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CAPTURE CROSS-SECTION for ^{238}U

V.A. Konshin
International Atomic Energy Agency

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IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

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1. Introduction

Almost all works relating to the measurement or compilation of capture cross-sectionsfor fissionable elements begin by describing the importance of these cross-sections for reactor calculations and the required degree of accuracy. Capture cross-sections both for fissionable and non-fissionable isotopes are indeed of considerable practical importance. This is indicated by, for example, the fact that in the latest issue of RENDA [1] the number of requests for measurments of nuclear data relating to neutron capture or gamma-ray production amounted to 377, or 36% of the total number of requests. The required accuracy in the measurements of capture cross-sections for fissionable isotopes is extremely high and often beyond the scope of present techniques.

One of the features of fast-reactor development in recent years has been the increase in the importance of large systems with significant fuel dilution and with softer neutron spectra, as a result of which neutron energies below 100 keV have become particularly important and it has become necessary to know with a high degree of accuracy the capture cross-sections for fissionable elements in this energy region.

In an exhaustive report on the required accuracy of cross-section determination in the range 0.1-100 keV, Greebler and Hutchins [2] pointed out that an accuracy of ±3% in the cross-section for capture in ^{238}U is necessary for calculating fissile mass to within ±1%, breeding ratio to within ±1%, Doppler coefficient to within ±5% and sodium void reactivity to within ±0.5%. However, the accuracy of existing cross-sections for capture in ^{238}U is such that, for example, the uncertainty in calculations of sodium void reactivity is ~50% when one uses the various group constants available - although the accuracy appears to be somewhat improved if one uses the latest resonance parameters [3].

The results of integral experiments on a number of critical assemblies indicate also that existing values for the cross-sections for capture in ^{238}U are too high.

2. Experiments still in progress or at the data analysis stage

As a result of steps to organize and co-ordinate experimental work in the field of cross-section measurements - undertaken during recent years by the European-American Nuclear Data Committee - the amount of experimental data, including data on the cross-section for capture in ^{238}U, is increasing rapidly and can be expected to increase during the next 2-3 years.

The following experiments involving measurement of the cross-section for capture in ^{238}U are still in progress or in the data analysis stage.

1. Moxon (Harwell, United Kingdom) [4] has just completed an analysis of measurements of the cross-section for capture in ^{238}U in the region 0.5-100 keV (we shall consider this work in greater detail in Section 5).

2. Weigmann and Winter (Central Bureau for Nuclear Measurements, EURATOM, Belgium) [5] have performed measurements on a linear accelerator of the cross-section for capture in ^{238}U for energies between 5 eV and 30 keV with a resolution from 1.8 nsec/m to 22 nsec/m. For normalization purposes they used the resonances at 6.67 eV and 81.1 eV in ^{238}U and resonances in Ag. The neutron spectrum was measured both with the help of BF_3 counters and with a ^{10}B-slab viewed by a NaI crystal. The measurements have been made, but the results have not yet been analysed.

3. Colvin and Bowen (Harwell, United Kingdom) [6] are in the first stages of measuring the cross-section for capture in ^{238}U using a 45-MeV linear electron accelerator and an 80-cm liquid scintillator. They plan to carry out the measurements at high energies.

4. Nellis et al. (Nuclear Physics Laboratory, Texas Nuclear, USA) [7] are measuring the spectra of gamma radiation from the capture of 1-MeV neutrons in ^{238}U. It is also possible to obtain values for $\sigma_{n\gamma}$ at neutron energies of 1 MeV and less, although this question is not clarified in this work.

5. Rahn et al. (Colombia University, USA) [8] are preparing to measure the cross-section for capture in ^{238}U in the low keV region. In this experiment, which is planned for the summer of 1969, particular attention will be paid to the measurement of Γ_γ. The measurements will be made by the time-of-flight method using a "fast" electronic system with 2^{19} channels and a channel width of 20 nsec.

6. Poenitz (Argonne National Laboratory, USA) [9] has measured the ratios $\sigma_{n\gamma}(^{238}U)/\sigma_f(^{235}U)$ and $\sigma_{n\gamma}(^{238}U)/\sigma_f(^{239}Pu)$ in the neutron energy range 130-1400 keV. In the measurements of the ratio $\sigma_{n\gamma}(^{238}U)/\sigma_f(^{235}U)$, to determine the efficiency of the recording of fission and capture events, he used cross-sections for capture in ^{238}U and for ^{235}U fission at thermal neutron energies. In the measurements of the ratio $\sigma_{n\gamma}(^{238}U/\sigma_f(^{239}Pu)$ these efficiencies were determined absolutely. The results for the ratio $\sigma_{n\gamma}(^{238}U/\sigma_f(^{235}U)$ in the energy region 200-1000 keV confirm the cross-

sections for capture in ^{238}U obtained by Barry et al. [10] and Poenitz et al. [11]; at 130 keV and at energies above 1000 keV, however, the results are somewhat lower than the values reported by Barry [10]. The analysis of the experimental data is nearing completion and the results will soon be made available.

7. Glass et al. have measured the cross-section for capture for ^{238}U with the help of underground nuclear explosions. Their results for the energy range 30-2050 eV were published in the proceedings of the Conference on Neutron Cross-sections and Technology [47, 48], while the most recent (preliminary) results for the energy range 1-20 keV are quoted in the latest work of Schmidt [59].

3. Situation regarding the measurement of $\sigma_{n\gamma}$ for Au

Before reviewing the data on the cross-section for capture in ^{238}U it is perhaps worth dwelling briefly on the present situation regarding the measurement of the capture cross-section in gold. The capture cross-section in gold is the most frequently used standard cross-section, because it has been measured most carefully and because gold can be studied with all the principal methods currently used for measuring cross-sections.

Some idea of how the capture cross-section in gold has changed over the years is given by Table 1 (data from the Brookhaven centre).

Table 1

Cross-section for the reaction $^{197}Au(n,\gamma)^{198}Au$ at 30 keV

Capture cross-section (barn)	Method of measurement	Date of measurement
0.515	Scintillation tank; normalization to In	April 1961
1.129	Activation; normalized to boron	May 1961
0.809	Activation; normalized to boron	May 1961
0.947	Activation; normalized to ^{235}U	December 1962
0.513	Time-of-flight; Moxon-Rae detector	1963
0.565	Time-of-flight; scintillation tank	1964
0.598	Activation; normalization to a manganese bath	October 1966

The agreement was particularly bad at energies below 200 keV, where the experimental results differ in some cases by a factor of two. After many renormalizations and data evaluations the situation improved significantly [12].

The major differences between the shapes of the curves obtained with a liquid scintillator and by activation measurements were reduced; differences in absolute values were reduced to 20%. In particular, discrepancies between the results of experiments performed in a spherical geometry at 24 keV and results obtained with the help of a scintillation tank at 30 keV were found to be due to multiple scattering in the spherical geometry experiments.

In 1967, Poenitz et al. [13] began in Karlsruhe a series of absolute experiments, measuring the shape of the curve of the cross-section for capture in gold in the energy region 25-500 keV with normalization to the "better" value at 30 keV obtained from the results of a number of independent absolute measurements:
$\sigma_{n\gamma}(Au) = 0.596 \pm 0.012$ barn at 30 keV.

The different measurements in the low-energy region (~30 keV) are in fairly good agreement. The measurements at higher energies (above 200 keV) are also in good agreement if one normalizes them to the same ^{235}U fission cross-sections. However, the results based on normalization to the fission cross-section values are found to be about 15% higher than the values obtained by normalization to the "better" value at 30 keV. There is a difference of 15-20% in normalization between these two energy regions [12]. The reason lies in the accuracy of the capture cross-section in gold or in the accuracy of the ^{235}U fission cross-section for energies above 100 keV. Consequently, the accuracy of the cross-section for gold is at present 15-20% at energies above 100 keV and somewhat better (about 10%) below 100 keV.

The latest measurements performed by Spitz et al. [14] and by Lopez et al. [15] confirm this. The measurements by Spitz et al. [14] of ratios of capture cross-section in gold to indium capture cross-section in the energy region 8-120 keV have yielded cross-sections for capture in gold that are 10% lower than the values of Poenitz et al. in this energy region, although the shapes of the curves are similar. On the other hand, the mean capture cross-sections in gold, measured by the time-of-flight method by Lopez [15] in the energy region 1-700 keV and normalized to resonances at low energies, are consistently 10-15% higher than the data of Poenitz in the energy region 25-500 keV in spite of the fact that the curves have the same shape.

4. Experimental data on the capture cross-sections in ^{238}U available at the centres in Saclay, Brookhaven, Vienna and Obninsk

Since there is not very much new experimental data on the cross-section for capture in ^{238}U, before embarking on a review of this material we felt that it would be interesting to collect all the experimental data relating to this question. Appropriate requests were submitted to the centres at Brookhaven, Saclay and Obninsk. All information about the capture cross-section in ^{238}U available at these centres is presented in Fig. 1.

The data presented in Fig. 1 are fairly old, the most recent relating to September 1965. Some are perhaps mainly of historical interest, although those in the energy region above 500 keV of course retain their significance.

The following signs have been used in Fig. 1:

– Stavissky et al. [16];

– Weston et al. [17] (the authors used for normalization $\alpha(^{235}U)$ - α = 0.375 and 0.315 at 30 keV and 64 keV respectively, with $\sigma_f(^{235}U)$ = 2.58 ± 0.16 barn and 2.05 ± 0.12 barn at 30 keV and 64 keV respectively);

– Hanna et al. [18] (absolute measurements using activation method; detecting of beta particles from ^{239}U decay);

⊗ – Batchelor et al. [19] (time-of-flight measurements);

– Belanova et al. [20] (absolute measurements by the transmission method in a spherical geometry; no corrections for resonance shielding);

– Bilpuch et al. [21] (activation method; detecting of beta particles from ^{239}U decay; data renormalized at BNL to values given by Barry et al. [10] and De-Saussure et al. [31]);

– Broda [22] (measurements relative to the capture cross-sections in ^{238}U and Au at thermal neutron energies);

○ – Leipunsky et al. [23] (activation method; measurements relative to $\sigma_{n\gamma}(^{127}I)$ = 23 mbarn);

⊙ – Barry et al. [10] (activation method; detection of beta particles from ^{239}Np decay; normalized to the (n,p)-scattering cross-section);

□ – Linenberger et al. [24] (activation method; measurements relative to the ^{235}U fission cross-section; data renormalized in 1964 to $\sigma_f(^{235}U)$ = 3.95 barn at 5 keV [32]);

– Macklin [25] (normalized to the capture cross-section of 735 mbarn in ^{181}Ta; measurements made with Moxon-Rae detector);

– Moxon [26] (measurements with Moxon-Rae detector);

◇ – Macklin et al. [27] (activation method; recording of gamma rays from ^{239}Np decay; normalized to $\sigma_{n\gamma}(^{127}I)$ = 820 mbarn at 24 keV);

– Lyon et al. [28] (activation method; normalized to the capture cross-section of 195 mbarn for ^{115}In leading to 54-min ^{116}In activity);

◆ – Diven et al. [29] (scintillation tank for recording gamma rays; normalized to the value (fission + capture) in ^{235}U);

⊕ – Gibbons et al. [30] (scintillation tank; measurements relative to capture cross-sections of 760 mbarn and 450 mbarn in indium at 30 keV and 65 keV respectively).

It can be seen from Fig. 1 that in the neutron energy range 1-40 keV Macklin's results are consistently higher than those of Moxon by an average of 30-40%. In the energy range 40-200 keV measurements have been made by various authors (Bilpuch, Moxon, Linenberger's renormalized data); they differ by about 20-25%. Lastly, at energies between 200 keV and 10 MeV the accuracy of the measured capture cross-sections is about 15%. The measurements of Barry et al. [10] in this energy range are the most accurate since the results are normalized to the best known standard - the cross-section for elastic scattering in hydrogen. The recent measurements of Poenitz have confirmed the results of this work.

As can be seen, the divergence of the data is fairly considerable. A single renormalization may reduce this divergence somewhat, but it would appear that the matter is not simply one of renormalization.

5. New experimental data on $\sigma_{n\gamma}(^{238}U)$

In this section we describe recent experimental results relating to the cross-section for capture in ^{238}U.

Schuman [33], of the Idaho Nuclear Corporation, has measured the ^{238}U activation cross-section for 2-keV neutrons obtained with the help of a scandium filter. The number of ^{239}Np nuclei with $T_{\frac{1}{2}}$ = 2.35 days formed after irradiation of the uranium sample was determined by isolating the 228-keV gamma line by means of a gamma spectrometer; the neutron flux was measured using gold as a standard and taking a gold cross-section of 4.8 barn at 2 keV. The following result was obtained: $\sigma_{n\gamma}(^{238}U) = 1.68 \pm 0.12$ barn at 2 keV.

Poenitz and Miller [35, 34] recently reviewed the results of Belanova et al. [20] relating to the capture cross-section in ^{238}U at 23 keV. Taking resonance parameters from various published sources, they used the Monte Carlo method to calculate corrections for resonance shielding in the uranium sample. Introducing these corrections, they obtained the following capture cross-section in ^{238}U at 23 keV: 495 ± 40 mbarn (instead of the value 412 ± 18 mbarn reported by Belanova). This value was not corrected for the intermediate structure of the cross-section and it is by no means clear that a correction should be made, although such a structure may exist (measurements of Moxon and Chaffey [32]).

As already mentioned in Section 2, the capture cross-section in ^{238}U has also been measured in the energy range 1-20 keV, on the underground nuclear explosion "Petrel". The results are represented by the dashed line in Fig. 2. Since the details of the experiment are not known and the results only preliminary ones, we simply present the curve in question.

Poenitz et al. [11, 13] measured the cross-section for capture in ^{238}U in the energy range 25-500 keV with an accuracy of about 5% at 30 keV and of the order of 9% at 500 keV. The capture cross-section was measured absolutely at 30 keV using neutrons from the reaction $^{7}Li(p,n)^{7}Be$. The cross-section values obtained appear in Table 2.

Table 2

Cross-sections for capture in ^{238}U obtained by Poenitz et al. [11]

Average neutron energy (keV)	$\sigma_{n\gamma}$ (mbarn)
24.4 ± 0.9	516 ± 27
30.0 ± 1.5	479 ± 14
43.8 ± 1.3	404 ± 19
63.3 ± 0.7	302 ± 14
97.3 ± 2.8	201 ± 11
157.0 ± 3.0	153 ± 9
264.0 ± 3.0	126 ± 9
373.0 ± 12.0	123 ± 11
503.0 ± 12.0	110 ± 10

The latest work devoted to the measurement of the capture cross-section in ^{238}U is that of Moxon [36]. Since this is one of the most recent works in this field and perhaps one of the most accurate (particularly as regards the shape of the capture cross-section curve), we shall consider it in greater detail.

The capture cross-section was measured by the time-of-flight method with a flight distance of 32.5 m on the Harwell 45-MeV linear electron accelerator; the booster target was used as a pulsed neutron source and a Moxon-Rae detector for recording the gamma rays.

The measurements were performed with uranium and boron samples inserted alternately into the detector. The count ratio of the uranium and boron samples was determined for each channel (after subtracting the background). The background was measured with the help of Al, Zn and Ag resonance filters placed in the neutron beam. The background measurements were made at energies corresponding to "black" resonances, with subsequent interpolation. Above the 90-keV resonance in Al it was naturally difficult to determine the background in this manner. In the worst case (at 5 keV and 10 keV) the ratio of the signal to the total background for the uranium sample was 1:1 and increased with both increasing and decreasing energies (e.g. 2.2 at 100 keV and 1.6 at 1 keV). The error of the background measurements was greatest at 50 keV (4.7%), decreasing to 2% at 1 keV. The count ratios for the uranium and boron samples in those energy ranges where the effect of the filters (and hence the resolution) was small agree well with data obtained without filters in the beam, thereby confirming that the background was handled correctly.

In order to determine the cross-section for capture in ^{238}U it was necessary to measure:*

(1) The efficiency ratio for recording capture gamma rays in the ^{238}U sample and 480-keV gamma rays emitted in the reaction $^{10}B(n,\alpha\gamma)^{7}Li$;

(2) The fraction of the interactions per incident neutron in the boron sample leading to the production of 480-keV gamma rays.

The efficiency ratio was determined by Moxon to within 1.25% at the 6.7-eV resonance peak, where the fractions of the interactions yielding gamma rays per incident neutron for uranium and boron samples approach unity and are very weakly dependent on the cross-sections and resonance parameters.

In order to determine the fraction of the interactions in boron yielding 480-keV gamma rays one needs to know:

(1) The number of boron nuclei in the sample (this was measured to within 1% by the transition method);

(2) The corresponding cross-sections (the total boron cross-section was taken from measurements by Diment [37], and the scattering cross-section from the work of Asami and Moxon [38]; the absorption cross-section in the energy region below 10 keV was taken as $\sigma_\alpha(E) = \frac{610.3}{\sqrt{E}} - 0.28$ barn; in

the energy region above 10 keV, where the deviation from the "1/v" law decreases, the curve passed through the experimental points);

(3) The fraction of neutrons which was initially scattered and then - during subsequent collisions - captured to produce 480-keV gamma rays (the appropriate correction was made).

The uncertainty associated with the cross-section for the reaction $^{10}B(n,\alpha\gamma)^{7}Li$ is the only external source of uncertainties in this experiment and amounts to about 3% in the energy range 100-10 keV, decreasing to 2% at 1 keV.

The mean cross-sections for capture in ^{238}U measured in this way are presented in Table 3 and Fig. 2.

Table 3

Mean capture cross-sections for ^{238}U measured by Moxon [35]

Energy range (keV)	$\sigma_{n\gamma}$ (mbarn)	Energy range (keV)	$\sigma_{n\gamma}$ (mbarn)
0.5 - 0.6	3845 ± 126	8.0 - 9.0	701 ± 45
0.6 - 0.7	2995 ± 105	9.0 - 10.0	701 ± 43
0.7 - 0.8	1712 ± 78	10.0 - 20.0	594 ± 35
0.8 - 0.9	2782 ± 102	20.0 - 30.0	460 ± 28
0.9 - 1.0	3121 ± 109	30.0 - 40.0	380 ± 33
1.0 - 2.0	1772 ± 75	40.0 - 50.0	351 ± 22
2.0 - 3.0	1372 ± 64	50.0 - 60.0	305 ± 18
3.0 - 4.0	1156 ± 59	60.0 - 70.0	253 ± 15
4.0 - 5.0	921 ± 52	70.0 - 80.0	208 ± 13
5.0 - 6.0	856 ± 54	80.0 - 90.0	192 ± 16
6.0 - 7.0	825 ± 49	90.0 - 100.0	183 ± 15
7.0 - 8.0	760 ± 46		

The cross-sections given in the above table are mean values for the corresponding energy ranges and were obtained by Moxon by summing the cross-sections multiplied by the corresponding energy range and divided by the sum of the energy ranges:

$$<\sigma_{n\gamma}> = \frac{\sum_i \sigma_{n\gamma_i} \Delta E_i}{\sum_i \Delta E_i}$$

The total error in the measured capture cross-section is 5.7% at 100 keV, decreasing to 3.4% at 1 keV.

Moxon's results for the energy range 1-100 keV are presented in Fig. 2. There appears to be no sense in including in this figure all the points which appear in Fig. 1. We shall therefore confine ourselves to the most recent data. The results of Poenitz [11] are approximately 15% higher than those of Moxon, but the shapes of the curves are very similar. The results of Belanova at 30 keV coincide with those of Moxon (see below). The value obtained by Schuman at 2 keV is 12% higher than Moxon's results. The results obtained earlier by Moxon and Chaffey using the time-of-flight method [41] give a similarly shaped curve, but the points lie somewhat lower (3-8%). These results were renormalized by Moxon [36] in the energy range 1-30 keV to the same value as the new experimental results.

The remaining known results are either higher or lower than those of Moxon. This applies to the results of Bilpuch [21], which (although they were renormalized by Moxon to the same value as the new experimental results) differ both absolutely (about 20-30% higher) and in the shape of the curve. The values of Hanna et al. [18] at 30 keV are approximately 10% lower and those of Gibbons [30] about 12% higher for the same energy.

The undoubted merit of Moxon's work [36] is the fact that he measured simultaneously the yields of the reactions $^{238}U(n,\gamma)^{239}U$ and $^{10}B(n,\alpha\gamma)^{7}Li$ with the same detector. The measured cross-sections cover the energy range 0.5-100 keV. Possible systematic errors in the measurement have been analysed with extreme care. The shape of the curve of the capture cross-section for ^{238}U in the energy range 1-100 keV measured by Moxon appears to be the most accurate, so that it may be recommended for use. The absolute value of the capture cross-section for ^{238}U at 30 keV is somewhat less than other known values obtained absolutely (Moxon's value is 418 ± 29 mbarn at 30 keV). It is therefore better to take for purposes of normalization the weighted mean of all the existing absolute measurements, including those of Moxon.

Comparison of the results obtained by Moxon with those of other authors and calculation of the weighted mean cross-section is done most easily at 30 keV by means of extrapolation using the shape of Moxon's curve when this is necessary.

In addition to the measurements of Hanna et al. [18], Bilpuch et al. [21], De-Saussure et al. [31], Gibbons et al. [30], Macklin et al. [39], Poenitz [11], Bergquist [40] and Moxon and Chaffey [41] - quoted by Moxon - it is also worth considering the experimental results of Belanova et al. [20] with corrections [34] (495 ± 40 mbarn at 22.8 keV). Extrapolation to 30 keV using the shape of Moxon's curve [36] (with a coeffieient of 1.18) gives a cross-section value of 422 ± 34 mbarn at 30 keV, which coincides with Moxon's measurements: 418 ± 29 mbarn. One should also bear in mind the absolute cross-section measurements made by Miessner and Arai [42], which give a capture cross-section value of 500 ± 30 mbarn at 30 ± 6 keV without self-shielding correction in the uranium sample. With allowance for self-shielding, the authors give a value of 540 mbarn. The results of the measurements of Tolstikov et al. [43] have not been taken into account since their measurements were not absolute ones and were normalized to the old measurements of Belanova (1960).

The results of the measurements enumerated above can be seen in Table 4.

Table 4

Capture cross-sections for ^{238}U at 30 keV

Neutron energy (keV)	$\sigma_{n\gamma}$ (mbarn)	References	Remarks
30 ± 8	375 ± 51	Hanna et al. [18]	Threshold of the reaction Li(p,n)
30	460 ± 48	Bilpuch et al. [21]	Renormalized to the same ^{10}B cross-section value as in [36]
30 ± 8	531 ± 53	De-Saussure et al. [31]	Threshold of the reaction Li(p,n)
30 ± 8	473 ± 43	Gibbons et al. [30]	Threshold of the reaction Li(p,n)
30	530 ± 106	Macklin et al. [39]	Interpolation in [36] from data normalized to the cross-section of tantalum [30]
30	422 ± 34	Belanova et al. [20] with corrections [34]	Extrapolation from 22.8 keV using the shape of Moxon's curve [36]
30 ± 8	479 ± 14	Poenitz [11]	Threshold of the reaction Li(p,n)
30	308 ± 31	Bergquist [40]	Threshold of the reaction Li(p,n); the error in the cross-section is double due to the very large corrections
30 ± 8	403 ± 62	Moxon et al. [41]	Normalization as in [36]
30 ± 6	540 ± 50	Miessner and Arai [42]	Threshold of the reaction Li(p,n); the error of ± 50 mbarn is a tentative estimate
30 ± 8	418 ± 29	Moxon [36]	Normalization to the resonance peak at 6.7 eV; the reaction $^{10}B(n,\alpha\gamma)^{7}Li$ was used for measuring the relative neutron flux
30	448 ± 10	Present work	Weighted mean value obtained from all the above data

The weighted mean value was calculated from the formula

$$\overline{\sigma_{n\gamma}} = \frac{\sum_i \left(\frac{\sigma_i}{\Delta\sigma_i^2}\right)}{\sum_i \left(\frac{1}{\Delta\sigma_i^2}\right)} \; ; \quad \overline{\Delta\sigma_{n\gamma}} = \sqrt{\frac{1}{\sum_i \left(\frac{1}{\Delta\sigma_i^2}\right)}}$$

This weighted mean value (excluding Moxon's data) is 452 ± 10 mbarn. We should include also Moxon's value when calculating the weighted mean capture cross-section so as to be able to use the result as a recommended value. The result is 448 ± 10 mbarn at 30 keV, which is 7% higher than the value obtained by Moxon [36].

It is reasonable to use this value for normalizing the entire Moxon curve at 30 keV - i.e. to raise the entire curve by 7%. Poenitz's results are then only 5-7% higher than those of Moxon - i.e. they coincide with them within the error limits in the 25-100 keV region where comparison is possible. The cross-section value obtained by Schuman [33] at 2 keV is also 5% higher than the renormalized Moxon curve.

When normalized to the weighted mean value of 448 mbarn at 30 keV, all these results virtually coincide.

6. Group cross-sections for capture in ^{238}U in the resonance region 10 eV-1 keV

For the sake of generality let us discuss briefly the resonance energy range. Due to the pronounced resonance structure, the capture cross-section for ^{238}U in this region is usually represented in the form of group cross-sections obtained from resonance parameters. In the old data files, parameters obtained from the early measurements of Firk et al. [44] were used. However, recent measurements [45, 47, 48] and the calculations of Schmidt [46] point to a change in the resonance parameters and to an expansion of the resolved resonance region from 1.8 keV to 3.9 keV. The measurements we have in mind are those of Ashgar et al. [45] for capture and elastic scattering between 5 eV and 1000 eV and the measurements of Glass et al. [47, 48] for capture in the range 30-2050 eV carried out with the help of an underground nuclear explosion. Ashgar et al. give the following value for the mean radiation width: $\bar{\Gamma}_\gamma = (23.74 \pm 1.09) \times 10^{-3}$ eV. The value of Glass et al. is $\bar{\Gamma}_\gamma = (19.1 \pm 2.0) \times 10^{-3}$ eV. The reason for the discrepancy between the mean widths is not clear at present. The only indication that the value for $\bar{\Gamma}_\gamma$ obtained by Glass is too small (as pointed out by Schmidt et al. [49]) is the fact that the resonance integral calculated with this width is approximately 10 barn less than the most accurately known experimental values. We therefore need further careful evaluations and measurements of the resonance data in this energy region.

Using the resonance parameters given by Wallin [50], Häggblom [51] calculated group cross-sections for capture in ^{238}U in the resonance region. There are 57 energy groups between 4 eV and 30 keV. Below 1 keV the groups contain on an average about three resonances and are significantly wider above 1 keV.

The breakdown into energy groups was performed in a rather arbitrary manner with the following assumptions: when there was strong absorption in a group (i.e. for large resonances at low energies or for a large number of resonances in the group) it was assumed that the neutron flux varied in inverse proportion to the total cross-section. No allowance was made for the contribution of the tails of the resonances from other groups to a given group or for the overlapping of different groups.

The cross-sections for capture in ^{238}U in cases of infinite dilution are presented in Fig. 3, where the solid curve represents the cross-sections obtained by Häggblom [51] on the basis of the latest resonance parameters and the dashed line represents cross-sections obtained with the old resonance parameters. The two curves differ most (by ~30%) in the region 2-4 keV; according to Häggblom, this may be due either to the use of incorrect statistical resonance parameters or - partly - to omitted resonances in this region, since the curve rises sharply in the 4-keV region (in the region of unresolved resonances).

The solid curve in Fig. 3 can therefore be used for reactor calculations at energies from 20 eV to 0.5-1.0 keV. Above this energy range one should use the more recent experimental data discussed in Section 5.

Using both the series of constants shown in Fig. 3, Häggblom [51] calculated (for three different reactor spectra and in the one-dimensional diffusion approximation) the cross-section ratios $\frac{\sigma_{n\gamma}(^{238}U)}{\sigma_f(^{235}U)}$ and $\frac{\sigma_{n\gamma}(^{238}U)}{\sigma_f(^{239}Pu)}$. The ratios of the above reactions were also measured for the same reactor spectra. The results of these experiments and calculations are presented in Table 5.

Table 5

Ratios of reaction cross-sections

Type of reaction	Experiment	Calculation using dashed curve in Fig. 3 (old data)		Calculation (solid curve in Fig. 3)		Facility in which experiment performed
		Value	Deviation from experiment (%)	Value	Deviation from experiment (%)	
$\frac{\sigma_{n\gamma}(^{238}U)}{\sigma_f(^{235}U)}$	-	0.1333		0.1288		
	0.138	0.133	3.6	0.129	-6.5	In the centre of the ZPR-3/48 facility
$\frac{\sigma_{n\gamma}(^{238}U)}{\sigma_f(^{239}Pu)}$	-	0.1515		0.1372		-
	0.141	0.148	+5.0	0.136	-3.3	In the centre of the ZPR-3/48 facility
	0.1310 ± 0.004	0.154	+17.7	0.1282	-2.1	In the centre of the Dimple fast reactor

Of course, the absolute capture reaction values are affected by the uncertainty associated with the ^{235}U and ^{239}Pu fission cross-sections. However, the general trend is clear: calculations performed with the more recent data (the solid curve in Fig. 3) give results which are consistently lower than the results obtained with the older data and in general 2-6% lower than the experimental reaction values. This may be due to the excessively low capture cross-section values in the region 1-4 keV which were used in the calculations.

The results of Moxon [36] in the energy region 0.5-7.0 keV and the group cross-sections obtained by Häggblom are presented in Fig. 4. These values agree to within 10-15%, except for the regions 0.5-0.6 keV and 0.9-1.0 keV, where there is a divergence of ~30%. It is difficult in general to make a rigorous comparison, both because it is not quite clear which resonance parameters are the most reliable at present and because in the resulting group cross-sections no allowance was made for the contribution of the tails of the resonances from other groups to a given group or for overlapping of energy groups. It would appear that the greatest uncertainty may be in those groups where the resonances are not entirely in a given energy range - for example, in the groups 0.5-0.6 keV and 0.9-1.0 keV (resonances at 597 eV and 900 eV).

7. Evaluated capture cross-section for ^{238}U

In each of the best-known libraries of evaluated data - in the UK, USA (ENDF/B library) and Germany (KEDAK library) - there is a series of evaluated data on the capture cross-section in ^{238}U.

A description of the UK library as of February 1968 has been given by Norton [52], who points out that the latest evaluation of data on the cross-section for capture in ^{238}U was performed by Vastel et al. [53] in France in February 1968. Their results follow the measurements of Poenitz [11] in the region 20-100 keV and the results of Barry [10] in the region above 300 keV, and hardly differ from the evaluated data of Wittkopf et al. [54] at the Brookhaven centre (ENDF/B library) and the evaluated data of Schmidt [46] (KEDAK library). It is true that Vastel et al. [53] make the reservation that the results of the integral experiments suggest that the capture cross-section curve recommended by them should be approximately 20% lower.

In the resolved resonance region (5 eV-4 keV) Wittkopf et al. [54] used in their capture cross-section calculations the resonance parameters given in the BNL atlas [32] for the energy range 5 eV-1.782 keV and resonance parameters from the measurements of Garg et al. [53] in the region 1.782-3.904 keV. The radiation width was taken as constant ($\bar{\Gamma}_\gamma$ = 24.6 meV) and all the levels were considered as S-levels. In the region 3.92-50.0 keV the capture cross-section was calculated theoretically by using the corresponding parameters for s- and p-neutrons; the smooth curve from BNL-325 was used in the region 50-100 keV and the curve passing through Barry's data [10] in the region 0.1-7.6 MeV.

Finally, the well-known evaluated data in the KEDAK library were obtained by Schmidt [46] in 1966 and reproduced without changes in January 1968 [56].

All these three series of evaluated data agree to within 3-5%.

The data obtained by Berlijn, Hunter and Cremer [57] are less well known. These authors used available experimental data on the cross-section for capture in ^{238}U (data from BNL-325, old evaluated data of Parker [58], and Barry's data [10]) in calculating the results of the various integral experiments performed on fast critical assemblies: measurements of the ratios of the reaction cross-sections, criticality measurements, reactivity measurements. The highest degree of certainty is in the region 0.1-6 MeV since fast critical assemblies were used. It was possible to obtain agreement between the experimental data available at that time (indicated above) and the results of the integral experiments only by reducing the experimental capture cross-sections in the energy range 0.1-5 MeV. Unfortunately, the resulting curve is not unique and the authors therefore give two curves (see the dashed and dotted curves in Fig. 5). Varying the cross-section values between these curves one can obtain equally good agreement with the results of the integral experiments.

The evaluated data of Vastel et al. [53], which are the most recent, are presented in Fig. 5 (the dot-dash line). The two other evaluated data series described above are not shown in this figure since they are very similar (they have been compared by Vastel et al. [53]). The solid curve represents the results recommended in the present paper. In the energy range 1-500 keV this curve is obtained by normalizing the results of Moxon [36] and Poenitz [11] at 30 keV to the weighted mean cross-section value of 448 mbarn.

When normalized in this way Moxon's values increase by 7%, while those of Poenitz decrease by 7% - i.e. they virtually agree (to within 2-3%). In Fig. 5 the renormalized results of Moxon are indicated by dots and the renormalized results of Poenitz by crosses. The smooth curve passing through them is parallel to the curve of Berlijn [57] in the region 1-10 keV (it is about 20% higher); in the region 10-50 keV it lies between the data of Vastel et al. and Berlijn et al., at an approximately equal distance from the two curves. In the energy range 80-500 keV the curve passes very close to one of Berlijn's recommended curves, indicated by dots in Fig. 5.

Since there are still no new data for the region above 500 keV (the data of Poenitz [9] for energies up to 1.3 MeV would be particularly interesting in this connection), it is reasonable for the time being to use in this energy range the Berlijn's upper curve, indicated by dots.

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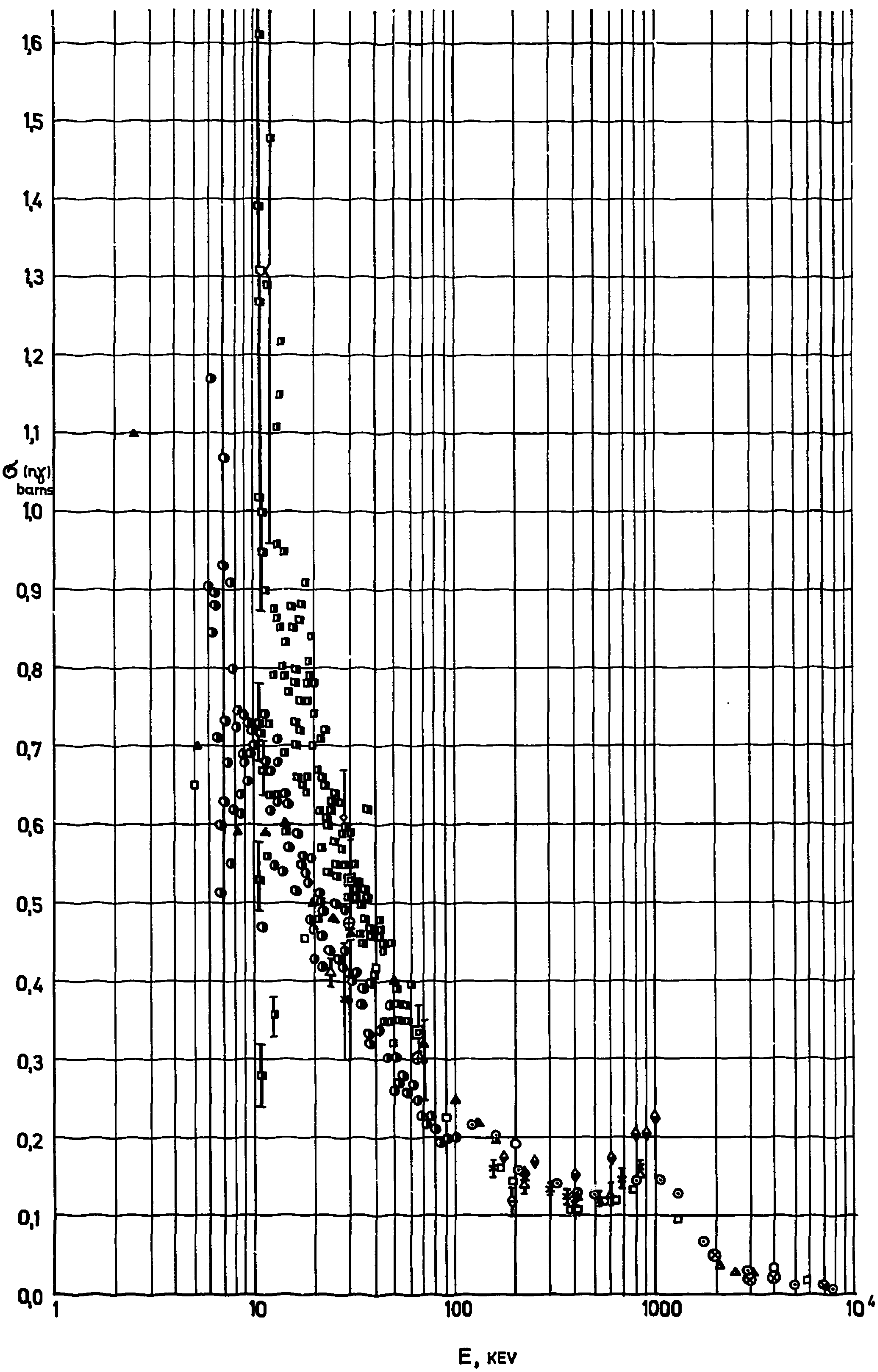

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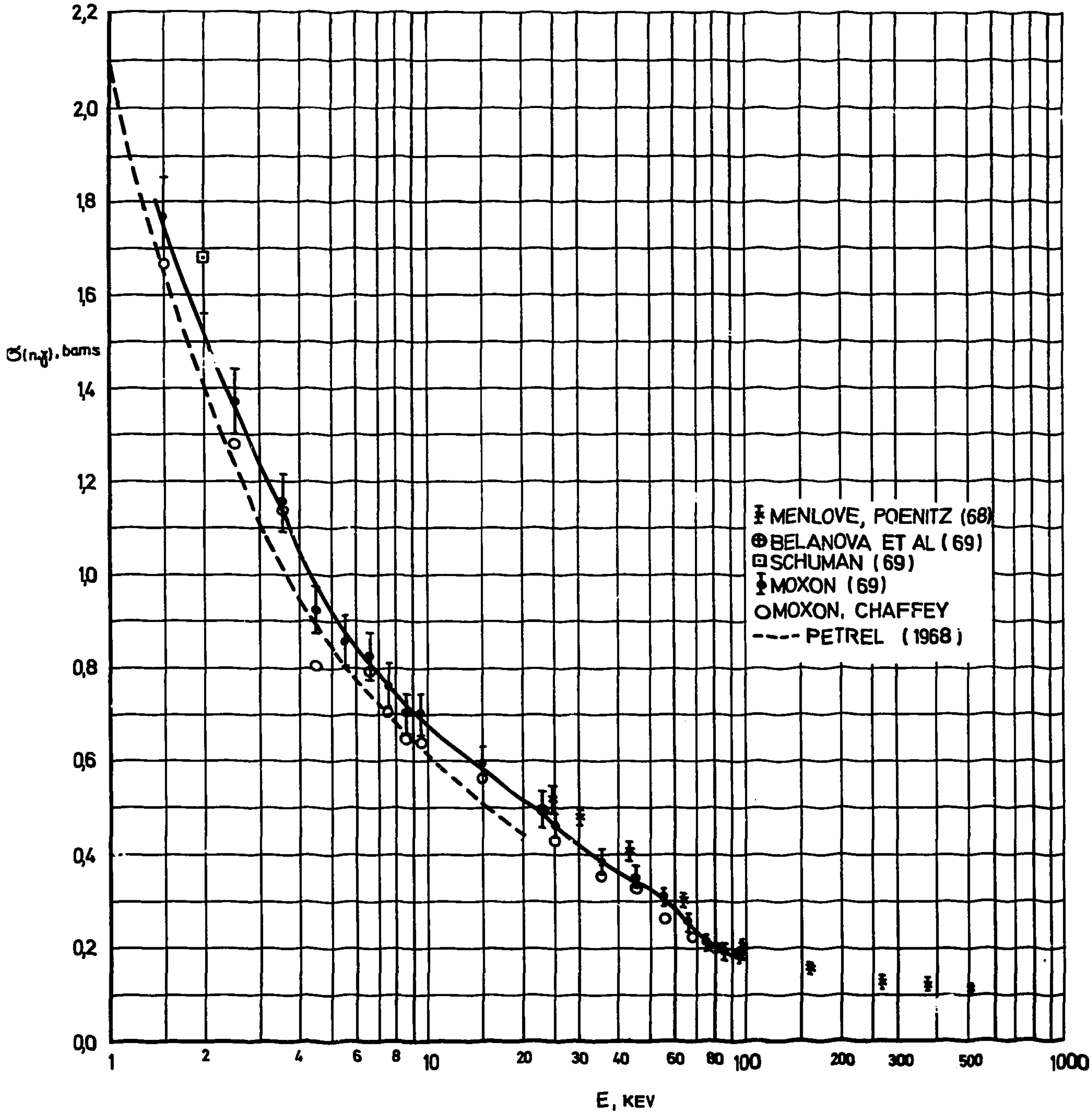
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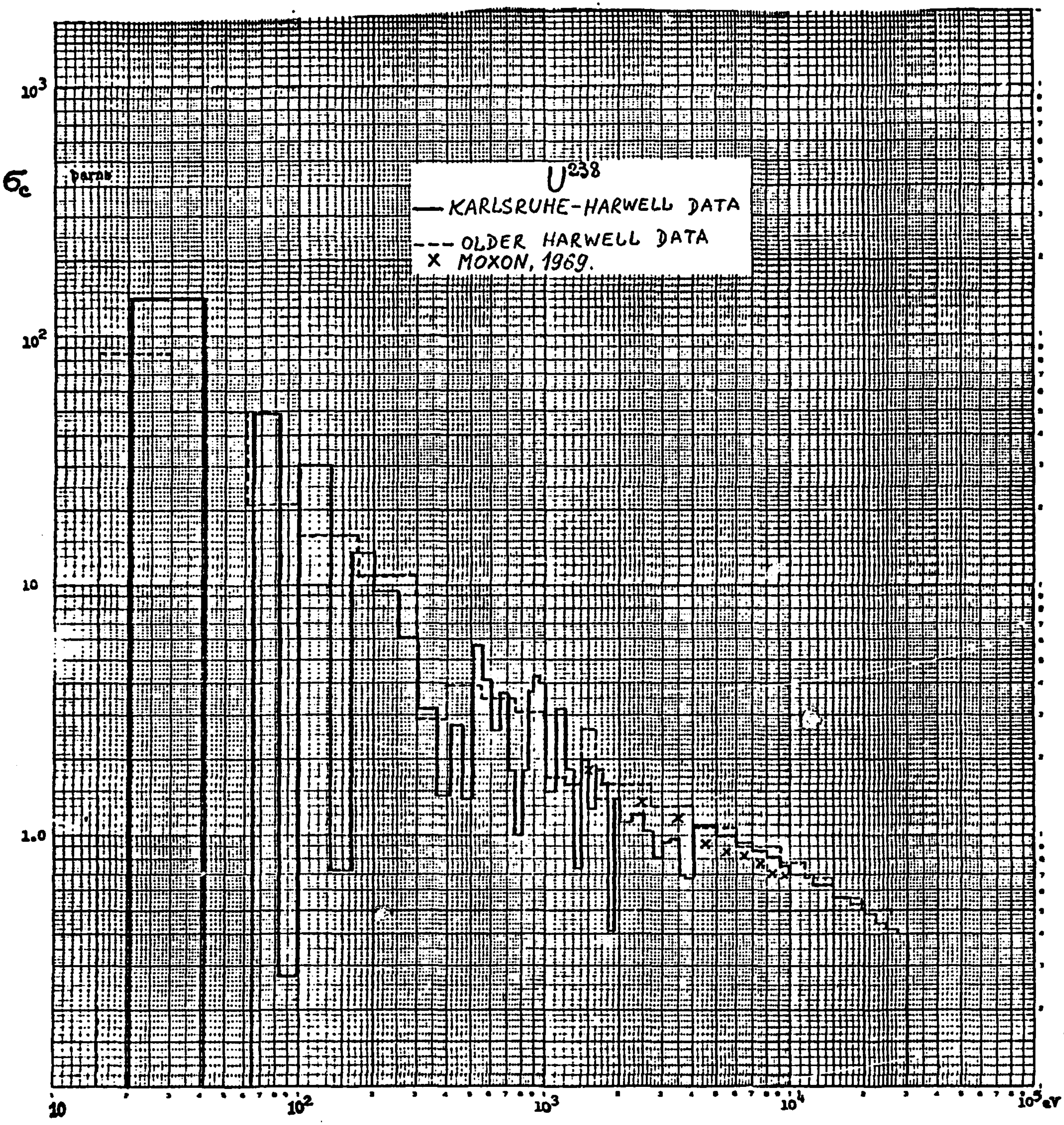

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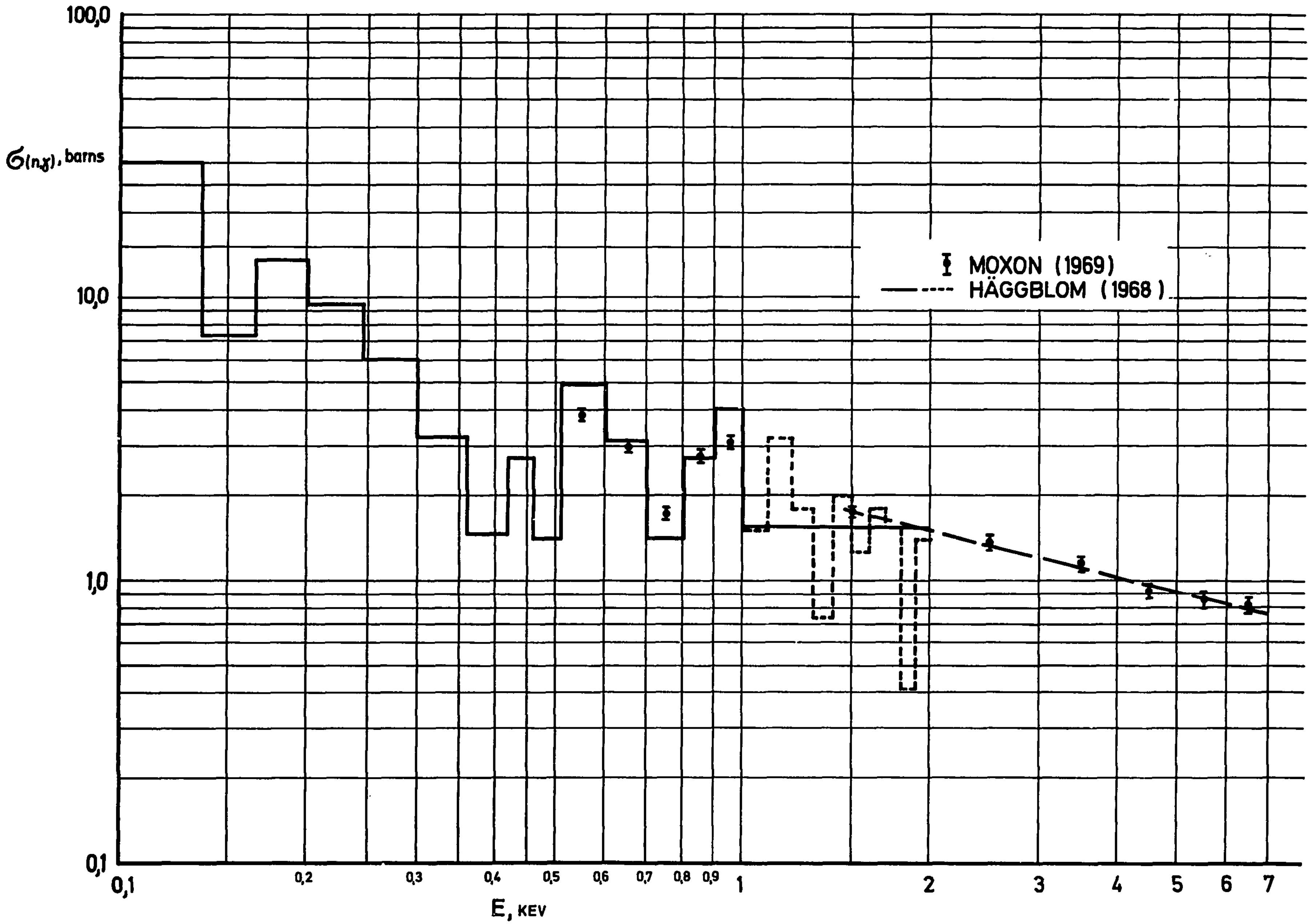
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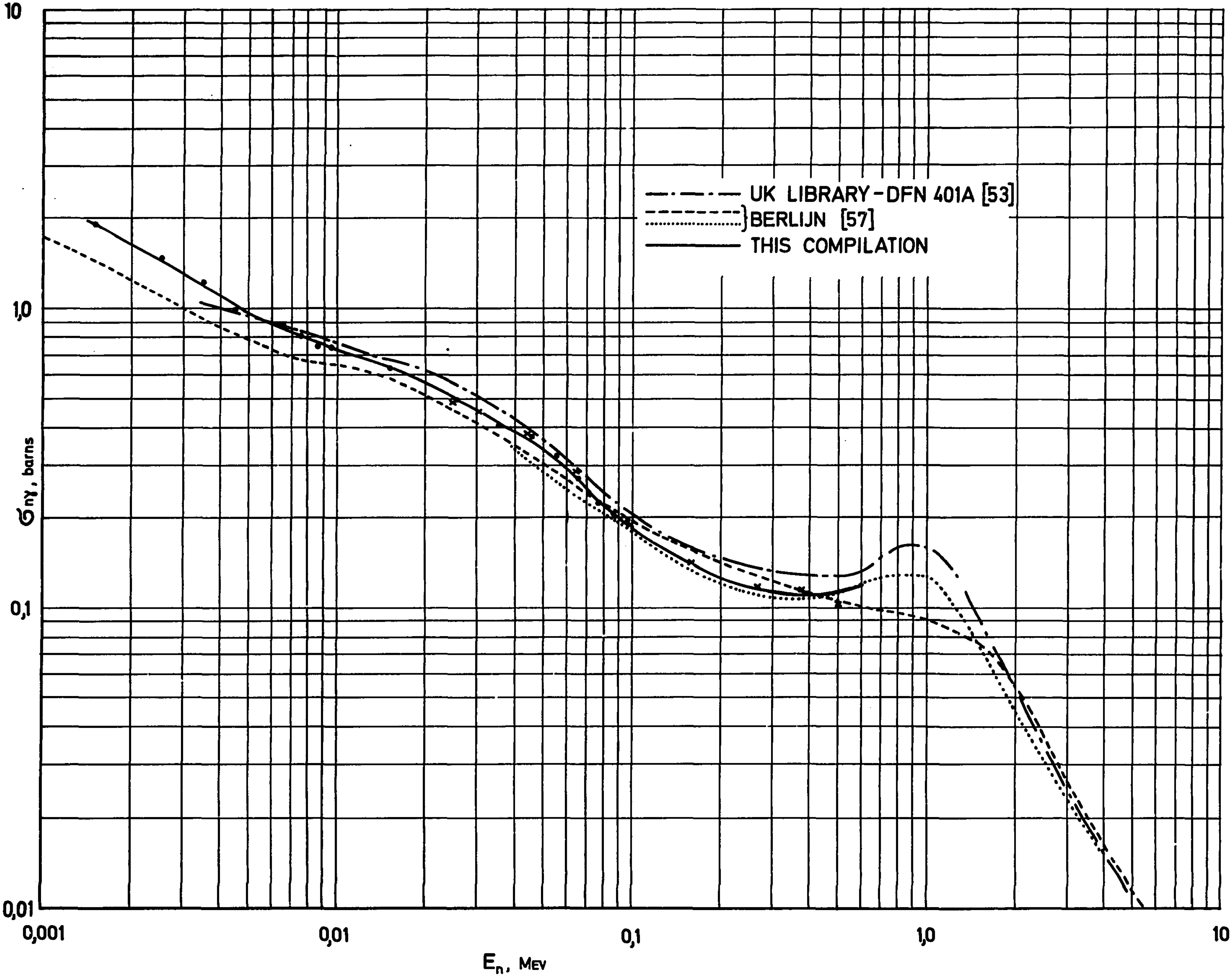

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