ALPHA-CLUSTERING IN SLOW AND FAST NEUTRON INDUCED (n,α) REACTIONS

G. Khuukhenkhuu[1], M. Odsuren[1,2], J. Munkhsaikhan[1], B. Batchimeg[1],
Yu.M. Gledenov[3], E. Sansarbayar[1,3], and M.V. Sedysheva[3]

[1]*Nuclear Research Center, National University of Mongolia, Ulaanbaatar, Mongolia*

[2]*School of Engineering and Applied Sciences, National University of Mongolia, Ulaanbaatar, Mongolia*

[3]*Frank Laboratory of Neutron Physics, JINR, Dubna, Russia*

1. INTRODUCTION

Alpha-particle clustering in nuclei is one of the important subjects for understanding of α-decay, α-particle transfer and emission reactions, and nuclear structure [1]. The α-clustering effect was investigated for long time by many authors (see, for example, [2–17]) who used different theoretical approaches to this problem.

In order to evaluate the α-particle formation probability for nucleus Bethe first assumed [2] to use the emission probability of neutron with the same energy. This hypothesis was considered by Popov *et al.* [3−5] using the experimental data of (n,α) reactions for resonance neutrons and found a ratio of the reduced average neutron-width to the alpha-width in the range of 2.5÷8.0.

In the framework of the pre-compound mechanism Bonetti and Milazzo-Colli suggested [6] the preformed α-particle model which was used in analysis of experimental data for α-decay, (n,α) and (p,α) reactions. From such analyses the α-particle preformation probability was found to be $\phi_\alpha = 0.7 \div 0.01$. Tonozuka and Arima [7] obtained a ratio of the calculated reduced α-width to the observed value and estimated surface α-clustering in the α-decay for ^{212}Po. It was shown that the surface α-clustering effect produces a tremendous enhancement of the α-decay widths of the ^{212}Po.

In the framework of the pre-equilibrium approach to the nuclear reactions with complex particle emission Hogan calculated [8] the rates of nucleon-nucleon and nucleon-alpha interactions in nuclear matter and obtained the α-particle preformation factor $\phi_\alpha = 0.075 \div 0.4$.

A rough estimate of the probability of occurrence of an α-cluster in a nuclear surface was made by Chang [9,10] using the ratio of volume of the surface region to the volume of the nucleus. The probability of occurrence of the α-cluster in a surface of ^{212}Po was $6.2 \cdot 10^{-4}$.
Knellwolf and Rossel obtained [11] the α-particle preformation probability in the compound nucleus ^{41}Ca to be 0.57 by comparison of (n,α) and (n,p) cross sections for the same neutron energy.

Using the exciton model Iwamoto and Harada suggested [12] a method to calculate the α-particle formation factor from the overlap integral between the wave functions of the α-particle and four nucleons. In this method the excitons are formed from not only particles above the Fermi level but from nucleons below, also. They gave the relative α-particle formation factors normalized to unity as a function of the α-particle energy.

Zhang, Royer and Li using the semiclassical approach to frequency of the α-cluster motion inside daughter nucleus obtained [13,14] the α-particle preformation probability for α-decay of some heavy nuclei to be 0.0065÷0.244. Kadmensky and Furman developed [15] the α-cluster model and obtained the surface α-clustering probabilities $7\cdot10^{-4}$, $3\cdot10^{-5}$ and $8\cdot10^{-7}$ for favoured, semifavoured and unfavoured α-transitions, respectively. Because of the large binding energy of a free α-particle, it can be presumed that the α-cluster is a rather stable substructure particularly in light nuclei [16]. Two body α+ α and three body α+ α+ n cluster structures of the ^{8}Be and ^{9}Be, respectively, were, for example, studied [17,18] and the relative probabilities of such configurations were obtained. However, serious difficulties occur in the theoretical calculation of the absolute α-clustering probability.

So, from the above mentioned approaches to the α-clustering problem it is seen that up to now a common opinion to explain the α-clustering effect and an unified method to obtain the α-clustering probability there are no.

In this work, we from the unified view point, namely, in the framework of the statistical model evaluated the α-clustering factor for slow and fast neutron induced (n,α) reactions. Our results are compared with values of the α-clustering probability which were obtained by other authors.

2. FORMULAE

2.1. Slow Neutron Induced (n,α) Reaction Formulae

2.1.1. Resonance Neutron Induced (n,α) Reaction

Using the statistical model and taking into account the α-clustering in the surface of the compound nucleus the Weisskopf's formula [19] for the average α-width of level can be written in the following form:

$$<\Gamma_\alpha(J)>=\frac{D(J)}{2\pi}T_\alpha(l)\phi_\alpha\,, \tag{1}$$

where *D(J)* is the average level spacing for given *J*; T_α is the transmission factor of α-particle through potential barrier of the daughter nucleus; ϕ_α is the α-clustering factor. From (1) the α-clustering factor is given by

$$\phi_\alpha=2\pi\frac{<\Gamma_\alpha(J)>}{D(J)T_\alpha(l)}\,. \tag{2}$$

To simplify calculations we neglect the angular momentum dependence of the transmission factor. Then the formula (2) can be rewritten as following:

$$\phi_\alpha=2\pi\frac{<\Gamma_\alpha(J)>}{D(J)T_\alpha}\,. \tag{3}$$

Here the average level spacing for given *J*, *D(J)*,is expressed by

$$D(J)=\frac{D_0}{g(J)}\,, \tag{4}$$

where D_0 is the observed level spacing for s-resonances; *g(J)* is the spin factor:

$$g(J)=\frac{2J+1}{2(2I+1)}\,. \tag{5}$$

Here J is the compound nucleus spin; I is the target nucleus spin.

It is possible to calculate by using the formula (3) the α-clustering factor for resonance neutron induced (n,α) reaction.

2.1.2. Intermediate Neutron Induced (n,α) Reaction

In the framework of the statistical model an averaged (n,α) cross section by analogy with (n,γ) reaction is given by [20,21]:

$$<\sigma(n,\alpha)>=2\pi^2\lambda\!\!\!^{-}{}_n^2\sum_l\sum_J\frac{g(J)}{D(J)}\frac{<\Gamma_n(J,l)><\Gamma_\alpha(J,l)>}{<\Gamma(J,l)>}F_l. \qquad (6)$$

Here: $\lambda\!\!\!^{-}{}_n$ is the wave length of the incident neutron divided by 2π:

$$\lambda\!\!\!^{-}{}_n^2=2.07\cdot10^{-22}\frac{cm^2}{E_n(keV)}; \qquad (7)$$

E_n is the incident neutron energy; $<\Gamma_n(J,l)>$, $<\Gamma_\alpha(J,l)>$ and $<\Gamma(J,l)>$ are the average neutron, alpha and total level widths;

F_l is the level width fluctuation factor which is occurred in the range of 0.6÷1.0.

The average total level width can be expressed as

$$<\Gamma(J,l)>=<\Gamma_n(J,l)>+<\Gamma_\gamma(J,l)>+<\Gamma_\alpha(J,l)>+... \qquad (8)$$

In most cases for intermediate neutrons can be assumed $\Gamma_n>>\Gamma_\gamma>>\Gamma_\alpha$. So, the total level width is given by

$$<\Gamma(J,l)>\approx<\Gamma_n(J,l)>. \qquad (9)$$

From (1), (6) and (9) can be gotten

$$<\sigma(n,\alpha)>\approx\pi\lambda\!\!\!^{-}{}_n^2\sum_l\sum_J g(J)T_\alpha(l)\phi_\alpha F_l. \qquad (10)$$

If we neglect the angular momentum and spin dependences of the total (n,α) cross section averaged over the wide neutron energy range and assume $F_l\approx1$ can obtain from (10) following simple formula for α-clustering factor:

$$\phi_\alpha\approx\frac{<\sigma(n,\alpha)>}{\pi\lambda\!\!\!^{-}{}_n^2T_\alpha}. \qquad (11)$$

This formula can be utilized to calculate the α-clustering factor using the averaged experimental (n,α) cross section.

2.2. Alpha-Clustering in Fast Neutron Induced (n,α) Reaction

By analogy with formula (11) the proton clustering factor can be written in the following form:

$$\phi_p \approx \frac{<\sigma(n,p)>}{\pi\bar{\lambda}_n^2 T_p} \tag{12}$$

From formulas (11) and (12) can be obtained following ratio:

$$\frac{\phi_\alpha}{\phi_p} \approx \frac{<\sigma(n,\alpha)>}{<\sigma(n,p)>} \cdot \frac{T_p}{T_\alpha}. \tag{13}$$

If we assume $\phi_p = 1$ the α-clustering factor for (n,α) reaction induced by quasimonoenergetic fast neutrons is expressed as following:

$$\phi_\alpha \approx \frac{\sigma(n,\alpha)T_p}{\sigma(n,p)T_\alpha}. \tag{14}$$

The α-clustering factor in (14) is defined as the relative probability of interaction of an incident neutron with an α-cluster to that with proton.

The transmission factors T_α and T_p in the formulas (3), (11) and (14) are calculated by Rasmussen's formula [22,23].

3. RESULTS AND DISCUSSION

3.1. Alpha-Clustering in the Slow Neutron Induced (n,α) Reaction

3.1.1. Alpha-clustering for Resonance Neutron Induced (n,α) Reaction

Table 1. Experimental data and results of our calculations for resonance neutrons

Target Isotopes	Γ_α (exp) (μeV) [5]	D_o (eV) [24]	T_α	ϕ_α
^{64}Zn	12	2940	8.63E-08	0.30
^{67}Zn	580±340	367	2.75E-05	0.21
^{95}Mo	26±18	81	1.58E-06	0.53
^{123}Te	7.3±3.7 (3.0±2.0)*	25.1	2.32E-07	1.97 (0.81)*
^{143}Nd	21±8	37.6	4.12E-06	0.37
^{145}Nd	0.32±0.19	17.8	1.41E-07	0.35
^{147}Sm	2.3±0.6	5.7	4.67E-06	0.24
^{149}Sm	0.21±0.06	2.2	5.12E-07	0.52

*) Previous data [25]

The formula (3) is utilized for some isotopes to estimate the α-clustering factor for the (n,α) reaction induced by resonance neutrons. Experimental data of the average α-widths were taken from Ref. [5]. Average level spacing for s-resonances [24] was used in this calculations. The transmission factors were calculated, as mentioned above, by Rasmussen's formula for zero angular momentum $l_\alpha=0$. Values of the experimental data and results of our calculations for some isotopes are given in Table 1.

3.1.2. *Alpha-Clustering in the Intermediate Neutron Induced (n,α) Reaction*

The formula (11) is used to estimate the α-clustering factor for 24÷30 keV neutron induced (n,α) reactions. Experimental data of the (n,α) cross sections were taken from Ref. [5]. Values of the experimental averaged (n,α) cross sections for 24 or 30 keV neutrons and results of our calculations for α-clustering factor are given in Table 2.

Table 2. Experimental (n,α) cross sections and results of our calculations for 24÷30 keV neutrons

Target nuclei	E_n (keV)	σ(n,α) (μbarn)	T_α ($l_\alpha=0$)	ϕ_α by formula (11)
Mo-95	30	20±4	1.75E-06	0.53
Te-123	24	2.8±0.7	2.48E-07	0.52
Nd-143	30	20±3	4.5E-06	0.20
Sm-147	30	28±5	5.14E-06	0.25

In the case of slow neutrons from Tables 1 and 2 can be obtained following common results for α-clustering factors (see Table.3)

Table 3. Alpha-clustering factors for slow neutron induced (n,α) reactions

Target Nuclei	ϕ_α for resonance neutrons	ϕ_α for intermediate neutrons
Mo-95	0.53	0.53
Te-123	1.97 (0.81)*	0.52
Nd-143	0.37	0.20
Sm-147	0.24	0.25

3.2. Alpha –Clustering in (n,α) Reaction Induced by 4÷6 MeV Neutrons

The formula (14) is used to estimate the α-clustering factor for the (n,α) reaction induced by 4÷6 MeV neutrons where experimental (n,α) and (n,p) cross sections simultaneously there are for the same isotopes [26]. The experimental data and results of our calculations are given in Table.4.

Table 4. Experimental data and results of our calculations for 4÷6 MeV neutrons

E_n (MeV)	Target Nuclei	Reaction	$Q_{(n,p/\alpha)}$ (MeV)	$E_{p/\alpha}$ (MeV)	$\sigma_{(}n,p/\alpha)$ (mbarn)	$T_{p/\alpha}$	ϕ_α by formula (14)	$\overline{\phi}_\alpha$
4	^{40}Ca	(n,α)	1.748	5.18	156.4	0.282	0.29	0.0655
		(n,p)	-0.529	3.38	300	0.161		
	^{54}Fe	(n,α)	0.841	4.49	0.76	5.32E-4	0.02	
		(n,p)	0.088	4.01	276	0.0041		
	^{58}Ni	(n,α)	2.89	6.43	13.4	0.056	0.0024	
		(n,p)	0.395	4.32	352.4	0.0035		
	^{63}Cu	(n,α)	1.715	5.36	0.281	0.0015	0.013	
		(n,p)	0.716	4.64	74.8	0.0053		
	^{64}Zn	(n,α)	3.867	7.38	59.6	0.162	0.0022	
		(n,p)	0.208	4.14	132.9	8E-4		
4.5	^{39}K	(n,α)	1.363	5.28	145	0.78	0.19	0.19
		(n,p)	0.217	4.6	280	0.292		
5	^{41}K	(n,α)	-0.111	4.42	3.4	0.123	0.04	0.0232
		(n,p)	-1.71	3.21	14.1	0.0206		
	^{54}Fe	(n,α)	0.841	5.42	2	0.014	0.013	
		(n,p)	0.088	4.99	406.1	0.038		
	^{58}Ni	(n,α)	2.89	7.36	47.4	0.382	0.0073	
		(n,p)	0.395	5.3	509	0.0302		
	^{59}Co	(n,α)	0.320	4.96	0.13	0.0017	0.037	
		(n,p)	-0.783	4.15	8.1	0.004		
	^{63}Cu	(n,α)	1.715	6.29	1.69	0.0247	0.037	
		(n,p)	0.716	5.62	73.22	0.0396		
	^{64}Zn	(n,α)	3.867	8.32	79.1	0.841	0.0051	
		(n,p)	0.208	5.12	181	0.0099		
6	^{41}K	(n,α)	-0.111	5.32	7.5	0.92	0.08	0.0656
		(n,p)	-1.71	4.19	16.8	0.165		
	^{54}Fe	(n,α)	0.841	6.35	8	0.147	0.02	
		(n,p)	0.088	5.97	465	0.177		
	^{55}Mn	(n,α)	-0.626	4.99	0.5	0.0089	0.097	
		(n,p)	-1.806	4.12	5.65	0.0099		
	^{59}Co	(n,α)	0.320	5.9	1.09	0.0315	0.085	
		(n,p)	-0.783	5.13	14.52	0.0357		
	^{63}Cu	(n,α)	1.715	7.24	5.01	0.21	0.046	
		(n,p)	0.716	6.61	88.7	0.172		

3.3. Discussion

It is seen from Tables 1 and 2 that the α-clustering factors for the (n,α) reactions induced by resonance and intermediate neutrons are varied in the range of 0.20 to 0.53 for all isotopes except ^{123}Te. As to ^{123}Te-target nucleus new value $\Gamma_\alpha^{\exp} = 7.3 \pm 3.7$ μeV gives the α-clustering factor $\phi_\alpha = 1.97$ which is not possible to be $\phi_\alpha > 1$. At the same time from the previous datum $\Gamma_\alpha^{\exp} = 3.0 \pm 2.0$ for the ^{123}Te(n,α)^{120}Sn reaction the α-clustering factor was found to be $\phi_\alpha = 0.81$ (see Table 1) that is plausible.

Also, Table 3 shows that the α-clustering factors for each given isotopes are almost the same on resonance and intermediate neutrons.

In the case of fast neutrons (E_n=4÷6 MeV) the α-clustering factors are varied from 0.0022 to 0.29 (see Table 4). It is not seen from here an energy regular dependence of the α-clustering factor for considered isotopes. In the energy range of 4 to 6 MeV common arithmetic average value of the $\overline{\phi}_\alpha$, which obtained at each neutron energy point, can be found to be $< \phi_\alpha >= 0.086$.

This value of $< \phi_\alpha >= 0.086$ can be compared with our previous results of $\phi_\alpha = 0.22 \div 0.28$ at the same neutron energy range of E_n=4÷6 MeV [27]. It can be seen that our present results for α-clustering factor are a little less than previous ones, although main conception of the two approaches is very similar and methods of calculation are different.

In addition, it should be noted that our present results of the α-clustering factor $\phi_\alpha = 0.20 \div 0.53$ for slow neutrons are close to our previous ones $\phi_\alpha = 0.22 \div 0.28$ for fast neutrons. So, in future more detailed consideration of these facts is needed.

Our values of the α-clustering factor obtained in this work are satisfactorily in agreement with results of Popov *et al.* [3÷5], Bonetti and Milazzo-Colli [6], Hogan [8], and Knellwolf and Rossel [11].

4. CONCLUSION

1. The α-clustering factors for (n,α) reactions induced by slow (resonance and intermediate) and fast neutrons were obtained for some isotopes using the statistical model of nuclear reactions.
2. In the case of slow neutrons the α-clustering factors are varied in the range of 0.20 to 0.53. At the same time the α-clustering factors for fast neutron induced (n,α) reaction were found in the range of 0.0022 to 0.29.
3. The present arithmetic average value $< \phi_\alpha >= 0.086$ for neutron energy E_n= 4÷6 MeV is a little less than our previous results of the α-clustering factor $\phi_\alpha = 0.22 \div 0.28$ for the same neutron energy range. At the same time the present values of the α-clustering factor $\phi_\alpha = 0.20 \div 0.53$ for slow neutrons are close to our previous ones of $\phi_\alpha = 0.22 \div 0.28$ for fast neutrons.
4. Our values of the α-clustering factor for slow and fast neutron induced (n,α) reactions on an average are satisfactorily in agreement with most of evaluations which obtained by other authors using the different approaches to this problem.

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