclear data in the fusion technology has a great importance in the domains of nuclear structure, nuclear decay, and nuclear reaction. The experimental measurements, model theory calculations and systematic predictions are rather useful to provide this knowledge, especially for predicting the cross-sections of nuclear reaction.

The use of systematics for nuclear reaction cross-section evaluation is important, if experimental data are absent or results of nuclear model calculation are not reliable. Systematics of cross-sections has a special importance as an additional tool for the cross-section evaluation [1–3]. Many studies on systematics of cross-sections have been done in the literature [4–16]. Formulas obtained from this systematics have been used in the present study for Li and Be target nuclei irradiated with neutrons and alphas. Li and Be elements are candidate materials to be used as advanced blanket materials in fusion reactors [17, 18]. Lithium (Li) never occurs freely in nature, instead, it appears only in ionic compounds. It has two isotopes such as ^{6}Li and ^{7}Li and, both isotopes have low binding energy per nucleon compared to the neighbor lighter (helium) and heavier (beryllium) elements. The transmutation of lithium to helium is the first fully man-made nuclear reaction (1932). There are transmutation reactions from both ^{6}Li and ^{7}Li to tritium. However, the enrichment of ^{6}Li up to 40–90 % reaction is the dominant to be used in the fusion blanket for adequate tritium breeding.

It occurs a fusion reaction with capturing neutron with Li in blanket in fusion reactors and then is produced tritium (^{3}H) element used as a fuel in fusion reactor. On the other hand, and ^{9}Be(n,2n)^8 Be which is used as a neutron source in reactors is the most useful reaction. Beryllium (Be) which is known as a key element in fusion reactor is an attractive material as a neutron moderator and is a also light structural material with unique properties that make it very desirable for certain nuclear applications as a neutron reflector [19, 20].

Up to now, various studies on Li and Be isotopes have been made to be understood the nuclear structure and features of these isotopes. Some of these studies are summarized in next sentences. The nuclear structure of the Be isotopes by using the Hartree–Fock method with Skyrme forces was investigated by Tel et al. [21]. Neutron and proton distributions of Li and Beisotopes were studied using the new Skyrme-force parameters by Baldik et al. [22]. Tel et al. [23] made a study of $^{8-18}$Be isotopes using as a neutron multiplier in reactor design using Hartree–Fock approximation. The calculations of double-differential neutron emission cross sections for ^{9}Be target nucleus at 14.2 MeV neutron energy has been investigated by Şahan et al. [24]. Sahan et al. [25] investigated neutron-emission spectra induced by (n,xn) nuclear reactions for the ^{7}Li structural fusion material at 14.2 MeV neutron energy. Theoretical estimations of excitation functions of neutron-induced reactions on ^{6}Li and ^{9}Be nuclei at low energies have been carried out by Yigit [26].

In the present study, the cross sections of nuclear reactions occurring with ^{7}Li and ^{9}Be target nuclei interacted with both neutrons and alphas were predicted by using the available cross-section formulas. The cross-section formulas include some approximations for some models as the pre-equilibrium exciton model, evaporation model, semi-empirical mass formula, statistical model, and droplet model. For ^{7}Li and ^{9}Be target nuclei, the calculated cross-section values from the formulas were compared with the each other and with the available experimental data from EXFOR[1] [27].

Literature Studies and Basic Systematics Used in the Cross Section Calculations

There are several empirical and semi-empirical cross-section formula having different parameters that are available for charged (proton, deuteron, alpha, etc..) and uncharged (gamma, neutron) particles induced (n,p), (n,α), and (n,2n) reactions at different neutron energies in the literature. The systematic (n,p), (n,α), and (n,2n) formulas proposed by different authors are given in Tables 1, 2, and 3, respectively. Some of their names are Levkovskii [4], Broeders and Konobeyev [10], Tel et al. [28, 29], Bychkov et al. [30], Kumabe and Fukuda [31], Konno et al. [32], Adam and Jeki [33], Kasugai et al. [34], Ait-Tahar [7], and Habbani and Osman [35].

Levkovskii [4] expressed that (n,p) cross sections of many isotopes of one element decrease regularly with increasing mass number A for 14–15 MeV incident neutron energies. The cross section was showed with an exponential function depending on asymmetry term (s = N − Z/A), where Z and N are the proton and neutron numbers of the target nuclei, respectively. Levkovskii defined $\sigma_c(n)$ geometrical cross section of the nucleus as follows;

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

where the radius of nucleus is taken as $r_0 = 1.2 \times 10^{-13}$ cm. The (n,p) empirical cross section formula of Levkovskii [4] is given as follows;

$$\sigma_{n,p} = 45.2 (A^{1/3} + 1)^2 \exp[-33s] \quad (2)$$

The Levkovskii formula has been supported by many authors. Pai and Andrews [36] added an effective Q-value, defined as an energy of nuclear reaction. Habbani and Osman [35] proposed systematic based on the statistical model including odd–even effect for (n,p), (n,α), and (n,2n) reaction cross-sections for 14.5 MeV neutrons. Tel et al. [28] obtained a new empirical (n,p) cross-section formula taking shell model and pairing effects into account. Broeders and Konobeyev [10] proposed a semi-empirical formula with contribution of both non-equilibrium and equilibrium proton emissions for (n,p) reaction cross-section at 14.5, 20, and 30 MeV neutron energies. Many studies on (n,p), (n,α) and (n,2n) reaction cross-section formulas for 14–15 MeV neutrons have been made by the authors [7, 30–37]. These formulas are given for (n,p), (n,α) and (n,2n) reactions in Tables 1, 2 and 3, respectively. Newly modified empirical and semi-empirical formulas including non-elastic scattering and coulomb effects for (α,n) reaction cross-section at 18.5 ± 3 MeV for the nuclei of mass number in the range of 41 ≤ A ≤ 209 was proposed by Akça et al. [16]. In Tables 1, 2, 3, and 4, first columns give author names who proposed semi-empirical formulas for (n,p), (n,α) and (n,2n) cross sections, respectively. Mass regions and semi-empirical formulas are listed in second and third columns.

Many of formulas given in Tables 1, 2, 3, and 4 including interaction reaction cross sections (σ_{int}). Interaction cross section can be calculated with geometrical cross section as given below,

$$\sigma_{\text{int}} = \pi (R_{prj} + R_{tar})^2 \quad (3)$$

where R_{prj} and R_{tar} are the nucleus radii of projectile and target, respectively. From the Eqs. 1 and 3, the interaction reaction cross section for projectile nucleus as neutron (or proton) for ^{7}Li and ^{9}Be target nuclei are calculated to be 382 and 428 mb, respectively.

The (n,p) reaction cross-section systematics at 14–15 MeV incident energy belonging to Levkovskii [4], Broeders and Konobeyev [10], Tel et al. [28, 29], Kumabe

[1] https://www-nds.iaea.org/exfor/exfor.htm.

Table 1 The (n,p) reaction cross-section (mb) systematics at 14–15 MeV incident energy

References	Mass region	Formula, $\sigma(n,p)$ (mb)
Levkovskii [4]	$40 \leq A \leq 208$	$= 45.2(A^{1/3}+1)^2 \exp[-33s]$
Broeders and Konobeyev [10]	$Z < 50$	$= \pi r_0^2(A^{1/3}+1)^2 \exp[A^{0.5}(-4.4785s + 0.047174Z/A^{1/3} - 0.27407)]$
	$Z > 50$	$= \pi r_0^2(A^{1/3}+1)^2 A^{0.75718}(-0.61348(N-Z+1)/A + 0.1511)$
Tel et al. [28]	$17 \leq A \leq 239$	$= 14.56(A^{1/3}+1)^2 \exp[-26.58s]$
	for even —Z, even —N	$= 16.33(A^{1/3}+1)^2 \exp[-26.17s]$
	for even —Z, odd—N	$= 9.71(A^{1/3}+1)^2 \exp[-21.87s]$
	for odd —Z, even—N	$= 7.31(A^{1/3}+1)^2 \exp[-20.21s]$
Kumabe and Fukuda [31]	$19 \leq A \leq 62$	$= 21.84 \exp[-34s]$
	$63 \leq A \leq 89$	$= 0.79A^2 \exp[-43.2s]$
	$90 \leq A \leq 160$	$= 0.75A^2 \exp[-45.0s]$
Konno et al. [32]		$= 31.42(A^{1/3}+1)^2 \exp[-29.07s]$

Table 2 The (n,α) reaction cross-section (mb) systematics at 14–15 MeV incident energy

References	Mass region	Formula, $\sigma(n,\alpha)$ (mb)
Levkovskii [37]	$30 \leq A \leq 150$	$= 18.1(A^{1/3}+1)^2 \exp[-33s]$
Kasugai et al. [34]	$19 \leq A \leq 187$	$= 277.86 \exp[-24.66s]$
Ait-Tahar [7]	$40 \leq A \leq 188$	$= 31.66(A^{1/3}+1)^2 \exp[-37.75(N-Z+1)/A]$
Habbani and Osman [35]	$26 \leq A \leq 238$ (even—A)	$= 3.6(A^{1/3}+1)^2 \exp[-25(N-Z-3)/A]$
	$27 \leq A \leq 209$ (odd—A)	
Tel et al. [29]	$20 \leq A \leq 209$	$= 16.15(A^{1/3}+1)^2 \exp[-33.01s]$
	for even —Z, even— N	$= 14.43(A^{1/3}+1)^2 \exp[-32.17s]$
	for odd —Z, even —N	$= 17.93(A^{1/3}+1)^2 \exp[-34.04s]$
	for even Z, eodd —N	$= 19.41(A^{1/3}+1)^2 \exp[-35.97s]$

and Fukuda [31], and Konno et al. [32] are given in Table 1. The (n,α) reaction cross-section systematics at 14–15 MeV incident energy developed by Tel et al. [29], Ait-Tahar [7], and Habbani and Osman [35], Levkovskii [37] are given in Table 2. The (n,2n) reaction cross-section (mb) systematics at 14–15 MeV incident energy belonging to Bychkov et al. [30], Konno et al. [32], Tel et al. [29], Habbani and Osman [35], and Adam and Jeki [33] are given in Table 3. The (α,n) reaction cross-section systematics at 18.5 ± 3 MeV including non-elastic scattering and coulomb effects are given in Table 4.

Results and Discussions

There are very limited researches on light nuclei reactions in the literature. The earlier studies on reaction cross-section systematics are generally made on the medium and heavy nuclei. The studies on systematics have been performed in two categories: empirical and semi-empirical systematics. While the empirical formulas use only the evaporation model, the semi-empirical systematics usually use both evaporation model and pre-equilibrium exciton model. Our previous studies forming the basis of this study, including (n,p), (n,α) and (n,2n) reaction cross-section systematics are on semi-empirical systematics.

In this work, the cross-sections of various reactions occurred with ^{7}Li and ^{9}Be targets used as blanket materials in fusion reactors are evaluated by using the cross-section formulas in Tables 1, 2, 3, and 4. The formulas given in Tables 1, 2, 3, and 4 have been applied to the ^{7}Li and ^{9}Be target nuclei for understanding the nature of nuclear reactions and cross section results given in Tables 5 and 6 have been obtained. These results are then compared with each other and the available experimental data from EXFOR library.

The comparison of the (n,p), (n,α) and (n,2n) reaction cross-sections for ^{7}Li light nuclei at 14–15 MeV incident energy is given in Table 5. According to Table 5, the (n,p) reaction cross-section values for ^{7}Li target nuclei are

Table 3 The (n,2n) reaction cross-section systematics at 14–15 MeV incident energy

References	Mass region	Formula, $\sigma(n,2n)$ (mb)
Adam and Jeki [33]	28 ≤ A ≤ 50	$= 2050(A^{1/3}+1)^2 \exp[-8.6s]$
Konno et al. [32]	45 ≤ A ≤ 238	$= \exp\{7.434[1-1.484\exp(-27.37s)]\}$
Bychkov et al. [30]	40 ≤ A ≤ 188	$= 1000 + 7.5A(7.8s - 0.234)$ *for* $s \le 0.13$
		$= 1000 + 7.5A(0.65 + s)$ *for* $s \le 0.13$
Habbani and Osman [35]	*even* —*A*	$= 20.82(A^{1/3}+1)^2 \exp[-3.76(N-Z+1)/A]$
	odd—*A*	$= 23.53(A^{1/3}+1)^2 \exp[-3.5s]$
Tel et al. [29]	$20 \le A \le 209$	$= \exp\{7.43[1-1.71\exp(-24.99s)]\}$
	even —*A*	$= \exp\{7.15[1-2.45\exp(-31.62s)]\}$
	odd—*A*	$= \exp\{7.65[1-1.59\exp(-23.06s)]\}$

Table 4 The (α,n) reaction cross-section (mb) systematics including non-elastic scattering and coulomb effects at 18.5 ± 3 MeV incident energies

References	Mass region	Formula, $\sigma(\alpha,n)$ (mb)
Akça et al. [16]	$41 \le A \le 209$	$= 4.558(A^{1/3}+4^{1/3})\exp(-39.648s)$
	odd—*Z* *even* —*N*	$= 7.072Z^2(A^{1/3}+4^{1/3})\exp(-42.745s)$
	even —*Z*, *even*—*N*	$= 2.293Z^2(A^{1/3}+4^{1/3})\exp(-33.575s)$

Table 5 The comparison of the (n,p), (n,α) and (n,2n) reaction cross-section results (mb) for ^{7}Li ($s = 0.143$) at 14–15 MeV incident energy

References	σ(n,p)	σ(n,α)	σ(n,2n)
Levkovskii [37]	3.38	1.36	
Broeders and Konobeyev [10]	6.07		
Kumabe and Fukuda [31]	1.18		
Konno et al. [32]	4.13		1357.74
Tel et al. [28]	3.41		
Kasugai et al. [34]		6.70	
Ait-Tahar [7]		0.023	
Habbani and Osman [35]		1.339	119.96
Tel et al. [29]		1.159	1340.90
Adam and Jeki [33]			1742.54
Bychkov et al. [30]			1041.63
Exp. data: EXFOR [27]			130 ± 30

between 1.18 and 6.07 mb. The cross-section value of 3.38 mb obtained from Levkovskii [37] is very close to the cross section value of 3.41 mb obtained from and Tel et al. [28]. The (n,α) reaction cross-section values are between 0.023 and 6.70 mb. The (n,α) cross-section values obtained from the formulas of Levkovskii [37], Habbani and Osman [35] and Tel et al. [29] are found to be 1.36, 1.339 and 1.159 mb, respectively. There is no experimental data belonging to the (n,p) and (n,α) reactions for ^{7}Li target nuclei. While the (n,2n) reaction cross-section values obtained from four formulas are between 1041.63 and 1742.54 mb, the cross-section value obtained from Ait-Tahar [7] formula and experimental data taken from EXFOR [27] are 119.96 and 130 ± 30 mb, respectively.

Table 6 The comparison of the (n,p), (n,α) and (n,2n) reaction cross-section results (mb) for ^{9}Be ($s = 0.111$) at 14–15 MeV incident energy

References	σ(n,p)	σ(n,α)	σ(n,2n)
Levkovskii [37]	11	4.40	
Broeders and Konobeyev [10]	8.5		
Kumabe and Fukuda [31]	4.5		
Konno et al. [32]	11.8		998.34
Tel et al. [28]	8.12		
Kasugai et al. [34]		14.75	
Ait-Tahar [7]		0.207	
Habbani and Osman [35]		5.044	151.25
Tel et al. [29]		3.395	820.57
Adam and Jeki [33]			1593.64
Bychkov et al. [30]			1042.64
Exp. data: EXFOR [27]	10.4 ± 1.5	11 ± 4	566 ± 84

The comparison of the (n,p), (n,α) and (n,2n) reaction cross-sections for ^{9}Be light nuclei at 14–15 MeV incident energy are given in Table 6. From Table 6, it is seen that the (n,p) reaction cross-section values for ^{9}Be target nuclei change between 4.5 and 11.8 mb. The cross-section values obtained from the formulas of Levkovskii [37] and Konno et al. [32] are closer and, 11 and 11.8 mb, respectively. These results are in good agreement with the experimental (n,p) cross-section value taken from EXFOR [27] and 10.4 ± 1.5 mb for ^{9}Be. The (n,α) reaction cross-section values vary in the range of 0. 207–14.75 mb. The experimental (n,α) cross-section value taken from EXFOR [27] is 11 ± 4 mb, which is agreement with experimental data, and the cross-section value obtained from the formulas by

Kasugai et al. [34] is within was calculated to be 14.75 mb. When the (n,2n) reaction is investigated, it is seen that the cross-section values obtained from the formulas are between 151.25 and 1593.64 mb. The experimental data for (n,2n) cross-section value taken from EXFOR [27] is 566 ± 84 mb and it is only close to the cross-section value obtained from the formula of Tel et al. [29].

Newly modified formulas including non-elastic scattering and coulomb effects for (α,n) reaction cross-sections have been proposed by Akça et al. [16]. The interaction reaction cross section of $^{7}_{3}Li(\sigma_{int,^{7}_{3}Li})$ is approximately 554 mb for alpha projectile and ^{7}Li target nuclei, and $\sigma_{int,^{9}_{4}Be} \approx 608$ mb for alpha projectile nucleus and ^{9}Be target nuclei. In the present study, when the (α,n) reaction cross-section formula at 18.5 ± 3 MeV in Table 4 is applied to ^{7}Li and ^{9}Be target nuclei, the cross-section $\sigma(\alpha,n)$ values are found 0.498 mb for ^{7}Li and 3.266 mb for ^{9}Be.

Conclusion

The cross-section systematics developed by some authors in past has focused on the nuclei of medium and heavy mass number. The systematics in this range has been applied to ^{7}Li and ^{9}Be light target nuclei for (n,p), (n,α), (n,2n) and (α,n) reaction. While some results are compatible with the results of other proposed systematics and experimental data, the some results illustrate the differences. As seen in Table 5, for (n,p) reaction cross-section values from the formulas of Levkovskii [37], Konno et al. [32] and Tel et al. [28] and for (n,α) reaction cross-section by Levkovskii [37], Habbani and Osman [35], and Tel et al. [29] have very close values for ^{7}Li nuclei. The cross-section result obtained from Ait-Tahar [7] formula and experimental data taken from EXFOR [27] for the (n,2n) reaction also have similar values. This accordance could be considered to come from odd–even effects and the Q-value dependence based on the statistical model. From Table 6, it is seen that some of the (n,p), (n,α), (n,2n) reaction cross-section values for ^{9}Be target nucleus are compatible with experimental results. The differences between the results of the cross-section could result from the fact that some of the proposed systematics are empirical and some of them are semi-empirical. Additionally, in this study, the (α,n) reaction cross-section formulas at 18.5 ± 3 MeV including non-elastic scattering and coulomb effects have been applied to ^{7}Li and ^{9}Be target nuclei and the cross-section values are found rather small. Since there is no experimental data related to the (α,n) reaction cross-section for ^{7}Li and ^{9}Be in the literature, the comparison could not be done to compare the results.

With this study, the (n,p), (n,α), (n,2n) and (α,n) reaction cross-section formulas proposed earlier for the nuclei of medium and heavy mass numbers have been applied to light nuclei and the behavior of this cross-section formulas has been evaluated for light nuclei.

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