Analysis of averaged (n,p) reaction cross sections for fission neutron spectrum

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1. Introduction

The (n,p) reaction cross sections averaged over the fission neutron spectrum are important in reactor engineering for calculations of the nuclear transmutation rate, nuclear heating, radiation damage and related safety problems. On the other hand, it is necessary in practice to evaluate the neutron cross sections of the nuclides, for which no experimental data are available. Because of this, we carried out the systematic analysis of known (n,p) cross sections for fission neutron spectrum and observed so-called isotopic effect in this energy range [1]. To explain the isotopic effect of (n,p) cross sections for fast neutrons the statistical and exciton models and PWBA were suggested [2-4].

In this paper the systematical analysis of known experimental (n,p) cross sections averaged over the fission neutron spectrum of ^{235}U by thermal neutrons [5], using the statistical model [2], is described.

2.The Statistical Model

For fission neutrons we can neglect the direct and pre-equilibrium mechanisms and consider the compound mechanism only. Then, using the statistical model of nuclear reactions, constant nuclear temperature approximation and Weizsacker's formula for binding energy we obtain the following formula for (n,p) reaction cross section [2]:

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

Here: R is the target nucleus radius; $\lambdabar$ is the wavelength of the incident neutrons divided by 2π; A, N and Z are the mass number, number of neutrons and number of protons for the target nucleus, respectively; C and K are the parameters which are determined as follows

$$C = \exp\left(ZA^{1/6} \frac{2\gamma - 1}{\sqrt{13.5(E_n + Q_{np})}} \right) \tag{2}$$

and

$$K = 4\xi \sqrt{\frac{A}{13.5(E_n + Q_{np})}} . \tag{3}$$

Here: E_n is the neutron energy; Q_{np} is the reaction energy; γ and ξ are the constants of Weizsaker's formula.

From (2) and (3) for parameters C and K the following relation can be written:

$$\ln C = \frac{Z}{A^{1/3}} \left(\frac{2\gamma - 1}{4\xi} \right) K . \tag{4}$$

It can be rewritten the relation (4) in the following form:

$$C = e^{BK}, \tag{5}$$

where

$$B = \frac{Z}{A^{1/3}} \frac{(2\gamma - 1)}{4\xi}. \tag{6}$$

3. Systematical Analysis of (n,p) Cross Sections

Systematical analyses of (n,p) cross sections for neutron energy $E_n = 6 - 16$ MeV and $E_n = 18 - 20$ MeV were published in [2] and [6], respectively. Now the systematics of known experimental (n,p) cross sections for fission neutron spectrum [5] will be considered using the statistical model formulae (1)-(6). The result of the systematical analysis for (n,p) cross sections averaged over the fission neutron spectrum is shown in Fig.1. The values of C and K from formula (1), as fitted to experimental data parameters, are given in Fig.1, also.

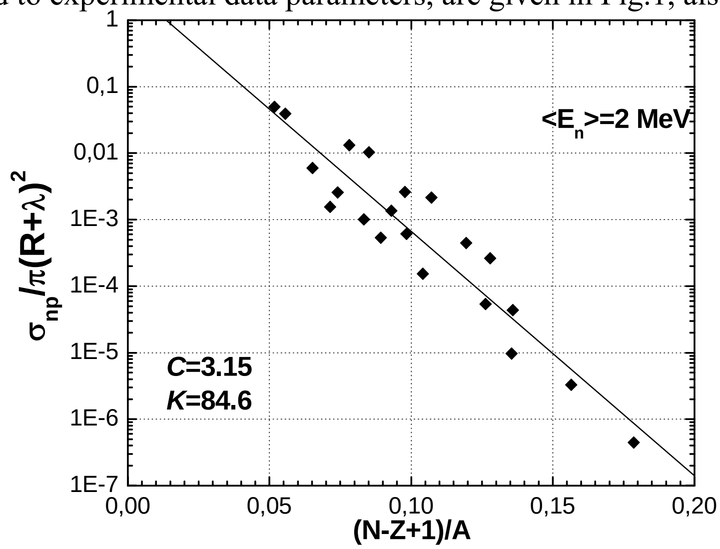

Fig. 1. *The dependence of reduced (n,p) cross sections on the relative neutron excess parameter (N-Z+1)/A*

It is seen that the theoretical line is in agreement with experimental data. However, these values of parameters C and K are in disagreement with systematical regularities which were observed in the neutron energy of $E_n = 6 - 20$ [2, 6]. In order to clarify a reason of this disagreement we considered in detail the possibilities of the other values for C and K parameters and an effective average neutron energy for fission neutron spectrum. Average neutron energy of fission spectrum for ^{235}U by thermal neutrons should be around 2 MeV [7]. Nevertheless, for (n,p) reaction cross sections the effective average neutron energy is perhaps different from 2 MeV (see section 3.). Taking into account this possibility and observed systematical regularity for C and K we found to be $C = 60$, $K = 110$ and $\langle E_n \rangle_{eff} = 4$ MeV. These values with other data for $E_n = 6 - 20$ MeV [2, 6] are given in Table.1 and are shown in Figs.2-4.

Table 1. *C and K parameters*

E_n (MeV)	4	6	8	10	13	14.5	16	18	20
C	60	17.5	11.9	6.8	2.7	2.4	1.4	0.39	0.23
K	110	75.5	62.8	52.1	38.8	37.3	33.5	22.4	17.9

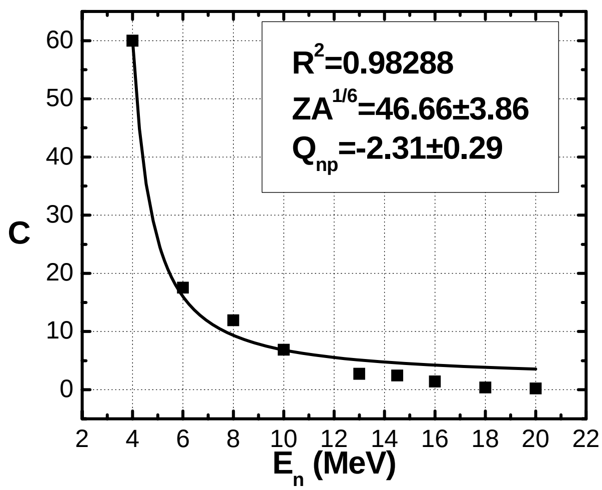

Fig. 2. *Eenergy dependence for C parameter*

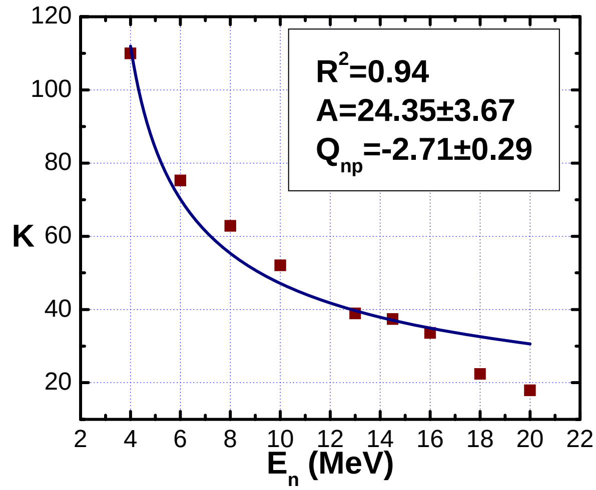

Fig. 3. *Energy dependence for K parameter*

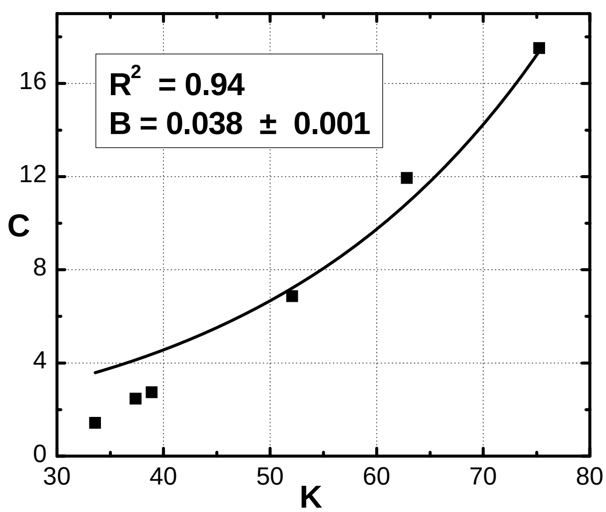

Fig. 4. *The relationship between the parameters C and K*

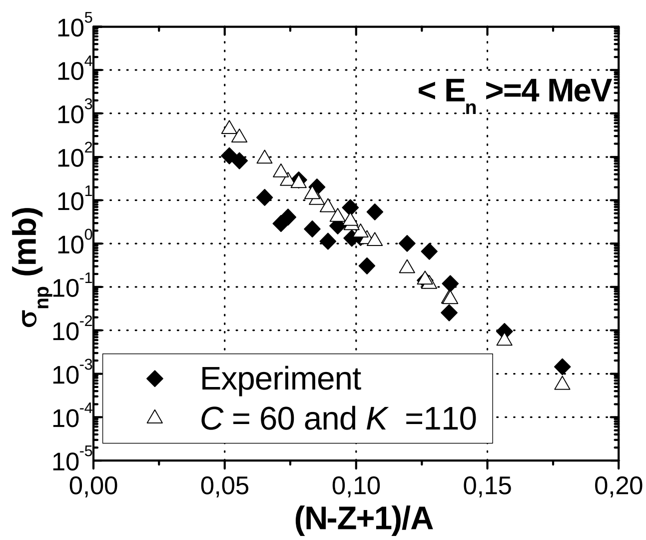

Fig. 5. *Calculated by formula (1) (n,p) cross section (for C=60 and K=110) and experimental data*

In these figures solid squares are the fitted values for C and K parameters and the solid curve is the theoretical one calculated by (2), (3) and (5). Also, calculated by (1) with parameters $C = 60$ and $K = 110$ theoretical (n,p) cross section and experimental data are shown in Fig.5. It is seen that the statistical model formulae satisfactorily describe experimental data.

4. The Effective Neutron Energy

Fission neutron spectrum of ^{235}U for thermal neutrons [7] is shown in Fig.6. The excitation function of the $^{58}Ni(n,p)^{58}Co$ reaction is, also, displayed in Fig.6, as example.

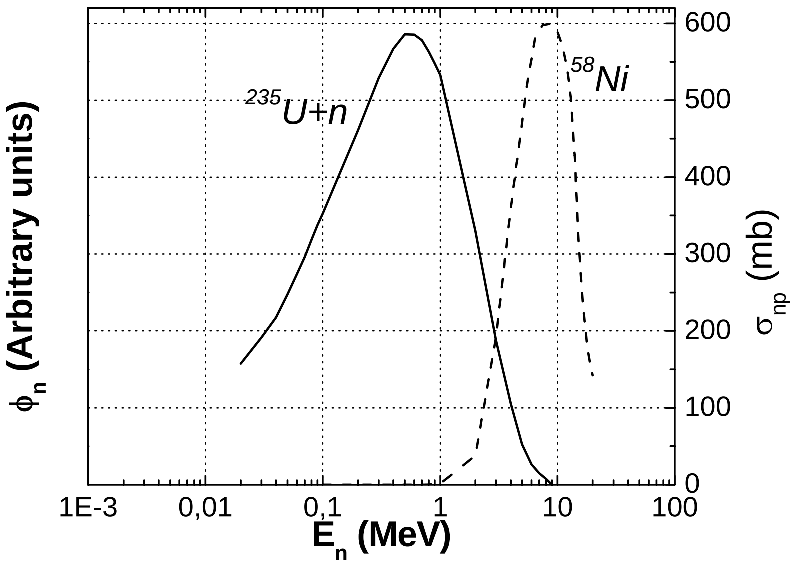

Fig.6. *Fission neutron spectrum of ^{235}U [7] and cross section curve of the $^{58}Ni(n,p)^{58}Co$ reaction [8]*

It is seen that an average (n,p) cross section is determined by overlap of two curves for neutron energy spectrum and excitation function. The average (n,p) cross section weighted by neutron spectrum is expressed as follows:

$$\langle \sigma(n,p) \rangle = \frac{\int \sigma_{np}(E_n)\phi(E_n)dE_n}{\int \phi(E_n)dE_n} \quad (7)$$

Here: $\phi(E_n)$ is the neutron spectrum.

For most of isotopes the threshold energy of (n,p) reaction lies in the region of $E_{th} \approx 2-5$ MeV [8]. So, from Fig.6 and expression (7), taking into account the systematical regularity of parameters C and K (see Figs. 2, 3 and 4), we concluded that the average neutron energy for the fission neutron induced (n,p) reactions is around 4 MeV.

5. Conclusion

1 Using the statistical model known experimental (n,p) cross sections for fission neutron spectrum of ^{235}U were analyzed and certain systematical regularities were observed.
2 It was shown that the experimental data of (n,p) cross sections for fission neutrons is satisfactorily described by the statistical model.
3 Average effective neutron energy for (n,p) reactions induced by fission neutrons of ^{235}U was found to be ~4MeV.

Acknowledgements

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References

1. G. Khuukhenkhuu, Yu. M. Gledenov, M. V. Sedysheva.
   JINR Communication. E3-93-205. 1993, Dubna.
2. G. Khuukhenkhuu, G. Unenbat, M. Odsuren, Yu. M. Gledenov, M. V. Sedysheva, B. Bayarbadrakh.
   JINR Communication. E3-2007-25. 2007, Dubna.
3. G. Khuukhenkhuu, G. Unenbat, M. Odsuren, Yu. M. Gledenov, M. V. Sedysheva, B. Bayarbadrakh.
   JINR Communication. E3-2007-26. 2007, Dubna.
4. G. Khuukhenkhuu, G. Unenbat, M. Odsuren, Yu. M. Gledenov, M. V. Sedysheva, B. Bayarbadrakh.
   JINR Communication. E3-2007-27. 2007, Dubna.
5. O. Horibe, Y. Mizumoto, T. Kusakobe, H. Chatani.
   In book: 50 Years with Nuclear Fission (Proceedings of the International Conference, April 25-28, 1989).vol.2, Washington, D.C., Editors: J.W.Behrens and A.D.Carlson. pp.923-930.
6. G. Khuukhenkhuu, Yu. M.Gledenov, M. V. Sedysheva, M. Odsuren.
   In book: Neutron Spectroscopy, Nuclear Structure, Related Topics. (Proceedings of the XVI International Seminar on Interaction of Neutrons with Nuclei, ISINN-16, June 11-14, 2008). Dubna (in press).
7. B. I. Starostov, A. F. Semenov, B. N. Nefedov
   Voprocy Atomnoy Nauki i Tekhniki, Seriya Yadernye Konstanty, N 2(37), 1980, pp.3-44. (in Russian)
8. Handbook on Nuclear Activation Data. IAEA Technical Reports, Series N273, 1987, Vienna.