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ABSTRACT

With a view to establishing reasonable energy resolution and measurement accuracy requirements in respect of cross-sections for the radiative capture of neutrons by uranium-238 nuclei, an analysis was made of the requests contained in RENDA and elsewhere for these cross-sections in the energy range 1 eV - 15 MeV. The published results of experimental work are considered and their reliability and possible reasons for discrepancies analysed, particular attention being paid to the choice of reference cross-sections and to the calculation of the self-shielding effect. It is noted that the spread of σ_γ (^{238}U) values remaining after all renormalizations far exceeds the accuracy required by the users. The authors discuss methods of calculating cross-sections for capture in uranium-238 and present results. On the basis of selected experiments and calculations an evaluation is made of cross-sections for neutron capture by uranium-238 nuclei, the results being presented in the form of a smooth curve $\sigma_\gamma = \sigma_\gamma(E)$, recommended for use in various calculations. This curve is compared with similar curves obtained by other authors. The authors describe methods of obtaining group cross-sections and present new values of group cross-sections for neutron capture in uranium-238. These are compared with the cross-sections from the 26-group system of constants which used to be employed.

ACCURACY REQUIREMENTS FOR $\sigma_\gamma(^{238}U)$ VALUES FOR REACTOR CALCULATIONS

Together with the fission cross-sections and the α and $\bar{\nu}$ data for uranium-235 and plutonium-239, the cross-section for radiative neutron capture by uranium-238 nuclei is one of the most important nuclear data quantities that determine to a very large extent the development prospects of various types of nuclear reactor. The cross-sections for the capture of fast neutrons by uranium nuclei above 1 keV are of particular interest in view of the possibilities offered by breeding of nuclear fuel in fast breeder reactors. This explains why $\sigma_\gamma(^{238}U)$ data have attracted considerable attention both from reactor design specialists and from physicists concerned with the measurement, interpretation and calculation of neutron cross-sections. This interest is shown by the large number of requests in the latest issues of RENDA (1) for data on the ^{238}U neutron capture cross-sections. In view of the fact that it is very important to meet the requirements of reactor construction for neutron constants - indeed every effort should be made to do so - and that each attempt to define physical constants more precisely calls for considerable effort and extensive facilities, it is necessary to ensure the highest possible degree of objective judgement when estimating the true requirements for accuracy in the $\sigma_\gamma(^{238}U)$ values needed by present-day reactor design.

An examination of the requests contained in RENDA and in a number of other papers (2,3) shows that the views of various authors differ on this point (Fig. 1). The present situation is obviously due to the different approaches used to decide which are the most important reactor characteristics (i.e. critical mass, fuel element in-core-irradiation time, fuel conversion ratio and cost of the electrical power produced), how accurate the final result should be and which type of reactor is the subject of the analysis. Whatever the reason may be, the accuracy requirements with respect to the experimental data for $\sigma_\gamma(^{238}U)$ differ in the individual energy intervals by a factor of between 20 and 50, even inside the group of first priority requests alone.

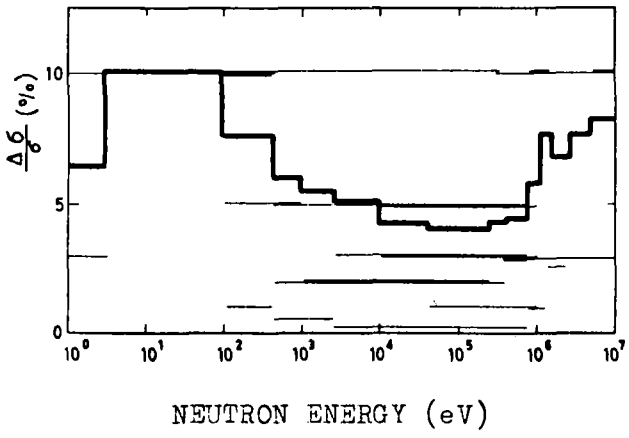


Fig. 1. Accuracy requests for the neutron capture cross-section of ^{238}U, for the purpose of reactor design.

It is quite obvious that it is unrealistic, and, perhaps, unreasonable, to ask experimenters to satisfy immediately the requirements for the highest accuracy requested by the designers. It is much wiser to try to establish an average set of requirements which will provide the experimenters with a few indicative figures that they should try to achieve as their principal aim. Since the authors of many requests do, in fact, indicate the priority with which their request should be met (priority P = 1 denotes the most urgent requirements), this type of average value can be determined by taking into account this priority, if one considers, for example, that the weighting of each request is inversely proportional to its priority. The average value of the accuracy required for each energy interval is then:

$$\langle \delta \rangle = \frac{\sum\left(\frac{\delta_i}{p_i}\right)}{\sum\left(\frac{1}{p_i}\right)}$$

where δ_i is the accuracy of $\sigma_\gamma(^{238}U)$ specified by the author of the i^{th} request, and p_i is the priority given to this request. The result of processing in this way the requests contained in papers (1-3) is shown in the form of a histogram in Fig. 1 (here, the detailed requests from paper (2) have been given a value $p_i = 1$, whereas, for the requests of (3), the values $p_i = 1$ and $p_i = 3$ denote a rougher and a more precise degree of accuracy respectively). An examination of Fig. 1 shows that

the greatest accuracy in measuring $\sigma_\gamma(^{238}U)$ is required in the 1 keV to 1 MeV energy range, where $\langle \delta \rangle$ is of the order of 4-5%. At higher and lower energies the accuracy requirements for $\sigma_\gamma(^{238}U)$ are less stringent, but in the range of thermal neutron energies the accuracy required is again of the order of 4-5%. It should be noted that if the δ values are averaged by other methods (for example, by the least-squares method) practically the same results are obtained. This factor, as well as the relative smoothness of the histogram obtained, points to the acceptability of the approach described above. We are therefore inclined to believe that the $\langle \delta \rangle$ values given in the histogram of Fig. 1 can be considered as the primary problem to be solved by the experimenters; achieving an accuracy which is roughly twice as good ($\langle \delta \rangle \cong 2\%$ for $E_n = 10^4$ eV) can be considered as the second stage, whilst a measurement accuracy better than 1% is a problem to be dealt with at a later date.

EXPERIMENTAL DATA FOR $\sigma_\gamma(^{238}U)$

Fig. 2 shows $\sigma_\gamma(^{238}U)$ values, reproduced, without modification, from different experimental papers. It is seen that at energies less than 10 keV a number of points were obtained by the activation method (10,34), but there are also measured data from a lead slowing-down-time spectrometer (5) together with averaged results of measurements obtained by the time-of-flight method in a linear accelerator (18) and in an underground nuclear explosion (57). In the 10-200 keV range, data are available in a very much larger number of papers. The substantial discrepancies between them seem to suggest the existence of certain systematic errors due, for example, to differences in the choice of the standard cross-sections. For energies of 0.2 - 1 MeV there are much fewer data, which is also probably the reason why there is an apparent decrease in the spread among individual points. Finally, for energies above 1 MeV the only results are those given in a few papers based on the activation method. The measurements in this range are considerably handicapped by the fission of uranium-238 nuclei, which necessitates taking special steps to prevent fission fragment activity from influencing the experimental results.

Generally speaking, Fig. 2 shows that the scatter observed in the data given by various authors is, on the average, $\pm$ 20% in the various energy ranges (and even higher at certain individual points). This exceeds by far the above-mentioned accuracy for the values of $\sigma_\gamma(^{238}U)$ which is needed for calculations.

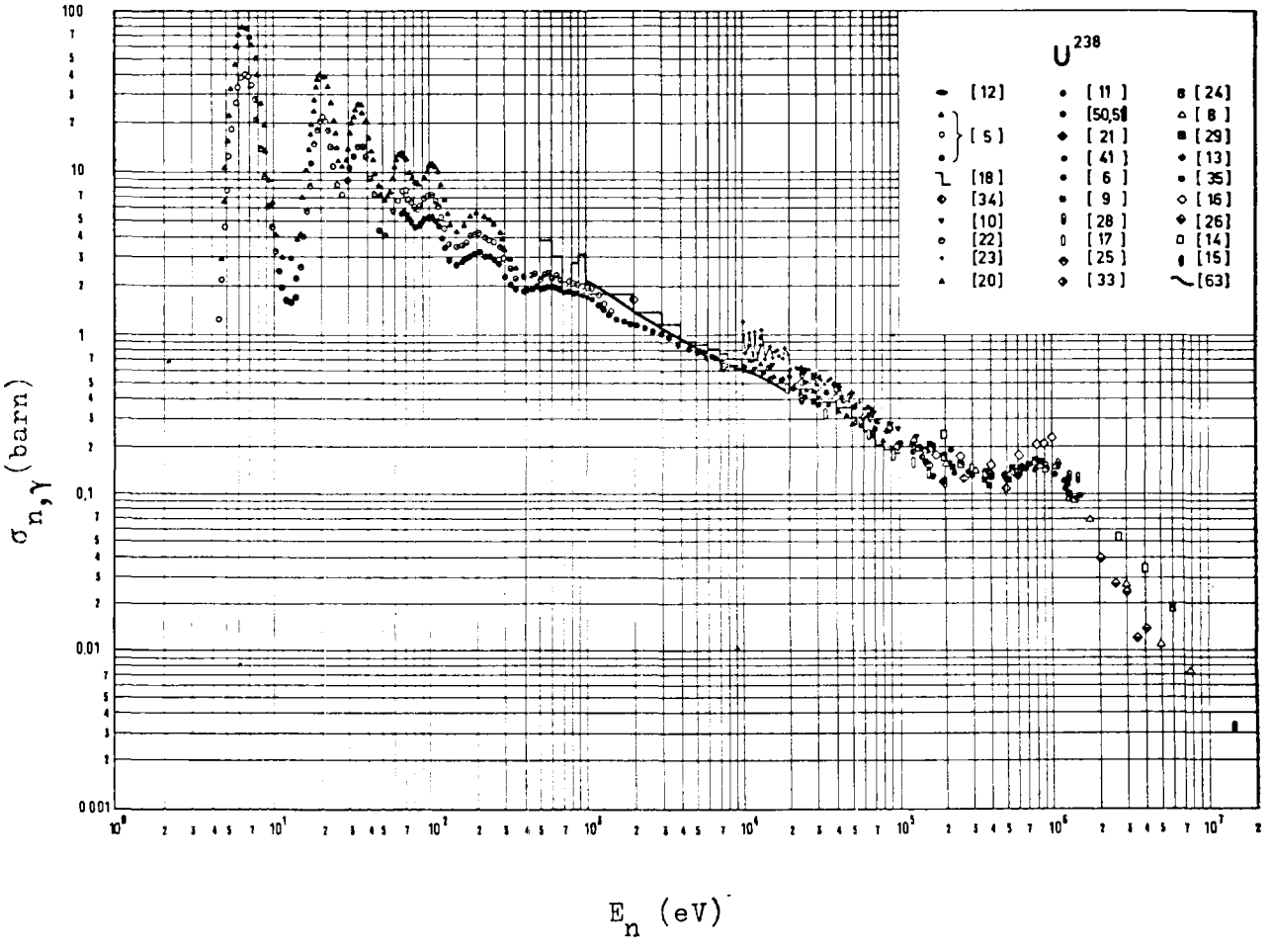


Fig. 2. Experimental data for the capture cross-section of uranium-238, as given in the quoted references.

TABLE 1. EXPERIMENTAL DATA FOR THE CAPTURE CROSS-SECTION OF ^{238}U, USED IN THE PRESENT PAPER.

Author	Year	Ref.	Results of an evaluation of the data when deriving the recommended values of $\sigma_\gamma(^{238}U)$ with indication of a selection criterion (see text)
Broda	1945	26	not used ("b")
Linenberger	1946	24	not used ("b")
Macklin	1957	12	used without modification
Kafalas	1958	28	not used ("b")
Perkin	1958	15	used without modification
Leipunsky et al.	1958	14	renormalized for E = 2.7 and 4 MeV to new values of $\sigma_\gamma(^{127}I)$, i.e. 32 and 14 mbarn respectively; the point at 0.2 MeV was not used because insufficiently correct account was taken of the correction for the "soft" group of $T(p,n)^3He$ neutrons.
Belanova	1958	51	not used ("a", see (7))
Hanna	1959	9	the renormalized data from (40) were used; the point at 29 keV was not used because the authors of the paper themselves said that it was not reliable.
Lyon	1959	13	used without modification, but the point at E_n = 195 keV was not taken into account ("c")
Belanova	1960	50	not used ("a", see (7))
Bilpuch	1960	10	renormalized to the value of $\sigma_\gamma(^{238}U)$ at E = 207keV in accordance with (8)
Diven	1960	16	not used ("c", see also (40))

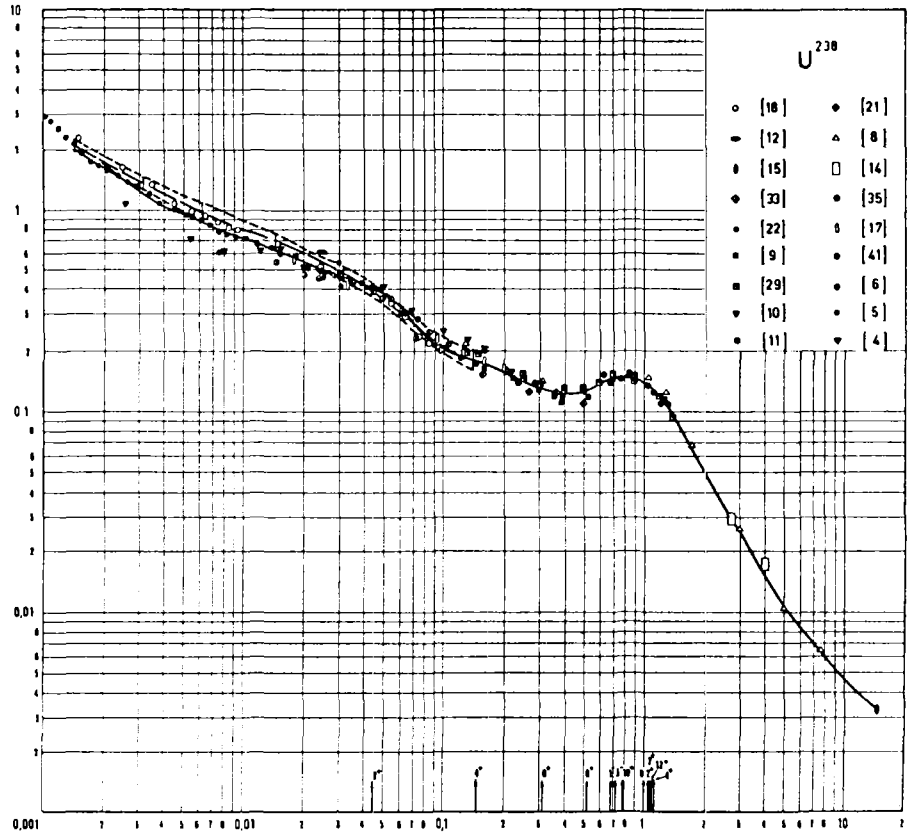
Neiler	1961	43	see (33)
Gibbons	1961	42	see (33)
De Saussure	1962	25	renormalized to the current values of α and σ_f for uranium-235 from (39)
Macklin	1963	33	used without modification
Weston	1963	49	not used ("b")
Tolstikov	1963	11	renormalized to a value of $\sigma_\gamma(^{238}U)$ = 495 mb at 24 keV (31). The points for E_n = 53; 158 and 171 keV were not used as they were clearly too low ("c").
Tolstikov	1963	35	renormalized to new values of $\sigma_f(^{238}U)$ (39)
Bergqvist	1963	17	renormalized to the value of $\sigma_\gamma(^{238}U)$ at E_n = 207 keV in accordance with (8) with extrapolation to an energy of 200 keV. The point at E_n = 300 keV was not used ("c").
Moxon	1963	20	not used ("a" see (18))
Belanova	1963	7	not used
Barry	1964	8	used without modification for $E_n \leq 1$ MeV; renormalized to the values of $\sigma_f(^{238}U)$ from (39) for $E_n > 1$ MeV.
Macklin	1964	33	not used ("b")
Belanova	1965	4	see (48)
Belanova	1966	48	the value of $\sigma_\gamma(^{238}U)$ from (31) was used, after correction for self-shielding.
Arai	1966	22	the values of σ_γ were used, after taking into account the self-shielding factors indicated by the authors.

Koroleva	1966	6	the σ_γ values corrected for the self-shielding effect in accordance with the results of (31) were used.
Kompe	1967	47	not used ("b")
Beckurts	1967	46	see (21)
Menlove	1968	21	used without modification
Moxon	1968	45	see (18)
Schuman	1968	44	not used ("a" see (34))
Moxon	1969	18	renormalized to a weighted mean value of $\sigma_\gamma(^{238}U)$ at 30 keV, of 468 mb, and corrected for self-shielding (see text).
Schuman	1969	34	not used, as data only preliminary.
Poenitz	1969	29	renormalized to values of $\sigma_f(^{238}U)$ and ^{239}Pu (39).
Panitkin	1970	41	used without modification
Bergman	1970	5	used with a factor of 1.098, to account for the revised normalization, and corrected for self-shielding (see text).

EVALUATION OF THE EXPERIMENTAL DATA FOR $\sigma_\gamma(^{238}U)$

To reduce the scatter observed in the results quoted in the various papers, a number of attempts have been made in the past to carry out a critical evaluation of the experimental data (36,19,27,30,37,38). The main requirements for any evaluation of this type are, as we know: (1) the selection of the most reliable measurements by analysing them carefully, (2) the recalculation of their results, taking into account the current values for the standard cross-sections, and (3) the plotting of smooth curves, on the basis of the selected and recalculated data, which may then be recommended for practical calculations. If the last-mentioned

operation can be formalized and done with a computer in a fairly objective manner, then, in the execution of the second and, in particular, the first operation the author's subjective interpretation will inevitably be revealed to a certain extent. It is not surprising, therefore, that there are fairly marked differences in the recommended curves evaluated by different authors (see Fig. 8): in the $\sim$10 keV energy range these departures from the average values are as much as 16%; in the 100 keV range, 13% and in the 550 keV range $\sim$ 5%. The marked discrepancies in the results of earlier evaluations of $\sigma_\gamma(^{238}U)$ prompted us to make a further attempt in this direction. The present paper gives the results of the second stage of this operation; the preliminary results have already been published (38).



$\delta_{n,\gamma}$ (barn)

E_n (MeV)

Fig. 3. Selected and renormalized data for the capture cross-section of uranium-238.

When selecting the experimental data, we followed the following general rules: (a) if it was known that several measurements of the same type had been carried out by the same authors using identical equipment, the results of only the latest work were used; (b) if any papers did not give certain experimental details which were essential for the analysis (values of the reference cross sections, correction methods, etc.) or, if they did, and this was not yet known to the authors of the present report (because the paper was not available), these papers were not used; (c) similarly, no use was made of works which contained obvious errors or which gave data that seriously departed from the results given in several other papers. Once the selection had been made, the data were, if necessary, renormalized to new values of the reference cross sections. The main results obtained at this stage of the work, for the energy range above 1 keV, are shown in Table 1, and the values obtained for the selected and renormalized cross-sections are given in Fig. 3.

PLOTTING AN AVERAGE CURVE FOR THE DEPENDENCE OF $\sigma_\gamma(^{238}U)$ ON NEUTRON ENERGIES HIGHER THAN 1 KEV

When the average curve was plotted, the energy range from 1 keV to 1.3 MeV was broken down into 23 unequal intervals, each of which contained closely-grouped points. Next, the average values of the energies and capture cross-sections were determined in each interval, and a "rough" curve was plotted by joining the adjacent average points for each interval with straight lines. After this, by taking into account the average slope of the curve $\sigma_\gamma = \sigma_\gamma(E)$ the individual capture cross-sections were modified from their original energies to the average energy value in the interval; averaging was again performed and the whole operation repeated once more. Usually, after three or four such operations the shape of the curve became stabilized, i.e. the average values of σ_γ obtained no longer varied. Then, on the basis of these energy averaged cross section values, the final values of the weighted mean of the average capture cross-section, together with its LMS error, for each of the energy intervals, was determined for each of the considered references.

For neutron energies above 1.3 MeV the average curve was plotted through the renormalized points given in papers (29), (8), (14) and (15).

EVALUATION OF THE AVERAGE RESONANCE PARAMETERS BY USING THE DATA FOR RESOLVED RESONANCES

The large number of resolved uranium-238 resonances gives reason to believe that a relatively reliable evaluation of the average resonance parameters can be obtained by averaging the parameters of the resolved resonances and calculating from these the cross-section characteristics for uranium-238.

The initial data used for the parameters of the resolved resonances were those recommended in BNL-325 (19), which are based mainly on the results of papers (52, 53), (54) and (55) supplemented by papers (56) and (57), which were not taken into account in the above list. The separation into s- and p-wave resonances was performed initially in accordance with the data given in paper (57).

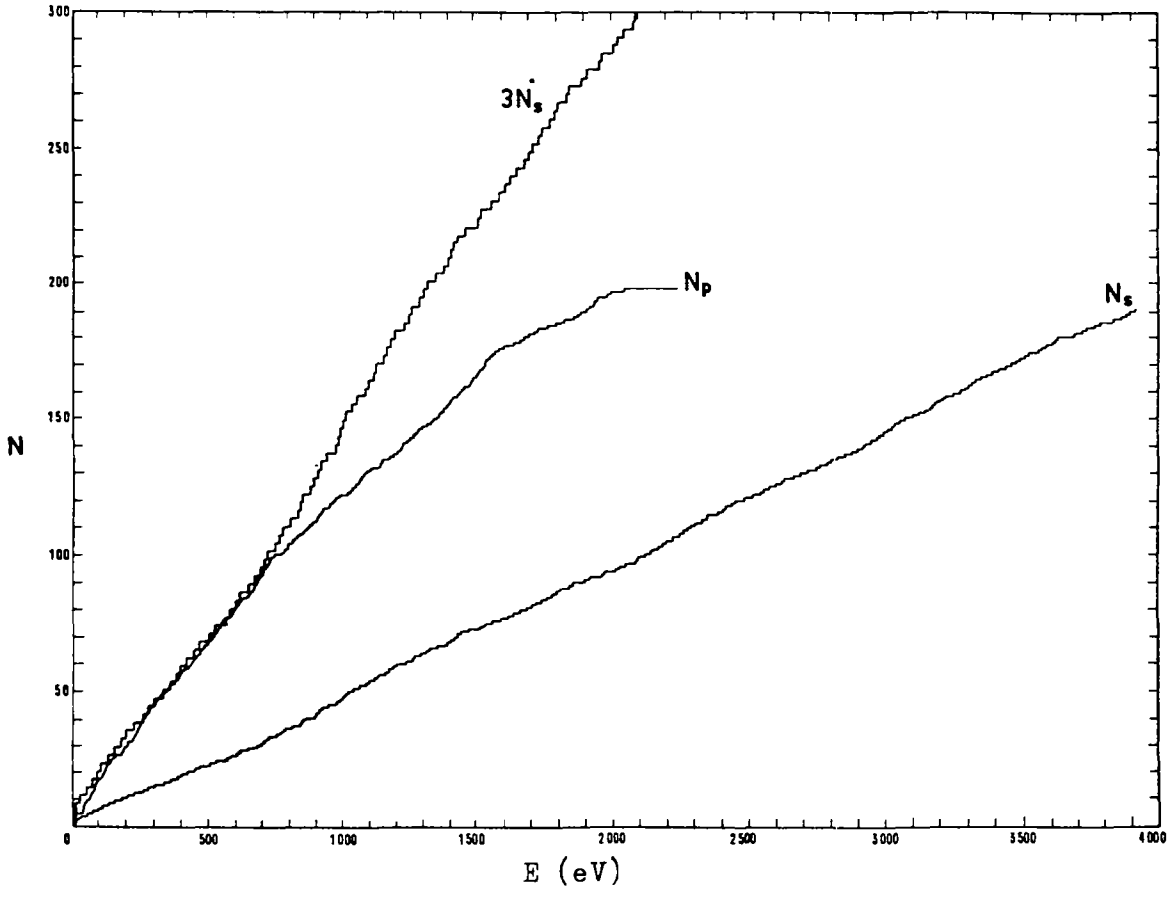


Fig. 4. Cumulative sums of numbers N(E) of s- and p-wave resonances having energies below a given value.

Fig. 4 gives the cumulative sums of numbers N(E) of s- and p-wave resonances having energies below a specified value. The linear nature of the $N_s(E)$ dependence suggests that all, or nearly all, s-wave resonances are resolved. Further proof may be obtained by comparing the observed distribution of the distances between the s-wave resonances D_i and the predicted Wigner distribution:

$$f_B(x) = \frac{\pi}{2} x e^{-\frac{\pi x^2}{4}} \qquad (1)$$

This comparison is shown in Fig. 5 (experimental histogram). It will be noticed that the number of large distances between the resonances is greater than that predicted. This discrepancy can be eliminated if it is assumed that the relatively wide resonances at 1363.4 eV, 1854.7 eV and 2051.1 eV, which in (57) were identified as p-levels, are in fact narrow s-wave resonances. Moreover, there are not enough short distances between the levels (0-0.2 $\bar{D}$) and too many intermediate distances ($\sim$0.7 $\bar{D}$). It should be pointed out that the distribution of the neutron widths quoted also displays similar systematic discrepancies (see Fig. 6): there appear to be fewer resonances with small reduced neutron widths ($< 0.016\bar{\Gamma}^{\circ}_n$) and more resonances with reduced neutron widths of $\sim 0.06\bar{\Gamma}^{\circ}_n$ than are predicted by the Porter-Thomas distribution. It is natural to assume that the reason for this discrepancy is the incorrect identification of very narrow s-wave resonances as p-wave resonances. It was found that the discrepancies in the distributions of the widths and the distances between the levels can be substantially reduced by replacing no more than five (out of 150) s-wave by p-wave-resonances. The resonances concerned were those at 721.8 eV, 779.1 eV, 909.6 eV, 1550 eV, 1797.7 eV, which were substituted by those at 729.9 eV, 787.4 eV, 918.2 eV, 1527.1 eV and 1803.5 eV respectively.

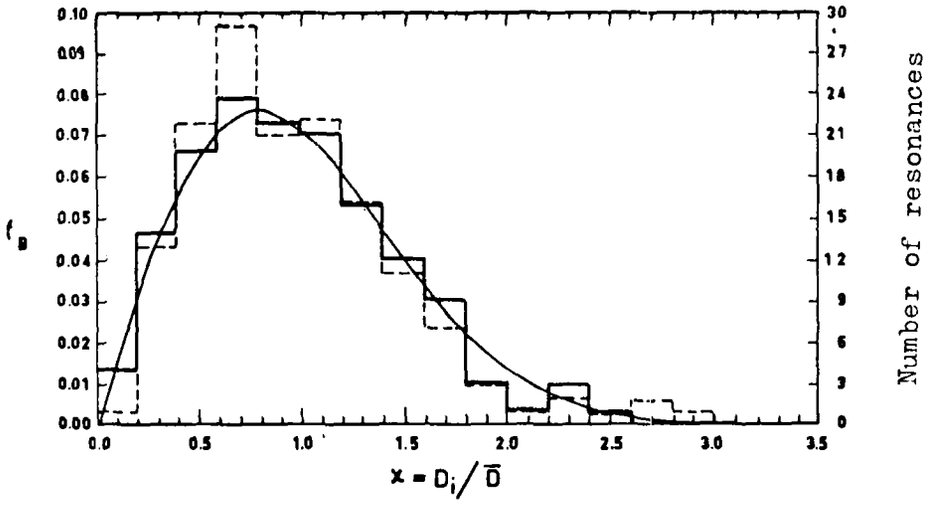


Fig. 5. Distribution of distances between the levels for the first 150 s-wave-resonances of uranium-238 (--- refers to the initial solution, —— refers to the final solution) compared with the Wigner distribution (shown by the curve).

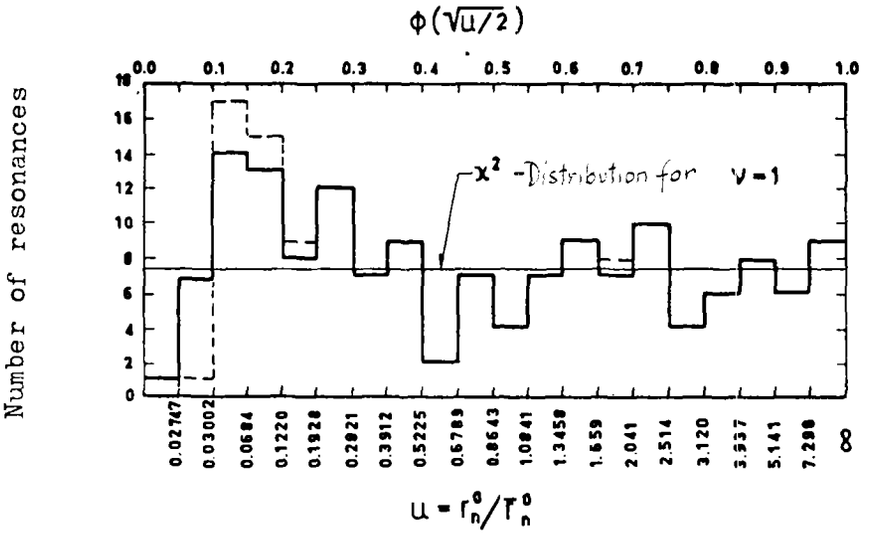


Fig. 6. Distribution of the "reduced" neutron widths of the first 150 s-wave resonances of uranium-238 (--- refers to the initial solution, —— refers to the final solution), compared with the Porter-Thomas distribution.

The D_i and Γ^{o}_{ni} distributions, which were modified to take account of all the changes, are represented in the form of continuous histograms in Figs. 5 and 6. All the data given in the remaining figures (including Fig. 4) relate to the modified system of resonances for uranium-238.

The mean distance between the s-wave resonances was determined in three ways:

(a) by simple averaging of the observed distances

$$\bar{D}_1 = \frac{\sum_{i=1}^{N_s} (E_{i+1} - E_i)}{N_s} \tag{2}$$

(b) from the slope of the $N_s(E)$ dependence; this was found by the least-squares method.

$$\bar{D}_2 = \frac{\sum_{i=1}^{N_s} E_i^2 - \frac{1}{N_s}\left(\sum_{i=1}^{N_s} E_i\right)^2}{\sum_{i=1}^{N_s} i E_i - \frac{N_s + 1}{2}\sum_{i=1}^{N_s} E_i} \tag{3}$$

(c) be recalculating from the root mean square distance

$$\bar{D}_3 = \sqrt{\frac{\pi}{4N_s}\sum_{i=1}^{N_s} (E_{i+1} - E_i)^2} \tag{4}$$

where N_s is the number of resonances considered.

The dispersion in the evaluated value D_1, which is due to the limited number of distances considered, is $\overline{D_1}^2/10\ N_s$ (58). A similar dispersion for $\bar{D}_2$ was estimated by using the sum of the squares of the differences between the observed dependence $N_s(E)$ and the best linear dependence $(\alpha + E_i/D_2)$

$$\delta^2(\bar{D}_2) = \frac{S\min}{(N_s - 1)} \cdot \frac{\bar{D}_2^2}{N_s \sum_{i=1}^{N_s} E_i^2 - \left(\sum_{i=1}^{N_s} E_i\right)^2} \tag{5}$$

where:

$$S_{min} = \sum_{i=1}^{N_s} \left[(i + \frac{1}{2}) - \left(a + \frac{E_i}{D_2} \right) \right]^2 \qquad (6)$$

To the above dispersion were added the dispersion in the number N_s of levels considered, which were due to an uncertainty in identifying the s-wave resonances. According to our own evaluations, this uncertainty amounts to about five resonances. The evaluated value $\bar{D}_3$, which is more sensitive to the omission of resonances than in the previous evaluations (58), was used to cross-check the assumption that the omission of s-wave resonances was not substantial.

Calculations showed that, when several tens of resonances (30 - 50) were considered, the evaluated values of $\bar{D}_1$ and $\bar{D}_2$ differ still significantly, but for $\gtrsim 100$ resonances they practically coincide. $\bar{D}$ does not depend on the number of resonances considered for N_s up to values ~ 150. When a large number of levels is taken into account the value of $\bar{D}$ is observed to decrease, which may be due to the fact that at energies higher than 3 keV part of the wide p-wave resonances were wrongly identified as s-levels. For the evaluation, therefore, we confined our examination to 150 s-wave resonances ($E < 3100$ eV): $\bar{D}_1 = 20.6 \pm 0.8$ eV; $\bar{D}_2 = 20.6 \pm 0.8$ eV; $\bar{D}_3 = 20.5$ eV. The fact that $\bar{D}_3$ is not greater than $\bar{D}_2$ and $\bar{D}_1$ confirms that the omission of s-wave resonances is not significant.

As far as p-resonances are concerned, it will be seen from Fig. 4 that the omission of levels becomes apparent at ~ 0.8 keV, if not before. Account was taken of the omitted resonances by means of a technique developed in reference (60) for the case in which the energy dependence was known and was of the form $\delta(E) \sim aE^b$. As we had insufficient information about the resolution of the experiments which had provided the results we were using, we determined the resolution parameters by means of a selection procedure. For this purpose, the dependence $N_p(E)$ was approximated by the form

$$N_p(E) \simeq \frac{E}{D_p} [1 + AE^b + BE^{2b}] \qquad (7)$$

in which the $\bar{D}_p$ parameters are the average distance between the p-wave resonances, and A, B and b were determined by the least-squares method. When up to 200 p-wave resonances were included in the analysis, $\bar{D}_p$, which amounted to 6.7 eV, proved to be only slightly dependent on their number. The error in $\bar{D}_p$ was estimated to be 0.3 eV.

The ratio $\bar{D}_s/3\bar{D}_p = 1.02 \pm 0.06$. This confirms the assumption that the density of the levels with spin I is proportional to 2I + 1 (for small and closely-spaced I values). Later, we shall use this assumption as a starting point when calculating the cross-sections. Here, however, we shall use it to evaluate the possible error in the number of s-levels due to the uncertainty in identifying the observed resonances as s-levels. If we assume that $\bar{D}_s = 3\bar{D}_p$ and consider the evaluation obtained for $\bar{D}_p$ to be independent, we have:

$$\bar{D}_{1/2} = \frac{\bar{D}_s/\delta^2(\bar{D}_s) + 3\bar{D}_p/9\delta^2(\bar{D}_p)}{1/\delta^2(\bar{D}_s) + 1/9\delta^2(\bar{D}_p)} = 20{,}4\ eV \qquad (8)$$

with an error of

$$\delta(\overline{D_{1/2}}) = \left[1/\delta^2(\bar{D}_s) + 1/9\delta^2(\bar{D}_p)\right]^{-1/2} = 0{,}6\ eV \qquad (9)$$

Here, $\delta^2(\overline{D_{1/2}})$ is the dispersion of $\bar{D}_{1/2}$.

Evaluation of average reduced neutron widths and strength functions.

The distribution of the "reduced" neutron widths of the first 150 s-wave resonances is shown in Fig. 6 and compared with the Porter-Thomas distribution. Along the x-axis we have plotted the boundaries of the groups which divide the area under the χ^2-distribution with one degree of freedom into 20 equal parts. The straight line which passes through 7.5 (150 resonances ÷ 20) corresponds to a theoretical distribution. The histogram, represented in the form of continuous straight

lines, includes the above-mentioned modifications.

Since there is a satisfactory agreement between the observed and predicted distributions, $\overline{\Gamma_n^o}$ was evaluated as

$$\overline{\Gamma_n^0} = \frac{\sum_{i=1}^{N_s} \Gamma_{ni}^0}{N_s} \qquad (10)$$

This evaluation conforms to a χ^2-distribution with n degrees of freedom, which for large n is almost Gaussian, with a dispersion of $2\overline{\Gamma_n^{o2}}/N_s$. The result of the averaging is $\overline{\Gamma_n^o} = 1.86 \pm 0.20$ eV. Hence, by using the value found above for $\bar{D}_{1/2}$, we find for the s-wave strength function

$$S_0 = \frac{\overline{\Gamma_n^0}}{\bar{D}_{1/2}} = (0{,}91 \pm 0{,}11)\cdot 10^{-4} \qquad (11)$$

When evaluating the errors in $\overline{\Gamma_n^o}$ we did not take into account the possible omission or incorrect identification of the s-levels, since this error is smaller than that due to limited available values of Γ_{ni}^o.

The "reduced" neutron widths for the p-wave resonances were calculated using the formula:

$$g\Gamma_n^1 = g\Gamma_n E_0^{-3/2}(E_0 + 3\cdot 10^5) \qquad (12)$$

where E_o is the resonance energy in eV.

To calculate $\overline{\Gamma_n^1}$ - the average "reduced" neutron width - the first 100 p-wave resonances were used (up to an energy of 743 eV), since it may be assumed from an analysis of the distances between the p-wave levels that, on the average, only 10 p-wave levels are omitted in this energy region.

The p-wave strength function, calculated as

$$S_1 = \frac{\sum_{i=1}^{N_p} g\Gamma_{ni}^1}{N_p \cdot \bar{D}_{1/2}} \qquad (13)$$

for N_p = 100, gave a value of 2.2 x 10^{-4}. Taking into account the omission of 10 weak levels will not have any effect on $\sum_{i=1}^{N_p} g\,\Gamma_{n_i}^{l}$, but will give a lower value of S_l, owing to the increase of N_p in the denominator. If the omission of the levels is taken into account, $S_l = (2.0 \pm 0.3) \times 10^{-4}$, where the error is determined by the statistical uncertainty of the sum of the widths.

Unfortunately, the error thus obtained is insufficient for an evaluation of the reliability of the p-wave strength function. This is because the observed overall distribution of the "reduced" neutron widths of the two systems of p-wave resonances (with I = 1/2 and I = 3/2) differs considerably from the theoretical χ^2-distribution with a number of degrees of freedom ν = 3/2. A comparison of these distributions in Fig. 7 shows that, apart from the lack of resonances with small neutron widths, there is also a shortage of relatively broad levels (with $\Gamma_n^l \sim 6\,\overline{\Gamma}_n^l$). It proved impossible to eliminate this discrepancy by a reasonable transfer of part of the narrow s-wave resonances into the category of p-wave levels. The above discrepancy reduces the reliability of evaluating S_l by using the parameters of the resolved resonances. To make allowance for this, we increased the error of S_l by 25%, i.e. we took S_l as $(2.0 \pm 0.5) \times 10^{-4}$.

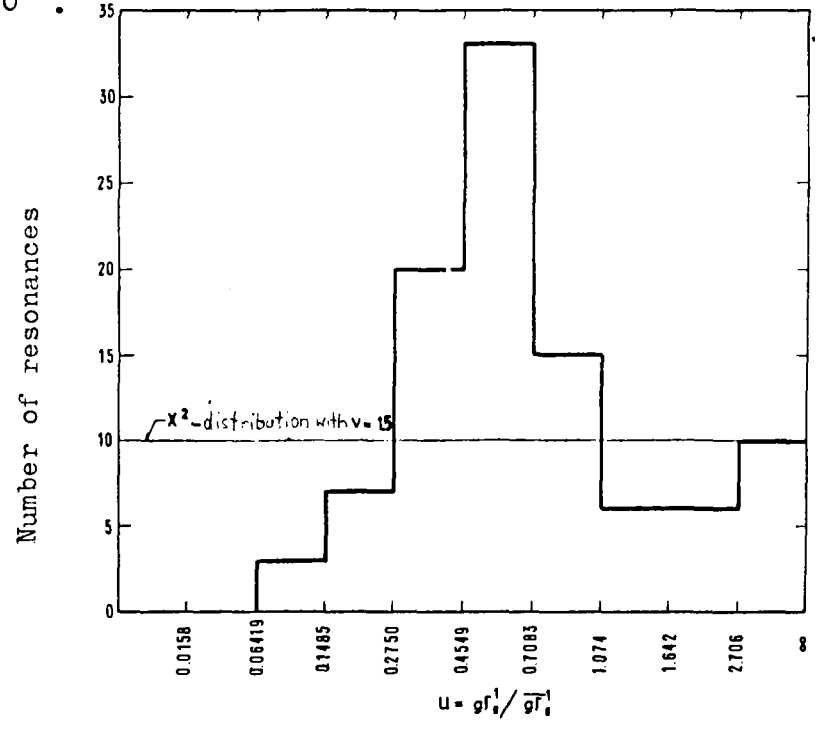


Fig. 7. Distribution of the "reduced" neutron widths for the first 100 p-wave resonances of uranium-238, compared with a χ^2 distribution with ν = 1.5.

Evaluation of the average capture width

Data are available for the radiative capture widths of 72 resonances of uranium-238; for 31 of these, the results are known from at least two papers. A comparison of the data given by various authors showed that the discrepancies between them very frequently exceeded by far the error which the authors themselves had indicated. Therefore these errors cannot be considered as a measure of the accuracy of these results, and they must not be used for calculating the statistical weightings for averaging. The obvious existence of systematic errors in the results given by various authors prevents us also from using, as a measure of the accuracy, the number of resonances for which the capture widths were determined in various papers. Consequently, we had no better alternative, when evaluating $\overline{\Gamma}_\gamma$, than simply to average the results obtained for this value in 7 papers produced after 1956.

TABLE 2. VALUES OF THE AVERAGE CAPTURE WIDTHS $\overline{\Gamma}_\gamma$, ACCORDING TO DATA SUPPLIED BY DIFFERENT AUTHORS

Bollinger (55)	24 ± 2
Rosen (54)	24,7
Moxon (45)	23,2
Firk (53)	$27,6 \pm 1,3$
Garg (52)	25
Asghar (56)	$23,7 \pm 1,1$
Glass (57)	$19,1 \pm 2$
average value	$\overline{\Gamma}_\gamma = 23,9 \pm 0.9$

The error in the average value of Γ_γ was evaluated from the root mean square spread of the data given by different authors. The largest deviation from this mean value is that found in the data presented by Glass (57). In addition to the low value of Γ_γ, the paper in question also contains considerable fluctuations in the capture widths, and these

have the characteristics of a kind of intermediate structure. It is difficult to explain the nature of these fluctuations. It is natural in this case where radiative capture represents a multi-channel process, to assume that Γ_γ fluctuates only slightly. Consequently, the fluctuations revealed in (57) should be considered as an instrumental effect which sharply lowers the reliability of the data. If the data of (57) are not taken into account when Γ_γ is averaged, we obtain $\bar{\Gamma}_\gamma = 24.7 \pm 0.7$ eV, i.e. if the data of Glass et al. are taken into account this affects both the value and accuracy of $\bar{\Gamma}_\gamma$. The value we finally chose was $\bar{\Gamma}_\gamma = 24.3 \pm 0.9$ eV.

CALCULATION OF THE RADIATIVE CAPTURE CROSS-SECTION FROM THE MEAN RESONANCE PARAMETERS

The URAN programme (62) was used when calculating the uranium-238 capture cross-sections from the evaluated resonance parameters $\bar{D}_{1/2} = 20.4 \pm 0.6$ eV; $S_o = (0.91 \pm 0.11)10^{-4}$; $S_1 = (2.0 \pm 0.5)10^{-4}$; $\bar{\Gamma}_\gamma = 24.3 \pm 0.9$ meV. The average cross-section (which corresponded to the case of infinite dilution or which took into account resonance self-shielding in the approximation of narrow resonances) was obtained at each corresponding energy point by averaging the detailed cross-section energy dependence in the region of twenty effective resonances. The parameters of these resonances were chosen so that the result of averaging would correctly allow for the fluctuations in the widths and distances (61). This quasi-random sequence of resonances displayed the following characteristics:

1. The distribution of the "reduced" neutron widths for twenty resonances enabled $\bar{\Gamma}^o_n$ to be preserved accurately; it enabled $(\bar{\Gamma}^o_n)^{1/2}$ to be preserved with an accuracy of up to 3%, $(\bar{\Gamma}^o_n)^{3/2}$ with an accuracy of up to 1.6% and $(\bar{\Gamma}^o_n)^2$ with an accuracy of 5.6%. The accuracy of the allowance made for fluctuations in the neutron widths when calculating radiative capture for the case of infinite dilution is better than 1% for any ratio of $\Gamma_\gamma / \bar{\Gamma}^o_n$.

2. The distribution of the distances between the resonances of the quasi-random sequence is described by the Wigner distribution with

an even better degree of accuracy than for the distribution of neutron widths, i.e. the Porter-Thomas distribution.

3. The sequence of resonance widths was chosen so that the relationships of the neutron widths of adjacent resonances satisfied the theoretical distribution obtained on the assumption that the fluctuations in the widths of adjacent resonances were not inter-dependent.

4. The sequence of distances between the resonances was chosen in such a way as to describe the theoretical distribution of the relationships of the widths and the distances between the levels (this distribution being obtained on the assumption that they were not inter-dependent).

The quasi-random series of resonances which we used is given in Table 3. By using it, fairly correct account can be taken of the distributions of the widths and distances between the levels in order to compute the average cross-sections by means of a programme for calculating the cross-sections based on known resonance parameters.

TABLE 3. QUASI-RANDOM SEQUENCE OF RESONANCES TO TAKE ACCOUNT OF FLUCTUATIONS IN THE WIDTHS AND DISTANCES BETWEEN LEVELS

i	$x = \frac{\Gamma_m^0}{\Gamma_n^0}$	$y = \frac{E_{i+1} - E_i}{D}$	i	$x = \frac{\Gamma_m^0}{\Gamma_n^0}$	$y = \frac{E_{i+1} - E_i}{D}$
1	0,00134	0,7728	11	0,5112	1,822
2	5,577	1,492	12	1,476	0,1694
3	3,203	1,282	13	0,1763	1,0436
4	0,04922	1,197	14	0,1241	0,3142
5	0,08217	0,7070	15	1,174	0,8400
6	0,6376	1,378	16	0,2392	0,5692
7	0,02502	0,4952	17	0,7881	0,9732
8	0,9704	1,628	18	0,4071	0,6404
9	0,3151	1,119	19	1,846	0,4110
10	0,00915	0,9060	20	2,368	2,240

It is of great importance, when calculating the cross-sections in the region of unresolved resonances, to take proper account of the contributions of the various systems of levels to the average cross-section, calculated with due allowance for resonance self-shielding. In the approximation of narrow resonances, the effective capture cross-section in a medium for a barn-per-atom dilution of absorber, σ_0, is:

$$\bar{\sigma}_c = \frac{\langle \sigma_c/(\sigma_t+\sigma_0)\rangle}{\langle 1/(\sigma_t+\sigma_0)\rangle} \tag{14}$$

where the angled brackets denote energy averaging in a certain lethargy interval Δu . The average values presented here may be expressed in the form of a transmission function

$$T(t) = \frac{1}{\Delta u}\int e^{-\sigma_t(E)t}\cdot\frac{dE}{E} \tag{15}$$

as follows:

$$\langle \sigma_c/(\sigma_t+\sigma_0)\rangle = \int_0^\infty T_c(t)\,e^{-\sigma_0 t}\cdot dt;\quad \langle 1/(\sigma_t+\sigma_0)\rangle = \int_0^\infty T(t)\,e^{-\sigma_0 t}\cdot dt \tag{16}$$

The energy dependence $\sigma_t(E)$ and $\sigma_c(E)$ represent the sum of the fluctuating functions of the energy dependences of the cross-sections for individual resonance systems, which differ in respect of spin and parity. If we take advantage of the independence of the positions and widths of the levels of the various systems, we have:

$$T(t) = \prod_{m=1}^{M} T_m(t);\quad T_c(t) = \sum_{m=1}^{M}\left[T_{cm}(t)\prod_{m\neq m'} T_{m'}(t)\right] \tag{17}$$

where T_{cm} and T_m are transmission functions calculated for the system m of resonances on the assumption of the absence of other systems: M is the total number of systems. The functions $T_{cm}(t)$ and $T_m(t)$ were calculated from the detailed energy dependence of the cross-sections in the region of the quasi-random sequence of 20 resonances, produced at each

energy for every system of levels. The significance of these functions was such as to enable calculation of the total transmission functions, and, from these, of the effective cross-sections, due account being taken of self-shielding. Averaging of these cross-sections over the group intervals gave for each group the average cross-sections and self-shielding factors shown in Table 5 (for a temperature of 300°K).

RECOMMENDED CROSS-SECTIONS

The results of the evaluation of the radiative capture cross-section in the energy range above 1 keV are given in Fig. 3.

As has already been stated, the continuous curve was obtained by averaging selected and renormalized experimental data for the cross-sections.

The accuracy of this evaluation reflects the dispersion of the data presented by various authors, and the error, in the 16 eV - 1.5 MeV energy range, is 5-8%. At higher energies, the errors increase to 20-30%, which agrees with the evaluation of the authors of the experimental works concerned.

The accuracy of the calculated curve (shown as the long-dashed curve in Fig. 3) was evaluated on the assumption that there was no interdependence between the errors of the average resonance parameters. The band of error is marked by the short-dashed curves.

As can be seen from Fig. 3, the results of the two independent evaluations are in agreement within the limits of the errors.

Table 4 gives the final recommended values for the capture cross-section of uranium-238 above 1 keV.

TABLE 4. RESULTS OF THE EVALUATION OF CROSS-SECTIONS FOR RADIATIVE NEUTRON CAPTURE BY ^{238}U NUCLEI.

Neutron energy (keV)	$\sigma_\gamma(^{238}U)$ (barn)	Neutron energy (MeV)	$\sigma_\gamma(^{238}U)$ (barn)
1.0	3.00	0.12	0.187
1.2	2.52	0.14	0.176
1.4	2.20	0.16	0.167
1.6	2.00	0.18	0.160
1.8	1.84	0.20	0.155
2.0	1.72	0.25	0.142
2.5	1.52	0.30	0.131
3.0	1.40	0.35	0.124
3.5	1.28	0.40	0.121
4.0	1.21	0.50	0.124
5.0	1.09	0.60	0.135
6.0	0.99	0.70	0.144
7.0	0.93	0.80	0.146
8.0	0.88	0.90	0.143
9.0	0.84	1.0	0.136
10	0.80	1.2	0.115
12	0.74	1.4	0.092
14	0.70	1.6	0.074
16	0.66	1.8	0.060
18	0.63	2.0	0.050
20	0.60	2.5	0.033
25	0.54	3.0	0.025
30	0.49	3.5	0.0185
35	0.46	4.0	0.0153
40	0.42	5.0	0.0110
50	0.375	6.0	0.0086
60	0.33	7.0	0.0070
70	0.277	8.0	0.0060
80	0.240	9.0	0.0052
90	0.215	10.0	0.0047
100	0.200	12	0.0038
		14	0.0033

In the energy region below 1 keV the capture cross-section was calculated from known parameters of resolved resonances. In the range of energies between 1 keV and 10-20 keV, in which substantial corrections were made to the experimental data to take account of self-shielding of the cross-sections in the sample, the continuous line shown in Fig. 3 is comparatively less reliable. Consequently, in this region the recommended data used were the results of a calculation based on the average parameters.

For energies above 30 keV the results of both evaluations coincide.

Table 5 gives the average radiative capture cross-sections for each group in the various intervals of the 26-group system of constants (32), together with their errors. It also gives the parameters for resonance self-shielding as determined in accordance with (32).

Fig. 8 compares the recommendations of this work with the evaluations made by other authors.

TABLE 5. AVERAGE GROUP CROSS-SECTIONS FOR RADIATIVE CAPTURE IN THE INTERVALS OF THE 26-GROUP SYSTEM OF CONSTANTS (32), TOGETHER WITH THEIR ERRORS. RESONANCE SELF-SHIELDING FACTORS.

	E_n	Δu	σ_c	$\Delta\sigma_c$	f_c when σ_0 is:				
					10^4	10^3	10^2	10	0
1	6,5 - 10,5 Мэв	0,48	0,007						
2	4,0 - 6,5 Мэв	0,48	0,012						
3	25 - 4,0 Мэв	0,48	0,024						
4	1,4 - 2,5 Мэв	0,57	0,06						
5	0,8 - 1,4 Мэв	0,57	0,13						
6	0,4 - 0,8 Мэв	0,69	0,13						
7	0,2 - 0,4 Мэв	0,69	0,14						
8	0,1 - 0,2 Мэв	0,77	0,18	,0,02	1,000	1,000	0,999	0,994	0,989
9	46,5 - 100 кэв	0,77	0,29	0,02	1,000	1,000	0,997	0,986	0,977
10	21,5 - 46,5 кэв	0,77	0,48	0,04	1,000	0,999	0,991	0,960	0,936
11	10,0 - 21,5 кэв	0,77	0,70	0,06	1,000	0,997	0,975	0,905	0,857
12	4,65 - 10,0 кэв	0,77	0,98	0,09	0,999	0,990	0,934	0,802	0,727
13	2,15 - 4,65 кэв	0,77	1,36	0,10	0,994	0,969	0,833	0,628	0,537
14	1,0 - 2,15 кэв	0,77	2,1	0,12	0,990	0,917	0,665	0,420	0,340
15	465 - 1000 эв	0,77	3,2	0,2	0,978	0,839	0,462	0,222	0,166
16	215 - 465 эв	0,77	4,4	0,2	0,961	0,745	0,343	0,150	0,112
17	100 - 215 эв	0,77	20	1	0,811	0,390	0,129	0,058	0,048
18	46,5 - 100 эв	0,77	17	2	0,800	0,373	0,124	0,055	0,044
19	21,5 - 46,5 эв	0,77	57	3	0,601	0,203	0,071	0,038	0,031
20	10,0 - 21,5 эв	0,77	83	5	0,677	0,230	0,061	0,025	0,019
21	4,65 - 10 эв	0,77	174	3	0,703	0,263	0,082	0,037	0,028
22	2,15 - 4,65 эв	0,77	0,68	0,02					
23	1,0 - 2,15 эв	0,77	0,48	0,01					
24	0,465 - 1,0 эв	0,77	0,52	0,01					
25	0,215 - 0,465 эв	0,77	0,76	0,01					
T	0,0252		2,73	0,04					

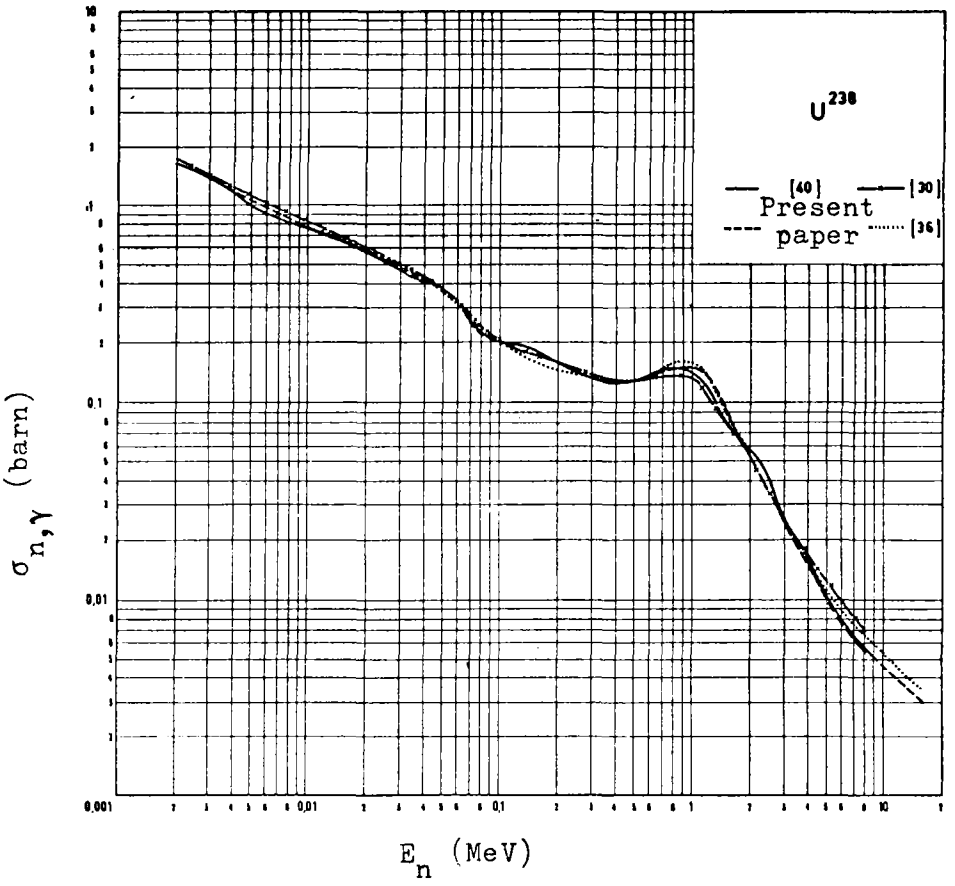


Fig. 8. Comparison of the results of the present paper with evaluations made by other authors.

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