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ALPHA CLUSTERING IN (n,α) REACTIONS INDUCED BY SLOW AND FAST NEUTRONS*

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Methods to derive α-clustering factors from the analysis of experimental data for slow ($E_n \lesssim 30$ keV) and fast ($E_n = 4$–6 MeV) neutron-induced (n,α) reactions using the statistical model are described. In this way, the dependence of the α-clustering factor for the (n,α) reaction on the incident neutron energy can be followed. The resulting α-clustering factors are compared with our previous results and those obtained using other approaches.

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1. Introduction

Alpha clustering in nuclei is important for the understanding of α-decay, α-particle scattering, α-particle transfer and emission reactions, and nuclear structure [1, 2]. The α clusterization of four nucleons before the emission is usually described by a preformation (or clustering) factor, which is defined as the probability of finding an α cluster inside the parent nucleus. Consequently, this factor should be less than or equal to one.

The α-clustering effect has been investigated for a long time using different methods based on various theoretical approaches. To give some examples, the one-body model [3, 4], preformed α-particle model [5], α-cluster model [6], α-particle occurrence on the surface of a nucleus [7], α-particle formation through the spectroscopic factor [8, 9], ratio of the nucleon–nucleon and nucleon–α interaction rates [10, 11], classical formula for the assault

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frequency of an α-particle inside a nuclear potential barrier [12, 13], cluster formation model [14], density-dependent cluster model [15], binary cluster model [16] and exciton model [17] were used to evaluate the α-clustering probability. Most of these studies were focused on the α-decay. Several papers were dedicated to the determination of the α-particle formation factor in the (n,α) reaction. However, the results of these studies are not consistent and up to now, a common explanation of the α clustering in a nucleus and an unified method to obtain the α-clustering probability are not available.

Recently, we have determined the α-clustering factors for fast neutron ($E_n = 2$–20 MeV) induced (n,α) reactions using the ratio of experimental cross sections to theoretical ones calculated by means of the statistical model [18]. In this work, we suggest some methods to derive α-clustering factors from the analysis of experimental data of the slow ($E_n \lesssim 30$ keV) and fast ($E_n = 4$–6 MeV) neutron-induced (n,α) reactions using the statistical model. In this way, the dependence of the α-clustering factor for the (n,α) reaction on the incident neutron energy can be followed. The obtained α-clustering factors are compared with our previous results and those determined using other approaches.

2. Formulae and results

2.1. Slow neutron-induced (n,α) reaction

2.1.1. Resonance neutron-induced (n,α) reaction

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

$$\langle \varGamma_\alpha(J)\rangle = \frac{D(J)}{2\pi} T_\alpha \phi_\alpha \,, \qquad (1)$$

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

$$\phi_\alpha = 2\pi \frac{\langle \varGamma_\alpha(J)\rangle}{D(J) T_\alpha} \,. \qquad (2)$$

To simplify the calculations, in Eq. (2), the angular momentum dependence of the transmission factor is neglected. Then we apply Eq. (2) to some isotopes in order to estimate the α-clustering factor for the (n,α) reaction induced by resonance neutrons, see Table I. Experimental data on the average α widths were taken from Ref. [20]. The average level spacing for s-resonances [21] was used in the calculation. The transmission factors, T_α, were calculated using Rasmussen's formula [22] for zero angular momentum, $l_\alpha = 0$, of α particles.

TABLE I

Experimental data and results of our calculations for resonance neutrons ($E_n \lesssim$ 5 keV). The ϕ_α values in the last column are calculated using Eq. (2).

Isotopes	Γ_α(exp) [μeV] [20]	D_0 [eV] [21]	T_α	ϕ_α
^{64}Zn	12	2940	8.63×10^{-8}	0.30
^{67}Zn	580 ± 340	367	2.75×10^{-5}	0.21
^{95}Mo	26 ± 18	81	1.58×10^{-6}	0.53
^{123}Te	7.3 ± 3.7 $(3.0 \pm 2.0)^*$	25.1	2.32×10^{-7}	1.97 $(0.81)^*$
^{143}Nd	21 ± 8	37.6	4.12×10^{-6}	0.37
^{145}Nd	0.32 ± 0.19	17.8	1.41×10^{-7}	0.35
^{147}Sm	2.3 ± 0.6	5.7	4.67×10^{-6}	0.24
^{149}Sm	0.21 ± 0.06	2.2	5.12×10^{-7}	0.52

* From previous data [23].

2.1.2. Intermediate neutron-induced (n,α) reaction

In the framework of the statistical model, by analogy with the (n,γ) reaction, the average (n,α) cross section can be expressed as [24, 25]

$$\langle\sigma(n,\alpha)\rangle = 2\pi^2\left(\frac{\lambda_n}{2\pi}\right)^2\sum_l\sum_J\frac{g(J)}{D(J)}\frac{\langle\Gamma_n(J,l)\rangle\langle\Gamma_\alpha(J,l)\rangle}{\langle\Gamma(J,l)\rangle}F_l\,, \tag{3}$$

where λ_n is the wave length of the incident neutron; $\langle\Gamma_n(J,l)\rangle$, $\langle\Gamma_\alpha(J,l)\rangle$ and $\langle\Gamma(J,l)\rangle$ are the average neutron, alpha and total level widths, respectively; F_l is the level width fluctuation factor comprised within the range of 0.6–1.0. For the intermediate neutrons, one can usually assume $\Gamma_n \gg \Gamma_\gamma \gg \Gamma_\alpha$ and so the total level width is given by $\langle\Gamma(J,l)\rangle \approx \langle\Gamma_n(J,l)\rangle$. Then, from Eqs. (1) and (3), the average (n,α) cross section is given by

$$\langle\sigma(n,\alpha)\rangle \approx \pi\left(\frac{\lambda_n}{2\pi}\right)^2\sum_l\sum_J g(J)T_\alpha(l)\phi_\alpha F_l\,. \tag{4}$$

If we neglect the angular momentum and spin dependence of the total (n,α) cross section averaged over the wide neutron energy range, and assume $F_l \approx 1$, one can obtain from Eq. (4) the following simple formula for the α-clustering factor:

$$\phi_\alpha \approx \frac{\langle\sigma(n,\alpha)\rangle}{\pi\left(\frac{\lambda_n}{2\pi}\right)^2 T_\alpha}\,. \tag{5}$$

Equation (5) is then used to estimate the α-clustering factor for 24–30 keV neutron-induced (n,α) reactions, see Table II. Experimental data on the (n,α) cross sections were taken from Ref. [20].

TABLE II

Experimental (n,α) cross sections and results of our calculations for 24–30 keV neutrons. The ϕ_α values in the last column are calculated using Eq. (5).

Target nuclei	E_n [keV]	$\sigma_{(n,\alpha)}$ [μb]	T_α ($l_\alpha = 0$)	ϕ_α
^{95}Mo	30	20 ± 4	1.75×10^{-6}	0.53
^{123}Te	24	2.8 ± 0.7	2.48×10^{-7}	0.52
^{143}Nd	30	20 ± 3	4.5×10^{-6}	0.20
^{147}Sm	30	28 ± 5	5.14×10^{-6}	0.25

2.2. *Alpha clustering in fast neutron-induced* (n,α) *reaction*

By analogy with Eq. (5), the proton-clustering factor can be written as

$$\phi_p \approx \frac{\langle\sigma(n,p)\rangle}{\pi\left(\frac{\lambda_n}{2\pi}\right)^2 T_p} . \tag{6}$$

If we assume $\phi_p = 1$, one can obtain from Eqs. (5) and (6) the following expression for the α-clustering factor for the (n,α) reaction induced by quasi-monoenergetic fast neutrons:

$$\phi_\alpha \approx \frac{\sigma(n,\alpha)}{\sigma(n,p)} \frac{T_p}{T_\alpha} . \tag{7}$$

The α-clustering factor in (7) is defined as the probability of an interaction of the incident neutron with an α-cluster relative to that with a proton. Equation (7) is used to estimate the α-clustering factor for the (n,α) reaction induced by 4–6 MeV neutrons using the experimental (n,α) and (n,p) cross sections determined for the same isotopes [26]. The experimental data and the results of our calculations are given in Table III.

3. Discussion and conclusions

Tables I and II show that the α-clustering factors for (n,α) reactions induced by resonance and intermediate neutrons vary from 0.20 to 0.53 for all isotopes except for ^{123}Te. For ^{123}Te, the new value $\Gamma_\alpha(\mathrm{exp}) = 7.3 \pm 3.7$ μeV gives the α-clustering factor of $\phi_\alpha = 1.97$ which is larger than 1 and thus not possible. In contrast, the $\Gamma_\alpha(\mathrm{exp}) = 3.0 \pm 2.0$ μeV measured previously in the $^{123}\mathrm{Te}(n,\alpha)^{120}\mathrm{Sn}$ reaction yields a plausible α-clustering

TABLE III

Experimental data and results of our calculations for 4–6 MeV neutrons. The ϕ_α values in the last column are calculated using Eq. (7).

E_n [MeV]	Target nuclei	Reaction	$Q_{(n,p/\alpha)}$ [MeV]	$E_{p/\alpha}$ [MeV]	$\sigma_{(n,p/\alpha)}$ [mb]	$T_{p/\alpha}$	ϕ_α
4	^{54}Fe	(n, α) (n, p)	0.841 0.088	4.49 4.01	0.76 276	0.00053 0.0041	0.02
	^{58}Ni	(n, α) (n, p)	2.89 0.395	6.43 4.32	13.4 352.4	0.056 0.0035	0.0024
	^{63}Cu	(n, α) (n, p)	1.715 0.716	5.36 4.64	0.281 74.8	0.0015 0.0053	0.013
	^{64}Zn	(n, α) (n, p)	3.867 0.208	7.38 4.14	59.6 132.9	0.162 0.0008	0.0022
5	^{54}Fe	(n, α) (n, p)	0.841 0.088	5.42 4.99	2 406.1	0.014 0.038	0.013
	^{58}Ni	(n, α) (n, p)	2.89 0.395	7.36 5.3	47.4 509	0.382 0.0302	0.0073
	^{63}Cu	(n, α) (n, p)	1.715 0.716	6.29 5.62	1.69 73.22	0.0247 0.0396	0.037
	^{64}Zn	(n, α) (n, p)	3.867 0.208	8.32 5.12	79.1 181	0.841 0.0099	0.0051
6	^{54}Fe	(n, α) (n, p)	0.841 0.088	6.35 5.97	8 465	0.147 0.177	0.02
	^{63}Cu	(n, α) (n, p)	1.715 0.716	7.24 6.61	5.01 88.7	0.21 0.172	0.046

factor of $\phi_\alpha = 0.81$ (see Table I). One can see also from Tables I and II that the α-clustering factors for each isotope are almost the same for the resonance and intermediate neutrons. In the case of fast neutrons ($E_n =$ 4–6 MeV), the α-clustering factors vary in the range of 0.0022 to 0.046 (Table III). These values are on average lower than those for slow neutrons (Tables I and II) and our previous results of 0.02–0.33, which were obtained from the ratio of experimental (n, α) cross sections to the theoretical ones for $E_n = 2$–20 MeV [18]. The α-clustering factors obtained in the present work are on average in a satisfactory agreement with most of the above-mentioned results, they have, however, a wide dispersion. At the same time, our results are appreciably different from the values of α-clustering probability obtained in Refs. [6, 7]. Future more detailed investigations are needed.

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