NEA/WPEC–3

International Evaluation Co-operation

VOLUME 3

ACTINIDE DATA
IN THE THERMAL ENERGY RANGE

A report by the Working Party
on International Evaluation Co-operation
of the NEA Nuclear Science Committee

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FOREWORD

A Working Party on International Evaluation Co-operation was established under the sponsorship of the OECD/NEA Nuclear Science Committee (NSC) to promote the exchange of information on nuclear data evaluations, validation, and related topics. Its aim is also to provide a framework for co-operative activities between members of the major nuclear data evaluation projects. This includes the possible exchange of scientists in order to encourage co-operation. Requirements for experimental data resulting from this activity are compiled. The Working Party determines common criteria for evaluated nuclear data files with a view to assessing and improving the quality and completeness of evaluated data.

The Parties to the project are: ENDF (United States), JEF/EFF (NEA Data Bank Member countries), and JENDL (Japan). Co-operation with evaluation projects of non-OECD countries are organised through the Nuclear Data Section of the International Atomic Energy Agency (IAEA).

The following report was issued by a Subgroup investigating actinide data in the thermal energy range. Thermal nuclear constants for the primary actinides have been extensively studies, but the most recent evaluations are not in full agreement with thermal reactor calculations. The objective of the Subgroup was to identify the origin of these differences and to reassess the recent evaluations. A considerable effort was devoted to the η of U-235, where analysis of lattice temperature coefficient measurements has suggested an energy dependent shape below thermal energy.

The opinions expressed in this report are those of the authors only and do not represent the position of any Member country or international organisation. This report is published on the responsibility of the Secretary-General of the OECD.

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THERMAL NEUTRON ACTINIDE DATA*

1. Introduction

During the 70's, the physicists involved in the cross-section measurements for the low-energy neutrons were almost exclusively interested in the resonance energy range. The thermal range was considered as sufficiently known. In the beginning of the 80's, reactor physicists had again to deal with the delicate problem of the power reactor temperature coefficient, essentially for the light water reactors. The measured value of the reactivity temperature coefficient does not agree with the computed one. The later is too negative. For obvious safety reasons, it is an important problem which must be solved. Several causes were suggested to explain this discrepancy. Among all these causes, the spectral shift in the thermal energy range seems to be very important. Sensibility calculations show that this spectral shift is very sensitive to the shape of the neutron cross-sections of the actinides for energies below 1 eV. Consequently, reactor physicists require new and accurate measurements in the thermal and sub-thermal energy ranges [1,2]. A part of these new measurement results was recently released and reviewed [3]. The purpose of this study is to complete the preceding review with the new information which is now available. In reactor physics the major actinides are the fertile nuclei, i.e., uranium-238, thorium-232 and plutonium-240 and the fissile nuclei, i.e., uranium-233, uranium-235 and plutonium-239. For the fertile nuclei the main datum is the capture cross-section, and for the fissile nuclei the data of interest are $\bar{\nu}$, the fission and capture cross-sections or a combination of these data such as η or α. In the following Sections, we will review the neutron data of the major actinides for the energy below 1 eV.

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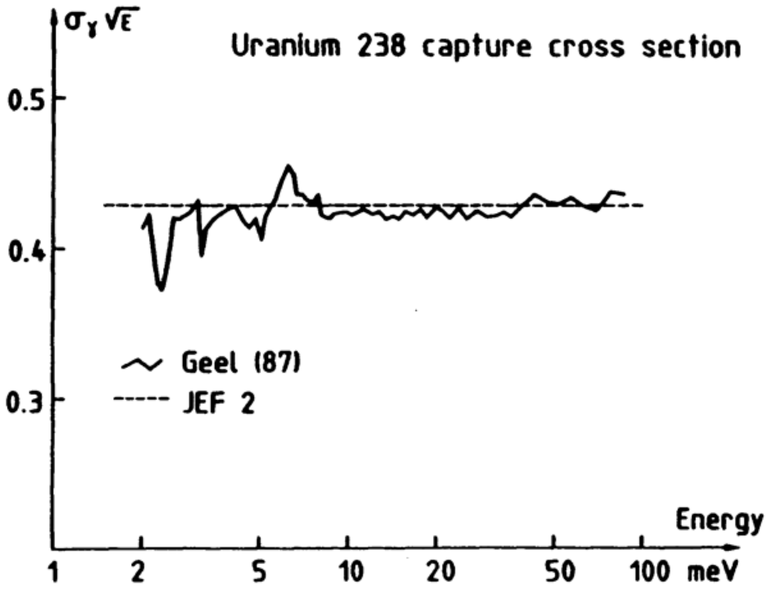

Figure A-1
Uranium-238 capture cross-section measurement comparison between Geel metal sample and JEF-2 evaluated values

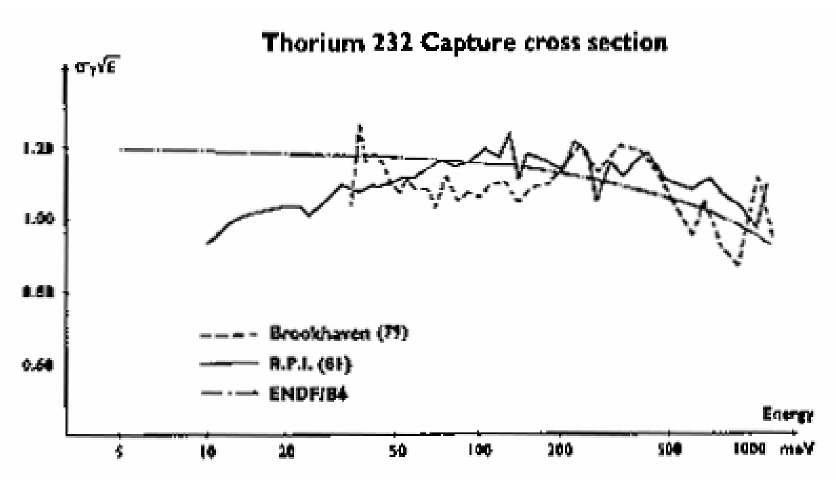

Figure A-2
Recent measurements of thorium-232 capture cross-section and comparison with ENDF/B-VI evaluated values

2. Uranium-238

At low energy, the cross-section shapes of uranium-238 are given by the 4.4 eV "*p*"-wave and the 6.67 eV "*s*"-wave resonances. These two resonances induce for capture cross-section a l/v behaviour in the thermal range. It is the shape which is universally adopted by all evaluated files. But part of the temperature coefficient discrepancy could be explain by a non-l/v-dependence on the uranium-238 capture cross-section for the low-energy neutron. The cross-section must decrease with the energy faster than the l/v shape. This effect can be obtained with the assumption of a weak bound level near the zero energy. L. Erradi proposed a small resonance at –0.005 eV [4]. This hypothesis was supported by the measurement of the fission cross-section at 0.025 eV which was performed in Grenoble [5]. The experimental value cannot be exclusively explained by the contribution of the nearby resonances. An extra resonance is needed. If this resonance is close to the zero energy as in the Erradi's assumption, it must have an impact on the cross-section shape in the thermal range. The non-l/v-shape which is obtained with the –0.005 eV resonance is not incompatible with the Harwell measurement of the uranium 238 capture cross-section [6] but only because the experimental uncertainties of this measurement are rather large. New and more accurate measurements of the uranium-238 capture cross-section were required. These measurements were performed at the Geel laboratory [7]. As it can be seen in Figure A-1 which represents the experimental variation of $\sigma_\gamma \sqrt{E}$ as a function of the neutron energy, and a comparison with the JEF evaluation, these results confirm without ambiguity a l/v behaviour for the capture cross-section. The assumption of the resonance in the immediate vicinity of the zero energy and the explanation of part of the temperature coefficient discrepancy by such a resonance must be dropped. Reasonably, we must consider that the uranium-238 capture cross-section problem is solved as far as the thermal energy range is concerned.

3. Thorium-232

Nowadays, the use of thorium fuel cycle in thermal neutron reactors is no longer a high priority and the physicists' interest for thorium nuclear data is less important in the case of low energy neutron than in the fast range. Consequently the situation is fundamentally different from that of uranium-238. That is why no request recently appeared for the thermal neutron energy range. In this energy domain there exists only two recent differential measurements which give access to the shape of the thorium-232 capture cross-section. These are respectively the measurement performed in Brookhaven for energies between 35 and 1000 meV [8] and the experiment of RPI which covered neutron energies above 10 meV [9]. These two sets of experimental data are compared in Figure A-2 which displays the variation of $\sigma_\gamma \sqrt{E}$ versus the neutron energy. If we take into account the experimental uncertainties, the agreement between both measurements is good enough above 50 meV. They are also in good agreement with the recommended value of the ENDF/B-VI evaluation. In the very low-energy domain, between 10 and 25 meV, only one measurement significantly deviates from the evaluated recommendation. The experimental cross-section decreases less than a l/v shape. We know that the temperature coefficient of a multiplying lattice is very sensitive to the shape of the fertile nucleus capture cross-section below 25 meV. In the case of a thorium cycle revival, the observed discrepancy between the measurement and the evaluation must be clarified as it was recently done for uranium-238. New and accurate measurement of the thorium-232 capture cross-section would be needed in the thermal and sub-thermal energy range.

4. Plutonium-240

For this isotope, the cross-section behaviour in the thermal energy range is mainly governed by the 1.056 eV resonance. Consequently it is necessary to have a very accurate knowledge of these resonance parameters. Only two measurements of the 1.056 eV resonance parameters were recently carried out: the Brookhaven experiment [10] and the Oak Ridge one [11]. In the Brookhaven experiment, total and capture cross-sections with room temperature and cooled samples were used. In the Oak Ridge measurement, transmission measurements with seven thicknesses of sample were performed. Thus it was expected that the results could be very satisfactory. Unfortunately, as it can be seen from Table 1, both sets of results are significantly discrepant.

Table A-1 : ***Parameters of the ^{240}Pu 1.056 eV resonance***

Γ_n (meV)	Γ_γ (meV)	LABORATORY
2.32 ± 0.06	32.4 ± 0.6	Brookhaven (81) [10]
2.45 ± 0.02	30.3 ± 0.3	Oak Ridge (87) [11]

A detailed analysis of both experiments leads to be more confident in the second set of results. But the interpretation of spent fuel isotopic composition suggests tendencies closer to the high value of radiative capture width. The difference between the two series of resonance parameters induces a change of 1.2% in the contribution of the 1.056 eV resonance to the capture cross-section at 0.025 eV and a change of 4.5% in the resonance integral value. These modifications become very important each time that plutonium-240 is significantly involved. It is mainly the case for irradiated fuel analysis or for plutonium recycling is light water reactor. The discrepancy between both differential measurements and the tendency deduced from the integral experiments must be clarified then.

5. Uranium-235

In the case of a fissile nucleus, the problem is even more complex than for a fertile nucleus. In addition to the capture cross-section, other fundamental nuclear data are involved, the number ν of neutrons which are emitted in a fission and the fission probability. These three quantities, or a combination of them such as η or α must be investigated. As the temperature coefficient is very sensitive to the shape of the various nuclear parameters versus the neutron energy (see above), several differential measurements were performed during the last years. They are relative to the fission cross-section, $\bar{\nu}$ and η in the very low-energy range.

a) $\bar{\nu}$

One measurement of $\bar{\nu}$ was recently performed in the energy range which we are interested in. The Oak Ridge experiment gives the ratio of the uranium-235 prompt $\bar{\nu}$ over the Californium ν_{sp} of spontaneous fission for the neutron energies between 5 meV and 1 eV [12]. According to these results, which are displayed in Figure A-3, nothing appears in the vicinity of the 0.29-eV resonance and we can reasonably keep the assumption of a constant value of $\bar{\nu}$ below 1 eV. This flat shape, which is adopted in all evaluated files, has important consequences for the capture cross-section behaviour at low energy.

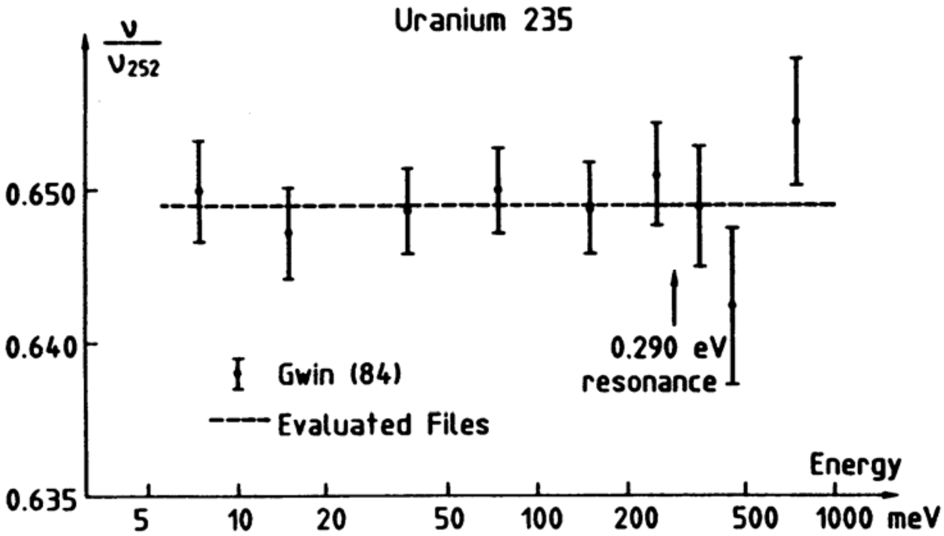

Figure A-3

Ratio of uranium-235 $\bar{\nu}$ to that of californium-252 in the thermal energy range and comparison with evaluated values

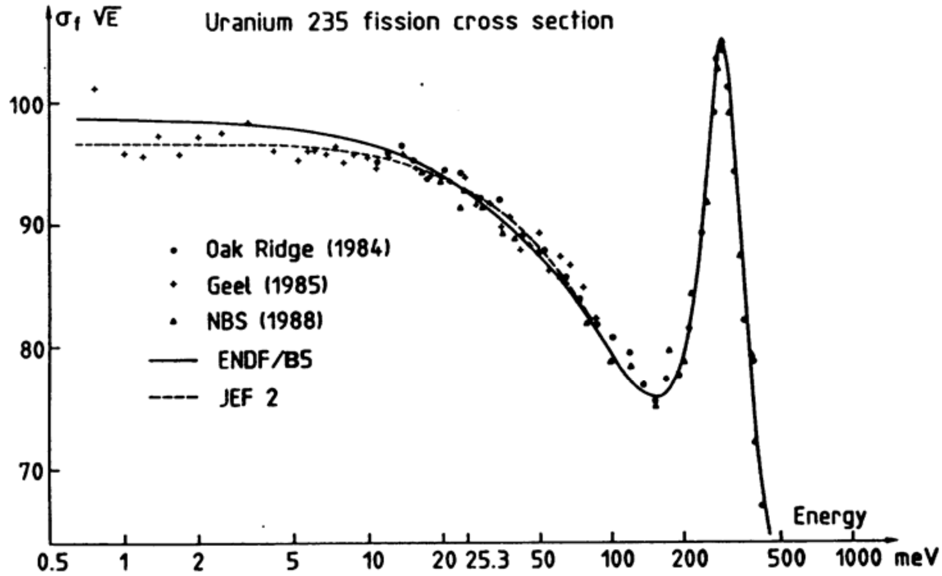

Figure A-4

Recent measurements of uranium-235 fission cross-section and comparison with ENDF/B-V and JEF-2

b) Fission cross-section

Since 1984, very accurate measurements were performed in the low-energy neutron range [13, 14, 15]. As it can be seen from Figure A-4, above 20 meV and in particular in the 0.290 eV resonance all these results are in agreement with each other and also with the most recent evaluated files ENDF/B-V and JEF-2. In the sub-thermal energy range, below 5 meV, only the Geel experiment gives information.

According to this measurement the uranium-235 fission cross-section reaches an l/v shape for energies higher than it was assumed in ENDF/B-V. On the contrary, JEF-2 which was released after the Geel experiment takes into account its results below 10 meV and adopts a fission cross-section shape closer to a l/v behaviour.

c) η measurements

To explain the temperature coefficient discrepancy of the uranium fuel reactor, it is $\eta = \nu \frac{\sigma_f}{\sigma_\alpha}$ which is the most sensitive parameter. In all previous evaluated files, including ENDF/B-V and JEF-1 η was assumed to have a constant value below 0.1 eV. As the reactor physicists proposed to increase η between 5 and 100 meV, measurements of this neutron parameter were needed to validate the shape modification. Four measurements of η were recently performed in the range of interest.

The first one is the Geel experiment [16]. This experiment was performed with a linac and a liquid methane moderator to enhance the importance of the low-energy neutrons. It covered the neutron energy between 2 and 450 meV. As shown in Figure A-5 the results suggest an increase of η between 2 and 80 meV, which would represent an improvement in reactor physics calculations.

A second measurement was carried out with the Harwell linac [17]. Unfortunately the number of low-energy neutron was not very high. Consequently the accuracy was not good enough. Nevertheless this experiment did not show a significant shape of η versus the neutron energy as displayed in Figure A-6. It is contradictory with the Geel results.

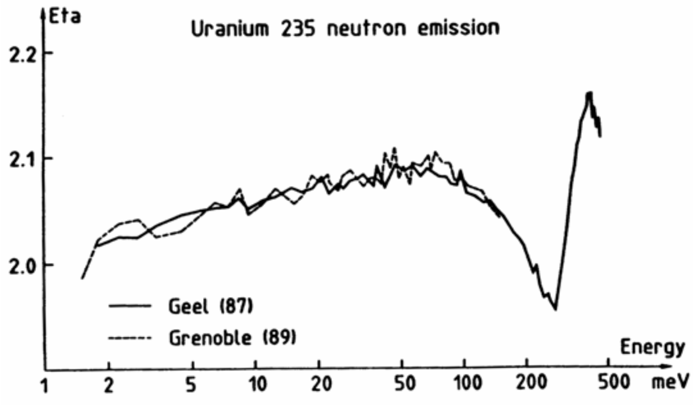

Figure A-5

Experimental results of uranium-235 η measurements of Geel and Grenoble in the low-energy neutron range

A third experiment was performed in Grenoble [18]. Instead of a linear accelerator, as in Geel, the neutron source was constituted by a cold neutron beam of the high flux reactor and more neutron of low energy were obtained. The accuracy was then expected to be better because the background would be lower. In the energy range between 2 and 150 meV, this experiment perfectly confirms the Geel results and the shape of η versus energy as shown in Figure A-5.

Finally a fourth experiment was carried out with the Oak Ridge linac [19]. The preliminary results of the last experiment are compared with the Harwell results in Figure A-6. These two series of results seem more or less in agreement and do not show a significant shape of η.

These four experimental results can be split into two sets: the first set indicates a shape of η (Geel and Grenoble data) and the second set does not (Harwell and Oak Ridge data). As the low neutron flux was higher in the Grenoble experiments, it is possible to given a more important weight to these results and to propose a slope for the η shape below 100 meV. This attitude was adopted for the preliminary version of JEF-2. But from the physical point of view, the disagreement between both sets of results is not acceptable. On behalf on the NEA Nuclear Science Committee, a working group carefully studied the various corrections (count loss, background subtraction, absorption...) which were applied to the raw data of the four measurements. The final recommendations of the working group have not been established yet but the preliminary results are encouraging. It seems that it may be quite possible to define a curve of η with an energy-dependent shape. η would increase by a factor of about 1.3 between 3 and 80 meV and this energy dependence would be compatible with the four experimental data [20]. This shape would be close to the reactor physicists' suggestion.

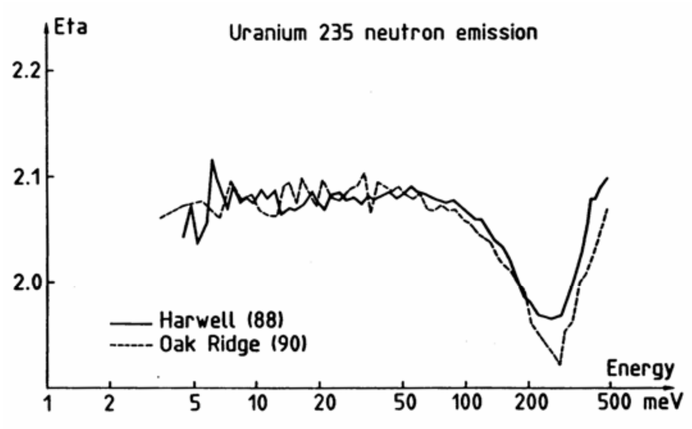

Figure A-6
Experimental results of uranium-235 η measurements of Harwell and Oak Ridge below 500 meV

d) α measurement

A complementary and important information upon the uranium-235 cross-section in the thermal energy range is given by the recent Geel measurement of α [21]. This result is very interesting because it constitutes an independent way of obtaining information about $\eta = \frac{\nu}{1+\alpha}$. As it can be seen in Figure A-7, the experimental values of α are not reproduced by the ENDF/B-V evaluation. As all previous files, ENDF/B-V recommends a flat shape of α below 100 meV. As ν is energy-independent, this shape corresponds to a constant value of η. On the contrary, a slope for η was adopted in JEF-2 and this file, which was released before the experimental values of η, is in good agreement with the measurement results. It is an important fact, because we now have a coherent set of experimental data for ν, σ_f, η and α, which confirm the slope of η, as it was suggested by the integral experiment.

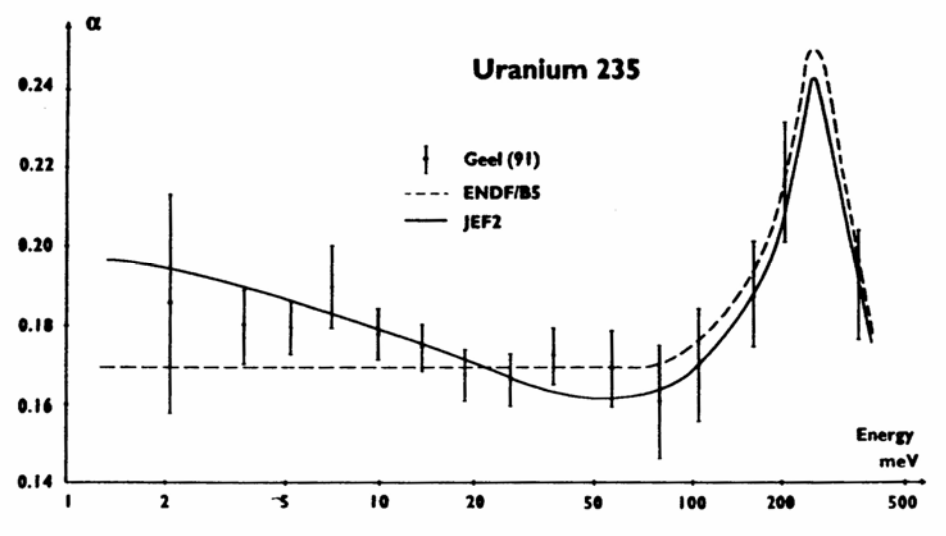

Figure A-7

Uranium-235 α-parameter measurement and comparison with ENDF/B-V and JEF-2 recommended values

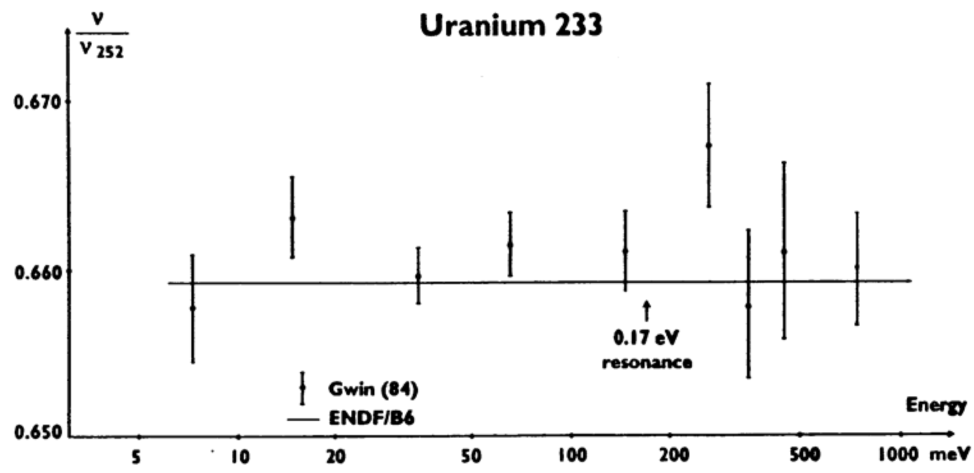

Figure A-8

Ratio of uranium-233 $\bar{\nu}$ to that of californium-252 and comparison with evaluated values below 1 eV

6. Uranium-233

For the same reasons as for thorium, the uranium-233 nuclear data in the low-energy range have not been systematically studied over these last years. Nevertheless there exist some scarce results, mainly for $\bar{\nu}$ and the fission cross-section. These measurements were generally performed in the same campaign as uranium-235 when physicists had uranium-233 samples at their disposal. For η and α, nothing new is available.

a) $\bar{\nu}$

The only result about $\bar{\nu}$ below 1 eV is the one of Oak Ridge [12] which gives the ratio of uranium-238 prompt $\bar{\nu}$ to the spontaneous fission $\bar{\nu}$ of californium-252. No significant structure was observed in this energy range, as shown in Figure A-8 and we can reasonably admit the flat shape which is adopted in ENDF/B-VI. *Note that the ENDF/B-VI absolute value of* $\bar{\nu}$ *is not in agreement with the tendency which is deduced from the buckling measurements* [22].

b) Fission cross-section

At the opportunity of the campaign of measurements on fissile nuclei, an accurate determination of the shape of the uranium-233 cross-section shape was carried out with the Geel linac [23]. In order to enhance the low-energy neutron flux and obtain a good accuracy in the thermal and sub-thermal energy range, a liquid nitrogen-cooled moderator was used. In these experimental conditions we can be very confident in the results which are displayed in Figure A-9. They are also in fair agreement with the ENDF/B-VI recommendation. Reasonably we can admit that the shape of the uranium-233 fission cross-section is well known below 1 eV.

7. Plutonium-239

All old evaluations of the plutonium-239 neutron data, including ENDF/B-V, are considered to be not satisfactory by reactor physicists. As a matter of fact, in all these files it was adopted a flat behaviour of $\bar{\nu}$ in the low-energy range, the spin of the resonances was not considered and it was used a Breit and

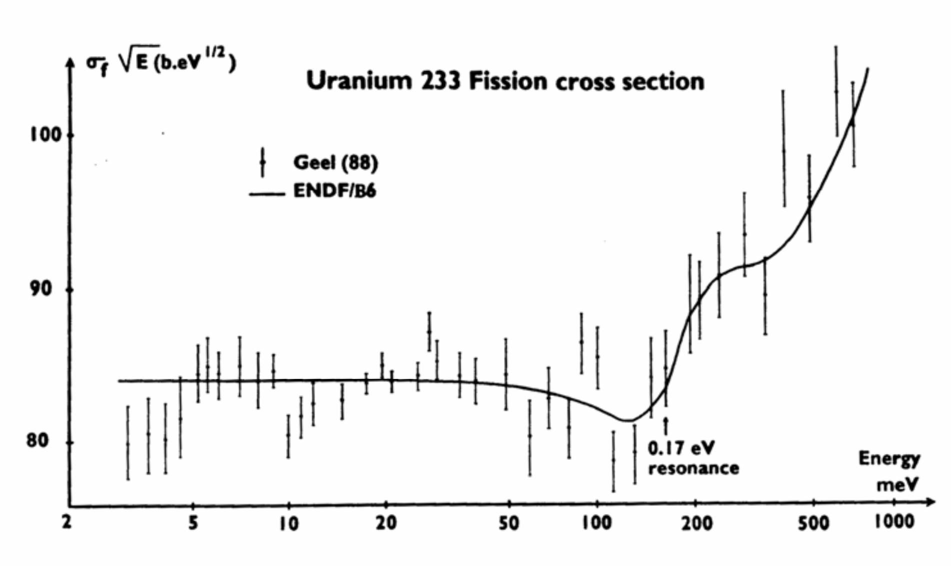

Figure A-9
Experimental fission cross-section of uranium-233 and comparison with ENDF/B-VI

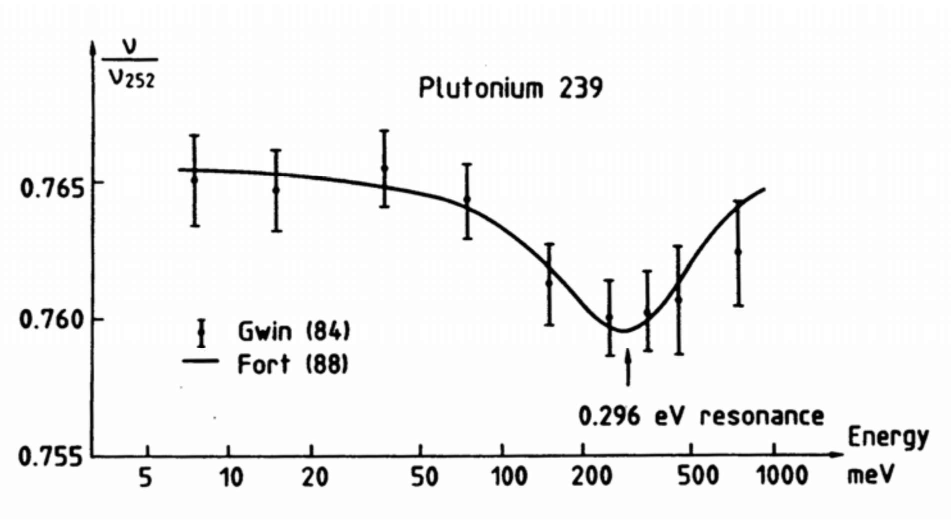

Figure A-10
Ratio of plutonium-239 $\bar{\nu}$ to that of californium-252 and comparison with Fort's theoretical calculation

Wigner formalism to compute the cross-sections. With high burnup fuels and recycling, plutonium has become more and more important in the thermal neutron reactors. An updating of the plutonium-239 neutron data was strongly required. This updating was performed by Derrien et al. [24] who took into account of new experimental results, concerning $\bar{\nu}$ [12], the fission cross-section [13] and the total cross-section [11], and used a Reich and Moore formalism which is more convenient for the fissile nuclei.

a) $\bar{\nu}$

As opposed to uranium-233 and uranium-235 cases, the recent measurement of plutonium-239 $\bar{\nu}$ [12] shows an important decrease in the vicinity of the low-energy resonance at 0.3 eV. This strong structure is well reproduced by the Fort's theoretical calculation which takes into account the spin effect and the (n,γf) effect of the J = 1 resonances of plutonium-239 [25]. Figure A-10 represents a comparison between the experimental values of $\bar{\nu}$, normalised to the spontaneous fission $\bar{\nu}$ of californium-252, and the evaluation of Fort et al. As the agreement is very good, this shape of $\bar{\nu}$ was included in JEF-2.

b) Fission cross-section

All new evaluated files use the resonance parameter set which was deduced from Derrien's analysis. The behaviour of plutonium-239 cross-sections in the thermal range is well reproduced by the contributions of low-energy resonances and bound level. Once the initial version of the recent evaluated files was released, a new measurement of the plutonium-239 fission cross-section became available [23]. Figure A-11 shows the comparison of these new experimental values with the recommended values of JEF-2 below 1 eV. The agreement is quite satisfactory and the new fission cross-section measurement constitutes a confirmation of the recommended values. Today, no request upon the plutonium-239 fission cross-section seems necessary as far as the low energy is concerned.

8. Conclusion

The status of the thermal neutron data for the major actinides has been greatly improved for the last few years. The recent measurements of the microscopic data led to a better knowledge of the cross-section shapes in the low-energy domain. Several problems of great importance in reactor physics were solved. Let us mention for instance the l/v-dependence of the uranium-238 capture cross-section and the behaviour of the uranium-235 fission cross-section below 20 meV. The structure of the plutonium-239 $\bar{\nu}$, which was not taken into account in the past, was well established and theoretically explained. We can reasonably expect that the uranium-235 η discrepancy will be solved in the near future. Nevertheless there remain some problems which have to be further investigated. The most important one today is the discrepancy between both sets of parameters of the 1.056 eV plutonium-240 resonance. This disagreement has an important impact on high burnup fuels or plutonium recycle studies. The difference between the evaluated values and the measured values of the thorium-232 capture cross-section below 20 meV and the problem of the absolute value of the uranium-233 $\bar{\nu}$ have a lower priority. But in the case of new interest for the thorium cycle, requests upon these two actinides will certainly be needed.

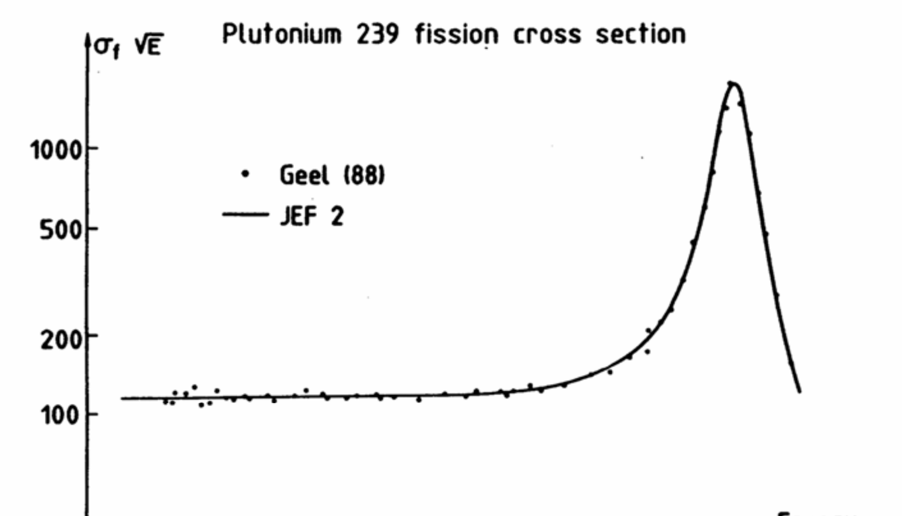

Figure A-11
Comparison between Geel last fission cross-section and JEF-2 recommended values for plutonium-239 below 500 meV

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ANALYSIS OF η MEASUREMENTS FOR URANIUM-235 IN THE THERMAL NEUTRON ENERGY REGION**

Abstract

Existing experimental data on η of ^{235}U in the thermal and sub-thermal energy regions are reviewed. Special attention is given to the various systematic uncertainties. When combined with recent fission cross-section data, an R-matrix fit yields a good representation of the data in the energy region below ~0.2 eV. At higher energies problems remain and they need further investigation.

1. Introduction

The detailed energy-dependence of neutron cross-sections and related parameters of fissile nuclei for sub-thermal neutron energies has recently found considerable attention because of its effect on the temperature reactivity coefficient of thermal reactors [1]. One of the quantities thus considered is η *** of ^{235}U.

Several measurements of the energy dependence of this quantity have been performed in recent years. The two earlier ones were carried out at Harwell [2] and Geel [3], and the later measurements at the ILL, Grenoble [4], and at ORELA by a Harwell-ORNL collaboration [5]. Finally a measurement of the related quantity α was done at Geel [6].

Preliminary analysis of some of these data seemed to show discrepant results, although the differences were at the limit of the combined systematic uncertainties. Therefore, a Subgroup of the NEA Working Party on International Evaluation Co-operation was set up to further investigate this problem. In this note the conclusions of the Subgroup are addressed.

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*** Number of fission neutrons emitted per neutron absorbed.

In Section 2 we will briefly discuss the experimental techniques applied and their difficulties. In Section 3 we will present our findings for the thermal and sub-thermal energy regions, and in Section 4 we will point out still existing problems at somewhat higher energies (above ~0.3 eV).

2. Experimental techniques and difficulties

As a general statement it may be said that systematic corrections which had to be applied to the measured data are important, and so are systematic uncertainties, as they are compared with the size of the effect under investigation. However, some of the experiments differ strongly in the applied techniques, and as a consequence the relative importance of the various systematic uncertainties is rather different.

The principle method to measure the energy dependence of η is simple: A beam of low-energy neutrons first passes through a flux monitor before it hits a “black” metallic U sample. The transmission of this sample is almost zero for neutron energies below 0.1 eV. Fission neutrons emerging from this sample are detected by a NE-213 liquid scintillation detector. Pulse shape discrimination is used to distinguish neutrons from γ-rays. The shape of the neutron flux is measured by replacing the black U sample by a neutron capture sample which is also “black” for neutrons in the energy range of interest. Samples of ^{10}B and Cd have been used. Thus the shape of the neutron flux is directly obtained from the yield of γ-rays from the capture sample. The flux monitor is used only to record possible changes of the neutron flux shape between the fission measurements with the black U sample and the flux measurement with the capture sample.

The earlier Harwell and Geel as well as the more recent Harwell-ORNL measurements used a linac pulsed white neutron source and conventional time-of-flight technique. The most difficult problem in these measurements is to determine backgrounds, especially in the sub-thermal region: Every fission event in the U sample produces neutrons which may be back-scattered from the surroundings and produce a delayed fission event in the sample at a later time. A decaying background with a few ms delay is indeed seen in measurements with a Cd filter. The true background cannot be readily measured because any background filter, e.g., Cd, will take away most of the source of the background as well.

In the latest analysis of the Harwell-ORNL data much effort has been devoted to reconstruct the background by folding the delayed component observed in the measurement with the Cd filter into the foreground fission rate. This and an extrapolation to zero filter thickness were best possible to be carried out on the Harwell-ORNL data. Measurements on samples of Pb and C provided an additional guideline for the determination of the background and the effect of the filters used to determine the background.

In the measurement at the ILL reactor the flux at the thermal neutron guide was sufficient to allow the use of a double chopper setup: Two choppers, separated by about 3 m, essentially produced a pulsed monoenergetic beam. The sample for the η measurement (or the capture sample for the flux measurement) was placed another 0.9 m downstream from the second chopper. Thus the time signal from the detector could be used to separate background events due to out-of-time neutrons from true events. With this method the uncertainty in background determination could be reduced. On the other hand, instantaneous count rates during the neutron pulse were high, and therefore also the count-loss corrections, which reach a maximum of ~6% at about a 60-meV neutron energy. In the original analysis no correction was applied for a count-rate dependent cross talk between γ-rays and neutron output channels of the PSD circuit. Recent inclusion of this effect resulted in a slight reduction of the energy dependence of η (by 0.2% between thermal and 2 meV).

In all the η measurements corrections have to be applied for incomplete absorption and for multiple scattering of the incident neutrons in the U sample. These finite sample size corrections are very small at low neutron energies, but increase sharply as the absorption cross-section drops at energies above 0.3 eV. We will come back to this point in Section 4.

In addition, a correction must be applied for absorption and multiplication of the emitted fission neutrons in the U sample: It depends on the place in the sample where the primary fission event took place and thereby on the incident neutron energy. The maximum amount of this correction reaches ~3.5% for the Geel and Grenoble measurements, whereas it is smaller for the Harwell-ORNL measurements due to the use of a detector which subtended a larger solid angle to the sample.

In contrast to the η measurements, in the α measurement performed at Geel, the count-loss and finite sample size corrections are both negligible. The method is based on the measurement of the intensity ratio of specific low-energy capture γ-rays and prompt fission γ-rays with a Ge-detector. However, it is based on the assumption that the relative yields of the measured γ-rays per capture and fission event, respectively, do not vary as a function of neutron energy. This will only be fulfilled as long as the relative contributions of different resonances to the cross-sections do not strongly vary, i.e. only for an energy interval which is smaller than the typical resonance width. The method is thus limited to the sub-thermal and near-thermal energy region. The main experimental uncertainty is due to a limited statistical precision.

3. Results

With the improved determination of the various corrections as described above, the different data are in fairly good agreement for neutron energies below ~0.3 eV. At higher energies some problems remain; they will be further discussed in Section 4.

In the "low-energy region" we attempted to produce a "best curve" representing the general behaviour of the experimental data. This was carried out by a simultaneous R-matrix fit of the fission and capture cross-sections of ^{235}U obtained from the following experiments:

- Fission cross-sections data of Wagemans et al. [7],
- η data from the experiments at Geel, Grenoble, and the Harwell-ORNL data,
- α data from Geel.

The Reich-Moore R-matrix routine MULTI [8] was used to carry out the fit to the data over the energy range 1.5 to 300 meV. We started from the resonance parameters as given by Leal et al. [9], omitting however the states at -3.49 and -1.50 eV as they were found to have very little effect on the cross-sections. We then iterated on the parameters of the resonances between -1.0 and 1.5 eV. The best overall fit to the data was obtained for the parameter set given in Table B-1.

Table B-1 ***Resonance parameters obtained from the R-matrix fit***

E [eV]	[meV]	[meV]	[meV]	[meV]	J
–0.4065	35.6	0.1339	–1.281	–191.4	3
–0.017	30.07	5.35 E-06	–3.31	0.68	4
0.2848	42.85	4.749E-03	107.4	–4.875	3
1.1418	62.92	17.03 E-03	0.107	104.	4

η-values calculated from the R-matrix fit are compared with some of the experimental data in Figure B-1a. The left part of Figure B-1a shows the calculated η (*full curve*) together with the experimental data from the Grenoble measurement (*circles*) and with η as calculated from the measured α values of the Geel α experiment (*crosses*). The *broken curve* represents η as calculated by NJOY from the resonance parameters of Leal et al. The right part of Figure B-1a shows the same curves together with the experimental data from the Harwell-ORNL measurement. The error bars indicated in Figure B-1a only represent statistical errors.

It is seen that the R-matrix fit of Figure B-1a is a good representation of both sets of data, especially at sub-thermal energies. It is also valid for the data from the earlier Geel η experiment (not shown), except for the lowest energies ($E < 3$meV) where background problems were severe. There is a slight systematic difference between this fit and the data in the 70-to-100-meV region, from the Grenoble and the Harwell-ORNL experiments. However, this difference is within the systematic uncertainties. The decrease of η from thermal energy to 2 meV as represented by the fit curve is 1.6%.

Figure B-1b shows the difference between the R-matrix fit and the experimental data of Figure B-1a. On the same scale, Figures B-1c and B-1d show the most important systematic uncertainties of the experimental data originating from the various sources discussed above. The numbers indicated in the figures have the following meaning:

1) Uncertainty due to background errors in the measurement of fission neutrons from the U sample,

2) Uncertainty due to background errors in flux measurement,

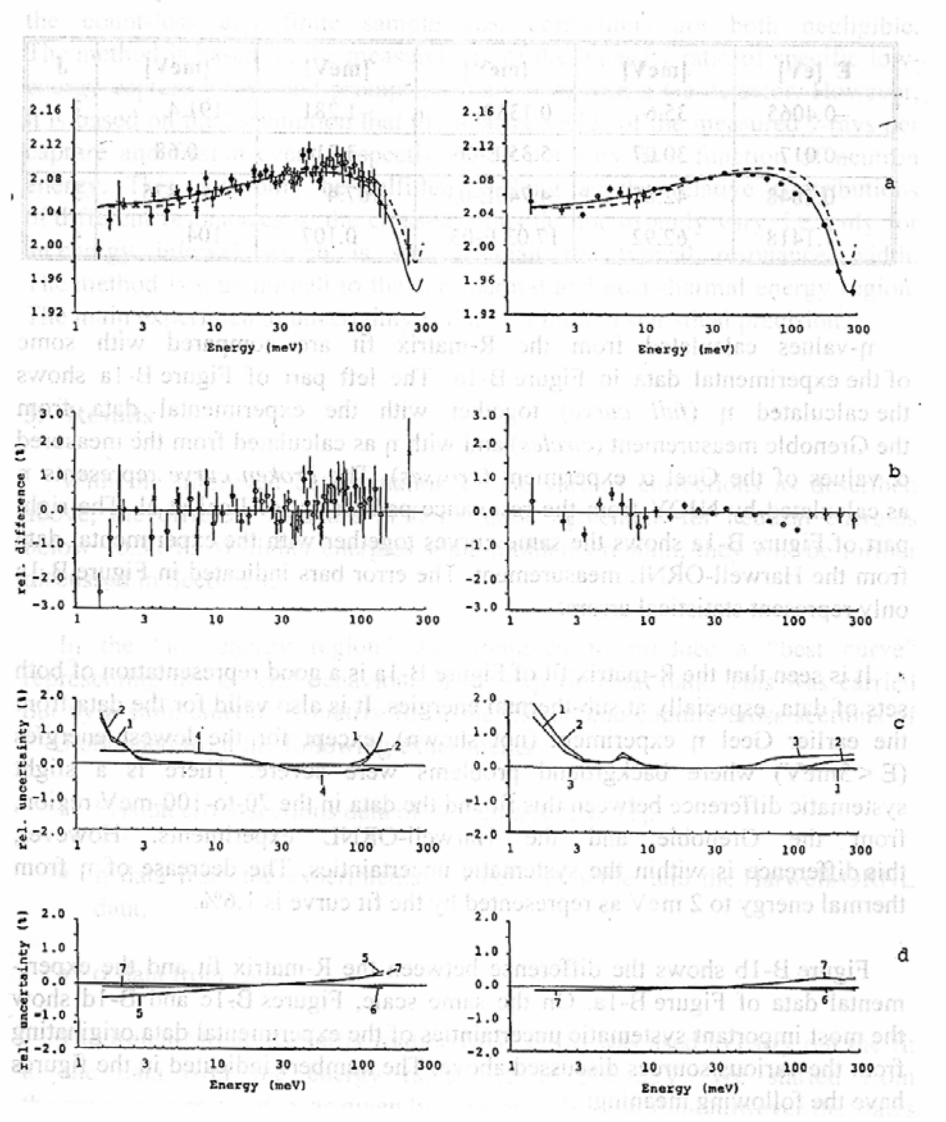

Figure B-1
a ***Experimental*** η ***data and R-matrix fit***
b ***Difference between fit curve and data***
c & d ***various systematic uncertainties***
left column refers to data from Grenoble (and Geel-α*) experiment*
right column to Harwell-ORNL experiment

3) Uncertainty due to possible changes in the shape of the incident neutron spectrum,

4) Uncertainty in the determination of count loss corrections,

5) Uncertainty in the correction for absorption and multiplication of fission neutrons,

6) Change in the finite sample size correction due to the addition of 1 b to the ^{235}U total cross-section,

7) Change in the finite sample size correction due to the addition of 1 b to the ^{235}U scattering cross-section.

It is seen from Figure B-1 that differences between the present fit curve and the experimental data are generally smaller than the combined systematic uncertainties, with the possible exception of the lowest data point from the Grenoble experiment. Furthermore, it is seen that the most important systematic uncertainties in the left (Grenoble) and right (Harwell-ORNL) columns of the figure originate from different sources: count loss corrections for the Grenoble case, backgrounds for the Harwell-ORNL one. The fact that there is nevertheless fair agreement now between these two data sets adds additional confidence in the final result.

4. Problems at higher energies.

At energies above 0.3 eV essentially, only the Harwell-ORNL measurements on the thickest sample yield potentially useful data. For the early Geel measurements final sample size corrections become too large and dependent on the input cross-section values, whereas the Geel α measurements become unreliable because of the reason previously mentioned in Section 2. At Grenoble, no neutron was available above about 0.15 eV.

From a preliminary analysis of the Harwell-ORNL data it seems that η would be significantly smaller than those resulting from the evaluation of Leal et al. in the region between 0.3 and 1 eV. However, finite sample size corrections become very large above 0.3 eV also for the Harwell-ORNL data. They depend on the cross-sections used in the calculation, and especially on the assumed value of the scattering cross-section. Various changes to the evaluated cross-sections in the region of about 0.3 to 1 eV were used in the calculation of the corrections in order to get agreement between the values of η determined from measurements on the three sample thicknesses. One of the least controversial modifications was to increase the elastic scattering cross-section by between 1 and 2 barns, keeping α and the total cross-section fixed. With such a modification resultant η-values would increase, but not by an amount sufficient enough to reach agreement with the evaluation of Leal et al.

On the other hand, inspecting the evaluation of Leal et al. in the low-eV region, two observations can be made:

1) In the minima between resonances the fission cross-section calculated from the resonance parameters stays slightly higher than the data points;

2) The average radiative width given by Leal et al., i.e. $\langle \Gamma_\gamma \rangle = 36\, meV$, is significantly smaller than in earlier evaluations. Both these observations indicate that η-values deduced from this evaluation may be slightly on the high side.

In view of these circumstances, it seems to us that a re-evaluation of all cross-sections and resonance parameters in the lower-eV region, taking into account the data obtained in the Harwell-ORNL η measurements, might be worth-while. Modified cross-sections, especially for elastic scattering, resulting from such a re-evaluation might lead to improved calculations of correction factors for the η measurements in the region above 0.3 eV. At present no definite η-value can be given for this energy region.

5. Conclusion

According to what has been said previously, we believe that below ~0.2 eV there is good agreement now between the different experiments measuring the neutron energy dependence of η for ^{235}U, and that the R-matrix fit shown in Figure B-1 is a good representation of these data. Possible modifications of the parameters of higher energy resonances will only have a minor effect on the fit below 0.2 eV. However, at higher energies some further investigations are necessary, possibly a re-evaluation of the lower resonance region. This lies beyond the scope of the present Subgroup.

The present shape of η in the thermal and sub-thermal energy regions have been recently used at Saclay [10] in a sophisticated re-analysis of the KRITZ and JAERI temperature coefficient experiments. The computed value of the temperature coefficient which is mainly sensitive to the low-energy shape of η is now in good agreement with the measurements: The difference between the computed temperature coefficient and the measured one is reduced to -0.2×10^{-5}/°C in the case of the KRITZ experiment and to -0.6×10^{-5}/°C for the JAERI experiment, as compared with 3 and 4×10^{-5}/°C for a flat shape of η [10].

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OECD Publications, 2 rue André-Pascal, 75775 PARIS CEDEX 16
PRINTED IN FRANCE