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MEASUREMENT AND ANALYSIS OF FAST NEUTRON RADIATIVE CAPTURE CROSS SECTIONS

Translation of Three Selected Papers
Presented at the Fourth USSR Conference on Neutron Physics
held in Kiev, 18-22 April 1977

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FAST NEUTRON RADIATIVE CAPTURE CROSS-SECTIONS AND MEAN RESONANCE PARAMETERS FOR EVEN-EVEN ISOTOPES OF NEODYMIUM, SAMARIUM, GADOLINIUM AND ERBIUM

V.N. Kononov, B.D. Yurlov, E.D. Poletaev, V.M. Timokhov
(Institute of Physics and Power Engineering of the
USSR State Committee on the Utilization of Atomic Energy)

ABSTRACT

The authors measured neutron radiative capture cross-sections in the energy range 5-350 keV for even-even isotopes of the rare earth elements by recording the prompt capture gamma rays and applying the time-of-flight technique in a pulsed Van de Graaff accelerator. The average capture cross-sections obtained were analysed in terms of the statistical theory of nuclear reactions and the s, p and d wave neutron and radiative strength functions were derived.

The study of the interaction between neutrons and rare earth element nuclei is interesting from the point of view of the effect of nuclear deformation on the behaviour of neutron strength functions and nuclear level density, but it is also of practical interest in obtaining nuclear data for fission fragments. In the reaction involving radiative capture of fast neutrons by even-even nuclei one observes a characteristic feature - at a neutron energy greater than that of the first level of the target nucleus 2^+, the capture cross-section exhibits a clear-cut dip due to competition from the opening channel of the inelastic scattering reaction. This fact is a reliable basis for extracting information about the d wave neutron strength function, since according to the laws governing conservation of momentum and parity, the dip is caused by exclusion, first and foremost, of d neutrons from the capture reactions [1].

We measured and analysed neutron radiative capture cross-sections for $^{142, 144, 146, 148, 150}$Nd, $^{144, 148, 150, 152, 154}$Sm, $^{156, 158, 160}$Gd, and $^{166, 168, 170}$Er over the 5-350 keV energy range. The measurements were made with samples of separated isotopes (0.5-1.5×10^{-2} atom/barn in thickness). The enrichment for the isotope studied was not less than 95%. The energy dependence of the radiative capture cross-sections was measured with respect to the cross-section for the $^{10}B(n, \alpha\gamma)^{7}Li$ reaction, and normalization was based on the use of the capture cross-section for gold - 596 mb at a neutron energy of 30 keV. A description of the experiment and also of the method for analysis of the averaged capture cross-sections in terms of the statistical theory of nuclear reactions is given in Ref. [2].

The experimental data obtained for radiative capture cross-sections, together with the results obtained by other authors [3] and our own theoretical calculations based on the statistical theory, are shown in Figs 1-4.

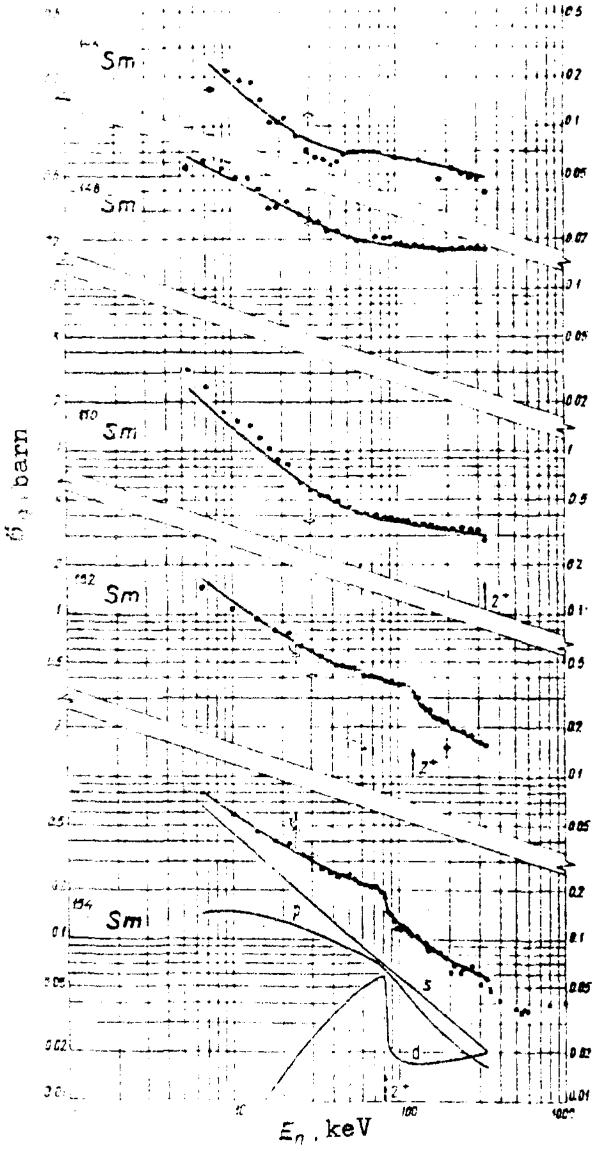
The total error for the measured cross-sections is (20-15)% for the light isotopes (^{142}, ^{144}Nd, ^{144}Sm), depending on the neutron energy, and is approximately the same for the remainder: (12-9)%. For a statistical analysis based on the maximum probability method, the description of the errors in the experimental data as a whole was made, as in the case of Ref. [2], with a covariance matrix.

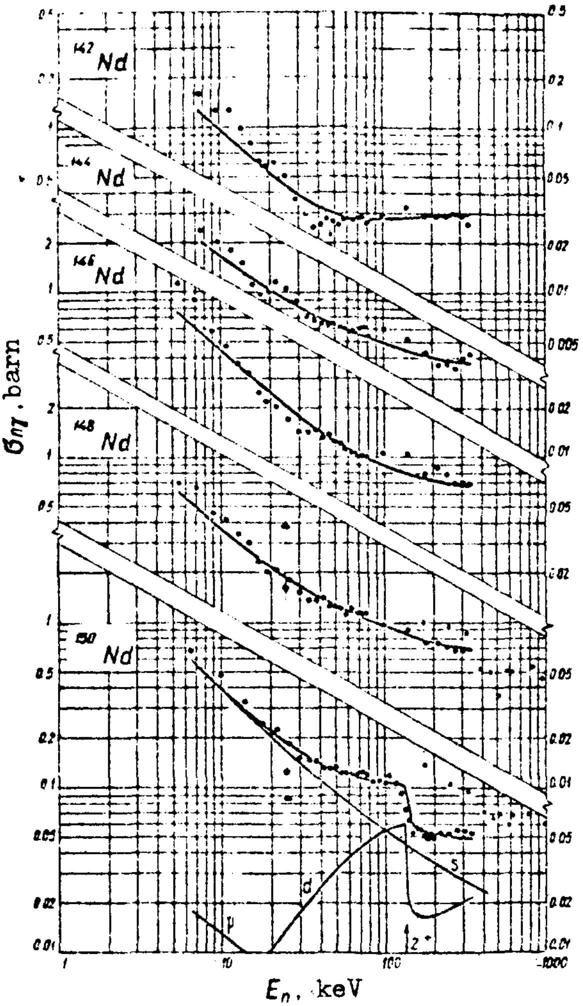
Experimental cross-section data over a broad neutron energy range were obtained for the first time in the case of most of the nuclei studied. The not very numerous data obtained by other investigators were measured in most cases by the activation technique and in a number of instances are not in good agreement with each other nor do they tally with our own results. This might be due to the difficulty of carrying out activation measurements involving long half-lives and the need to renormalize some of the results (for example, those of Rao and Johnsrud) to the present values of the reference capture cross-sections in the thermal region.

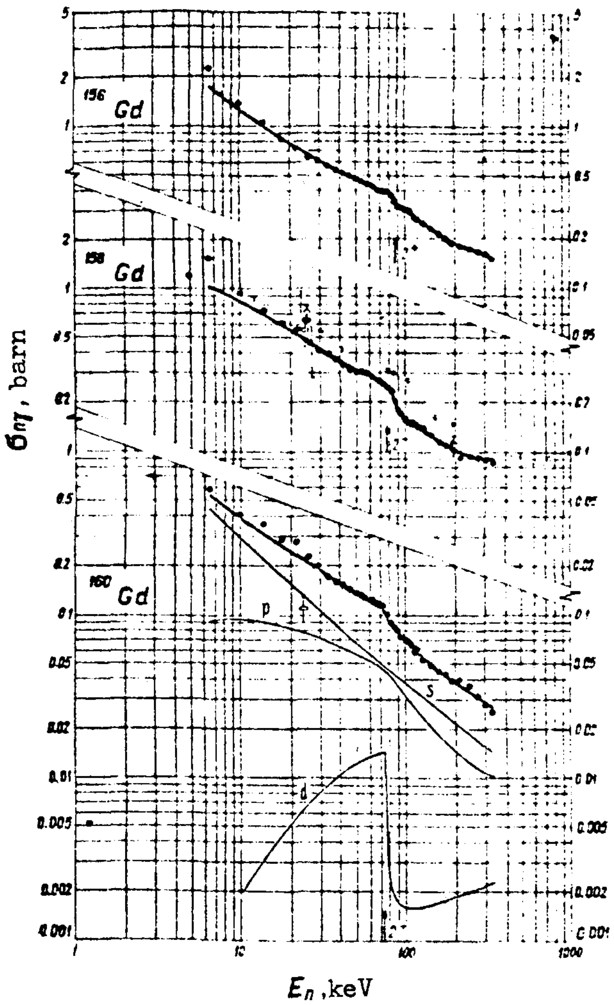
The feature noted earlier [1] of energy dependence of cross-sections for neutron radiative capture by even-even nuclei as a result of competition with inelastic neutron scattering at the first excited level 2^+ is clearly seen in the present results as well. For such nuclei as ^{150}Nd, ^{154}Sm and ^{170}Er the sharp drop observed in the cross-section indicates a large contribution by the d wave and, therefore, a high anticipated value of S_2. In nuclei in which the first inelastic scattering level 2^+ lies beyond the energy range being studied (light neodymium and samarium isotopes), the capture cross-sections become non-decreasing as the neutron energy rises; this is also evidence of a large contribution by the d neutrons.

Analysis of the cross-sections in terms of the statistical theory provides us with optimal values (optimal in the sense of the best description for the experimental data) for the neutron S_ℓ and radiative $S_{\gamma\ell} = (\bar{\Gamma}_\gamma/\bar{D}_0)_\ell$ strength functions for s, p and d neutrons. The optimum parameters are shown in the table and the theoretical radiative capture cross-sections calculated on the basis thereof are given in Figs 1-4. As in Ref. [2], the study of the parameters was based on the assumption of a possible dependence of the radiative strength function on ℓ, while S_0 was taken as equal to the resonance value [4].

The values of the neutron strength function S_2 for the nuclei investigated have been determined for the first time. Our results for S_2 do not run counter to the existing experimental data or predictions of the optical model. The radiative strength function $S_{\gamma 0}$ obtained is considerably greater than the resonance value and, apart from this, the values of $S_{\gamma\ell}$ for s, p and d neutrons were found to differ greatly.







<u>Figs 1-3</u>. Radiative capture cross-sections for even-even isotopes of samarium, neodymium and gadolinium: ● our results; — calculation based on optimum parameters in the table; ▬ Rao; ⬮ Johnsrud; ◊ ⬭ Macklin; ♦ Hasan; ▭ Chaubey; ◆ Lyon. The data obtained by these authors are taken from Refs [3, 4].

Table

Nucleus	S_0	S_1	S_2	$S_{\gamma 0}$	$S_{\gamma 1}$	$S_{\gamma 2}$
^{142}Nd	I.4	0.I0±0,05	0,60±0,12	I,2±0,3	0,I0±0,04	0,8±0,I5
^{144}Nd	3,9	0,50±0,I0	1,3±0,2	I,3±0,2	0,45±0,I2	0,43±0,05
^{146}Nd	2,3	0.II±0,03	I,25±0,27	6,5±I,5	I,I7±0,05	0,75±0,I2
^{148}Nd	3,0	0,08±0,02	0,98±0.20	4,9±0,6	4,8±I,8	0,4±0,I
^{150}Nd	3,2	0,80±0,25	2,8±0,5	5,5±0,6	0,I0±0,03	1,5±0,2
^{144}Sm	3,2±I,4	< 0,I0	2,53±0,44	2,4±0,4	2,5±0,5	0,9±0,2
^{148}Sm	3,8±I,I	I,9I±0,46	5,50±0,46	5,4±I,0	3,4±0,5	5,2±0,5
^{150}Sm	3.6	0,08±0,02	5,3±I,0	25±3	I9±6	4,5±0,7
^{152}Sm	2.7	0,55±0,08	3,5±0,6	I9±2	8,0±0,9	3,0±0,5
^{154}Sm	I,9	0,83±0,I5	4,6±0,7	7,2±0,8	I,7±0,3	I,3±0,2
^{156}Gd	I,8	0,55±0,I0	2,6±0,4	23,2±2,5	5,8±I,2	4,5±0,7
^{158}Gd	I,5	4,0±0,6	I,9±0,3	5,6±0,9	3,3±0,6	4,5±0,5
^{160}Gd	2,4	0,50±0,08	I,3±0,2	4,4±0,4	I,3±0,2	0,3±0,2
^{166}Er	I,7	0,94±0,I6	4,65±0,72	7,5±2,0	6,0±0,8	5,0±0,5
^{168}Er	I.5	I,I8±0.20	2,98±0.48	8,6±I,0	2,8±0,3	2,4±0,3
^{170}Er	I.5	I,08±0.32	2,35±0,30	8,I±I,2	0,24±0,I	I,6±0,2

Table note: The strength functions are given in units of 10^{-4}.

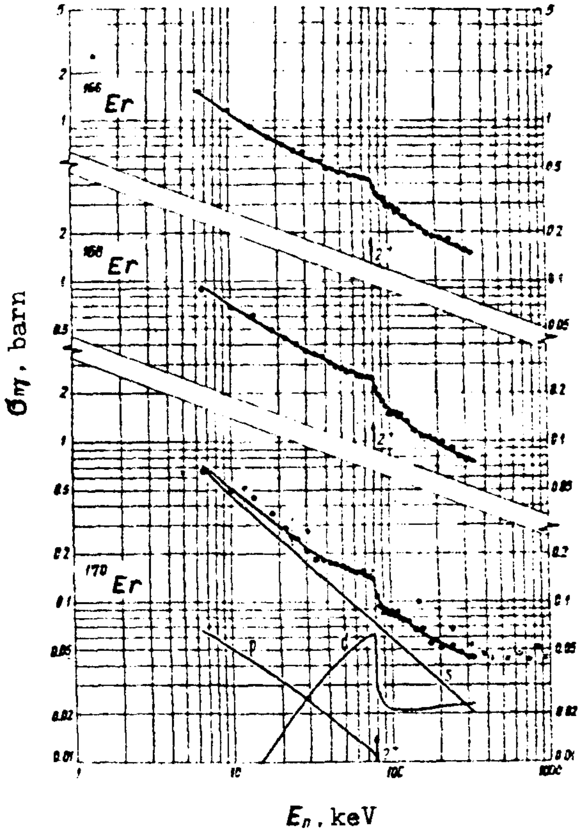


Fig. 4. Radiative capture cross-section for even–even isotopes of erbium:
● our results;
— calculation based on optimum parameters taken from the table; ◇ Macklin; Ⓘ Stupegia; ♦ Hasan. Data obtained by these investigations are taken from Ref. [3].

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ANALYSIS OF AVERAGE CROSS-SECTIONS FOR THE RADIATIVE CAPTURE OF FAST NEUTRONS BY NUCLEI OF In, Ta, Au AND ODD ISOTOPES OF Eu AND Sm

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ABSTRACT

The authors analyse experimental data on average cross-sections for the radiative capture of fast neutrons in the case of indium, tantalum, gold and odd isotopes of europium and samarium in terms of the statistical theory of nuclear reactions. From the analysis they obtain neutron and radiative strength functions for neutrons with orbital moments 0, 1 and 2.

We have measured [1, 2] the cross-sections for the radiative capture of fast neutrons over the energy range 5-350 keV for ^{115}In, ^{181}Ta, ^{197}Au, $_{62}$Sm, ^{147,149}Sm, $_{63}$Eu and ^{151,153}Eu by recording the prompt capture gamma rays and using the nanosecond time-of-flight technique in a pulsed electrostatic accelerator.

In this neutron energy region, the bulk of the radiative capture cross-section for intermediate and heavy nuclei is concentrated in the narrower resonances, which, however, cannot be resolved on account of Doppler broadening and the finite resolving power of the spectrometers. Hence the experimental results relate to cross-sections averaged over a large number of resonances that can be described in terms of the statistical theory of nuclear reactions by the mean values of the neutron resonance parameters:

$$\overline{\sigma_{n\gamma}}(E) = 2\pi^2\bar{\lambda}^2\sum_{\ell,J} g^J T_\gamma^{\ell J}\frac{T_n^{\ell J}}{T_\gamma^{\ell J}+T_n^{\ell J}+T_{in}^{\ell J}}F\left(\frac{T_\gamma}{T_n},\frac{T_{in}}{T_n}\right) \quad (1)$$

In this expression we use the conventional notation, while the penetration factors $T_{\gamma}^{\ell J}$ and $T_{n}^{\ell J}$ are related to the reduced neutron S_{ℓ} and radiative $S_{\gamma\ell}$ strength functions by the following expressions:

$$T_n^{\ell J} = \dot{\varepsilon}_{\ell\ell J}\, S_\ell\, v_\ell \sqrt{E}\left(1 + \frac{\pi}{2} S_\ell\, v_\ell \sqrt{E}\right)^{-2}$$

$$T_\gamma^{\ell J} = 2(2I+1)(2\ell+1)\, g^J S_{\gamma\ell}\, \xi(E)$$

The function $\xi(E)$ takes into account the energy dependence of the total radiative width, while the factor F does the same for the variations in neutron width in the elastic and inelastic scattering channels.

The problem of deriving strength functions from averaged capture cross-sections in the given neutron energy region can be reduced to breaking down the experimentally-measured cross-sections into three components corresponding to the contribution of the three partial waves and exhibiting different energy dependence. We analysed the experimental data by means of the maximum probability method, and to describe the errors in the experimental data we used the co-variance matrix V obtained by treatment of the experimental conditions and the various error components.

Optimum evaluation of the neutron and radiative strength functions $(\vec{P})$, i.e. optimum from the standpoint of the information contained in the experimental data, was made by minimizing the quadratic functional

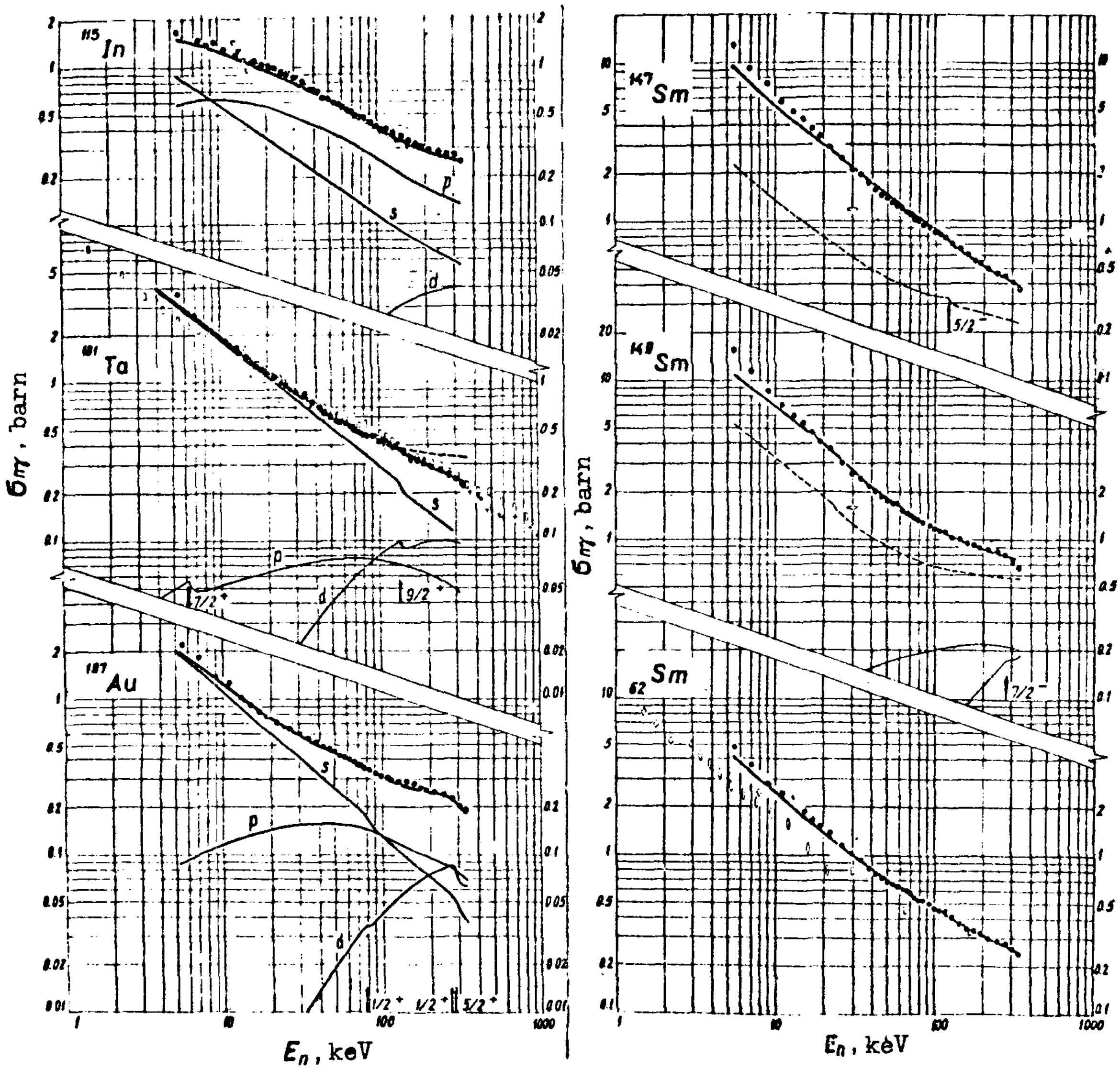
$$S^2 = [\vec{\sigma}_{\text{э}} - \vec{\sigma}_T]^T V^{-1} [\vec{\sigma}_{\text{э}} - \vec{\sigma}_T] + [\vec{P} - \vec{P}_0]^T W_0^{-1} [\vec{P} - \vec{P}_0]$$

while their error matrix was derived from the expression

$$W = [H^T V^{-1} H + W_0^{-1}]^{-1} \cdot \max\{1, \chi^2\}$$

In these expressions $\vec{P}_0$ and W_0 are the vector of the a priori parameter values and its co-variance matrix, H is the matrix of the sensitivity factors for the cross-section with respect to the parameters, σ_e and σ_t are the experimental and theoretical average capture cross-section as calculated from expression (1), and χ^2 is the test of goodness of fit.

We could have sought the parameters either on the normal assumption that the radiative strength function is independent of the orbital moment of the incident neutron or else without that assumption. The neutron strength function S_0 was not optimized for any nuclei, except ^{151}Eu, but was taken from the resonance region. The optimum neutron and radiative strength functions obtained from analysis of the average capture cross-sections on the assumption of a possible dependence of $S_{\gamma\ell}$ on ℓ, are shown in the table. Figures 1-3 show the experimental data obtained by us previously [1, 2], together with data taken from other authors [3], and the results of calculating the capture cross-sections in terms of the statistical theory from the optimum parameters given in the table. For tantalum we also give a calculation based on Kompe's parameters (- - - -) [4], while for the europium and samarium isotopes we show the results of the calculation at $S_{\gamma 0}$ from the resonance region, and also at a value of S_0 somewhat higher than the resonance value (-··-).



Figs 1 and 2. Neutron radiative capture cross-sections for indium, tantalum, gold, samarium and its odd isotopes: ● our results [1, 2]; —— as calculated from the optimum parameters in the table; ∇ Kompe; + Brzoska; O Fricke; □○ Macklin; ◇ Block; 0 Chou. The data taken from these authors are contained in Ref. [3].

Table

Nucleus	S_0	S_1	S_2	$S_{\gamma 0}$	$S_{\gamma 1}$	$S_{\gamma 2}$
$^{II5}\mathrm{In}$	0,26	4,35±0,65	I,I6±0,29	6,25±I,55	2,55±0,55	I,I±0,I5
$^{I47}\mathrm{Sm}$	4,35	0,I	I,29±0,28	43,8±7,4	I4,6±9,4	4,7±2,2
$^{I49}\mathrm{Sm}$	4,5	0,3±0,I	I,53±0,I8	65,4±3,2	35,6±30	20±II
$^{I5I}\mathrm{Eu}$	3,4±0,7	0,I	2,97±0,83	263,7±8	II7± 89	3I±II
$^{I53}\mathrm{Eu}$	2,5	0,202±0,I	5,35±I,I8	2I7 ±I4	28±24	II,3±2,7
$^{I8I}\mathrm{Ta}$	I,8	0,2±0,04	2,3±0,32	I3,6±0,8	5,3±I,5	3,I±0,5
$^{I97}\mathrm{Au}$	2,I	0,3±0,02	0,687±0,2	II,2±0,5	7,4±2,4	6,75±2,0

Note: The force functions are given in units of 10^{-4}.

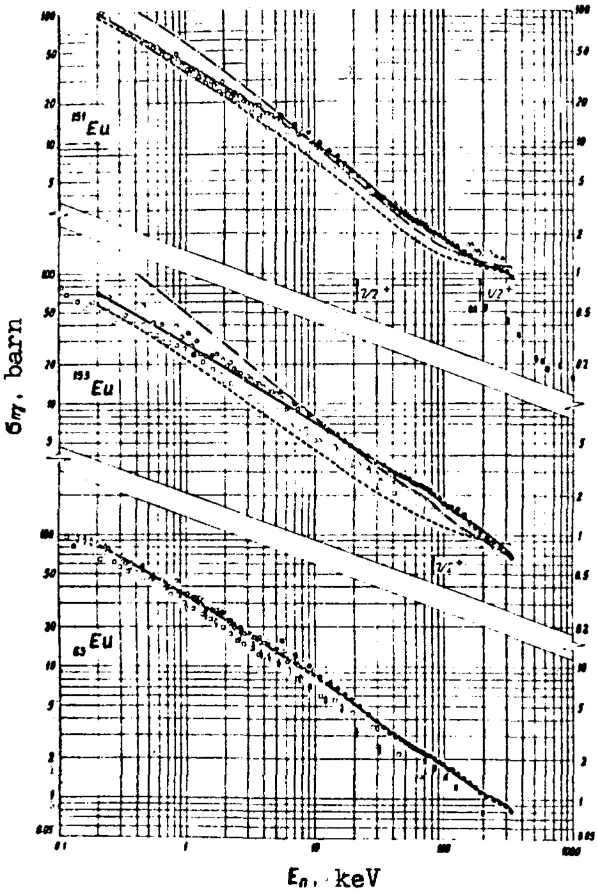


Fig. 3. Neutron radiative capture cross-sections for europium and its odd isotopes:
● our results [1, 2];
□ Konks; ⬨ Chou;
O Czirr; △ Hockenbury;
▯⬭ Macklin; ⬮ Johnsrud;
◊ Block. These data are taken from Ref. [3].

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p AND d WAVE NEUTRON STRENGTH FUNCTIONS FOR RARE EARTH NUCLEI

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USSR State Committee on the Utilization of Atomic Energy)

ABSTRACT

The authors obtained p and d wave neutron strength functions by analysis of average fast neutron radiative capture cross-sections for the isotopes $^{142, 144, 146, 148, 150}$Nd, $^{144, 147, 148, 149, 150, 152, 154}$Sm, $^{151, 153}$Eu, $^{156, 158, 160}$Gd and $^{166, 168, 170}$Er. The data are compared with results obtained by other authors, with calculations based on the optical model, and with computations based on the semi-microscopic approach.

The two usual sources of information for determining neutron strength functions are data for the region of isolated resonances, derived from experiments performed with a high energy resolution, and average neutron cross-section data for the keV neutron energy region.

Analysis of isolated resonances is a means of obtaining the strength functions directly, but it provides us with resonance parameters relating to interaction, mainly between s neutrons. The accuracy attainable in determining strength functions in the resonance region is rather low on account of a high degree of dispersion in the distribution of neutron widths and the distances between levels, and at best is only 15-20%. Moreover, the derived values of the p wave strength function depend to a large extent on correct identification of the resonances. The nature of these restrictions is such that we cannot hope for any great progress in the development of neutron resonance spectroscopy techniques.

In view of the fact that the averaged cross-sections in the keV region contain a contribution by a large number of neutron resonances, the statistical variations are usually small and analysis of the data for determining strength functions may provide functions of greater accuracy. Hence the main source for obtaining p and d wave strength functions is averaged total cross-sections (or transmission cross-sections) and average fast neutron radiative capture cross-sections.

The problem of deriving strength functions from the averaged neutron cross-sections can be reduced to breaking down the smooth cross-section curve into contributions by various processes and partial waves with different energy dependences calculated in terms of the statistical theory of nuclear reactions. Techniques based on the analysis of total and radiative capture cross-sections differ greatly as regards the possibility of deriving average resonance parameters and reliability of the results. The main difference is that for most of the intermediate and heavy nuclei in the keV energy region the elastic scattering of neutrons with orbital moment $\ell = 0$ (resonance and potential scattering) makes the principal contribution to the total cross-section. Hence analysis of the total cross-sections enables us to derive reliably only the strength function S_o and the potential scattering radius R'_o for s neutrons, while the result of our search for p and d wave strength functions depends greatly on the assumptions made with regard to S_o and R'_o when subtracting from the total cross-section the contributions made by resonance and potential scattering of the S wave.

At the same time, since barrier factors prevent the capture of p and d neutrons to a lesser extent than they hamper their scattering, and also in view of the fact that there is virtually no "potential" capture of neutrons, the contributions of s, p and d waves to the total radiative capture cross-section are intercomparable even for neutron energies of ~ 100 keV. Hence when analysing the average capture cross-sections we can hope for greater reliability and can accurately isolate the contributions of neutrons with orbital moment $\ell = 1.2$, and, in this way, determine the strength functions for p and d neutrons.

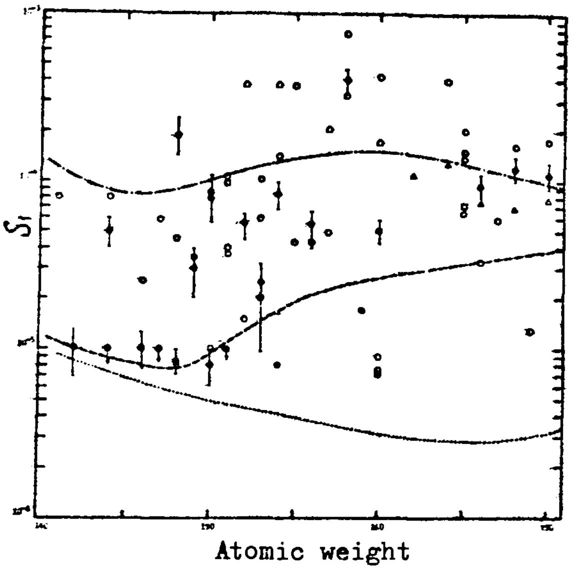
In this paper we consider p and d wave neutron strength functions which we derived from an analysis of averaged radiative capture cross-sections for the rare earth element isotopes: $^{142, 144, 146, 148, 150}$Nd, $^{144, 147-154}$Sm, $^{151, 153}$Eu, $^{156, 158, 160}$Gd and $^{166, 168, 170}$Er, together with indium, tantalum and gold isotopes, over the 5-350 keV neutron range [1]. The averaged neutron capture cross-sections were analysed in terms of the statistical theory of nuclear reactions on the basis of the maximum probability method and taking into account the correlation properties of the errors in the experimental data and derived parameters.

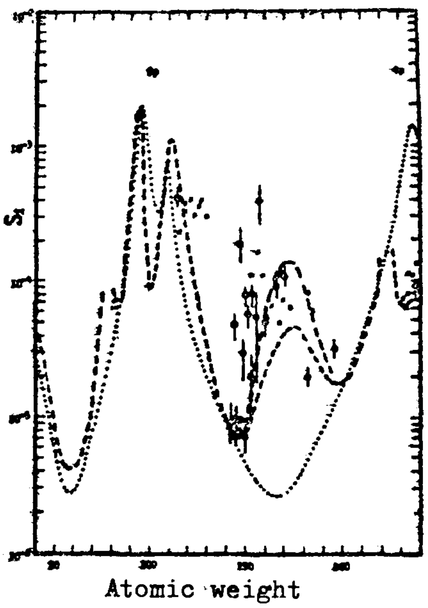
Rare earth nuclei are interesting from the standpoint of the behaviour of neutron strength functions in relation to atomic weight. In this region the 4S resonance lies in the s wave neutron strength function and, according to the predictions of the optical model, we can expect a deep minimum and 3d resonance in the force functions for p and d neutrons. If, however, there is a great deal of experimental data available for S_o, the results for S_1 and S_2 are considerably less reliable and detailed. The state of the experimental strength function data for p and d neutrons is shown in Figs 1-4 which, along with our results, also indicate those obtained by other authors and the results of theoretical calculations. It can be seen from Fig. 1 that the experimental data for p wave strength function in the region of nuclei under investigation lie in a broad band ranging from 0.07×10^{-4} to 7×10^{-4}, with a great deal of variation from one nucleus to another. However, closer scrutiny reveals that the results obtained by several authors seem to be unreliable. The reason for this is either the indefinite nature of the initial experimental values or the limitations of the procedure used to derive the strength functions from the data analysis (narrow range of neutron energies and only an approximate description of the cross-sections). The same can be said of most of the experimental data obtained earlier for the d wave neutron strength function. Our own results seem more valid for a number of reasons. First, they are derived from an analysis of capture cross-sections that have been measured over a broader neutron energy region and possess fairly high accuracy and reliability. Second, in the analysis based on the maximum probability method we determined both neutron S_ℓ and radiation $S_{\gamma\ell}$ strength functions at the same time, hence the mean resonance parameters obtained are consistent with one another. Third, by adopting a single approach we obtained systematic data for a large number of nuclei in the region of atomic weights under consideration.

Comparison of the experimental data for the p wave strength function for A = 140-170 with different theoretical calculations based on the optical model suggest the following conclusions: the calculations made at the RPI [2] from the spherical model give low values of S_1 for A = 155–170. This deep minimum is not confirmed by the bulk of the experimental data. Calculations based on the collective model (coupled channel method used at the RPI [2] and the Perey-Buck non-spherical potential [4]) provide a better description of the experimental data. The rather low minimum for A = 160–165 predicted by them is also in agreement with the experimental data. These conclusions are brought out all the more clearly by a comparison of our results with the RPI calculations based on the coupled channel method (Fig. 2).

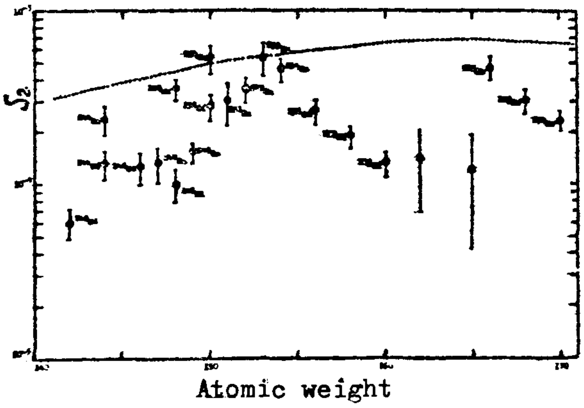
For the d wave neutron strength function the spherical optical model predicts a broad maximum at $A \sim 165$ [3]. Our values for S_2 confirm this result. Furthermore, our data show that the peak appearing in the dependence of S_2 on A in the region of $A \sim 165$ splits into two maxima lying in the region $A \simeq 153$ and A = 166. This behaviour on the part of $S_2(A)$ is similar to the well-known deformational split of the 4S resonance in the neutron wave function S_0 for $A \sim 160$.

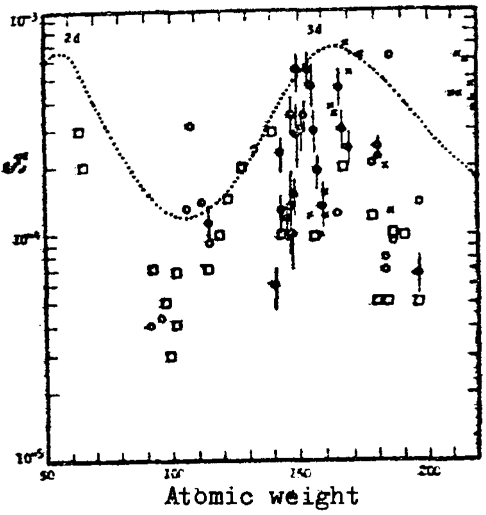
Over the last few years Solov'ev and co-workers have developed a semi-microscopic approach to describe the structure of the excited atomic nuclei state [5]. The neutron force functions S_1 and S_2 calculated in Ref. [6] on the basis of this approach are shown also in Figs 3 and 4. It should be pointed out that they agree satisfactorily with our own experimental data both for p and d wave neutron strength functions over a broad range of nuclei.





Figs 1 and 2. p-wave neutron strength function. Experimental data: ● our own data; △ data from analysis of isolated resonances; □ data from average total cross-sections or transmission sections; ○ data from average neutron capture cross-sections. Theoretical calculations: ••• spherical-optical model [2]; – – coupled channel method [2] for 100- and 300-keV neutrons; – • – • – non-spherical optical model of Perey and Buck [4]; X calculated by Solov'ev's semi-microscopic approach [6].





Figs 3 and 4. d-wave neutron strength function. Experimental results: ● our own data; ○ data from analysis of average neutron capture cross-sections; □ data from average total cross-sections. Theoretical calculations: ••• spherical optical model [3]; X calculations based on the semi-microscopic approach [6].

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