KNOCK-ON MECHANISM AND PROBABILITY OF ALPHA-CLUSTER FORMATION IN THE (*n,α*) REACTION

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1. Introduction

Alpha-clustering in nuclei is one of the important subjects for nuclear structure and reaction study [1-5]. 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 (or probability) should be less than or equal to one. Many attempts for evaluation of the α-cluster formation probability were carried out for a long time using different methods based on various theoretical approaches. For examples, the molecular viewpoints in nuclear structure [4,6–8], one-body model [9,10], preformed α-particle model [11], α-cluster model [12], α-particle occurrence on the surface of a nucleus [13], α-particle formation through the spectroscopic factor [14,15] ratio of the nucleon-nucleon and nucleon-alpha interaction rates [16,17], classical formula for the assault frequency of an α-particle inside a nuclear potential barrier [18,19], cluster formation model [20], density-dependent cluster model [21], binary cluster model [22], exciton model [23] and microscopic cluster model [24,25] were used to study the α-clustering effect. Most of these studies were focused on the α-decay. Several methods were suggested to determine the α-particle formation factor in the (n,α) and (p,α) reactions [10–12, 16,17,23,26]. However, the results of these attempts 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, from the unified viewpoint, namely, in the framework of the compound mechanism, using the statistical model we have determined the clustering factors for the resonance ($E_n \leq 5$ keV), intermediate ($E_n \approx 24 - 30$ keV), and fast ($E_n = 2 - 20$ MeV) neutron induced (n,α) reactions [27–30].

In this work we suggest a new method to derive α-clustering probability from the analysis of known experimental data of the fast neutron induced (n,α) reactions and total neutron cross sections for the ^4He using the knock-on mechanism. The obtained α-clustering probabilities are compared with our previous results and those determined by other approaches.

2. Method

The method suggested in this work for calculation of the α-clustering probability is based on the knock-on mechanism of nuclear reaction. In this case by analogy of Bohr's postulate of the compound mechanism, we assume that the (n,α) cross section for fast neutrons can be expressed as two stages process:

$$\sigma(n,\alpha) = \Phi_\alpha \cdot \sigma_n^{tot}(^4He). \tag{1}$$

Here, the (n,α) cross section is defined as the multiplication of the α-cluster formation probability on the surface of target nucleus, Φ_α, and total neutron cross section for the ^{4}He, $\sigma_n^{tot}(^4He)$. From (1) the α-cluster formation probability can be obtained as following:

$$\Phi_\alpha = \frac{\sigma(n,\alpha)}{\sigma_n^{tot}(^4He)}. \tag{2}$$

For evaluation of the α-clustering probability, the experimental data of the (n,α) cross sections and total neutron cross sections the ^{4}He were taken from the EXFOR [31] and other references.

3. Results and Discussion

3.1. Light nuclei

Energy dependence of the α-clustering probability obtained by formula (2) for 5 light nuclei of ^{6}Li to ^{20}Ne, for which fast neutron induced (n,α) reaction cross sections are available in the wide energy range, is shown in Fig.1.

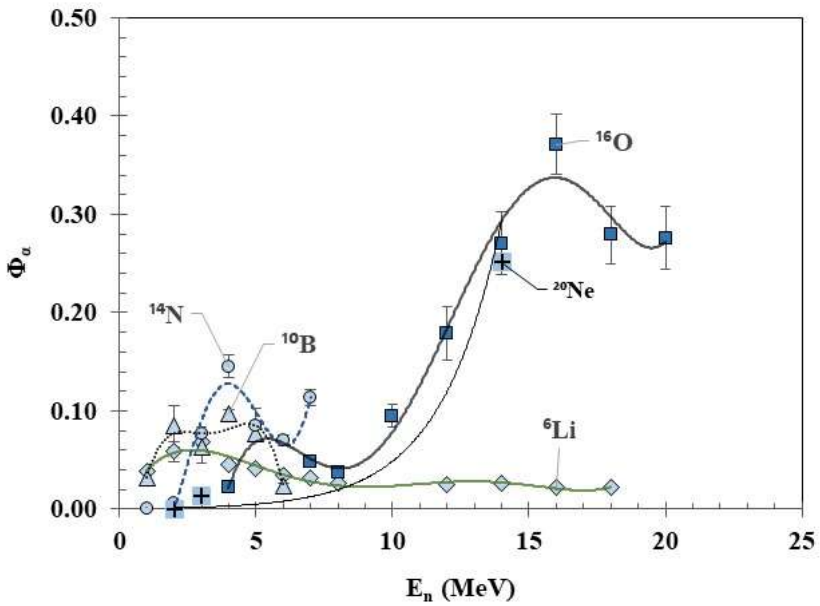


Fig.1. Energy dependence of the α-clustering probability for light nuclei.

The threshold energy calculated by binding energy [32] for some cluster structures of these nuclei is given in Table.1 together with values from Ikeda diagram [8].

Table.1. The threshold energy of some cluster structures for light nuclei

Isotope	Cluster structure	Threshold energy E_{th} (MeV)	
		Calculated values	From Ikeda Diagram [8]
^{6}Li	α+d	1.47	-
	t+t	15.81	-
^{10}B	^{6}Li+α	4.46	-
	d+2α	5.93	-
^{14}N	^{12}C+d	10.27	-
	^{10}B+α	11.61	-
	^{6}Li+2α	16.07	-
^{16}O	^{12}C+α	7.16	7.16
	4α	14.44	14.44
^{20}Ne	^{16}O+α	4.73	4.73
	^{12}C+2α	11.90	11.89
	5α	19.17	19.17

It is seen from Fig.1 that the α-clustering probabilities for given isotopes in the energy range of 1 to 10 MeV are varied not so much and with maximum value of $\Phi_\alpha = 0.145 \pm 0.011$ for the ^{14}N at the neutron energy of 4 MeV. Above 10 MeV the α-clustering probabilities are increased and reached $\Phi_\alpha = 0.371 \pm 0.031$ at $E_n = 16$ MeV and $\Phi_\alpha = 0.251 \pm 0.004$ at $E_n = 14$ MeV for the ^{16}O and ^{20}Ne, respectively. At the same time, the α-cluster formation probability of the ^{6}Li isotope with the lowest α-clusterization threshold energy (see Tab.1) among light nuclei has not the highest value and is varied in the narrow interval of 0.022 to 0.068. This fact shows that the α-clusterization threshold energy is not a single decisive factor in the α-clustering effect for these nuclei.

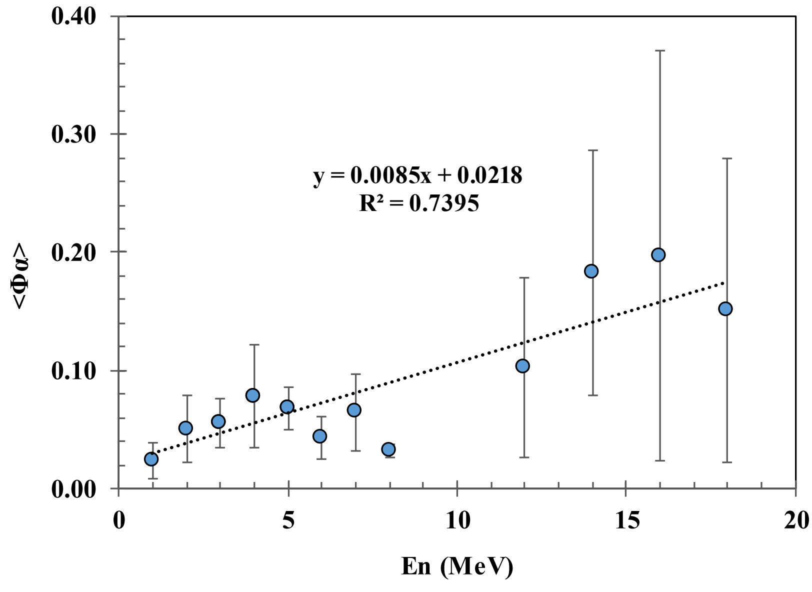
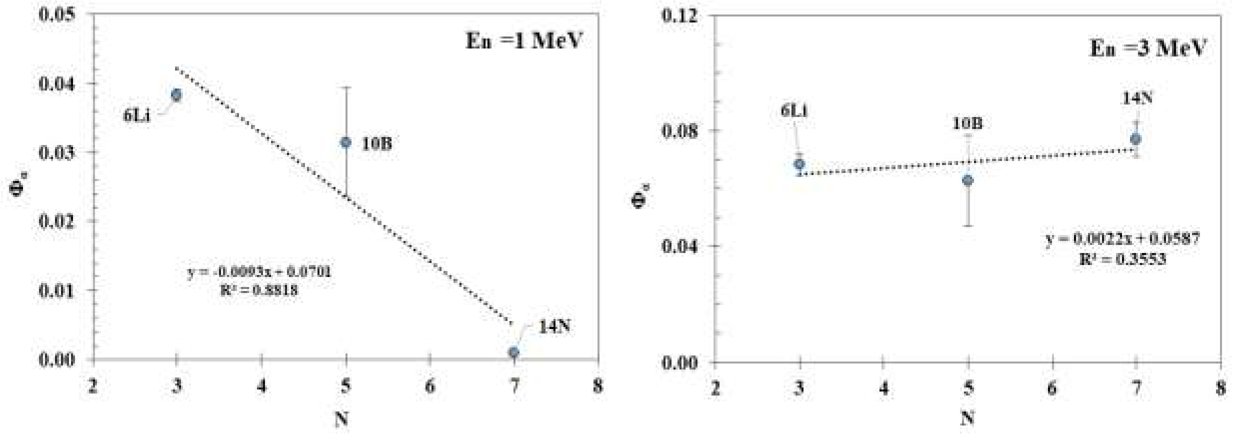


Fig.2. Energy dependence of average α-clustering probability for light target nuclei.

However, essential increasing of the α-clustering probability for the ^{20}Ne and ^{16}O in the energy region of 14 to 16 MeV is perhaps caused by opening the two α-particle (E_{th} =

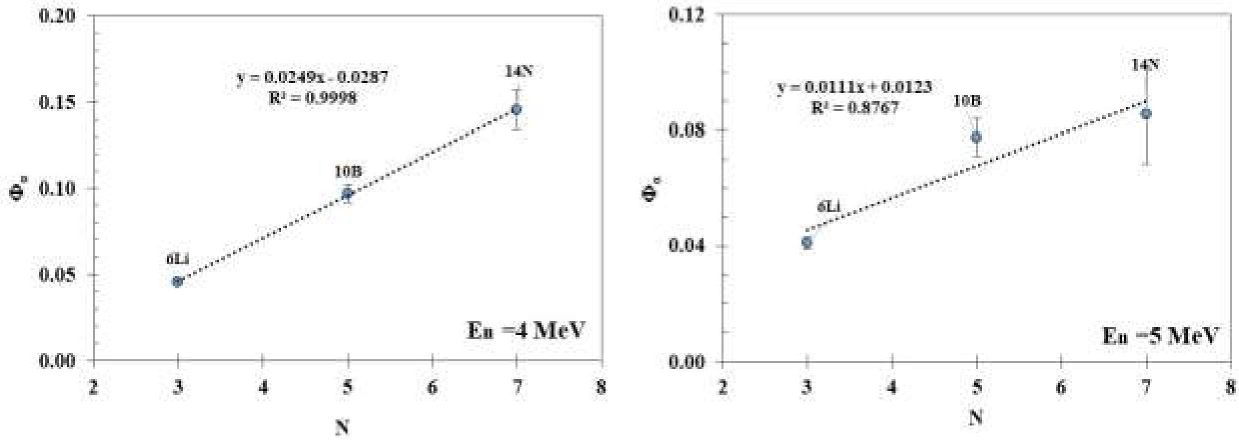
11.90 MeV for ^{20}Ne) and four α-particle (E_{th} = 14.44 MeV for ^{16}O) emission channels for these isotopes. Arithmetic mean values of the α-clustering probability averaged over all light isotopes at each energy point are increased nearly linearly depending on the neutron energy (see Fig.2).

The α-clustering probabilities for odd-odd isotopes ^{6}Li, ^{10}B and ^{14}N at the 1 MeV are decreased depending on the neutron (or proton) number (Fig.3a). At the same time, for these isotopes the α-clustering probabilities become nearly the same at the 3 MeV (Fig.3b) and are linearly increased at the 4 and 5 MeV (Fig.4) depending on the neutron number.



a) *b)*

Fig.3. The dependence of the α-clustering probability on neutron number for light odd-odd target nuclei at the 1 MeV (a) and 3 MeV (b).



a) *b)*

Fig.4. The same as in Fig.3 at the neutron energy 4 MeV (a) and 5 MeV (b).

3.2. Medium mass nuclei

Energy dependence of the α-clustering probability calculated by the formula (2) for 11 medium mass target nuclei is shown in Fig.5.

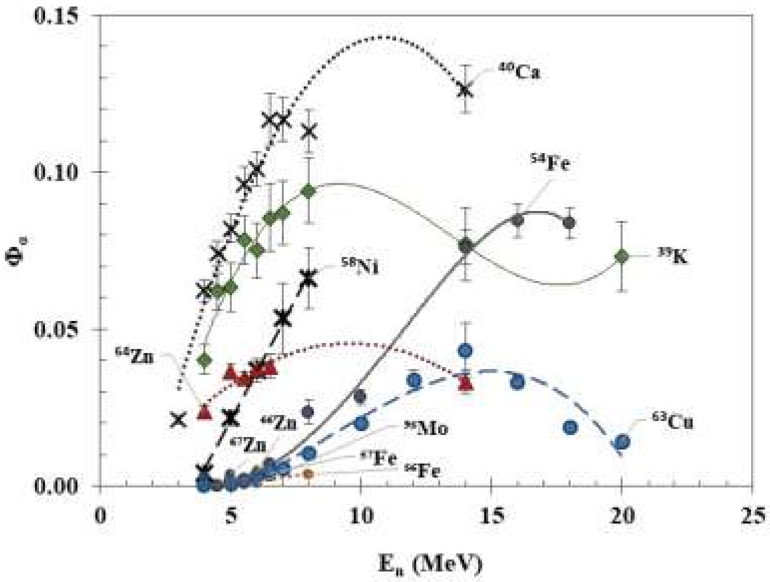


Fig.5. The same as in Fig.1 for medium mass nuclei

Some increasing tendency of the α-clustering probability for all nuclei was observed in the beginning of neutron energy. Among these isotopes the highest α-clustering probability was obtained for the double magic even-even ^{40}Ca. It can be seen that values of the α-clustering probability for the medium mass nuclei are on average lower than those for light nuclei.

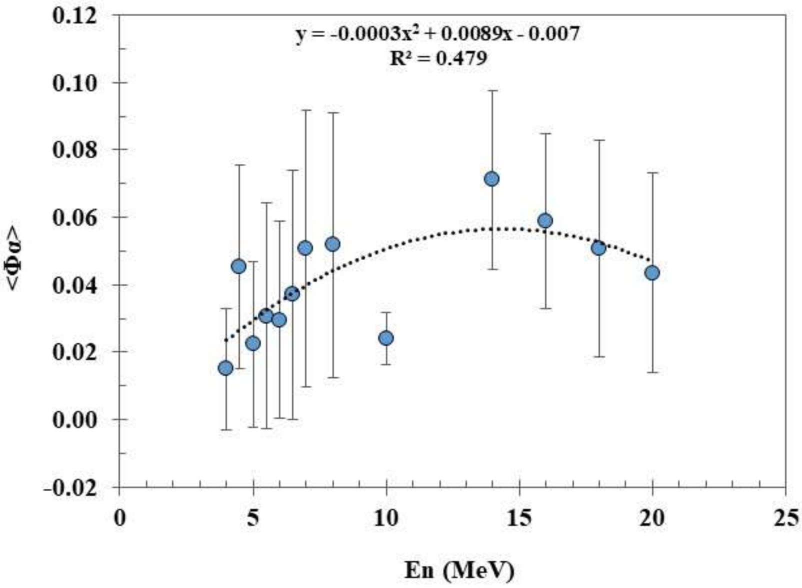


Fig.6. The same as in Fig.2 for medium mass nuclei.

Arithmetic average values of the α-clustering factor at each neutron energy for all medium mass nuclei are increased in the range of 4 to 14 MeV, except value at 10 MeV, after that are decreased, however they have wide dispersions (Fig.6).

3.3. Heavy nuclei

The (n,α) reaction experimental data base for heavy nuclei is very scarce for fast neutrons. In connection with this situation four isotopes of the neodymium and samarium are considered, only, for several MeV energy range. Fig.7 shows that the α-clustering probabilities for these nuclei are increased depending on the neutron energy. In addition, all values of the α-clustering probability for heavy nuclei are considerably lower than one for light and medium mass isotopes.

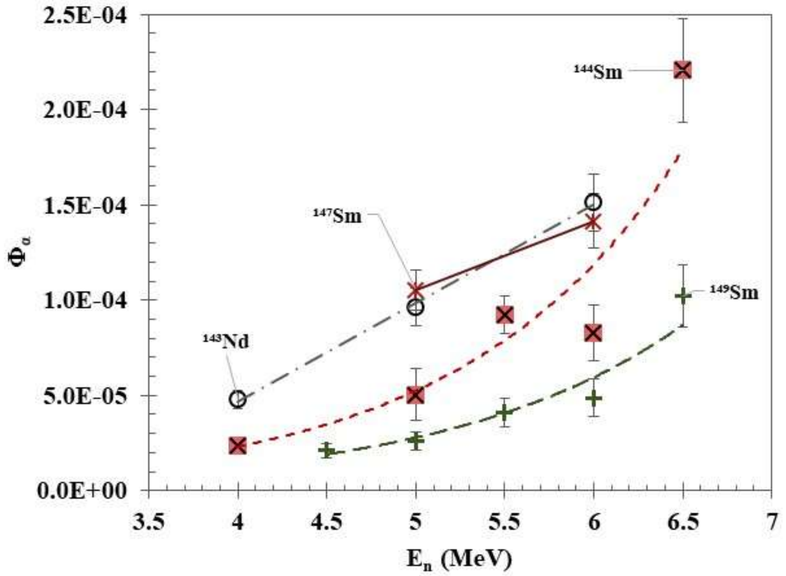


Fig.7. The same as in Fig.1 for heavy nuclei.

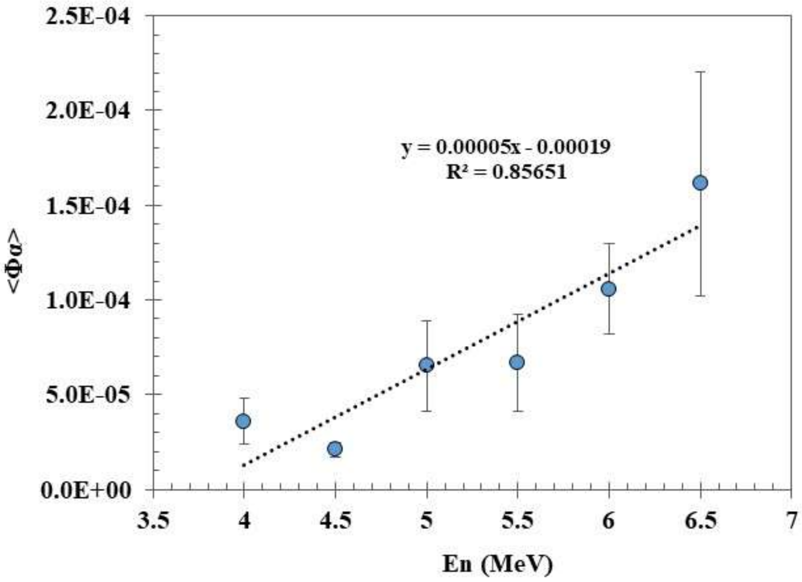


Fig.8. The same as in Fig.2 for heavy nuclei.

The arithmetic average values of the α-clustering probability for heavy nuclei at 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5 MeV are increased linearly depending on the neutron energy (Fig.8).

4. Conclusions

1. The α-clustering probability in the fast neutron induced (n,α) reactions for light, medium mass and heavy nuclei was obtained using the knock-on mechanism.
2. It was seen that the α-clustering probability at the same neutron energy is on average decreased depending on the mass number of the target nuclei.
3. The α-clustering probability for light and heavy nuclei is increased with growth of neutron energy. At the same time, for medium mass nuclei the α-clustering probability is increased in the range of 4 to 14 MeV and from 14 to 20 MeV is decreased.
4. The α-clustering probabilities found in the present work are on average in a satisfactory agreement with our previous results which were obtained in the framework of the statistical model using the comparison method of the (n,α) and (n,p) cross sections [30]. Our present values of the α-clustering probability are lower than those obtained by normalizing of theoretical (n,α) cross sections to experimental ones [27] and using the preformed α-particle model [11].

References

1. P.E.Hodgson, Alpha-clustering in Nuclei, In book: "The Uncertainty Principle and Foundations of Quantum Mechanics". Editors: W.C.Price and S.S.Chissick, Chapter 23, New York, John Wiley, 1977, p.485.
2. K.Wildermuth and Y.C.Tang, An Unified Theory of the Nucleus, Academic Press, Inc. New York, 1977.
3. Clusters in Nuclei, Editor: Christion Beck, vol.**1**, (2010), vol.**2**, (2012) and vol.**3**, (2014), Springer-Verlag, Berlin Heidelberg.
4. W.Von Oertzen, M.Freer and Y.Kanada-En'yo, Physics Reports, v.**432**, 2006, p.43.
5. H.Horiuchi, I.Ikeda and K.Katō, Progress of Theoretical Physics Supplement, N192, 2012, p.1.
6. J.A.Wheeler, Phys. Rev., v.**52**, 1937, p.1083.
7. Structure of Atomic Nuclei, Handbuch der Physik, vol.XXXIX, Edited by S.Flügge, Springer-Verlag, Berlin, 1957.
8. K.Ikeda, N.Takigawa and H.Horiuchi, Supplement of the Prog. Theor. Phys., Extra Number, 1968, p.464.
9. H.A.Bethe, Rev. Mod. Phys., v.**9**, 1937, p.69
10. Yu.P.Popov *et al*., Sov. J. Nucl. Phys., v.**13**, 1971, p.913.
11. R.Bonetti and L.Milazzo-Colli, Phys. Lett., v.**49**B, 1974, p.17.
12. S.G.Kadmensky and V.I.Furman, Physics of Particles and Nuclei, v.6 (2), 1975, p.469.
13. F.C.Chang, Phys. Rev., vol.**141**, 1966, p.1136
14. I.Tonozuka and A.Arima, Nucl. Phys., v.**323**A, 1979, p.45.
15. W.M.Seif, J.Phys.G: Nucl. Part. Phys., v.**40**, 2013, p.105102.
16. T.Knellwolf and J.Rossel, Helv. Phys. Acta., v.**39**, (1966), p.376.
17. J.I.Hogan, Z.Phys., v.**295** A, 1980, p.169
18. Shuqing Guo *et al.,* Nucl. Phys., v.**934**A, 2015, p.110.
19. G.L.Zhang *et al.,* Nucl. Phys., v.**823**A, 2009, p.16.
20. Saad M.Saleh Ahmed *et al.,* J. Phys. G: Nucl. Part. Phys., v.**40**, 2013, p.065105.
21. Dondong Ni and Zhongzhou Ren, Phys. Rev., v.**82**C, 2010, p.024311.

22. T.T.Ibrahim and S.M.Wyngaardt, J.Phys. G: Nucl. Part. Phys., v.**41**, 2014, p.055111.
23. A.Iwamoto and K.Harada, Phys. Rev., v.**26**C, 1982, p.1821
24. M.Freer *et al.,* Microscopic Clustering in Nuclei, arXiv: 1705.06192v1 [nucl-th] 17 May 2017.
25. Y.C.Tang, Nucl. Phys., v.**463**A, 1987, p.377c.
26. E.Gadioli and P.E.Hodgson, Pre-Equilibrium Nuclear Reactions, Clarendon Press, Oxford, 1992.
27. G.Khuukhenkhuu *et al.,* Proceedings of the XXIV International Seminar on Interaction of Neutrons with Nuclei, JINR, Dubna, 2017, p.166.
28. G.Khuukhenkhuu *et al.,* Proceedings of the XXV International Seminar on Interaction of Neutrons with Nuclei, JINR, Dubna, 2017, p.(in press).
29. G.Khuukhenkhuu *et al.,* Proceedings of the 8th AASPP Workshop on Asian Nuclear Reaction Database Development, INDC(MGL)-0001, IAEA, Vienna, Austria, 2018, p.70.
30. G.Khuukhenkhuu *et al.,* Acta Physica Polonica, v.**49**B, 2018, p.325.
31. http:/www-nds.iaea.org/exfor/exfor.htm
32. A.H.Wapstra and G.Audi, Nucl. Phys., v.**432**A, 1985, p.1.