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# RADIATIVE CAPTURE OF NEUTRONS BY THE $^{232}$THORIUM NUCLEUS IN THE ENERGY RANGE 0.01 - 15 MEV

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Translated from the Russian by W. Plotnikoff,
Australian Atomic Energy Commission
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# ABSTRACT

In this work, a critical examination of the experimental measurements of $\sigma(n,\gamma)Th^{232}$ for neutrons with energies above 10 keV, is made. In a number of cases the results of the measurements have been renormalised to values of the cross sections which are currently accepted as reference. A procedure for averaging cross sections is proposed which takes into account the form of the dependence of the cross section on energy. Based on the analysis of data from several authors, a recommended curve is given for the dependence of $\sigma(n,\gamma)Th^{232}$ on neutron energies in the interval 0.01-14.5 MeV. The numerical data used for renormalization and averaging is quoted in full. Also quoted is the recommended value of the radiative capture cross section of $Th^{232}$ for thermal neutrons.

## 1. RADIATIVE CAPTURE CROSS SECTIONS OF THERMAL NEUTRONS IN $^{232}$Th

Up to the present time (December 1969) ten reports have been published on the measurement of radiative capture cross section of $^{232}$Th nucleus for thermal neutrons; of these, four measurements used the activation method (2,3,4,6), four the cross section method (7,8,9,10) and two studies - other methods (11,12).

Where analysis of the measurements by the above authors have shown it to be necessary, the given data was renoralized; of the standard cross sections available, the recommended values from BNL-325, 2nd Ed. (1) were used. In those cases where errors are not quoted by the authors of the works on the standard cross sections, then errors in the recommended values of the standard cross section were taken into consideration in the normalized values of the measured cross sections.

All the reviewed data, together with the renormalized values, are contained in Table 1.

The atlas (1) contains the results of all these references (with the exception of the value of $\sigma_{n,\gamma}^{m}$ for the indium standard from reference (6)). The recommended value quoted is $\bar{\sigma}_{n,\gamma}^{m} = 7.4 \pm 0.1$ b. The authors also give one recommended value of the cross section for a Maxwellian spectrum, E = 0.0253 eV and a sub-cadmium spectrum, the facts suggesting that above the cadmium threshold, $\sigma_{n,\gamma}^{Th}$ obeys the 1/v law. However, a direct experiment (5) shows it to be otherwise.

We have investigated the given recommended value. The weighted mean value $\bar{\sigma}_{n,\gamma}^{m}$ of the results of 10 works (studies), referred to in (1) is 7.4 b. In addition, the root mean square error of the weighted mean before and after smoothing (13), were determined according to the formulae:

$$\Delta\sigma_{\text{mean weighted}} = \frac{1}{\sqrt{\sum_{i}^{n} p_i}} \; ; \quad p_i = \frac{1}{\sigma_i^2} \; ; \qquad \ldots(1)$$

$$\Delta\sigma^{*}_{\text{mean weighted}} = \sqrt{\frac{\sum_{i} p_i(\sigma_i - \sigma_{\text{mean weighted}})^2}{(n-1)\cdot\sum_{i}^{n} p_i}} \; . \qquad \ldots(2)$$

$\sigma_i$ = magnitude of cross section

$\Delta\sigma_i$ = root mean square error of given measurement

n = number of measurements

They turned out to be similar at $\Delta\sigma_\gamma = 0.06$ b and $\Delta\sigma_\gamma^* = 0.05$ b. Since $\Delta\sigma_\gamma > \Delta\sigma_\gamma^*$ it shows that their difference is fortuitous and that in the observed set of data, the systematic error depends less on the weighted mean than on the random errors.

Consequently, the systematic influence of the deviation of $\sigma_{n,\gamma}^{Th}$ from the 1/v law, on the value of $\sigma_{n,\gamma}^{m}$ may be ignored. As a result it should be pointed out that in (1) the error in the mean weighted value is high by almost a factor of two (0.1 barn instead of 0.06 barn) for no apparent reason.

For averaging we took all the more significant quoted values of $\sigma_{n,\gamma}^{m}$ with the exception of works(3,11,12) because they had insufficient data.

First of all, data from measurements of $\sigma_{n,\gamma}^{m}$ by activation and by absorption were examined in isolation. Accordingly the average values of the radiative capture cross sections obtained from measurements by different methods were $\sigma_{n,\gamma}^{m,\,\text{activation}} = 7.33 \pm 0.07$ barns and $\sigma_{n,\gamma}^{m,\,\text{absorption}} = 7.51 \pm 0.12$ barns. The difference obtained in the magnitudes of the cross sections point to the fact that in the methods employed there are unaccounted systematic errors. In the reactor oscillation method the sources of these errors could be: scattering of neutrons in the specimen during movement from one position to another, unaccounted deviation of the cross section from the 1/v law, the presence of resonant neutrons in the spectrum, etc. In the activation method a basic effect has turned out to be different $\beta$ emission detection efficiencies for the specimens, the spectrum of irradiating neutrons, deviation of the behaviour of the absorption cross section from the 1/v law.

On the other hand, a combined examination of these data shows that $\Delta\sigma_{\gamma} = 0.07$ b and $\Delta\sigma_{\gamma}^{\bigstar} = 0.05$ b and this, as well as the recommended value of $\bar{\sigma}_{n,\gamma}^{m}$ in (1), requires explanation. For the standards more than 8 values were obtained for the weighted mean value of radiative capture of thermal neutrons in $^{232}$Th:

$$\overline{\sigma_{n,\gamma}^{m}} = 7.37 \pm 0.07 \text{ b}$$

If one examines the whole set of available data, then the weighted mean value is similarly

$$\overline{\sigma_{n,\gamma}^{m}} = 7.39 \pm 0.06 \text{ b}$$

and hence $\Delta\sigma_{\gamma} = 0.05$ b and $\Delta\sigma_{\gamma}^{\bigstar} = 0.051$ b. These average values of the cross section differ by 0.3 per cent. Such a difference is unimportant in many applications. However in our opinion, the value (★) appears more reliable.

## 2. RADIATIVE CAPTURE CROSS SECTIONS OF NEUTRONS WITH ENERGIES 10 keV-14.5 MeV

In this evaluation, the results of 21 experiments on measurements of the radiative capture cross section in thorium for the indicated energy range were examined. Most of them, 14, were carried out by the activation method and were concentrated in the interval 100-1000 keV. For energies greater than 1 MeV there is virtually only one reliable measurement. The situation at energies less than 100 keV is little better where only 4 activation type measurements and 3 experiments using neutron capture gamma rays have been published. In addition, there are several experiments on capture cross section measurements spread over energies from 2 keV to 14.5 MeV.

We will not discuss each experiment in detail, however, before we start examining the aggregate of available results it is necessary to comment on some of them. In Tables 2 and 3 the unpublished results in references (14) and (15) taken from the corresponding graphs in references (15) and (16) are quoted. Since, relatively, practically nothing is known about these experiments, an arbitrary error of 15 per cent was attributed to them before averaging.

In Table 4 the absolute measurements from reference (21) are given. Two comments are made regarding these results. The magnitude of the cross section at $E_n$ = 100 keV is increased by the presence of groups of lower energy neutrons (3.3 keV), and hence in the course of correcting the results, the authors took a lower value of the cross section ($\sigma_{n,\gamma}$(3 keV) = 1 b). The magnitude of the cross section at neutron energies of 740, 990, 1,230 keV essentially lie below the results obtained by other authors. Taking into consideration the collective good agreement of the results in reference (21) with other measurements, the only reason for this might be a serious error in the measurements. These values of the cross section were omitted from the averages.

In Table 5 the results of corresponding measurements from reference (22) are presented, normalized to the radiative capture cross section for $^{238}$U at 600 keV, i.e. $\sigma_{n,\gamma}^{U_{238}}$ (600 keV) = 132 mb. These data do not require renormalization, but it is necessary to include the error of the reference cross section in the magnitude of the error (i.e. column 4 of Table 5).

Results of measurements of $\sigma_{n,\gamma}^{Th}$ relative to $\sigma_{n,\gamma}$ $^{127}$I from reference (23) are quoted in Table 6 (column 3). This table also quotes the capture cross sections for $^{127}$I taken from reference (38) and used in reference (23) (column 4) and used by us for renormalization (column 5). Since these values were taken from a curve drawn 'by eye', as noted by the authors, the error in the reference cross section was taken as 10 per cent. The error in the renormalized thorium cross section (column 6) includes errors due to experiment and errors in the reference cross section.

In Table 7, the results of thorium capture cross section measurements relative to the fission cross section of $^{235}U$ fission cross section (24) are given, as is the data for $^{235}U$ fission cross sections (26) used by the authors from reference (24) and used in this paper for renormalization. It is necessary to point out that on the whole, the results of reference (24) at energies greater than 200 keV, lie from 10-15 per cent higher than a significant number of other measurements.

In Table 8 the results from reference (27) are quoted, in which the radiative capture cross section of thorium was measured relative to the reaction cross section $B^{10}(n,\alpha)Li^{7}$ (assuming that the 1/v law holds to within 5 percent). Normalization is to $\sigma_{n,\gamma}^{Th}$ (24 keV) = 615 ± 25 mb (31). The indicated error is the total error.

In Table 9 the results from reference (28) are quoted. The measurements were made relative to the fission cross section of $^{235}U$. The authors of this reference do not show the source of their reference values, but this is evidently reference (25), from which the values in column 4 were also taken. Column 5 quotes $^{235}U$ cross sections which were used for renormalization (26). The renormalized thorium capture cross sections are given in column 6.

In Table 10 the results of measurements from several sources are quoted. The value of the cross section obtained in reference (18) must be increased if the previous results regarding the decay scheme of $^{233}Ra$ (19) are taken into consideration. Analysis of the preliminary results of measurement, published in (29) indicates that the measurements in this reference of the capture cross section at $E_n$ = 2 keV is obviously high, although data for estimating the discrepancy is not yet available. In column 4 of Table 10, the cross sections used for averaging are quoted.

In Table 11 are quoted the results of measurements by several authors who used the spherical shell transmission method. These results are quoted unchanged.

In tables 12-14 the results of 3 references are quoted on the measurement of radiative capture of thorium by the neutron capture gamma ray method. The whole of the numerical material was taken from graphs: from (33) for reference (34) and from (1) for references (35) and (36). Detailed information about these references is not available to us, however the results of (35) and (36) were used for averaging since in (35) and (36) the systematic errors have different signs and on averaging, in some cases, compensate each other.

## 3. AVERAGING EXPERIMENTAL DATA

Let us look at the total data available from the point of view of obtaining average values of radiative capture cross sections for $^{232}$Th in the whole energy range.

There are 11 references in which the cross section was measured over a wide energy interval, and 10 references on measurements of $^{232}$Th capture cross sections at various energies. The results of all these references are quoted in figure 2 and in tables 2-14. However, not all of those specified points are of equal value. Almost nothing is known about some of them, and therefore it is not desirable to use these results for averaging.

Taking into consideration what was said above, the averaging procedure was carried out twice. The first time only the more or less reliable data was used; the second average using all the available results (with few omissions). Recommended values of the cross section were chosen on the basis of an analysis of the results of both procedures.

### (a) Averaging of reliable results

Results were considered reliable if they were fully documented in published works and agreed well with the bulk of the measurements. Apart from that, it was required that a renormalisation should be possible to comparative measurements of the corresponding reference cross sections.

These requirements are fulfilled by the following references: measurements in a broad energy interval (21, 22, 23, 24, 27, 28); measurements at individual energies (18, 30, 31, 32) (e.g. figure 2a).

Several points were omitted before averaging since they lie outside the bulk of the data and they are indicated in the first column of the relevant tables by ★ or ★★.

The totality of points from the given references were divided into 15 groups, whereupon the energy intervals were located by the groupings in available measurements, and the interval width - by the energy scatter of measurements from which the cross sections are derived.

The mean weighted cross sections were calculated by

$$\sigma_{\text{mean weighted}} = \frac{\sum_i p_i \sigma_i}{\sum_i p_i} \qquad \ldots(3)$$

$$p_i = \frac{1}{\Delta \sigma_i^2} \qquad \ldots(4)$$

where $\sigma_i$ - magnitude of cross section;

$\Delta\sigma_i$ - root mean square error of an individual measurement

The error of the weighted mean value was calculated by the formula

$$\Delta \sigma_{\text{mean weighted}} = \frac{1}{\sqrt{\sum_i p_i}} \qquad \ldots(5)$$

that is, the set of data at a certain energy is considered as a normally distributed set of measurements since the authors generally give the average values measured.

The energy corresponding to the mean weighted value of cross section data was allocated in the same way as the mean weighted energy of those energies at which independent measurements were carried out:

$$E_{\text{mean weighted}} = \frac{\Sigma\, E_i\, P_i}{\Sigma_i\, p_i} \quad ; \qquad \ldots(6)$$

$$p_i = \frac{1}{\Delta\, E_i^2} \quad ; \qquad \ldots(7)$$

where $\Delta E_i$ - energy scatter in an actual measurement.

The number of points in a group varied from 4 to 9 (in two cases it worked out to 3- at 30 keV and 2- at 40 keV). In column 9 of Table 15 the results of this averaging are shown. These data refer not to the mean weighted energy in the given energy interval, but to the energy shown in column 3 of Table 15. The appropriate corrections were introduced by considering the form of the energy dependence of the cross section obtained from the results of the final reworking of the whole collection of data.

(b) Averaging of the whole collection of data

As may be seen from the results of section (a), sufficiently reliable results which might determine the form of a graph are available only in the interval 200-1,000 keV. At energies 1-200 keV and greater than 1,000 keV there is a deficiency of reliable data. Hence it is necessary to obtain, if possible, an estimate of the energy dependence for thorium in the given intervals.

At energies greater than 1,000 keV, in addition to the published results of reference (24), which our assessment indicates to be too low, there are data from the unpublished reference (17) and measurements at 14.5 MeV from reference (20). These data were used for averaging.

In the interval 10-140 keV there are relevant measurements by Moxon (36) and Macklin (35). As already mentioned, these works were unavailable to us, however, based on an evaluation of available data (37) one can anticipate that their inclusion will give a cross section value close to the true one.

Besides the references already mentioned, the rest of the available data were used for averaging, apart from a few points marked in the tables by ☆☆, and references (14) and (35). Data from reference (14) apparently gives an inaccurate energy dependence of cross section and in reference (34) the cross section at energies of 1-6 keV are high even after normalization by results from reference (29).

The energy range was divided into 25 intervals (see Table 15, column 2). The number of points in each averaging interval are shown in column 4. The averaging point on the energy scale was chosen approximately in the centre of the interval.

The measurements corresponding to a given energy interval, were carried out at energies independent of the central energy quoted for these energies and made use of information about the energy dependence of the cross sections. For the first average, a graph was used drawn sufficiently freely through the experimental points, but for the following averages a linear interpolation was used between neighbouring averaged points. If some point obviously deviated from the smooth curve then the smooth curve was used. In practice, to obtain the resulting average value of the cross section it required no more than four averaging procedures.

The method for obtaining averaged cross sections resulted from the characteristics inherent in the experimental data for fixed energy intervals.

1. In the interval 10-100 keV the greatest number of points are obtained from references (35) and (36), for which errors and corrections are not known. As a result, the only method for obtaining an estimate for these data is by regarding them as measurements of an equal weight of 1, and measurements with known errors occurring in this interval as also having a weight of 1. Since there are few of these measurements, then in this energy region the form of the curve will be determined basically by data from references (35) and (36). The average cross section and its error were calculated according to the formulae

$$\sigma_{\text{arithmetic mean}} = \sum_{i=1}^{n} \sigma_i/n \qquad \ldots(8)$$

$$\sigma_{\text{arithmetic mean}} = \sqrt{\frac{\sum_{i=1}^{n} (\sigma_i - \sigma_{\text{arithmetic mean}})^2}{n(n-1)}} \qquad \ldots(9)$$

2. By virtue of the energy increase, the proportion of measurements with known errors increases with energy. Therefore in these averaging intervals, which contain more than half of the measurements, an arbitrary error of 15 per cent was attributed to measurements taken from references (35) and (36). In that case $\sigma_{\text{arithmetic mean}}$ were calculated by formulae (8) and (9) and similarly $\sigma_{\text{mean weighted}}$ by formulae (3), (4) and (5).[†] Besides the error (5) for $\sigma_{\text{mean weighted}}$, the so called root mean square error was calculated after averaging (13), that is the set of data was regarded as a set of unequal accurate measurements with known weights but with unknown root mean square errors. This error was calculated by formula (2).

Averaged values of $\sigma_{\text{mean weighted}}$ and $\sigma^{*}_{\text{mean weighted}}$ allow an investigation of the presence of systematic errors in the measured data, that is, to evaluate the reliability of the value of $\sigma_{\text{mean weighted}}$ obtained. If the following holds

$$\frac{\left|\sigma^2_{\text{mean weighted}} - \sigma^{*}_{\text{mean weighted}}\right|}{\sigma^2_{\text{mean weighted}}} \sqrt{\frac{n-1}{2}} > 2 \qquad \ldots(10)$$

then this must be caused by the presence of a systematic error in data from reference (13); in these cases $\sigma_{\text{mean arithmetic}}$ reflects the accuracy of the average value since obviously, apart from experimental error one cannot determine true weighting values of individual measurements.

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[†] The meaning of $\sigma_{\text{arithmetic mean}}$ is explained in column 8, and $\sigma_{\text{mean weighted}}$ in column 5 of Table 15.

3. At energies greater than 1.5 MeV only results from two references are available, of which one of them presents no data and the other is none too reliable. Therefore in this region the same procedure was adopted as for the interval 10-100 keV.

4. At energies of 1-10 keV only the data from reference (34) is at our disposal - 7 points and one point each from references (29) and (27), even though it is evident (37) that in (35) and (36) measurements were carried out in this energy interval. Also with respect to (29) it is evident that the cross section value is too high (as must be (37)) so that in the interval 1-10 keV the curve may be smoothly extended towards smaller energies through the point from reference (27) and the lower bound from (29).

The final averaged results are presented in Table 15 in column 10.

In the interval 10-55 keV the averaged data are arithmetic means. These cross section values must be regarded as preliminary. Final values may be obtained after critical inspection and further analysis of the results of Moxon (36) and Macklin (35).

In the interval 55-1250 keV the averaged points are mean weighted. As a result not all of them are of equal reliability. On inspection some of the averaged points (at the beginning of the interval) are found to contain many systematic errors. A typical example is the point at $E_n$ = 100 keV where the systematic error is so dominant that for a weighted mean value it is more correct to take the arithmetic mean.

It is necessary to make one comment here. It is evident that during the averaging of the results from many experiments, it is necessary to use all the available data apart from obvious deviations from the bulk of the measurements. The use of only 'reliable' data leads to a loss of information contained in unreliable measurements. This is very essential in those cases where there are few 'reliable' data. An example of this could be cited for the point at $E_n$ = 140 keV. Averaging of 'reliable' data gives a value of $\sigma_{n,\gamma}$ = 282±13 mb. However, from the final results of averaging it is clear that this value is too large. For this reason the cross section values given in column 9 are averaged over all the available measurements.

At neutron energies greater than 1.5 MeV the averaged values are arithmetic means, since it is clear from the results of reworking the data that they contain a significant systematic error.

In the first column some points are marked with an asterisk. These values may be regarded as more or less reliable, resulting from smoothing of $\sigma_{\text{arithmetic mean}}$ and $\sigma_{\text{mean weighted}}$ and $\Delta\sigma_{\text{arithmetic mean}}$, $\Delta\sigma_{\text{mean weighted}}$ and $\Delta\sigma^{*}_{\text{mean weighted}}$.

Figure 3 is a plot of the averaged values of the capture cross section with errors and the results of reference (20) for $E_n$ = 14.5 MeV. A smooth curve is drawn through these data. Since the point for $E_n$ = 4700 keV clearly falls well outside the curve, it is replaced on the graph by data from (24): the average value of the cross section for points 25 and 26 (from table 7). On figure 2 and 2a the same cross section curve is depicted as on figure 3. The shape of the curve in the interval 1-6 keV on figure 2a is the consequence of including the results of reference (34), normalized to $\sigma_{n,\gamma}$ (2 keV) = 2.3 b (29). In order to present a full picture in figure 1, the results of measuring $\sigma_{n,\gamma}$ in the interval 1-100 keV from work (39) are added.

## 4. CONCLUSIONS

By examining the radiative capture cross section data of $^{232}$Th for neutrons in the interval 1 keV-14.5 MeV one can make the following observations:

1. In the interval 1-10 keV there are restrictively few data and the recommended graph has an accuracy of not better than 15 per cent. A more reliable dependence of the cross section

on energy may be obtained from a critical examination of the time of flight measurements of Moxon (36) and Macklin (35).

2. In the interval 10-200 keV there may well be sufficient data for obtaining more reliable results, but at the present time this data is unavailable and it has not been possible to utilize them.

Considering the preliminary agreement of references (35) and (36), one can infer that in the interval 10-40 keV the averaged data are slightly high, and in the interval 50-140 keV slightly low. The accuracy of the average in this interval improves approximatly from 15 per cent to 5 per cent as the energy increases. The points at 40 and 70 keV are exceptions and provide points of higher accuracy and can therefore be used for normalizing data of other authors in this band of energies.

In two energy ranges investigated, the bulk of data is derived from time of flight measurements. As a result, it would be extremely desirable to carry out detailed measurements of the cross sections of thorium by the activation method, since this will allow the systematic error to be reduced to a minimum in this region which is important for practical applications.

3. The bulk of the capture cross section data centered in the interval 200-1000 keV has been measured by the activation method and agree well with each other. This is the most reliable section of the recommended curve; the accuracy of the averaged values is approximately constant varying in the limits 2.9-4.4 per cent.

4. There are very few measurements of the thorium absorption cross section in the energy range 1-14.5 MeV, and most of these are unreliable. They are also very unevenly distributed in the energy interval. Therefore the result follows: that the energy dependence is known to be no better than 15 per cent and it appears no worse than 20 per cent. It is clear that in this region also it is necessary to carry out detailed measurements of the capture cross section.

## TABLE 1

## Radiative Capture Cross Section of Neutrons by $^{232}$Th for a Thermal Spectrum

| No. | Original capture cross section barns | Renormalized capture cross section barns | Method of Measurement | Reference |
|---|---|---|---|---|
| 1 | 7.75 ± 0.30 | 7.69 ± 0.31 | Activation | 2 |
| 2 | 7.58 ± 0.76 | | Activation | 3 |
| 3 | 7.31 ± 0.12 | 7.32 ± 0.12 | Activation | 4 |
| 4 | 7.31 ± 0.10 | 7.32 ± 0.10 | Activation | 6 |
| 5 | 6.52 ± 0.14 | 7.06 ± 0.33 | Activation | 6 |
| 6 | 7.00 ± 0.35 | 7.28 ± 0.36 | Capture | 7 |
| 7 | 7.57 ± 0.17 | 7.53 ± 0.17 | Capture | 8 |
| 8 | 7.55 ± 0.25 | 7.61 ± 0.29 | Capture | 9 |
| 9 | 7.50 ± 0.30 | 7.53 ± 0.30 | Capture | 10 |
| 10 | 7.2 ± 0.2 | | Slow | 11 |
| 11 | 7.60 ± 0.16 | | Total cross section | 12 |

## TABLE 2

### Thorium capture cross section from unpublished work of the Los Alamos Laboratory (14) (data obtained from graph in (15))

| No. | E keV | $\sigma_{n,\gamma}$ mbarn |
|---|---|---|
| 1 | 16 | 570 |
| 2 | 33 | 570 |
| 3 | 66 | 420 |
| 4 | 96 | 365 |
| 5 | 195 | 280 |
| 6 | 385 | 170 |

## TABLE 3

### The capture cross sections from unpublished work of the University of California (17) (data obtained from graph in (16)).

| No. | E keV | $\sigma_{n,\gamma}$ mbarn |
|---|---|---|
| 1 | 240 | 185 |
| 2 | 580 | 160 |
| 3 | 780 | 160 |
| 4 | 870 | 155 |
| 5 | 1000 | 140 |
| 6 | 1650 | 105 |
| 7 | 1900 | 84 |
| 8 | 2400 | 54 |
| 9 | 3000 | 28 |
| 10 | 3250 | 33 |
| 11 | 4000 | 21 |
| 12 | 4900 | 18 |
| 13 | 5700 | 22 |
| 14 | 5800 | 17 |

## TABLE 4

### Data from reference (21)

| No. | E keV | $\sigma_{n,\gamma}$ mbarn | No. | E keV | $\sigma_{n,\gamma}$ mbarn |
|---|---|---|---|---|---|
| 1 | 100 | 486 ± 45 | 13 | 350 | 175 ± 17 |
| 2 | 125 | 303 ± 19 | 14 | 400 | 183 ± 15 |
| 3 | 125 | 299 ± 27 | 15 | 429 | 195 ± 13 |
| 4 | 150 | 248 ± 15 | 16 | 429 | 192 ± 12 |
| 5 | 150 | 264 ± 22 | 17 | 450 | 190 ± 16 |
| 6 | 175 | 238 ± 16 | 18 | 500 | 167 ± 14 |
| 7 | 200 | 195 ± 14 | 19 | 580 | 190 ± 12 |
| 8 | 225 | 200 ± 16 | 20 | 620 | 189 ± 12 |
| 9 | 250 | 171 ± 14 | 21 | 630 | 189 ± 12 |
| 10 | 250 | 216 ± 16 | $22^{**}$ | 740 | 95 ± 9 |
| 11 | 297 | 219 ± 13 | $23^{**}$ | 990 | 67 ± 8 |
| 12 | 300 | 184 ± 17 | $24^{**}$ | 1230 | 65 ± 7 |

## TABLE 5

### Data from reference (22)

| No. | E keV | $\sigma_{n,\gamma}$ from (22) mbarn | Capture cross section with absolute errors mbarn |
|---|---|---|---|
| 1 | 300 ± 90 | 206 ± 17 | 206 ± 18 |
| 2 | 400 ± 80 | 190 ± 11 | 190 ± 12 |
| 3 | 500 ± 75 | 172 ± 11 | 172 ± 12 |
| 4 | 600 ± 73 | 195 ± 12 | 196 ± 13 |
| 5 | 700 ± 69 | 187 ± 12 | 187 ± 13 |
| 6 | 800 ± 67 | 172 ± 11 | 172 ± 12 |
| 7 | 900 ± 66 | 173 ± 10 | 173 ± 11 |
| 8 | 1000 ± 65 | 120 ± 8 | 120 ± 9 |
| 9 | 1100 ± 64 | 120 ± 8 | 120 ± 9 |
| 10 | 1200 ± 62 | 118 ± 8 | 118 ± 9 |

## TABLE 6

Data from reference$^{(23)}$

| No. | E<br>keV | $\sigma_{n,\gamma}$ Th from (23) mbarn | $\sigma_{n,\gamma}^{I_{127}}$ utilization in (23) mbarn | $\sigma_{n,\gamma}^{I_{127}}$ in (38) mbarn | Renormalized $\sigma_{n,\gamma}$ (after correction of $\sigma_{n,\gamma}$ Th and $I_{127}$ $\sigma_{n,\gamma}$ |
|---|---|---|---|---|---|
| 1 | 30 ± 14 | 596 ± 54 | 920 | 760 | 447 ± 62 |
| 2 | 41 ± 14 | 547 ± 55 | 800 | 640 | 398 ± 58 |
| 3 | 55 ± 14 | 569 ± 34 | 670 | 540 | 417 ± 51 |
| 4 | 76 ± 15 | 403 ± 26 | 530 | 440 | 303 ± 38 |
| 5 | 100 ± 15 | 330 ± 18 | 400 | 360 | 270 ± 32 |
| 6 | 133 ± 18 | 274 ± 14 | 285 | 290 | 253 ± 30 |
| 7 | 185 ± 22 | 218 ± 16 | 233 | 233 | 198 ± 25 |
| 8 | 221 ± 22 | 214 + 11 | 200 | 218 | 212 ± 28 |
| 9 | 296 ± 27 | 198 ± 14 | 175 | 172 | 185 ± 22 |
| 10 | 339 ± 51 | 167 ± 12 | 157 | 172 | 166 ± 22 |
| 11 | 313 ± 23 | 168 + 7 | 167 | 177 | 162 ± 18 |
| 12 | 403 ± 24 | 173 ± 11 | 145 | 160 | 173 ± 21 |
| 13 | 331 ± 23 | 161 ± 6 | 162 | 174 | 156 ± 17 |
| 14 | 422 ± 24 | 166 ± 8 | 141 | 150 | 161 ± 19 |
| 15 | 490 ± 25 | 150 ± 4 | 130.5 | 125 | 131 ± 15 |
| 16 | 513 ± 26 | 164 ± 7 | 128 | 123 | 143 ± 16 |
| 17 | 580 ± 26 | 167 ± 5 | 119 | 115 | 146 ± 16 |
| 18 | 605 ± 27 | 156 ± 12 | 116.5 | 112 | 136 ± 18 |
| 19 | 677 ± 28 | 165 ± 10 | 105 | 109 | 155 ± 19 |
| 20 | 696 ± 29 | 167 ± 7 | 103 | 107 | 158 ± 28 |
| 21 | 770 ± 28 | 173 ± 10 | 88 | 93 | 178 ± 22 |
| 23 | 865 ± 10 | 167 ± 10 | 82 | 88 | 163 ± 20 |
| 24 | 883 ± 30 | 153 ± 7 | 81 | 87 | 153 ± 17 |
| 25 | 964 ± 31 | 149 ± 5 | 81 | 82 | 138 ± 16 |

## TABLE 7

## Data from reference(24)

| No. | Neutron energy<br>keV | Capture cross section (24)<br>mbarn | Fission cross section of $^{235}$U from (25)<br>barns | Fission cross section of $^{235}$U from (26)<br>barns | Renormalized capture cross section<br>mbarn |
|---|---|---|---|---|---|
| 1 | 32 ± 9 | 819 ± 82 | 2.66 | 2.24 | 690 ± 69 |
| 2 | 42 ± 11 | 615 ± 62 | 2.46 | 2.06 | 515 ± 52 |
| 3 | 59 ± 13 | 409 ± 41 | 2.21 | 1.865 | 345 ± 35 |
| 4 | 69 ± 4 | 363 ± 36 | 2.10 | 1.79 | 309 ± 31 |
| 5 | 84 ± 16 | 350 ± 35 | 1.97 | 1.71 | 304 ± 30 |
| 6 | 118 ± 18 | 306 + 31 | 1.76 | 1.58 | 275 ± 28 |
| 7 | 112 ± 11 | 217 ± 22 | 1.79 | 1.595 | 193 ± 19 |
| 8 | 176 ± 21 | 204 ± 20 | 1.56 | 1.45 | 190 ± 19 |
| 9 | 240 ± 40 | 177 ± 18 | 1.45 | 1.358 | 166 ± 17 |
| 10 | 247 ± 24 | 219 + 22 | 1.44 | 1.35 | 205 ± 20 |
| 11 | 255 ± 10 | 141 ± 14 | 1.43 | 1.34 | 132 ± 13 |
| 12 | 430 ± 23 | 148 ± 15 | 1.27 | 1.207 | 141 ± 14 |
| 13 | 580 ± 70 | 153 ± 15 | 1.21 | 1.14 | 144 ± 14 |
| 14 | 710 ± 15 | 145 ± 15 | 1.18 | 1.137 | 140 ± 14 |
| 15 | 790 ± 21 | 157 ± 16 | 1.18 | 1.153 | 153 ± 15 |
| 16* | 850 ± 20 | 112 + 11 | 1.17 | 1.168 | 112 ± 11 |
| 17 | 870 ± 80 | 148 ± 15 | 1.17 | 1.175 | 148 ± 15 |
| 18 | 990 ± 50 | 133 ± 13 | 1.26 | 1.205 | 127 ± 13 |
| 19 | 1000 ± 90 | 138 ± 14 | 1.26 | 1.207 | 132 ± 13 |
| 20 | 1610 ± 40 | 99.6± 10 | 1.30 | 1.27 | 97.4± 10 |
| 21 | 1790 ± 80 | 84 ± 8 | 1.30 | 1.287 | 83.1± 8 |
| 22 | 2000 ± 90 | 61 ± 6 | 1.31 | 1.305 | 60.3± 6 |
| 23 | 2720 ± 40 | 28 ± 3 | 1.27 | 1.26 | 27.8± 3 |
| 24 | 3000 ± 40 | 23.1± 2.3 | 1.24 | 1.23 | 22.9±2.3 |
| 25 | 3650 ± 70 | 15.1± 1.5 | 1.21 | 1.175 | 14.7±1.5 |
| 26 | 3970 ± 70 | 13.5± 1.4 | 1.20 | 1.15 | 12.9±1.3 |

## TABLE 8

### Data from reference(27)

| No. | Neutron energy keV | Experimentally measured relationship $N_p/N_B$ (27) | Quantity $\frac{10\ N_\beta}{N_B\sqrt{E}}$ | Neutron capture cross section (based on data in (31)) mbarn | Capture cross section based on results of (27) |
|---|---|---|---|---|---|
| 1 | 5.5 ± 4.7 | 0.212 ± 0.006 | 0.904 ± 0.052 | 1308 ± 130 | 1648 ± 272 |
| 2 | 11.5 ± 4.8 | 0.207 ± 0.006 | 0.610 ± 0.035 | 883 ± 88 | 1112 ± 183 |
| 3 | 16.7 ± 4.9 | 0.181 ± 0.012 | 0.443 ± 0.036 | 641 ± 75 | 807 ± 141 |
| 4 | 19.7 ± 5.0 | 0.197 ± 0.013 | 0.444 ± 0.036 | 642 ± 75 | 809 ± 141 |
| 5 | 25.7 ± 5.1 | 0.212 ± 0.002 | 0.418 ± 0.021 | 605 ± 58 | 764 ± 124 |
| 6 | 30.9 ± 5.2 | 0.188 ± 0.019 | 0.338 ± 0.038 | 489 ± 68 | 616 ± 117 |
| 7 | 40.7 ± 5.4 | 0.207 ± 0.018 | 0.324 ± 0.032 | 469 ± 61 | 591 ± 109 |
| 8* | 51.1 ± 5.6 | 0.145 ± 0.006 | 0.203 ± 0.013 | 294 ± 31 | 370 ± 62 |
| 9 | 71.5 ± 6.1 | 0.181 ± 0.011 | 0.214 ± 0.017 | 310 ± 35 | 390 ± 60 |
| 10* | 102.1 ± 6.7 | 0.145 ± 0.009 | 0.143 ± 0.011 | 208 ± 24 | 262 ± 45 |

## TABLE 9

### Data from reference(28)

| No. | Neutron energy keV | Capture cross section from (28) mbarns | Fission cross section $^{235}U$ from (25) barns | Fission cross section $^{235}U$ from (26) barns | Renormalized capture cross section mbarns |
|---|---|---|---|---|---|
| 1 | 191 ± 38 | 217 ± 15 | 1.53 | 1.425 | 202 ± 14 |
| 2 | 290 ± 36 | 183 ± 13 | 1.39 | 1.305 | 172 ± 12 |
| 3 | 394 ± 36 | 164 ± 11 | 1.29 | 1.228 | 156 ± 11 |
| 4 | 482 ± 35 | 167 ± 11 | 1.25 | 1.18 | 158 ± 11 |
| 5 | 491 + 37 | 193 ± 13 | 1.24 | 1.175 | 183 ± 12 |
| 6 | 493 ± 36 | 178 ± 12 | 1.24 | 1.175 | 169 ± 12 |
| 7 | 493 ± 36 | 182 ± 12 | 1.24 | 1.175 | 172 ± 11 |
| 8 | 523 ± 50 | 180 ± 17 | 1.23 | 1.16 | 170 ± 16 |
| 9 | 590 ± 36 | 188 ± 13 | 1.20 | 1.138 | 178 ± 13 |
| 10 | 684 ± 38 | 220 ± 15 | 1.19 | 1.132 | 209 ± 14 |
| 11 | 689 ± 39 | 197 ± 14 | 1.19 | 1.132 | 187 ± 14 |
| 12 | 705 ± 50 | 210 ± 20 | 1.18 | 1.136 | 202 ± 19 |
| 13 | 785 ± 32 | 213 ± 14 | 1.18 | 1.152 | 208 ± 14 |
| 14 | 791 ± 37 | 196 ± 13 | 1.18 | 1.154 | 192 ± 13 |
| 15 | 809 ± 50 | 180 ± 17 | 1.18 | 1.157 | 176 ± 17 |
| 16 | 885 ± 38 | 176 ± 12 | 1.18 | 1.176 | 175 ± 12 |
| 17 | 887 ± 43 | 195 ± 13 | 1.18 | 1.176 | 194 ± 13 |
| 18 | 978 ± 38 | 165 ± 12 | 1.26 | 1.2 | 157 ± 12 |
| 19 | 988 ± 38 | 152 ± 11 | 1.26 | 1.203 | 145 ± 11 |
| 20 | 1086 ± 39 | 152 ± 11 | 1.26 | 1.218 | 147 ± 11 |
| 21 | 1091 ± 39 | 156 ± 10 | 1.26 | 1.219 | 151 ± 10 |
| 22 | 1170 ± 43 | 152 ± 11 | 1.27 | 1.227 | 147 ± 11 |

## TABLE 10

Results of measurements of radiative capture cross section for thorium by the activation method

| No. | Neutron energy keV | Experimental result cited by authors mbarns | Renormalized or modified cross sections (text meaning) mbarns | References |
|---|---|---|---|---|
| 1 | 25 | 500 ± 100 | 560 ± 150 | 18 |
| 2 | .14500 | 5.2 ± 0.8 | 5.2 ± 0.8 | 20 |
| 3 | 24 | 480 ± 50 | 480 ± 50 | 30 |
| 4 | 2 | 2300 ± 200 |  | 29 |

## TABLE 11

Results of measurements of cross sections by the method of spherical transmission

| No. | E keV | $\sigma$ capture | Reference |
|---|---|---|---|
| 1** | 25 ± 4 | 467 ± 4 | 41 |
| 2** | 220 ± 20 | 235 ± 6 | 41 |
| 3 | 830 ± 40 | 202 ± 6 | 41 |
| 4 | 220 ± 20 | 213 ± 5 | 42 |
| 5 | 24 ± 1.5 | 615 ± 25 | 31 |
| 6 | 24 ± 1.5 | 611 ± 40 | 32 |

TABLE 12

Results of measurements of cross sections
by the method of spherical transmission

| No. | E<br>keV | $\sigma_{n,\gamma}$<br>barns |
|---|---|---|
| 1 | 0.60 | 6 |
| 2 | 0.73 | 3.5 |
| 3 | 0.90 | 2.4 |
| 4 | 1.1 | 3.3 |
| 5 | 1.4 | 3.7 |
| 6 | 1.7 | 3.0 |
| 7 | 2.3 | 3.0 |
| 8 | 2.8 | 2.4 |
| 9 | 4.3 | 2.1 |
| 10 | 6.0 | 1.3 |

TABLE 13

Results from reference(36)
(taken from graph in (1))

| No | E<br>keV | $\sigma_{n,\gamma}$<br>mbarns | No | E<br>keV | $\sigma_{n,\gamma}$<br>mbarns |
|---|---|---|---|---|---|
| 1 | 10.6 | 560 | 13 | 29.7 | 375 |
| 2 | 11.5 | 650 | 14 | 33 | 365 |
| 3 | 12.5 | 600 | 15 | 37 | 425 |
| 4 | 13.6 | 580 | 16 | 42 | 380 |
| 5 | 14.7 | 615 | 17 | 48 | 350 |
| 6 | 15.8 | 520 | 18 | 56 | 310 |
| 7 | 17.1 | 520 | 19 | 64 | 290 |
| 8 | 18.5 | 495 | 20 | 77 | 250 |
| 9 | 19.8 | 460 | 21 | 92 | 228 |
| 10 | 21 | 475 | 22 | 115 | 200 |
| 11 | 24 | 520 | 23 | 143 | 190 |
| 12 | 27 | 440 | | | |

## TABLE 14

Results from reference(35)
(taken from graph in (1))

| No. | E keV | $\sigma_{n,\gamma}$ mbarns | No. | E keV | $\sigma_{n,\gamma}$ mbarns |
|---|---|---|---|---|---|
| 1 | 10.3 | 1100 | 22 | 21 | 670 |
| 2 | 10.7 | 1550 | 23 | 22 | 580 |
| 3 | 11.1 | 1550 | 24 | 23 | 680 |
| 4 | 11.7 | 780 | 25 | 24 | 660 |
| 5 | 12.0 | 1300 | 26 | 25 | 680 |
| 6 | 12.5 | 235 | 27 | 26 | 580 |
| 7 | 13 | 960 | 28 | 27 | 600 |
| 8 | 13.5 | 680 | 29 | 28.5 | 630 |
| 9 | 14 | 900 | 30 | 30 | 620 |
| 10 | 14.5 | 900 | 31 | 31 | 550 |
| 11 | 14.8 | 1100 | 32 | 32.5 | 540 |
| 12 | 15.2 | 800 | 33 | 34.5 | 540 |
| 13 | 15.8 | 900 | 34 | 36 | 500 |
| 14 | 16.2 | 880 | 35 | 38 | 520 |
| 15 | 16.8 | 720 | 36 | 40 | 520 |
| 16 | 17.3 | 760 | 37 | 42 | 510 |
| 17 | 17.8 | 720 | 38 | 45 | 480 |
| 18 | 18.5 | 860 | 39 | 48 | 450 |
| 19 | 19 | 720 | 40 | 51 | 430 |
| 20 | 19.5 | 750 | 41 | 54 | 430 |
| 21 | 20 | 770 | 42 | 58 | 460 |

## TABLE 15

### Results of averaging neutron capture cross sections for $^{232}U$ in the energy interval 10 keV-14.5 MeV

| No. 1 | Energy interval averaged over keV 2 | Central energy in interval keV 3 | No. of points in interval 4 | Weighted mean cross sections mbarn 5 | Error of weighted mean before averaging mbarn 6 | Error of weighted mean after averaging mbarn 7 | Arithmetic mean cross sections mbarn 8 | Weighted mean cross sections by renormalization of data mbarn 9 | Recommended value of cross section mbarn 10 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10- 13 | 12 | 9 | | | | 962 ± 128 | | 962 ± 128 (14%) |
| 2 | 13- 16 | 15 | 10 | | | | 729 ± 62 | | 729 ± 62 ( 9%) |
| 3 | 16- 20 | 18 | 13 | | | | 692 ± 36 | | 692 ± 36 ( 5%) |
| 4 | 20- 27 | 24 | 14 | | | | 576 ± 22 | 591 ± 21 | 576 ± 21 ( 4%) |
| 5 | 28- 33 | 30 | 9 | | | | 532 ± 36 | 495 ± 48 | 532 ± 36 ( 7%) |
| 6* | 33- 45 | 40 | 10 | | | | 480 ± 16 | 487 ± 34 | 480 ± 16 (3.3%) |
| 7 | 45- 55 | 50 | 6 | | | | 399 ± 26 | | 399 ± 26 ( 7%) |
| 8 | 55- 65 | 60 | 5 | 345 | ±20 | ±28 | 363 ± 33 | | 345 ± 28 ( 8%) |
| 9 | 65- 85 | 75 | 5 | 299 | ±15 | ±13 | 300 ± 15 | 297 ± 17 | 299 ± 15 ( 5%) |
| 10 | 85- 120 | 100 | 6 | 247 | ±11 | ±28 | 275 ± 26 | | 275 ± 26 (10%) |
| 11* | 120- 180 | 140 | 8 | 257 | ± 8 | ±11 | 256 ± 13 | 282 ± 13 | 257 ± 11 (4.2%) |
| 12* | 180- 250 | 200 | 11 | 207 | ± 6 | ± 6 | 212 ± 6 | 210 ± 7 | 207 ± 6 (2.9%) |
| 13* | 250- 350 | 300 | 8 | 190 | ± 6 | ± 6.5 | 190 ± 6.3 | 193 ± 7 | 190 ± 7 (3.7%) |
| 14* | 350- 450 | 400 | 9 | 177 | ± 6 | ± 6.5 | 178 ± 5 | 178 ± 5 | 177 ± 7 ( 4%) |
| 15* | 450- 550 | 500 | 10 | 169 | ± 5 | ± 3.7 | 168 ± 4.2 | 168 ± 5 | 169 ± 5 ( 3%) |
| 16* | 550- 650 | 600 | 9 | 178 | ± 5 | ± 6.2 | 173 ± 6.5 | 179 ± 5 | 178 ± 6 (3.4%) |
| 17* | 650- 750 | 700 | 7 | 182 | ± 6 | ± 9.2 | 181 ± 8.6 | 182 ± 6 | 182 ± 8 (4.4%) |
| 18* | 750- 850 | 800 | 9 | 182 | ± 6 | ± 6.4 | 184 ± 6.5 | 183 ± 6 | 182 ± 7 (3.9%) |
| 19* | 850- 950 | 900 | 7 | 172 | ± 6 | ± 5.6 | 168 ± 5.8 | 172 ± 6 | 172 ± 6 (3.5%) |
| 20 | 950-1050 | 1000 | 7 | 135 | ± 5 | ± 5 | 137 ± 4.5 | 133 ± 5 | 135 ± 5 (3.7%) |
| 21 | 1050-1250 | 1150 | 5 | 132 | ± 5 | ± 6.8 | 134 ± 6.5 | 131 ± 5 | 132 ± 7 (5.3%) |
| 22 | 1600-2400 | 2000 | 6 | 71.6 | ± 3.4 | ± 3.7 | 75.3 ± 3.7 | | 75.3± 3.7 ( 5%) |
| 23 | 2700-3300 | 3000 | 4 | 24.8 | ± 1.5 | ± 2.5 | 27.8 ± 3.5 | | 27.8± 3.5 (13%) |
| 24 | 3600-5800 | 4700 | 6 | 11.4 | ± 0.7 | ± 0.68 | 18.1 ± 3.0 | | 18.1± 3.0 (17%) |
| 25 | | 14500 | 1 | | | | 5.2 ± 0.8 | | 5.2± 0.8 (15%) |

## SYMBOLS USED IN FIGURES 2 AND 2a

▣ - [14]
⬯ - [20]
▽ - [23]
▯ - [28]
⬮ - [40]
● - [34]

◊ - [17]
△ - [21]
○ - [24]
◐ - [29]
• - [40]
× - [35]

◫ - [18]
□ - [22]
◊ - [27]
▬ - [30]
▭ - [31]
+ - [36]

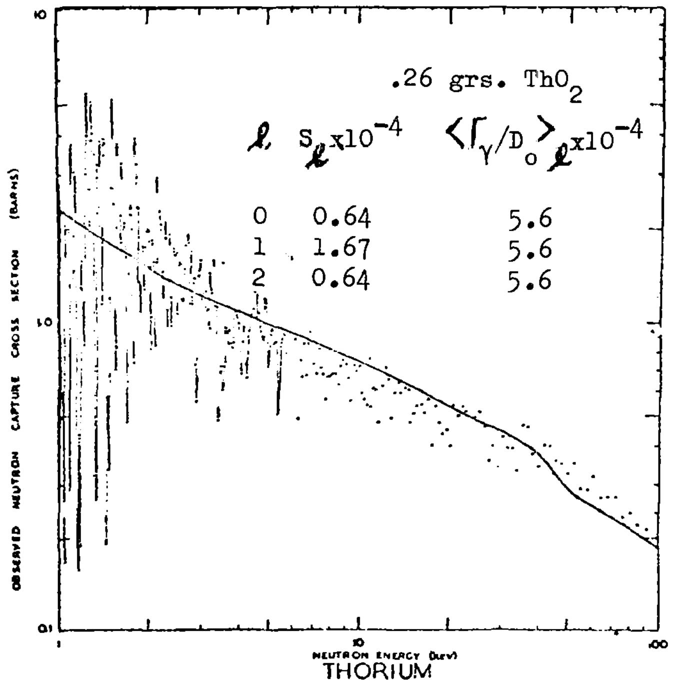

FIGURE 1: Results of measurements from work [39] .

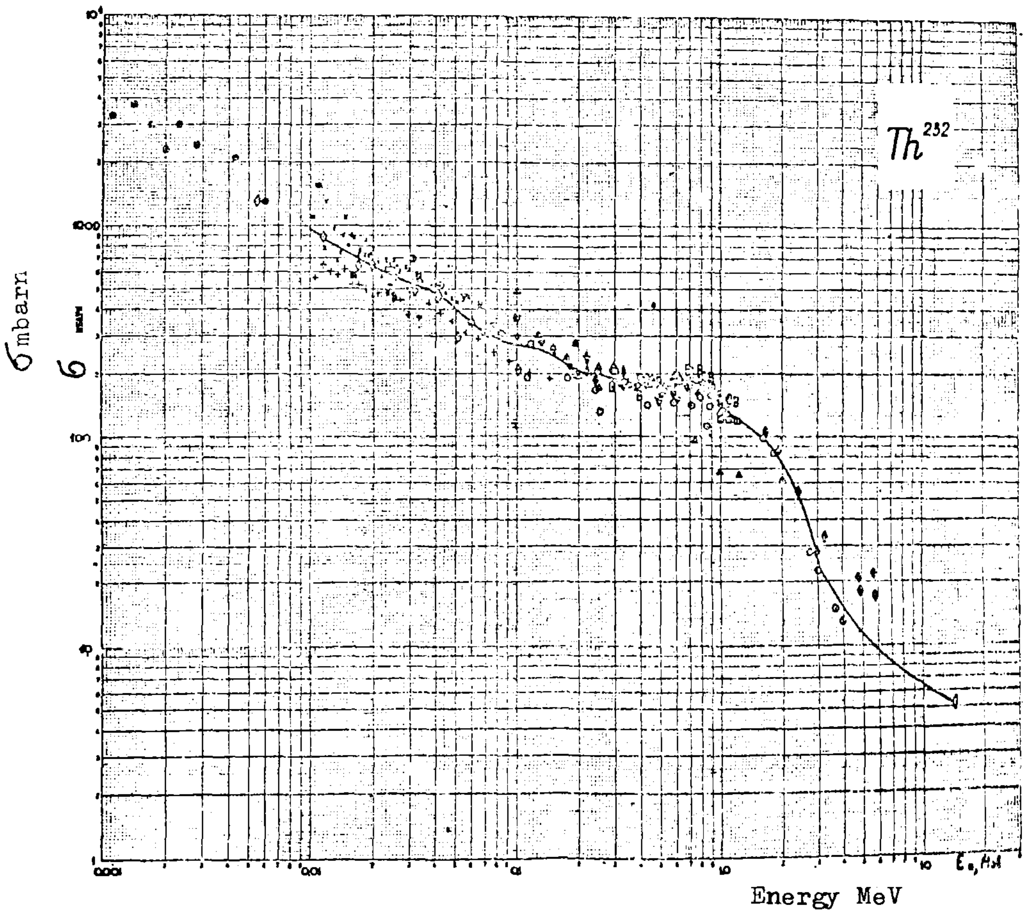

FIGURE 2: Original results of work to measure neutron radiative capture cross sections of thorium.

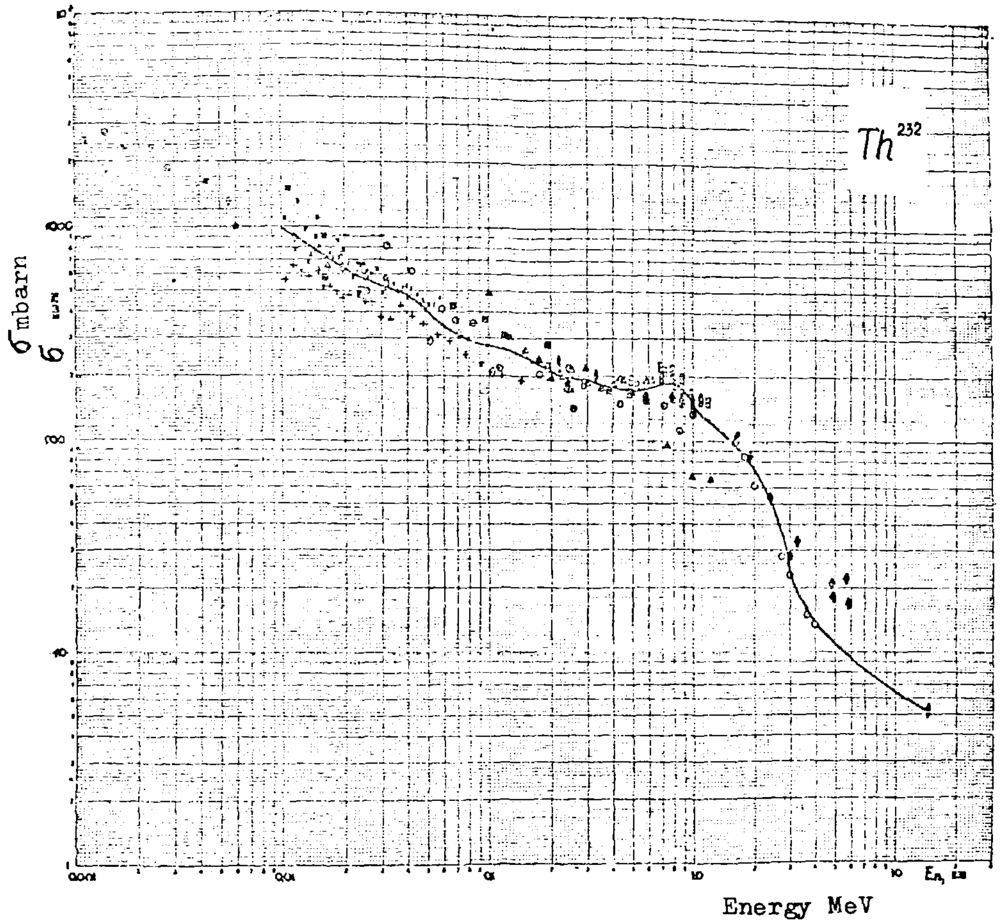

FIGURE 2a - Results of the more reliable work of $n,\gamma$ measurement for thorium (plot of renormalized values of cross sections).

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