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COMPARATIVE ANALYSIS OF (n,p) REACTION CROSS-SECTION SYSTEMATICS FOR ~ 14-15 MeV NEUTRONS

Report FEI-2055 (1989)
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Institute of Physics and Power Engineering
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INTRODUCTION

Measurements on neutrons in the 14-15 MeV energy range have an important place in the experimental study of cross-sections for neutron-induced reactions. The comparatively easy method of obtaining a strong flux of neutrons in that energy range from the $T(d,n)^4He$ reaction is the main reason for the large volume of experimental data that have been published on the (n,p), (n,α), (n,t) and (n,2n) reaction cross-sections for $E_n \approx 14.5$ MeV. By systematizing the considerable amount of experimental data, we can discover certain trends in the behaviour of the cross-sections for reactions involving 14 MeV neutrons.

In the last few years, research on fusion reactors has led to an increased demand for nuclear data for 14 MeV neutrons. It is well known that, unlike the neutron fluxes in conventional fission reactors, neutrons of these energies make up a significant part of the neutron field close to a D-T plasma, and therefore predictions of reactor parameters such as tritium breeding ratio, induced activity, nuclear heating and so on depend heavily on the accuracy of the cross-sections at $E_n \sim 14$-15 MeV. The cross-section systematics of threshold reactions at energies of 14-15 MeV can be used to evaluate the data in a region of nuclei where no experimental data are available. A reliable evaluation of the excitation functions of threshold reactions can be obtained with theoretical model calculations, normalized to the predictions made from the systematics.

In view of the above, it is very important to revise the systematics as more experimental data become available. This paper contains a comparative

analysis of the (n,p)-reaction cross-section systematics at E_n ~ 14.5 MeV based on experimental results published up to 1990.

1. ISOTOPIC DEPENDENCE OF CROSS-SECTIONS FOR THE (n,p) REACTION AT E_n ~ 14-15 MeV

Several formulas have been proposed to describe the isotopic dependence of cross-sections for the (n,p) reaction at a neutron energy of 14.5 MeV. The best-known are the following:

Levkovskij [1]
$$\sigma_{np}=45.2(A^{1/3}+1)^2\exp(-33.0s) \quad (1)$$

Kumabe, Fukuda [2]
$$\sigma_{np}=\begin{cases} 21.8A\ \exp(-34.0s) & 40\leqslant A\leqslant 62 \\ 0.75A^2\exp(-43.4s) & 63\leqslant A\leqslant 89 \\ 0.75A^2\exp(-45.0s) & 90\leqslant A\leqslant 160 \end{cases} \quad (2)$$

Bychkov et al. [3]
$$\sigma_{np}=0.706\pi r_0^2\cdot(A^{1/3}+1)^2\cdot\exp\left\{\sqrt{\frac{A}{145}}\left[-49.97\,\frac{N-Z+1}{A}+0.584\,\frac{Z-1}{A^{1/3}}-3.258\right]\right\} \quad (3)$$

Forrest [4]
$$\sigma_{np}=7.57(A^{1/3}+1)^2\exp(-28.8s-59.2s^2+0.237A^{1/2}), \quad (4)$$

where σ_{np} is the cross-section for the (n,p) reaction at $E_n \approx 14.5$ MeV in millibarns; $r_0 = 1.4 \times 10^{-13}$ cm; and A, Z, N, s are the mass number, charge, number of neutrons and asymmetry parameter (N-Z)/A of the target nucleus, respectively.

Despite certain individual characteristics (the number of parameters, the type of dependence in the exponent), formulas (1)-(4) are structurally identical. They represent the product of two factors, to each of which it is possible to assign one of the stages of the nuclear reaction within the framework of the statistical model. The pre-exponential term in fact models the formation of the compound nucleus, whereas the exponential term represents the escape of the proton from the compound nucleus. It should also be noted that the dependence in formulas (1)-(4) of σ_{np} on the parameter (N-Z)/A, as shown in Refs [3, 5 and 6], derives from the fundamental relationships of

the statistical model for nuclear reactions. Thus, formulas (1)-(4) can be partly explained within the framework of the statistical model for nuclear reactions.

However, it remains an open question whether formulas (1)-(4) can be used in the region of large mass numbers. It is well known that in order to achieve an accurate description of experimental data on the neutron and proton emission spectra and excitation functions for the (n,p) and (n,2n) reactions, it is necessary to take non-equilibrium processes as well as equilibrium processes into account in the nuclear reaction mechanism. Whereas for intermediate atomic weight nuclei the (n,p) reaction generally passes through a stage of compound nucleus formation, in the case of heavier nuclei ($A \geq 100$) non-equilibrium processes begin to play an increasing role. In order to answer the question, let us turn to Ref. [1] where it was first shown that, on a logarithmic scale, the dependence of the experimental values for σ_{np} at $E_n \approx 14.5$ MeV on the variable (N-Z)/A can be described by a straight line with a high degree of accuracy. Since this correlation is valid for a wide range of mass numbers, it can be concluded [7] that this characteristic is a unique property of the (n,p) reaction and is independent of the nucleus involved in the reaction and thus of the mechanism whereby it takes place. Thus, the correlation observed between the experimental values for σ_{np} and the parameter (N-Z)/A to some extent justifies the use of formulas (1)-(4) over a wide range of mass numbers.

2. DATA LIBRARY

There are several compilations of experimental data on (n,p) reaction cross-sections for 14.5 MeV neutrons [4, 8-11]. The most recent one dates from 1985 [4]. Since then, a substantial amount of experimental work has appeared which we believe enables a more reliable evaluation of the cross-sections around 14.5 MeV to be made.

The present data library is based on experimental results for (n,p) reaction cross-sections over the 13-15 MeV neutron energy range published before 1990. In preparing the library, we used the CINDA bibliographical catalogue of published neutron physics papers [12], the EXFOR world computerized library of experimental data and some recent publications [13-15]. References [13-15] deserve to be considered separately in view of the relatively wide range of nuclei studied and the careful account of various corrections to the measurement results. These papers present the results of systematic measurements of threshold reaction cross-sections for the main structural materials in a D-T neutron generator under identical experimental conditions. Measurements were made of the cross-sections for about 140 (n,p), (n,n'p), (n,α) and (n,2n) reactions leading to the formation of a residual nucleus with a half-life between one minute and one year. The data were obtained for several energy points in the range 13.3-15 MeV. The experimental errors, as demonstrated by the authors, are less than $\pm$ 5% for nearly all the data obtained.

Returning to the whole collection of experimental data which we used to establish the library, it should be pointed out that there are serious deficiencies in these data. In a relatively large number of cases, the discrepancy between the data of different authors exceeds the errors quoted by them. It seems that these discrepancies can be accounted for by:

- The difference in the conditions of the experiments performed by the various groups (method for measuring the induced activity of the samples, neutron field characteristics, method for monitoring the neutron flux);
- The difference in the reference cross-sections used for the relative measurements;
- The difference in nuclear data such as the quantum yields of gamma lines, half-lives, and isotopic abundance in the sample.

The publications and the EXFOR library do not always contain comprehensive

information so that the evaluator cannot always take proper account of all the factors listed above. Therefore, the critical analysis of the experimental data was followed by the selection of those evaluations of the measured cross-sections in which the authors had most confidence. Preference was given to work carried out using enriched isotopes and semiconductor detectors. Data which differed significantly from other authors' results that agreed to within the experimental error, were excluded from the study. Table 2 shows the evaluated (n,p)-reaction cross-sections from the data library for 14.5 MeV neutrons. In extrapolating the experimental data to this energy, the energy dependence of the cross-section for the analysed reaction obtained from theoretical calculations or taken from Ref. [16] was used.

3. STATISTICAL ANALYSIS METHOD

Statistical analysis of the results of the compilation was performed within the framework of the non-linear regression model [17]. In this model it is assumed that the "measured" values are the sum of the hypothetical "true" dependence and the experimental errors:

$$\sigma_i = \Phi(x_{i1},\ldots,x_{iK},\beta_1,\ldots,\beta_m)+\varepsilon_i, \quad i=1,\ldots,n \tag{5}$$

The minimizing functional has the form:

$$Q(\vec{\beta}) = \sum_{i=1}^{n} \frac{[\sigma_i - \Phi(x_{i1},\ldots,x_{iK},\beta_1,\ldots,\beta_m)]^2}{e_i^2} \tag{6}$$

In formulas (5) and (6) $\sigma = (\sigma_1,\ldots,\sigma_n)^T$ is the cross-section vector; $x_{i1},\ldots,x_{iK}$ are the values of the K independent variables corresponding to the cross-section σ_i; $\vec{\beta} = (\beta_1,\ldots,\ldots\beta_m)^T$ is the vector of the unknown parameters being estimated; and n is the number of nuclides in the data library. The random values ε_i are independent ($E\varepsilon_i\varepsilon_j = 0$, $i \neq j$), have a zero mathematical expectation ($E\varepsilon_i = 0$), and a variance which is known

with an accuracy up to a constant multiplier ($D\varepsilon_i = \Delta^2 e_i^2$, e_i being the error of the cross-section in the data library). The role of the function $\psi_i(\beta_1,\ldots,\beta_m) \equiv \psi(x_{i1},\ldots,x_{iK}, \beta_1,\ldots,\beta_m)$, which is non-linear with respect to the parameters, can be played by one of the dependences (3), (4) with unknown parameters. Without any loss of generality we can further assume

$$\Psi_\ell(\vec{\beta}) = \beta_1 (A_\ell^{1/3}+1)^2 \exp\left\{-\beta_2 \frac{A_\ell - 2Z_\ell}{A_\ell} - \beta_3 \frac{(A_\ell - 2Z_\ell)^2}{A_\ell^2} - \beta_4 A_\ell^{1/2}\right\}, \qquad (7)$$

where A_i, Z_i are the mass number and charge of the i-th nuclide in the data library. All the arguments given below are valid also for a dependence of type (3):

$$\Psi_\ell(\vec{\beta}) = \beta_1 (A_\ell^{1/3}+1)^2 \exp\left[\left(\frac{A}{145}\right)^{1/2}\left(-\beta_2 \frac{A_\ell - 2Z_\ell + 1}{A_\ell} + \beta_3 \frac{Z_\ell - 1}{A_\ell^{1/3}} - \beta_4\right)\right] \qquad (8)$$

Since a nuclear reaction cross-section is always a positive value, the range of permissible values for the parameters can be written as:

$$M = \{\vec{\beta}: \beta_1 > 0,\ -\infty < \beta_2, \beta_3, \beta_4 < \infty\}$$

Equation (5), taking into account Eq. (7), belongs to the class of regressions which are linear in logarithms [17]. In fact, Eq. (7) can be written:

$$\Psi_\ell(\vec{\beta}) = \exp\left((\vec{\alpha}, \vec{x}_\ell) + c_\ell\right)$$

where $\alpha = f(\beta) = (\ln\beta_1, \beta_2, \beta_3, \beta_4)^T$,

$$\vec{x}_\ell = \left(1, -\frac{A_\ell - 2Z_\ell}{A_\ell}, -\frac{(A_\ell - 2Z_\ell)^2}{A_\ell^2}, -A_\ell^{1/2}\right)^T$$

$c_i = \ln(A_i^{1/3} + 1)^2$, and the symbol $(\vec{\alpha}_i, \vec{x}_i)$ is the scalar product of the vectors. The sum of squares of the deviations (6) can be transformed as follows:

$$Q(\vec{\beta}) = S(\vec{\alpha}) = \sum_{\ell=1}^{n} (\sigma_\ell - \varphi_\ell(\vec{\alpha}))^2 \qquad (9)$$

where

$$\varphi_l(\vec{\alpha}) = \psi_l(\vec{\beta})/e_l = \exp((\vec{\alpha}, \vec{x}_l) + \bar{c}_l) \tag{10}$$

$\bar{c}_i = c_i - \ln e_i$, $\bar{\sigma}_i = \sigma_i / e_i$. Since the mapping of f is one to one, we have

$$\arg\min_{\vec{\beta} \in M} Q(\vec{\beta}) = f^{-1}(\arg\min_{\vec{\alpha} \in R^4} S(\vec{\alpha}))$$

As follows from Eqs (9) and (10), in order to find the unknown regression parameters we must solve the non-linear optimization problem. In doing so, we have to analyse the following points:

1. The existence of a solution;
2. The choice of an adequate minimization algorithm;
3. The uniqueness of the solution.

We shall discuss them in this order in relation to the minimization of the functional (9).

Existence of a solution. Until recently non-linear regression studies were as a rule limited to discussing the choice and numerical realization of a suitable algorithm for minimizing the corresponding functional, and questions related to the existence and uniqueness of the solution were left aside. Reference [18] puts forward criteria to answer these questions for a fairly wide range of problems, provided the "observation" vector $\vec{\sigma}$ lies within certain regions of the space R^n. In particular, a minimum of the sum of squares of the deviations for logarithmically linear regressions exists if all the co-ordinates of the "observation" vector are positive. Thus, since the values of σ_i in Eq. (9) are positive for any i, a minimum of the functional $S(\vec{\alpha})$ exists.

Selection of a minimization algorithm. The Newton-Gauss method has the reputation of being a reliable algorithm for minimizing the sum of squares of the deviations [17]. Consequently, we minimized the functional (9) using the FUMILI code [19], which incorporates this method. In the Newton-Gauss method, the unknown value of the parameter vector is calculated by the iterative

procedure:

$$\vec{\alpha}^{k+1}=\vec{\alpha}^{k}+\lambda_k(X_k^TX_k)^{-1}X_k^T(\vec{\sigma}-\vec{\varphi}(\vec{\alpha}))=\vec{\alpha}^{k}+\lambda_k\vec{\delta}^{k}, \tag{11}$$

where $\vec{\alpha}^{k+1}=(\alpha_1^{k+1},\ldots,\alpha_m^{k+1})^T$, $\vec{\alpha}^{k}$ is the (k+1)-th and k-th approximation to $\vec{\alpha}$, $\vec{\varphi}(\vec{\alpha})=(\varphi_1(\vec{\alpha}),\ldots,\varphi_n(\vec{\alpha}))^T$,

$(X_k)_{ij}=\frac{\partial\varphi_i(\vec{\alpha})}{\partial\alpha_j}$ is an n x m matrix,

$$\lambda_k=t^q,\ t=0.5, \tag{12}$$

q = 0.1,.... is a number such that

$$S(\vec{\alpha}^{k}+\lambda_k\vec{\delta}^{k})<S(\vec{\alpha}^{k}) \tag{13}$$

Determination of λ_k from conditions (12) and (13) is equivalent to the requirement of the FUMILI code to limit the change in the parameters at each iteration by some hypercube. The choice of the starting value in (11) is discussed below.

Note that the convergence of the Newton-Gauss method for functions linear in logarithms is proved in Ref. [17].

In order to check the efficiency of the FUMILI code, we approximated the results of the Forrest compilation [4] with formula (7). The calculated values coincided with the parameters published in Ref. [4] to three digits.

Uniqueness of the solution. In Ref. [18], sufficient criteria are proposed for recognizing the global minimum of the sum of squares for logarithmically linear regressions. The field of application of these criteria is very limited. In particular, they have proved inconsistent for the present problem. The global minimum was therefore found by realizing the minimization process for various starting values of $\vec{\alpha}^{0}$ (see formula (11)). The set of initial approximations always included the vector of the parameters resulting from the approximation of the Forrest compilation [4] using formula (7), and also the estimate of the linear least squares method for regression obtained by formally taking the logarithm of model (5) with $\vec{\sigma}_i$, $\vec{\varphi}_i(\vec{\alpha})$, $\bar{\varepsilon}_i(D\bar{\varepsilon}_i = \Delta)$ instead of σ_i, $\psi_i(\vec{\beta})$, ε_i, respectively,

$$Z_i = (\vec{\alpha},\vec{x}_i) + \bar{c}_i + \eta_i \qquad i = 1, \ldots, n,$$

where $Z_i = \ln\bar{\sigma}_i$, $\eta_i = \varepsilon_i/\bar{\sigma}_i$, $D\eta_i = \Delta^2/\bar{\sigma}_i^2$.

As a result of the operations described above we found for each of the approximation functions (7), (8), two local minima of the functional S, the lesser of which was recognized as the global one.

In concluding this section, we present formulas for calculating the covariance matrix of the parameters $D(\hat{\vec{\beta}})$ and the errors in the value of the approximation function in the point $\Delta\psi(\vec{x}_i, \hat{\vec{\beta}})$

$$D\hat{\beta} = \frac{Q}{n-m}(x^T x)^{-1} \tag{14}$$

$$\Delta\Psi(\hat{x}_l, \hat{\beta}) = \sum_k \sum_l \frac{\partial\Psi(\hat{x}_l, \hat{\beta})}{\partial\beta_n} \frac{\partial\Psi(\hat{x}_l, \hat{\beta})}{\partial\beta_l} \mathrm{COV}(\hat{\beta}_k, \hat{\beta}_l)$$

$$x_{lj} = \frac{\partial\Psi_l(\hat{\beta})}{\partial\beta_j}$$

Note that, although formula (14) is recommended in all of the papers on regression analysis (see, for example, Refs [20] and [21]), it has not yet been properly validated. However, the similarity of formula (14) with the corresponding formula of the linear least squares method and the theorems on asymptotic behaviour of estimates in the non-linear least squares method indicate that it is fairly accurate.

4. RESULTS

Table 1 shows the minimal values of the functional Q and the corresponding values of the parameters calculated through approximation of the data from the authors' compilation by means of formulas (7) and (8).

As can be seen from Table 1, the data are described more accurately by formula (7); consequently, it is proposed that the expression:

$$\sigma_{пр}(A,Z) = 5.2093(A^{1/3}+1)^2 \exp\left[-23.486\frac{A-2Z}{A} - 085.044\left(\frac{A-2Z}{A}\right)^2 + 0.25406A^{1/2}\right] \tag{15}$$

Table 1

Results of the approximation of the data from the authors' compilations by means of formulas (7) and (8)

Formula	Q	β_1	β_2	β_3	β_4
(7)	474.28	5.2093	23.486	85.044	-0.25406
(8)	588.68	34.597	51.520	0.5747	2.6679

should be used for the recommended isotopic dependence of the (n,p)-reaction cross-sections at $E_n \approx 14.5$ MeV.

The overall result of the data approximation from the compilation by means of formula (15) is given in Table 2. The first, second and third columns give the number, mass number and charge of the nucleus; the fourth and fifth columns, the recommended values for the cross-sections and their errors; the sixth and seventh, the cross-sections and their errors from the data library; and finally, the last column gives the components of the functional Q corresponding to the i-th point. According to Table 2, the average statistical component of the error in the recommended curve is 3.3%.

Table 2

Results of systematics for the (n,p) reaction

NUM	A	Z	CALC	ERR	EXPT	+/-EXPT	F^2
1	40	18	0.207D+02	0.104D+01	0.180D+02	0.200D+01	0.183D+01
2	39	19	0.254D+03	0.133D+02	0.179D+03	0.600D+02	0.157D+01
3	41	19	0.596D+02	0.203D+01	0.430D+02	0.500D+01	0.111D+02
4	40	20	0.508D+03	0.407D+02	0.470D+03	0.300D+02	0.156D+01
5	42	20	0.146D+03	0.524D+01	0.173D+03	0.100D+02	0.705D+01
6	43	20	0.718D+02	0.224D+01	0.920D+02	0.100D+02	0.409D+01
7	44	20	0.338D+02	0.128D+01	0.390D+02	0.400D+01	0.171D+01
8	45	21	0.851D+02	0.250D+01	0.580D+02	0.600D+01	0.205D+02
9	46	22	0.188D+03	0.707D+01	0.242D+03	0.300D+02	0.324D+01
10	47	22	0.997D+02	0.285D+01	0.130D+03	0.800D+01	0.138D+02
11	48	22	0.509D+02	0.151D+01	0.600D+02	0.300D+01	0.921D+01
12	49	22	0.251D+02	0.961D+00	0.295D+02	0.500D+01	0.759D+00
13	50	22	0.121D+02	0.619D+00	0.135D+02	0.200D+01	0.498D+00
14	51	23	0.313D+02	0.104D+01	0.330D+02	0.300D+01	0.322D+00

Table 2 (cont.)

Results of systematics for the (n,p) reaction

NUM	A	Z	CALC	ERR	EXPT	+/-EXPT	F^2
15	50	24	0.235D+03	0.961D+01	0.300D+03	0.500D+02	0.169D+01
16	52	24	0.724D+02	0.186D+01	0.780D+02	0.100D+02	0.319D+00
17	53	24	0.383D+02	0.112D+01	0.400D+02	0.300D+01	0.307D+00
18	54	24	0.198D+02	0.759D+00	0.150D+02	0.300D+01	0.258D+01
19	55	25	0.463D+02	0.122D+01	0.450D+02	0.100D+02	0.169D-01
20	54	26	0.287D+03	0.129D+02	0.295D+03	0.300D+02	0.702D-01
21	56	26	0.983D+02	0.258D+01	0.110D+03	0.100D+02	0.137D+01
22	57	26	0.552D+02	0.136D+01	0.800D+02	0.100D+02	0.614D+01
23	58	26	0.303D+02	0.880D+00	0.200D+02	0.300D+01	0.119D+02
24	59	27	0.651D+02	0.158D+01	0.465D+02	0.100D+02	0.347D+01
25	58	28	0.344D+03	0.171D+02	0.310D+03	0.250D+02	0.186D+01
26	60	28	0.129D+03	0.387D+01	0.137D+03	0.150D+02	0.290D+00
27	61	28	0.761D+02	0.190D+01	0.950D+02	0.100D+02	0.359D+01
28	62	28	0.440D+02	0.107D+01	0.370D+02	0.500D+01	0.195D+01
29	63	29	0.880D+02	0.234D+01	0.120D+03	0.300D+02	0.113D+01
30	65	29	0.303D+02	0.778D+00	0.197D+02	0.300D+01	0.124D+02
31	64	30	0.164D+03	0.581D+01	0.176D+03	0.200D+02	0.342D+00
32	66	30	0.611D+02	0.150D+01	0.660D+02	0.500D+01	0.977D+00
33	67	30	0.363D+02	0.872D+00	0.450D+02	0.500D+01	0.304D+01
34	68	30	0.213D+02	0.596D+00	0.140D+02	0.500D+01	0.211D+01
35	70	30	0.704D+01	0.331D+00	0.700D+01	0.500D+00	0.766D-02
36	69	31	0.430D+02	0.102D+01	0.340D+02	0.300D+01	0.907D+01
37	71	31	0.152D+02	0.473D+00	0.170D+02	0.300D+01	0.356D+00
38	70	32	0.819D+02	0.234D+01	0.770D+02	0.100D+02	0.236D+00
39	72	32	0.308D+02	0.732D+00	0.310D+02	0.300D+01	0.300D-02
40	73	32	0.186D+02	0.506D+00	0.220D+02	0.300D+01	0.130D+01
41	74	32	0.111D+02	0.385D+00	0.110D+02	0.200D+01	0.191D-02
42	76	32	0.385D+01	0.221D+00	0.300D+01	0.150D+01	0.320D+00
43	75	33	0.225D+02	0.553D+00	0.192D+02	0.200D+01	0.265D+01
44	74	34	0.107D+03	0.366D+01	0.147D+03	0.300D+02	0.181D+01
45	76	34	0.430D+02	0.106D+01	0.550D+02	0.500D+01	0.573D+01
46	77	34	0.269D+02	0.630D+00	0.350D+02	0.500D+01	0.264D+01
47	78	34	0.166D+02	0.437D+00	0.180D+02	0.400D+01	0.119D+00
48	81	35	0.125D+02	0.358D+00	0.210D+02	0.500D+01	0.290D+01
49	82	36	0.239D+02	0.553D+00	0.230D+02	0.400D+01	0.517D-01
50	84	36	0.952D+01	0.301D+00	0.800D+01	0.150D+01	0.103D+01
51	87	37	0.736D+01	0.257D+00	0.100D+02	0.200D+01	0.174D+01
52	84	38	0.764D+02	0.273D+01	0.960D+02	0.800D+01	0.600D+01
53	88	38	0.140D+02	0.340D+00	0.150D+02	0.200D+01	0.242D+00
54	89	39	0.256D+02	0.608D+00	0.246D+02	0.300D+01	0.108D+00
55	90	40	0.449D+02	0.138D+01	0.450D+02	0.300D+01	0.170D-02
56	91	40	0.300D+02	0.773D+00	0.325D+02	0.300D+01	0.695D+00
57	92	40	0.199D+02	0.452D+00	0.220D+02	0.200D+01	0.108D+01
58	94	40	0.863D+01	0.244D+00	0.800D+01	0.100D+01	0.402D+00
59	93	41	0.349D+02	0.996D+00	0.440D+02	0.350D+01	0.671D+01
60	95	42	0.404D+02	0.128D+01	0.420D+02	0.200D+01	0.624D+00
61	96	42	0.275D+02	0.724D+00	0.234D+02	0.150D+01	0.755D+01

Table 2 (cont.)

Results of systematics for the (n,p) reaction

NUM	A	Z	CALC	ERR	EXPT	+/-EXPT	F^2
62	97	42	0.186D+02	0.422D+00	0.168D+02	0.100D+01	0.311D+01
63	98	42	0.125D+02	0.281D+00	0.110D+02	0.400D+01	0.137D+00
64	100	42	0.556D+01	0.190D+00	0.520D+01	0.100D+01	0.133D+00
65	99	43	0.218D+02	0.533D+00	0.120D+02	0.300D+01	0.107D+02
66	96	44	0.153D+03	0.858D+01	0.150D+03	0.200D+02	0.214D-01
67	101	44	0.255D+02	0.690D+00	0.360D+02	0.400D+01	0.693D+01
68	104	44	0.814D+01	0.205D+00	0.720D+01	0.100D+01	0.889D+00
69	102	46	0.963D+02	0.500D+01	0.936D+02	0.150D+02	0.326D-01
70	104	46	0.485D+02	0.194D+01	0.580D+02	0.140D+02	0.463D+00
71	105	46	0.341D+02	0.115D+01	0.380D+02	0.800D+01	0.237D+00
72	106	46	0.239D+02	0.669D+00	0.250D+02	0.300D+01	0.139D+00
73	108	46	0.116D+02	0.250D+00	0.900D+01	0.200D+01	0.164D+01
74	109	47	0.195D+02	0.505D+00	0.140D+02	0.300D+01	0.331D+01
75	110	48	0.319D+02	0.112D+01	0.270D+02	0.500D+01	0.942D+00
76	111	48	0.226D+02	0.659D+00	0.500D+02	0.150D+02	0.334D+01
77	112	48	0.160D+02	0.387D+00	0.160D+02	0.200D+01	0.136D-03
78	113	48	0.113D+02	0.244D+00	0.800D+01	0.200D+01	0.265D+01
79	114	48	0.790D+01	0.181D+00	0.100D+02	0.200D+01	0.110D+01
80	116	48	0.386D+01	0.138D+00	0.250D+01	0.300D+00	0.206D+02
81	115	49	0.132D+02	0.302D+00	0.150D+02	0.500D+01	0.126D+00
82	116	50	0.216D+02	0.657D+00	0.220D+02	0.200D+01	0.456D-01
83	117	50	0.154D+02	0.390D+00	0.160D+02	0.400D+01	0.191D-01
84	118	50	0.110D+02	0.243D+00	0.900D+01	0.300D+01	0.456D+00
85	119	50	0.785D+01	0.175D+00	0.100D+02	0.200D+01	0.116D+01
86	120	50	0.557D+01	0.147D+00	0.430D+01	0.700D+00	0.330D+01
87	123	51	0.473D+01	0.136D+00	0.460D+01	0.150D+01	0.749D-02
88	122	52	0.150D+02	0.399D+00	0.120D+02	0.200D+01	0.230D+01
89	124	52	0.783D+01	0.173D+00	0.900D+01	0.200D+01	0.341D+00
90	126	52	0.404D+01	0.127D+00	0.500D+01	0.100D+01	0.917D+00
91	128	52	0.207D+01	0.101D+00	0.240D+01	0.400D+00	0.676D+00
92	130	52	0.106D+01	0.733D-01	0.180D+01	0.300D+00	0.617D+01
93	127	53	0.667D+01	0.153D+00	0.900D+01	0.300D+01	0.605D+00
94	130	54	0.571D+01	0.139D+00	0.900D+01	0.200D+01	0.270D+01
95	131	54	0.415D+01	0.123D+00	0.600D+01	0.100D+01	0.343D+01
96	132	54	0.301D+01	0.111D+00	0.300D+01	0.500D+00	0.635D-03
97	134	54	0.158D+01	0.869D-01	0.200D+01	0.500D+00	0.719D+00
98	133	55	0.492D+01	0.128D+00	0.113D+02	0.200D+01	0.102D+02
99	136	56	0.427D+01	0.120D+00	0.620D+01	0.110D+01	0.309D+01
100	138	56	0.229D+01	0.980D-01	0.280D+01	0.200D+00	0.642D+01
101	139	57	0.372D+01	0.113D+00	0.480D+01	0.400D+00	0.731D+01
102	140	58	0.592D+01	0.142D+00	0.650D+01	0.500D+00	0.136D+01
103	142	58	0.326D+01	0.107D+00	0.400D+01	0.100D+01	0.550D+00
104	141	59	0.924D+01	0.240D+00	0.900D+01	0.100D+01	0.595D-01
105	142	60	0.142D+02	0.479D+00	0.140D+02	0.200D+01	0.901D-02
106	143	60	0.107D+02	0.308D+00	0.120D+02	0.200D+01	0.427D+00
107	144	60	0.804D+01	0.205D+00	0.122D+02	0.240D+01	0.300D+01
108	145	60	0.604D+01	0.148D+00	0.750D+01	0.160D+01	0.831D+00

Table 2 (cont.)

Results of systematics for the (n,p) reaction

NUM	A	Z	CALC	ERR	EXPT	+/-EXPT	F^2
109	146	60	0.453D+01	0.121D+00	0.470D+01	0.600D+00	0.792D-01
110	148	60	0.254D+01	0.963D-01	0.350D+01	0.800D+00	0.144D+01
111	148	62	0.107D+02	0.333D+00	0.100D+02	0.100D+01	0.550D+00
112	150	62	0.618D+01	0.158D+00	0.720D+01	0.100D+01	0.104D+01
113	152	62	0.354D+01	0.107D+00	0.370D+01	0.400D+00	0.166D+00
114	154	62	0.202D+01	0.870D-01	0.350D+01	0.400D+00	0.138D+02
115	153	63	0.545D+01	0.142D+00	0.600D+01	0.100D+01	0.298D+00
116	157	64	0.369D+01	0.110D+00	0.540D+01	0.110D+01	0.242D+01
117	159	65	0.430D+01	0.121D+00	0.470D+01	0.700D+00	0.321D+00
118	160	66	0.650D+01	0.186D+00	0.700D+01	0.120D+01	0.177D+00
119	161	66	0.500D+01	0.140D+00	0.560D+01	0.500D+00	0.144D+01
120	162	66	0.385D+01	0.114D+00	0.500D+01	0.100D+01	0.133D+01
121	163	66	0.295D+01	0.991D-01	0.300D+01	0.100D+01	0.205D-02
122	164	66	0.227D+01	0.887D-01	0.280D+01	0.500D+00	0.113D+01
123	166	68	0.518D+01	0.152D+00	0.450D+01	0.700D+00	0.933D+00
124	167	68	0.401D+01	0.121D+00	0.340D+01	0.400D+00	0.234D+01
125	168	68	0.311D+01	0.102D+00	0.250D+01	0.100D+01	0.368D+00
126	170	68	0.186D+01	0.814D-01	0.180D+01	0.500D+00	0.137D-01
127	172	70	0.419D+01	0.129D+00	0.630D+01	0.800D+00	0.699D+01
128	174	70	0.255D+01	0.936D-01	0.350D+01	0.100D+01	0.911D+00
129	175	71	0.378D+01	0.121D+00	0.370D+01	0.500D+00	0.278D-01
130	181	73	0.312D+01	0.109D+00	0.450D+01	0.500D+00	0.760D+01
131	182	74	0.456D+01	0.154D+00	0.600D+01	0.500D+00	0.832D+01
132	183	74	0.360D+01	0.123D+00	0.410D+01	0.500D+00	0.984D+00
133	184	74	0.285D+01	0.103D+00	0.400D+01	0.100D+01	0.133D+01
134	186	74	0.178D+01	0.798D-01	0.170D+01	0.500D+00	0.229D-01
135	187	75	0.261D+01	0.989D-01	0.430D+01	0.500D+00	0.115D+02
136	184	76	0.940D+01	0.418D+00	0.550D+01	0.130D+01	0.899D+01
137	188	76	0.378D+01	0.134D+00	0.700D+01	0.200D+01	0.258D+01
138	189	76	0.301D+01	0.111D+00	0.500D+01	0.200D+01	0.990D+00
139	190	76	0.239D+01	0.949D-01	0.200D+01	0.500D+00	0.615D+00
140	192	76	0.151D+01	0.741D-01	0.210D+01	0.500D+00	0.140D+01
141	191	77	0.346D+01	0.127D+00	0.480D+01	0.800D+00	0.279D+01
142	193	77	0.220D+01	0.912D-01	0.380D+01	0.500D+00	0.102D+02
143	194	78	0.318D+01	0.120D+00	0.400D+01	0.500D+00	0.270D+01
144	195	78	0.254D+01	0.101D+00	0.200D+01	0.500D+00	0.117D+01
145	196	78	0.203D+01	0.877D-01	0.140D+01	0.300D+00	0.443D+01
146	197	79	0.292D+01	0.114D+00	0.210D+01	0.200D+00	0.170D+02
147	198	80	0.417D+01	0.163D+00	0.460D+01	0.300D+00	0.206D+01
148	199	80	0.335D+01	0.131D+00	0.350D+01	0.600D+00	0.588D-01
149	200	80	0.270D+01	0.109D+00	0.360D+01	0.100D+01	0.814D+00
150	201	80	0.217D+01	0.932D-01	0.180D+01	0.300D+00	0.151D+01
151	203	81	0.249D+01	0.104D+00	0.420D+01	0.100D+01	0.291D+01
152	205	81	0.162D+01	0.788D-01	0.190D+01	0.200D+00	0.197D+01
153	206	82	0.231D+01	0.999D-01	0.200D+01	0.400D+00	0.608D+00
154	207	82	0.187D+01	0.866D-01	0.160D+01	0.300D+00	0.797D+00
155	208	82	0.151D+01	0.762D-01	0.100D+01	0.500D+00	0.103D+01
156	209	83	0.215D+01	0.961D-01	0.800D+00	0.200D+00	0.454D+02

REFERENCES

[1] LEVKOVSKIJ, V.N., Empirical laws in (n,p) reaction cross-sections for neutron energies of 14-15 MeV, Zh. Ehksp. Teor. Fiz. 45 N2 (1963) 305. [In Russian]

[2] KUMABE, I., FUKUDA, K., NEANDC(J), 65/V, 45 (1978).

[3] BYCHKOV, V.M., PASHCHENKO, A.B., PLYASKIN, V.I., Interpretation of the N-Z dependence of the (n,p) reaction cross-section at 14-15 MeV, Preprint FEhI-809, Obninsk (1978). [In Russian]

[4] FORREST, R. A., Systematics of Neutron-Induced Threshold Reactions with Charged Products at about 14.5 MeV, AERE-R 12149, Harwell Laboratory (1986).

[5] LU, W., FINK, R., Physical Review C4 (1971) 1173.

[6] TROFIMOV, Yu. N., Calculated characteristics of excitation functions for (n,p) reactions, Vopr. At. Nauki i Tekhniki. Ser. Yad. Konstanty 33 2 (1979) 47. [In Russian]

[7] LEVKOVSKIJ, V.N., Cross-sections for (n,p) and (n,α) reactions at neutron energies of 14-15 MeV, Yad. Fiz. 18 4 (1973) 705. [In Russian]

[8] CUZZOCREA, P., PERILLO, E., NOTARRIGO, S., Shell Effects in (n,p) and (n,α) Cross-Sections at About 14 MeV, Nuovo Cimento, 4A, 2, 251.

[9] EDER, G., WINKLER, G., HILLE, P., On (n,p) Cross-Sections for 14 MeV Neutrons. Z. Physik 253 (1972) 335.

[10] QAIM, S.M., Handbook of Spectroscopy, CRC Press Inc., Florida 1 (1981).

[11] BYCHKOV, V.M., MANOKHIN, V.N., PASHCHENKO, A.B., PLYASKIN, V.I., Cross-sections for (n,p), (n,α), and (n,2n) threshold reactions, Vopr. At. Nauki i Tekhniki. Ser. Yad. Konstanty 32 1 (1979) 27, 33 2 (1979) 51, 33 4 (1979) 21. [In Russian]

[12] CINDA-A (1935-1976) I, II (1979); CINDA-83 (1977-1983) - May 1983; CINDA-83 Supplement - November 1983; CINDA-84 (1982-1984) - May 1984; CINDA-87 (1984-1987) - May 1987; "An Index to the Literature on Microscopic Neutron Data", IAEA, Vienna, Austria.

[13] IKEDA, Y., KONNO, C., OISHI, K., ET AL., Activation Cross-Section Measurements for Fusion Reactor Structural Materials at Neutron Energy from 13.3 to 15.0 MeV Using FNS Facility. Report JAERI-1312, March 1988.

[14] IKEDA, Y., KONNO, C., NAKAMURA, ET AL., Systematic Measurement of Neutron Activation Cross-Sections at Energy Range from 13.3 to 15.0 MeV Using FNS Facility. Nuclear Data For Science and Technology (Proc. Intern. Conf., May 30-June 3, 1988, Mito, Japan) (1988) 257.

[15] KATON, T., KAWADE, K., YAMAMOTO, Measusrement of Activation Cross-Sections, Report JAERI-M 89-083 (1989).

[16] BYCHKOV, V.M., MANOKHIN, V.N., PASHCHENKO, A.B., PLYASKIN, V.I., Cross-sections for Threshold Reactions Produced by Neutrons, Ehnergoatomizdat, Moscow (1982). [In Russian]

[17] DEMIDENKO, E.Z., Linear and Non-linear Regression, Finansy i Statistika, Moscow (1981). [In Russian]

[18] DEMIDENKO, E.Z., Optimization and Regression, Nauka, Moscow (1989). [In Russian]

[19] SOKOLOV, S.N., SILIN, I. N., Calculation of functional minima using the linearization method, Preprint OIYaI D-810, Dubna (1961). [In Russian]

[20] AJVAZYAN, S.A., ENYUKOV, I.S., MESHALKIN, L.D., Applied Statistics. Study of Dependencies, Finansy i Statistika, Moscow (1985). [In Russian]

[21] BARD, J., Non-linear Evaluation of Parameters, Statistika, Moscow (1979). [In Russian]