# SYSTEMATICS OF *(n,α)* CROSS SECTIONS FOR 4-6 MeV NEUTRONS

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## 1. Introduction

Neutron cross sections are usually studied by three methods: experimental measurement, theoretical calculation and systematical analysis. In the systematical analysis both of the experimental data and theoretical models are used. From the systematical analysis it is possible in practice to evaluate the neutron cross sections of the nuclides for which no experimental data are available. Also, the systematical analysis of the neutron cross sections is useful to clarify nuclear reaction mechanisms.

For last years we have been analyzing known experimental *(n,α)* cross sections in the energy range of $E_n$ =6-20 MeV [1] and around $E_n \approx$2 MeV [2] and observed some systematical regularity which in the literature is termed as the isotopic effect [3]. The statistical model, based on the Weisskopf-Ewing evaporation model [4] and constant nuclear temperature approximation [5], was suggested [1,6] to explain the isotopic effect.

In addition, the experimental study of the *(n,α)* reaction in the MeV neutron energy region for broad mass of target nuclei $(6 \leq A \leq 149)$ was carried out [7-17].

In this paper the results of the systematical analysis of our experimental *(n,α)* cross sections, using the statistical model, for new energy range of 4–6 MeV are described.

## 2. The *(n,α)* Cross Section Formulae

The direct and pre-equilibrium mechanisms are neglected for several MeV neutrons and the compound mechanism can be considered, only. Then, according to Bohr's postulate, the *(n,α)* cross section can be written as two stages process:

$$\sigma(n,\alpha) = \sigma_c(n) \cdot G(\alpha). \qquad (1)$$

Here:

$$\sigma_c(n) = \pi(R + \lambdabar_n)^2 \qquad (2)$$

is the compound nucleus formation cross section;

where: $R = r_0 A^{1/3}$ is the target nucleus radius;

$r_0 = 1.3 \cdot 10^{-13}\,cm$; $A$ is the mass number of the target nuclei;

$\lambdabar_n = 4.55 \cdot 10^{-13} cm / \sqrt{E_n(MeV)}$ is the wavelength of the incident neutrons divided by $2\pi$ and $E_n$ is the incident neutron energy.

The $\alpha$-decay probability of the compound nucleus is expressed as

$$G(\alpha) = \frac{\Gamma_\alpha}{\Gamma} = \frac{\Gamma_\alpha}{\sum_i \Gamma_i}, \qquad (3)$$

where: $\Gamma_i$, $\Gamma_\alpha$ and $\Gamma$ are the partial, alpha and total level widths, respectively.

In the framework of Weisskopf-Ewing theory [4], using the constant temperature approximation [5] and the semi-classical formula for the inverse reaction cross section we can get following expression for the $\alpha$-width:

$$\Gamma_{\alpha} = \frac{2S_{\alpha}+1}{\pi\hbar^{2}} M_{\alpha} R^{2} \int_{V_{\alpha}}^{E_{\alpha}^{max}} E_{\alpha} \left(1 - \frac{V_{\alpha}}{E_{\alpha}}\right) e^{-\frac{B_{\alpha}+\delta_{\alpha}+E_{\alpha}}{\theta}} dE_{\alpha} \cdot \tag{4}$$

Here: $S_{\alpha}$, $M_{\alpha}$, $E_{\alpha}$ and $V_{\alpha}$ are the spin, mass, energy and the Coulomb potential for the outgoing $\alpha$-particle, respectively; $B_{\alpha}$ is the binding energy of $\alpha$-particle for daughter nucleus; $\delta_{\alpha}$ is the odd-even effect parameter for the Weizsacker's formula [18]; $\theta = kT$ is the thermodynamic temperature, where $k$ is the Boltzmann constant. Similar formulae can be written for all partial level widths $\Gamma_{i}$ .

Then, neglecting the $\gamma$-emission and using the approximation $\Gamma \approx \Gamma_{n}$ for fast neutrons, from (1), (2), (3) and (4) the fast neutron induced *(n,α)* reaction cross section is determined as follows

$$\sigma(n,\alpha) = 2\pi\left(R + \lambdabar_{n}\right)^{2} e^{\frac{Q_{n\alpha}-V_{\alpha}}{\theta}} . \tag{5}$$

Similar formula was obtained by Cuzzocrea *et al.* [19].
The Coulomb potential of $\alpha$-particle can be written [20]:

$$V_{\alpha} = 2.058 \frac{Z-2}{(A-3)^{1/3} + 4^{1/3}} MeV . \tag{6}$$

The *(n,α)* reaction energy $Q_{n\alpha}$ can be determined by the Weizsacker's formula for binding energy. Then, if we neglect the odd-even effect parameter $\Delta = \delta_{f} - \delta_{i}$, from (5) can write the *(n,α)* cross section as following

$$\sigma(n,\alpha) = C\pi\left(R + \lambdabar_{n}\right)^{2} e^{-K\frac{N-Z+0.5}{A}} , \tag{7}$$

where: $N$, $Z$ and $A$ are the neutron, proton and nucleon numbers, respectively, for the target nucleus;

$$C = 2\exp\frac{1}{\theta}\left(-3\alpha + \beta\left[A^{2/3} - (A-3)^{2/3}\right] + \gamma\left(\frac{Z^{2}}{A^{1/3}} - \frac{(Z-2)^{2}}{(A-3)^{1/3}}\right) + \varepsilon_{\alpha} - V_{\alpha}\right); \tag{8}$$

and

$$K = \frac{2\xi}{\theta} . \tag{9}$$

Here: $\alpha$, $\beta$, $\xi$ and $\gamma$ are the Weizsacker's formula constants; and $\varepsilon_{\alpha} = 28.2$ MeV is the internal binding energy of $\alpha$-particle.

Using the Fermi gas model for level density parameter [21] the nuclear thermodynamic temperature [5] is expressed as follows

$$\theta = \sqrt{\frac{U_{\alpha}^{max}}{a}} = \sqrt{\frac{13.5(E_{n} + Q_{n\alpha})}{A-3}} \tag{10}$$

The parameters $K$ and $C$ in formula (7) can be determined by two methods. First, they can be found by fitting of theoretical cross sections to experimental data as constant parameters at each energy point for all isotopes. Second, $K$ and $C$ parameters can be directly obtained from the formulae (8), (9) and (10).

## 3. Analysis of *(n,α)* Cross Sections

### *3.1. Systematics of the (n,α) Cross Sections*

The results of the systematics for experimental *(n,α)* cross sections of the medium mass and heavy nuclei (40≤A≤149) at neutron energies of $E_n$ =4, 5 and 6 MeV [9–17] by using the formula (7) are shown in Figs.1, 2 and 3.

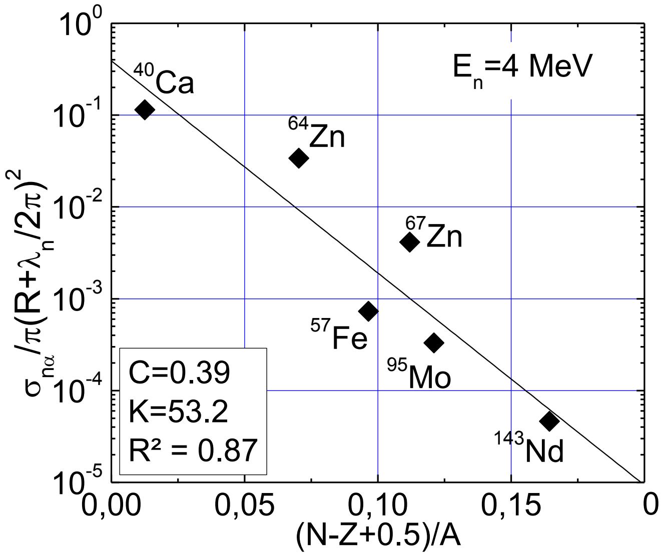


Fig.1. The dependence of the reduced *(n,α)* cross sections on the neutron excess parameter at $E_n$ =4 MeV.

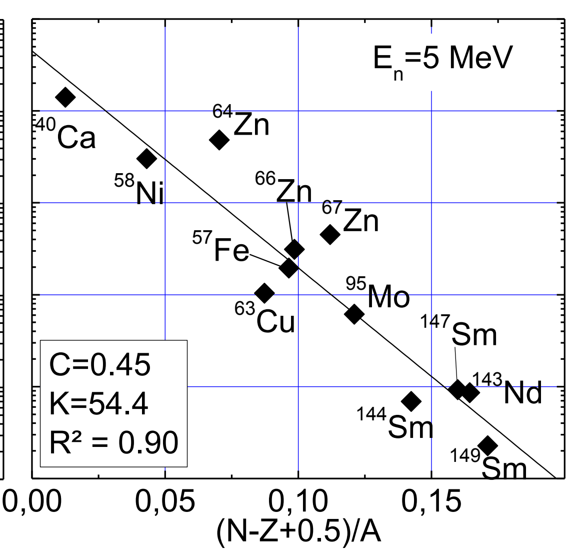


Fig.2. The same as in Fig.1 for $E_n$ =5 MeV.

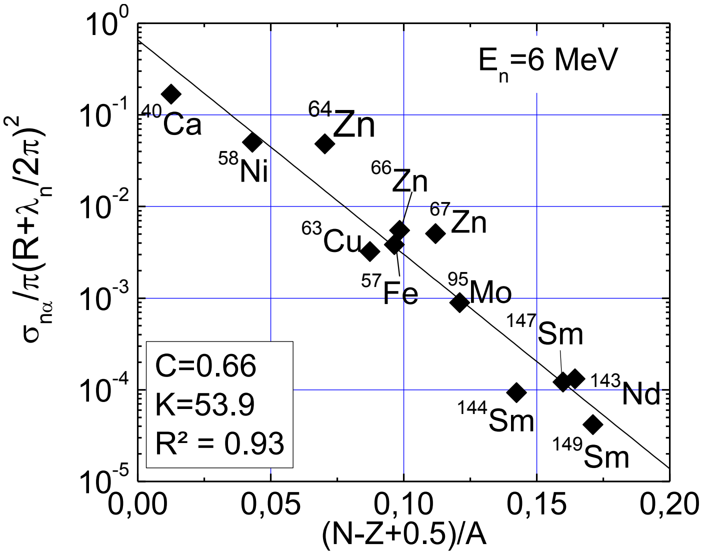
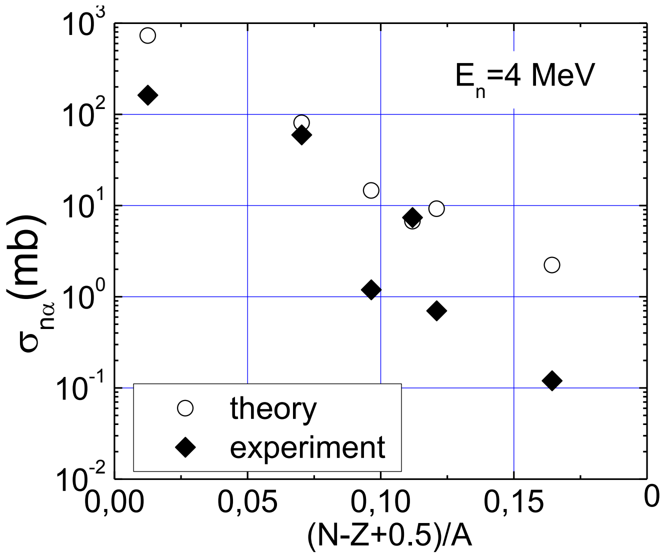


Fig.3. The same as in Fig.1 for $E_n$ =6 MeV.

The values of fitted parameters $C$ and $K$ are given in Figs.1, 2 and 3, also. It is seen that the experimental data of the energy range of 4 to 6 MeV is satisfactorily described by the theoretical line drew by formula (7) with the fitted parameters $C$ and $K$.

### *3.2. The (n,α) Cross Sections and α-clusterization Factor*

The values of the theoretical and experimental *(n,α)* cross sections for neutron energies of 4 to 6 MeV are shown in Figs.4, 5 and 6. The theoretical *(n,α)* cross sections were calculated by statistical model formulas (7), (8), (9) and (10).



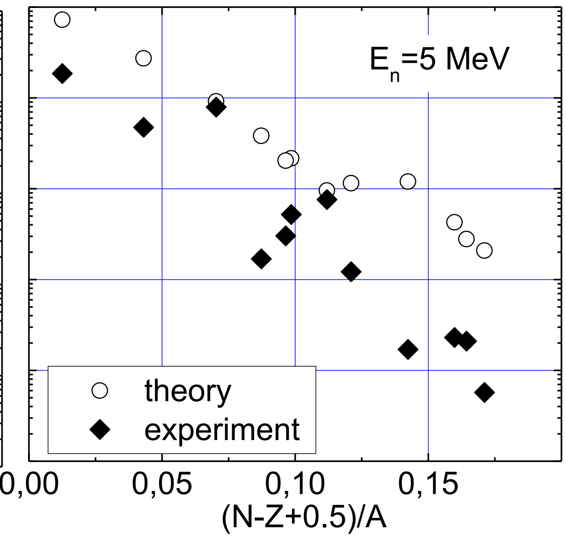


Fig.4. Theoretical and experimental (n,α) cross sections at $E_n$=4 MeV.

Fig.5. The same as in Fig.4 at $E_n$ =5 MeV.

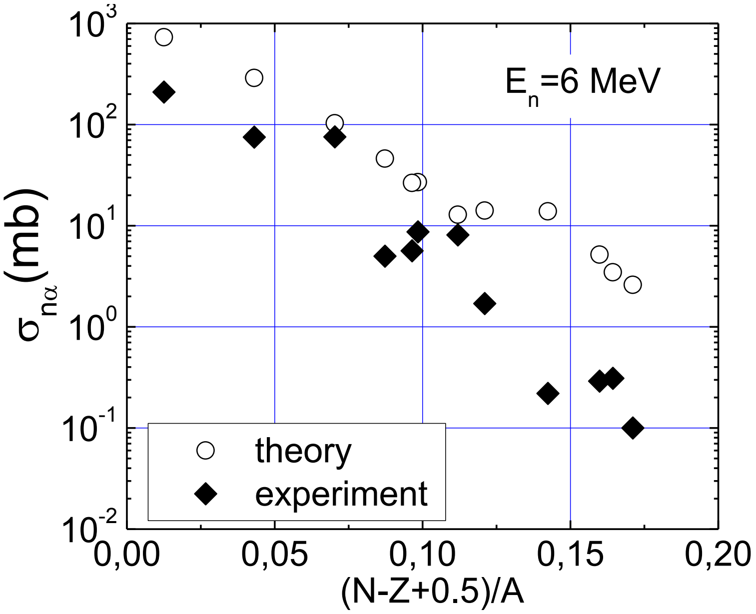


Fig.6. The same as in Fig.4 at $E_n$ =6 MeV.

It is seen that the statistical model formulae give overestimated values for the *(n,α)* cross sections at all neutron energies. We assume that these results, perhaps, are caused by the *α*-particle clusterization effect [22–24].

The *α*-clusterization factor, which takes into account α-particle formation probability on the surface of the compound nucleus, was not considered in formulae (7), (8) and (9).

So, these formulas should be correct for neutron induced nucleon emission reactions [25]. As to *(n,α)* reaction, the *α*-clusterization effect should be considered in the cross section formula.

In order to evaluate the *α*-particle formation factor or reduced *α*-width Bethe suggested [26] to use a reduced neutron width:

$$\gamma_n^2 \approx \gamma_\alpha^2 . \tag{11}$$

Popov *et al.* investigated this hypothesis by using the experimental data of the *(n,α)* reaction for resonance neutrons [22–24] and obtained a following relation for the average reduced neutron-and alpha-widths:

$$W_{n/\alpha} = \frac{\langle \gamma_n^2 \rangle}{\langle \gamma_\alpha^2 \rangle} \approx 2.5 - 8.0. \tag{12}$$

In the case of fast neutron induced *(n,α)* reaction we suggest to obtain the *α*-clusterization factor by normalization of theoretical cross section to experimental data. This method means that *α*-clusterization factor for *(n,α)* reaction is determined in comparison with *(n,p)* reaction assuming the neutron and proton formation factors are the same:

$$W_{n/p} = \frac{\langle \gamma_n^2 \rangle}{\langle \gamma_p^2 \rangle} = 1. \tag{13}$$

Then, from the normalization of theoretical *(n,α)* cross section to experimental data the *α*-cluster formation factor was found to be:

$$W_{p/\alpha} = \frac{\langle \gamma_p^2 \rangle}{\langle \gamma_\alpha^2 \rangle} = 4.5. \tag{14}$$

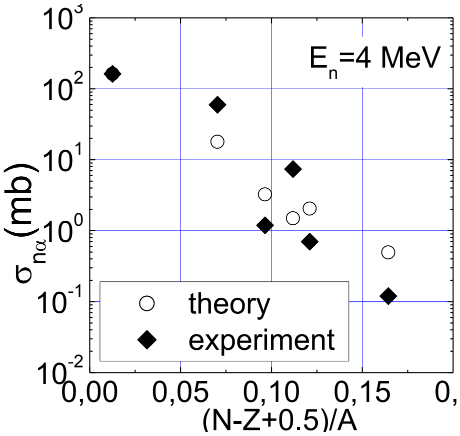


Fig.7. Experimental and theoretical *(n,α)* cross sections with α-cluster formation factor $W_{p/\alpha}$ =4.5 for $E_n$ =4 MeV.

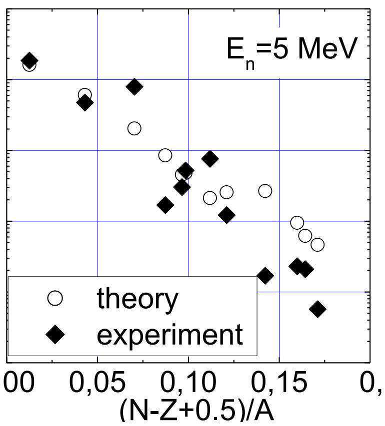


Fig.8. The same as in Fig.7 for $E_n$ =5 MeV.

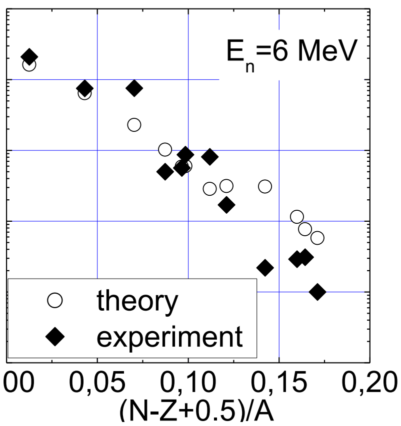


Fig.9. The same as in Fig.7 for $E_n$ =6 MeV.

Figs.7, 8 and 9 show that the theoretical *(n,α)* cross sections calculated by statistical model with the clusterization factor $W_{p/\alpha}$ =4.5 are satisfactorily in agreement with experimental data for $E_n$ =4, 5 and 6 MeV. So, taking into account the *α*-clusterization factor, the *(n,α)* cross section formula (7) can be rewritten in the following form:

$$\sigma(n,\alpha) = C\pi\left(R + ƛ_n\right)^2 e^{-K\frac{N-Z+0.5}{A}} \frac{1}{W_{p/\alpha}} . \tag{15}$$

### 3.3. *Analysis of Existing (n,α) Cross Sections at $E_n$ =6 MeV*

The Fig.10 shows that our and other existing *(n,α)* cross section data at $E_n$ =6 MeV have the same regularity which is described by the statistical model line.

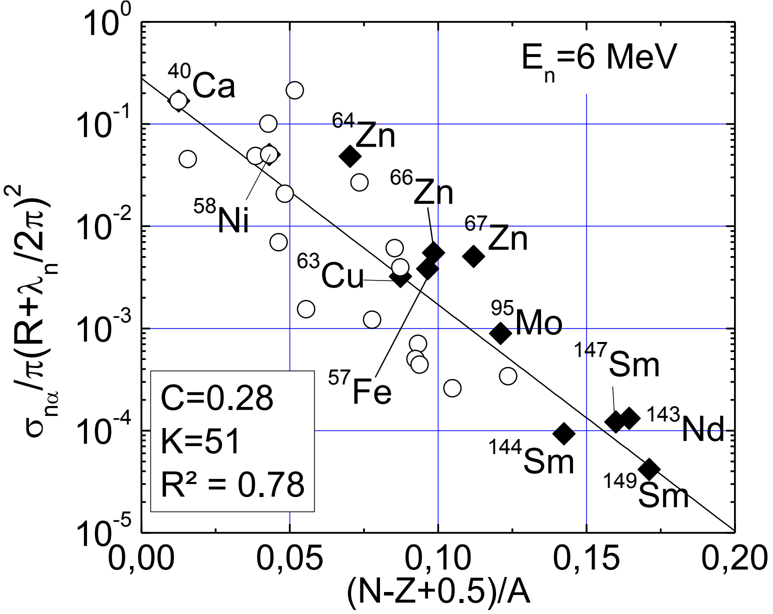


Fig.10. The dependence of our (♦) and other existing (o) experimental reduced *(n,α)* cross sections on the neutron excess parameter.

## 4. Conclusions

1. The systematical analysis of *(n,α)* cross sections for $E_n$ =4-6 MeV neutrons using the statistical model was carried out. Some systematical regularity of the reduced *(n,α)* cross sections on the relative neutron excess parameter was observed. The trend of the *(n,α)* cross sections is satisfactorily described by the statistical model.
2. At the same time, statistical model formulas give overestimated values for the absolute *(n,α)* cross sections. We assume that these results, perhaps, are caused by the α-particle clusterization effect. The clusterization factor was found to be 4.5 for $E_n$ =4–6 MeV neutrons by normalization of the theoretical *(n,α)* cross sections to experimental one. This value of the *α*-clustering factor is in good agreement with the result of Popov *et al*. for resonance neutrons.
3. Both of our experimental *(n,α)* cross sections and other existing data at 6 MeV have the same systematical trend which is described by the statistical model, also.

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