NEANDC (E) 163 U

SPECIALISTS MEETING ON "RESONANCE PARAMETERS OF FERTILE NUCLEI AND 239 Pu"

SACLAY, 20 - 22 May 1974

Proceedings edited by P. RIBON

January 1975

ERRATUM

Page 13 - § 11, livre 7 - Read.

"Average fission width of the J = 1 (one) state...".

Page 139, Table -

For the resonance at 1660 eV, $\Delta\Gamma_{\gamma}$ (stat) = 4.

Page 174 to 181

The order of tables of ^{238}U resonance parameters has to be inverted.

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SPECIALISTS MEETING ON "RESONANCE PARAMETERS OF FERTILE NUCLEI AND 239 Pu"

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This meeting was held at Saclay from Monday 20th to Wednesday 22nd May 1974. The list of participants is given in page 5.

The aim was to bring together experimenters, evaluators and users of resonance parameters in order to compare their points of view, and to try to clear up the status of the needs and of the accuracy of the available data.

To this end several papers have been presented at this meeting - four of them being reviews whose aim was to recommend sets of evaluated data. The texts of these contributions and review are published in this report (see "Table of contents", next page).

These contributions and reviews have been used as basis for the discussions during the various plenary or parallel sessions. The summary of these discussions during the last two days have been drawn up by their chairmen and submitted to all participants : then they represent the general view of this meeting. They are given in pages 6 to 18 (Conclusions and recommendations).

The organisers thank all the participants to this meeting and, mostly, the reviewers and the chairmen of the various sessions.

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LIST OF CONTRIBUTIONS AND REVIEWS

List of participants to the specialist meeting on Resonance parameters of fertile nuclei and 239 Pu

Saclay, 20-22 May 1974

BELGIUM -	H. CEULEMANS	
	F. POORTMANS	
	C. WAGEMANS	
GERMANY -	B. GOEL	
	R. SPENCER	
ITALY -	F. CORVI	
	M. MOTTA	
SWITZERLAND -	E. OTTEWITTE	
U.K. -	M. JAMES	
	M.C. MOXON	
	M.G. SOWERBY	
U.S.A. -	G. de SAUSSURE	
B.C.M.N. (GEEL) -	G. ROHR	
	H. WEIGMANN	
C.C.D.N. (Saclay) -	F. FROHNER	(part time)
	M. LESCA	(part time)
	K. OKAMOTO	(part time)
FRANCE -	J.Y. BARRE	(part time)
	J.BLONS	(part time)
	H. DERRIEN	
	E. FORT	(part time)
	D. GRENECHE	(part time)
	R. JOLY	(part time)
	A. KHAIRALLAH	(part time)
	G. LE COQ	(part time)
	D. PAYA	(part time)
	P. REUSS	
	P. RIBON	
	H. TELLIER	

CONCLUSIONS AND RECOMMENDATIONS

A - SESSIONS ON RESONANCE PARAMETERS OF FERTILE NUCLEI

1. Interpretation of measurements with respect to accuracy limitations

It was generally agreed among experimenters at this meeting that with a few exceptions resonance parameters for the resolved regions in ^{232}Th and ^{238}U are determined with approximate precisions of $\pm$ 5% for Γn and $\pm$ 10% for $\Gamma\gamma$. It was clear from the data presented, however, that the dispersion in values from various experimenters is still frequently greater than this.

1.1. Transmission experiments

Transmission measurements present little experimental difficulties. The analysis of the data is straightforward, at least in principle, and is done by area or shape analysis. It was pointed out that shape analysis is to be preferred, even if Doppler and resolution broadening mask the true shape of the resonance, because the conditions for good area analysis are rarely fulfilled.

In order to avoid systematic errors in the determination of Γn from transmission results a range of sample thicknesses should be measured such that for each resonance the condition $n\sigma_0 \leqslant 1$ is fulfilled by at least one sample. If this condition is not fulfilled, large systematic errors are to be expected. If these precautions are taken it should be possible to determine Γ_n to better than 5%.

1.2. Scattering experiments

From a contribution on scattering measurements in the resolved resonance energy range performed on ^{238}U given by Poortmans and the ensuing discussion came the following conclusions.

An accuracy of about 5% on the scattering area can be obtained if samples with $n\sigma_0 \leqslant 0.1$ are used. Normalizing the data with the σ_s of Pb introduces systematic errors estimated at $\pm$1%. For the larger resonances ($\Gamma n \geqslant \Gamma\gamma$) the background subtraction introduces another 1%. Multiple interaction and self screening corrections are difficult to calculate and it is also difficult to estimate the error they introduce. From the results which have been published up to now, 5% seems to be a lower limit on the accuracy that can be attained at the present time.

1.3. Capture experiments

An accurate knowledge of the energy dependence of the incident neutron flux and the relative efficiency of the capture detector, together with corrections for finite sample thickness and multiple interaction of the scattered neutrons, are the minimum requirements for the calculation of the capture cross-section from the observed data.

In the energy region below 100 keV detectors using the ^{10}B, (n,α) and/or $(n,\alpha\gamma)$ reactions are possibly the best means of measuring the neutron flux.

All types of γ-ray detector must approach an efficiency for detecting a neutron capture event that is independant of the γ-ray cascade and have an efficiency for detecting the scattered neutron that is very low compared with the capture detecting efficiency, i.e. $(\varepsilon_n/\varepsilon_\gamma \lesssim 10^{-4})$.

The general remarks concerning multiple interactions which were made in relation to scattering experiments apply also here, including the recommendation to use samples with $n\sigma_0 \leq 0.1$. In view of present uncertainties, capture areas have (mostly hidden) errors of 5 - 10%. At higher energies (a few keV) the capture cross-section should be measurable absolutely to between ± 5 and ± 10% : the shape is probably obtainable to within ± 2%.

According R.SPENCER, for large scintillation tanks, the uncertainty in shape of the capture γ ray pulse height response below threshold (2 - 3 Mev energy) limits the overall precision to about ± 10%.

1.4. General remarks

α) At least some of the individual discrepancies observed are due to non-ideal sample thicknesses used in the cross section measurements.

β) Some errors have occurred due to inconsistent treatment of backgrounds or off-resonant contributions in the analyses of cross section data.

γ) The accuracy of derived resonance parameters should be better than ± 5%.

δ) 'Complete' experiments, that is scattering measurements as well as of capture and total measurements, would be desirable.

2. Distributions

2.1. Spacing distribution

There seem to exist several methods to determine <D>, the average spacing between resonance levels and the (standard) deviation and error on this value. Very often it is not even clear which one is given. The Wigner distribution gives for the observed $\bar{D}$ a fractional standard deviation of $0.52/\sqrt{N}$ where N is the number of spacings counted. This expression is most frequently used. This formula, however, does not take into account the long-range ordering effects described in a series of papers by Dyson and Mehta (1) and applied to a specific case by Liou et al (2). If the levels belong to an orthogonal ensemble which implies that they form a complete set of s-wave levels with no levels missed and without p-wave contamination, the fractional standard deviation of $\bar{D}$ is $\approx 1/N$, due to long-range ordering effects which exist for such ensembles. However, the Working Group had the feeling that such a standard deviation is probably an underestimate due to systematic errors. In practice the value of N is given by the following formula

$$N = N_{obs} + N_s - N_p$$

where N_{obs} is the number of observed s-wave levels in the energy interval considered, N_s is the number of s-wave levels missed and N_p is the number of p-wave levels accidently included; the values of N_s and N_p can be derived from the Porter-Thomas distribution of reduced neutron widths. The Working Group felt that the error in <D> should include the contributions from the errors in N_s and N_p as well as the error in N associated with the spacing distribution. This suggestion requires further consideration but it should be remembered that for reactor calculations <D> is required in the unresolved energy range where there must be additional uncertainty because one is extrapolating data from the resolved region.

2.2. Neutron width distribution

The importance of the neutron width distribution for level counting was already mentioned in the discussion on everage level spacings. This implies that

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(1) F.J. Dyson, J. Math. Phys. 3 (1962), 140, ibid. 157, ibid. 166, ibid. 1199 and M.L. Mehta and F.J. Dyson ibid. 4 (1963) 701, ibid. 713.

(2) H.I. Liou et al., Phys. Rev. 5C (1972) 974.

the assumptions underlying the Porter-Thomas distribution are valid for a single population of neutron widths, which is generally accepted. Discrepancies are usually an indication of unknown experimental errors but if not they need careful attention and more experimental confirmation. The existence of such deviations in 232Th is emphasized by E.OTTEWITTE.

The subject of the various methods of comparing a Porter-Thomas distribution with experimental data was not included in the discussion although it would be worthwhile to come to an agreement on standard practice for this important distribution.

2.3. Correlations between Γn and $\Gamma\gamma$

Such a correlation was found for 238 U ; nevertheless no definitive conclusion was reached as to its origin : is it a nuclear effect (i.e. : a correlation between Γ_n^o and $\Gamma\gamma$) or an experimental effect ?

The importance of this possible nuclear correlation for the calculation of the cross sections in the tens of kev range was emphasized, and it has been suggested as a possible explanation for a part of the unexplained discrepancies.

2.4. Dependance of the radiative width with the parity

Presumptive evidence of a dependence of $\Gamma\gamma$ on the orbital momentum of the incoming neutrons has been put forward in the case of 232Th and 238U. It has been suggested that this may also solve some of the unexplained discrepancies between average resonance parameters and integral data.

3. Status of the recommended values

Agreement between different measurements of neutron widths is poor. It would help in evaluation if measurers would quote, or send to the data centres, either the areas measured, or the covariance between the derived Γ_n and $\Gamma\gamma$ as well as their variances.

A few values and recommendations regarding the parameters of the individual nuclei were agreed upon. For 232Th the current recommended value of the average radiation width from the resonance data is 21.45 $\pm$ 0.25 meV. The resonance integral calculated from the parameters recommended by Derrien and Ribon is 83.7 $\pm$ 2.7 meV compared with the measured value of 85.8 $\pm$ 2.5 meV.

For the individual resonance parameters of 232 Th, it is recommended that the critical discussions given by Derrien and Ribon at this meeting be consulted.

The situation in ^{238}U is not so clear. A more detailed summary of discussions about this nuclei is given in § 4. The present situation including a comprehensive discussion of possible sources of error has been given in the paper at this meeting by Moxon. The large discrepancy between various experimenters for the shape of the capture cross section of ^{238}U in the keV neutron energy region still remains but should be at least partially resolved by data presented.

For the fertile nuclei 240 Pu the paper by Weigmann et al. at this meeting gives a detailed and thorough summary.

4. Summary of the Present Situation regarding U238 (n,γ) for Neutron Energies below about 25 kev

We wish to bring to the attention of nuclear physicits the present situation concerning differential and integral data for U238 (n,γ) for neutron energies below about 25 kev. This cross section is of great importance to reactor physicists, and in particular the temperature dependence of the shielded cross-section is the main contributor to the Doppler effect in a fast reactor.

There are three sources of information for the data :

(i) The parameters of the resolved resonances (measured so far up to 5 kev) allow the estimation of mean widths and spacings, at least for the s-wave resonances. Note that a very large proportion (∿80%) of the U238 Doppler effect of a fast reactor under normal operating conditions arises from these resolved resonances.

(ii) Measurements of the infinitely dilute average cross section $\bar{\sigma}_{\infty}(E)$

(iii) Integral measurements in reactors, leading (via data adjustment programmes) to estimates of the shielded average cross section $\bar{\sigma}_{sh}(E)$

The derivation of average resonance parameters from (i) is very difficult ; this is clear from the widely discrepant values obtained by different workers (see paper by Sowerby). Hence, by itself (i)

cannot give reliable cross sections in the unresolved region, but it is possible to obtain mean parameters that are consistent either with (i) and (ii), or with (i) and (iii). Reactor integral measurements imply a capture cross-section about 12%, or two standard deviations, below broad resolution measurements between 1 and 10 keV.

However, it is not possible at present to obtain data that are consistent both with average unshielded cross sections and with reactor integral measurements. This is so for the following reason.

If we write :

$$\bar{\sigma}_{sh}(E) = f\,\bar{\sigma}_{\infty}(E)$$

where f is the shielding factor, then f is only weakly dependent on the resonance parameters, as has been shown by Barre at this meeting, and by unpublished work in the UK. Consequently, since reactor measurements imply a reduction in $\bar{\sigma}_{sh}$ of about 12% it is also necessary to reduce $\bar{\sigma}_{\infty}$ by about the same amount : making the usual assumptions about mean parameters and distributions we cannot find a set of resonance parameters that will decrease $\bar{\sigma}_{sh}$ without also decreasing $\bar{\sigma}_{\infty}$.

Summarising, there is a discrepancy of about 2 standard deviations between measurements of the average unshielded cross section for U238 (n,γ) and between reactor integral measurements that lead to values for the shielded cross section. Possible explanations of the discrepancy could include :

(a) systematic errors in either the measurements of $\bar{\sigma}_{\infty}$ or in reactor measurements or in their interpretation.

(b) systematic faults in the adjustment procedure ; for example other cross sections used in the interpretation may be erroneous ;

(c) some new physical effect in the U238 resonance parameters (for example, a correlation between Γ_n and $\Gamma\gamma$; or different $\Gamma\gamma$'s for s and p-wave resonances).

The best experimental value for $\bar{\Gamma}\gamma$ is 24.14 meV (M Moxon) : but reactor measurements would be better

fitted by a smaller value.

Very different values of strength functions have been obtained by different workers (see the paper by M G Sowerby). The mean resonance spacing, $\bar{D}$, also differs in different analyses : Rahn obtained (20.8 ± 0.3) eV from his own measurements, but these same data have been used by H Weigmann, and independently by M James, to give values of about (22.5 ± 2) eV. The larger figure is in better agreement with reactor measurements. There is conflicting evidence about whether $\Gamma\gamma$ is the same for s-wave and p-wave resonances.

The adjusted data may appear adequate for most reactor calculations, but in our opinion the discrepancy should not be overlooked, for two reasons. First, it is undesirable to cover-up a discrepancy, which implies that we do not fully understand the physics of the problem. Secondly, it may be dangerous to use the data in situations very different from those considered in the adjustment studies, for example in extreme accident conditions.

Recommendations for further measurements on ^{238}U

The following types of measurements are recommended :

(i) High resolution thin sample measurements, either to give resonance parameters or to be used directly in reactor calculations.

(ii) Low resolution thick sample measurements, preferably at several temperatures, to compare with reactor integral measurements.

(iii) High resolution thick sample measurements to indicate which resonances are not s-wave.

(iv) Whenever possible, total, capture are scattering measurements should be carried out and the resonance parameters obtained from area analysis used to calculate cross section curves for comparison with the obtained data.

B - SUB-GROUP SESSION ON 239 PU

The main subjects discussed were as follows :

I - M. JAMES and M. SOWERBY reviewed the requirements of the reactor physicist for Pu-39 cross sections. Those are mostly for the fission cross section above I KeV for which a 3% accurecy is desired, and for the capture cross section for which the accuracy requirement is approximately 3 to 5% in α-.

At the present time the cross section uncertainties for Pu-239 based on differences between integral data and predictions from differential data are small compared to those of other materials (particularly U-238) hence there is no pressing need for improvement in the Pu 239 data, although any significant improvement in accuracy reduces the margin of acceptable adjustments and hence will help.

However, more precise measurements for ^{239}Pu would add to the constraints imposed on the less well-known cross-sections in the least squares adjustment computations. Present requests are for an accuracy of $\pm$ 3% in the fission cross section above 1 keV, and + 3 - + 5% for $\alpha=\sigma_c/\sigma_F$.

Self indication and transmission measurement as a function of temperature would be of considerably less interest for Pu-239 than for U-238.

II - P. RIBON inquired about the treatment of intermediate structure in the generation of "statistical cross section" in the U.K. - M. JAMES described how statistical resonance parameters are generated by the code GENEX which uses the Vogt multilevel formalism, and adjusts the strength function and the average fission width of the J = I state so as to reproduce the evaluated average total and fission cross sections for each energy group.

Generation of resonance parameters from statistical distributions for reactor calculations should take account of the observed intermediate structure in the cross sections. The 'ladders' of these pseudo-resonances should include the effect of long-range ordering if possible : this applies also to ladders for other nuclides such as ^{238}U, ^{235}U.

III - A discussion followed on whether the structure of the cross section in the unresolved resonance region could be measured with sufficient details to eliminate the need for mock-ups by the generation

of statistical parameters. It appears that the resolution is available in principle and, if good measurements of the fluctuations of the cross sections were made, these could be used directly by the reactor designers. But this approach needs to be discussed more extensively.

IV - F. CORVI proposed a new technique to measure α by detecting a low energy gamma ray transition simultaneously with some characteristic fission gamma ray line. The method, although very interesting, has many inherent assumptions, so that it would probably not be an improvement over the more classical methods used in measuring α.

V - P.RIBON was curious to know why, for instance, the SACLAY evaluation of the Pu-239 resonance parameters was not adopted for the ENDF/B Version IV evaluation. A discussion followed on a comparison of the cross sections obtained with the resonance parameters published by P.RIBON and those obtained with the preliminay parameters of ENDF/B - IV. One of the conclusion of this discussion was that it would be desirable that evaluators discuss their evaluation with respect to previous evaluations and state clearly the shortcomings of previous evaluations so that evaluators know in which respect their work needs to be improved.

VI - It is now feasible in principle to measure ^{239}Pu cross-sections with sufficient resolution to show all the resonance structure up to perhaps 25 keV. If this could be done consistently for all cross sections (or at least for the total, capture and fission cross sections) the results could be Doppler broadened and used directly in reactor calculations without analysis into resonance parameters. This would also avoid the need for generation of pseudo-resonances.

VII - The two latest evaluations for ^{239}Pu, by Ribon and LeCoq, and for ENDF/BIV, differ in a number of respects. It was not thought possible to recommend one rather than the other : indeed, it is probably desirable to have the two alternatives for comparison.

C - SUB-GROUP DISCUSSION ON "THERMAL RANGE"

I - P.Reuss presented an evaluation of the uncertainties on the thermal temperature coefficient due to the uncertainties on the slopes of $\sigma\sqrt{E}$ in the thermal range and commented specially two points :

- the uncertainties, particularly the ones due to the capture cross sections of fissile nuclides, are not negligible and can have some implications for reactor design.

- there are some significant discrepancies between measurements of the temperature coefficient and the calculation with the UK library.

The precision of calculated temperature coefficients is not well-known, due principally to uncertainties in the low energy fission cross sections of ^{235}U and ^{239}Pu. Discrepancy between the calculated and measured temperature coefficient of thermal reactors, is not inconsistent with the uncertainties in the low energy cross sections, particularly in their shapes. The observed temperature coefficient could be used bo calculate the slope of the cross sections with energy.

II - The recent CBNN measurements of the fission cross section of ^{239}Pu, presented by C.WAGEMANS, have been carried out on the BR2 reactor and the CBNM Linac. Two points were made :

- The problem of obtaining the 2200 m/s cross section : an error of 0.1% has been added to account for the differences in the value obtained by several different fitting procedures ; the proposed value is 741.9 ± 3.4 b.

- Calculation of the Westcott's g-factor between 0 and 1000°C from the data were carried out and the value obtained at room temperature (1.0522 ± 0.0035) is in perfect agreement with AIEA recommended value.

III - Experiments are being considered that will measure η and σ_f for ^{235}U and ^{239}Pu with great precision below 1 eV (± 0.5% for η).

D - SUMMARY OF RECOMMENDATIONS.

I - Where possible, shape fitting routines with a chi-square least error determination are preferred over area analyses since the former should result in a more consistent treatment of backgrounds or off-resonant contributions particularly when multiple sample thicknesses are used.

II - Data from several sample thicknesses are desired both to obtain near optimal thicknesses for as many resonances as possible and also to help in the proper determination of such difficult corrections as multiple scattering effects, etc.

III - High resolution thin sample measurements should be made on ^{238}U, either to give resonance parameters or to be used directly in reactor calculations.

IV - Low resolution thick sample measurements, preferably at several temperatures, should be made on ^{238}U, to compare directly with reactor integral measurements.

V - High resolution thick sample measurements should be made on ^{238}U to give an indication of resonances that are not possible due to s-wave neutrons.

VI - Whenever possible, total, capture and scattering cross sections should be measured and resonance parameters obtained from area analyses should be used to calculate cross section curves for comparison with the observed data.

VII - The feasibility should be investigated of measuring the cross sections of ^{239}Pu up to about 25 keV with sufficiently high resolution to show all the fine structure. These cross sections could then be used directly, without analysis into resonance parameters, in reactor calculations.

VIII - Experimenters should in all cases state clearly any parameters used to fit background and/or off-resonant cross sections in their analyses. When experimental values of parameters are interdependent, covariances such as cov (Γ_n, $\Gamma\gamma$) should be given.

Experimenters making area measurements are asked to send to the Data Centres for each sample either the actual area measured, or the covariances between the derived neutron and capture widths. This will help evaluators to obtain a better weighting for each experiment and a more consistent set of parameters.

IX - Further experimental study is needed of the shape of the fission and capture cross sections (or of η) below 1 eV of ^{239}Pu (and of ^{235}U).

X - Methods of deriving the mean spacing of resonances from observed resonance parameters, and allowing for missed resonances, should be compared.

XI - The large discrepancy between the measured capture cross section for ^{238}U below 10 keV and that required to explain reactor integral measurements should be investigated.

XII - 'Ladders' of pseudo-resonances generated in the unresolved resonance region for use in reactor calculations should allow for intermediate structure where that has been observed, and for long-range ordering in resonance energies.

XIII - There should be a specialist meeting on resonance formalisms for use in reactor calculations.

APPENDIX

A - Expressions used for Porter-Thomas distribution

a) $P_1(x)\,dx = (2\pi x)^{-1/2} \exp(-x/2)\,dx$

with $x = \Gamma_n^o / \langle\Gamma_n^o\rangle$

This is the standard expression.

b) if $\langle\Gamma_n^o\rangle$ is used explicitly as a parameter :

$P_2(y,u)\,dy = (2\pi u y)^{-1/2} \exp(-y/2u)\,dy$

with $y = \Gamma_n^o$ and $u = \langle\Gamma_n^o\rangle$

c) the integral distribution

$P_i(x \geqslant z) = \int_z^\infty P_1(x)\,dx = \int_z^\infty (2\pi x)^{-1/2} \exp(-x/2)\,dx$

This form has the disadvantage of not showing clearly the interesting region of small widths.

d) $P_4(w)\,dw = (2/\pi)^{1/2} \exp(-w^2/2)\,dw$

with $w = x^{1/2} = (\Gamma_n^o / \langle\Gamma_n^o\rangle)^{1/2}$

This form of the distribution has many advantages over the other formulas because of the regular behaviour near the origin, its closer connection to the nuclear matrix quantities and the more restricted range of values of interest for w as evidenced by the shape of the distribution.

SPECIALIST MEETING ON RESONANCE PARAMETERS OF FERTILE NUCLEI AND 239 Pu ISOTOPE.

IMPORTANCE OF RESONANCE PARAMETERS OF FERTILE NUCLEI AND OF 239 Pu ISOTOPE FOR FAST POWER REACTORS .

J.V.BARRE - A. KHAIRALLAH

INTRODUCTION

The importance of resonance parameters of fertile nuclei and of 239 Pu isotope for fast power reactors will be restricted, in this presentation, to mixed - oxide - uranium - plutonium fuelled , sodium-cooled and uranium - oxide - sodium reflected fast reactors. The power range lies between 200 and 2000 MWe.

Among the topics of this specialist meeting, the isotopes to be considered are, primarly 239 Pu, then 238 U and 240 Pu.

Resonance parameters are mainly used in fast power reactor calculations through the well-known concept of self shielding factors. After a short description of the determination and the use of these self-shielding factors, their sensitivities to resonance parameters are characterized from some specific examples : those sensitivities are small.

Then, the main design parameters sensitive to the amplitude of self-shielding factors are considered : critical enrichment, global breeding gain. The relative importance of isotope, reaction rate and energy range are mentionned.

In a third part, the Doppler effect , sensitive to the temperature variation of self-shielding factors, is considered in the same way.

Finally, it is concluded that the present knowledge of resonance parameters for 238 U, 239 Pu and 240 Pu is sufficient for fast power reactors from a designer point of view.

All this analysis is based on the Cadarache multigroup cross section set and code CARNAVAL Version III [1] and the CEA fast reactor physics programme [2,3]. In this CEA approach, it must be mentionned that the used cross section adjustment procedure allows to consider well-known the average multigroup cross sections from systematic integral measurements on several typical fast reactor lattices. This is specially true for 238U , 239 Pu and 240 Pu capture cross sections and 239 Pu fission one.

II - USE OF RESONANCE PARAMETERS IN FAST REACTOR CALCULATIONS

II-1. SELF-SHIELDING FACTOR CONCEPT

1- It should be recalled that multigroup calculations with an ultrafine energy mesh allowing to describe point-by-point cross sections in the heavy isotope resonance energy region cannot be considered in a standard way. To take into account, in standard multigroup calculations, the fine structure of the spectrum inside the energy limits of a broad group g, the well-known self-shielding factor concept is used.

2- The spectrum fine structure depends on the relative contributions of all the resonances from all the isotopes to the total macroscopic cross section. An average cross section $\sigma^{\infty}_{g,i}$, over the group g energy limits, obtained by weighting the point-by-point cross section $\sigma_i(E)$ with an energy-flat spectrum is called " infinite diluted " cross section. An average cross section $\tilde{\sigma}_{g,i}$ over the group g energy limits obtained by weighting the point-by-point cross section $\sigma_i(E)$ with the re" spectrum, i.e. taking into account the fine structure inside the group g due to the isotope i, is called effective cross section. The self-shielding factor f g,i,x for one isotope i, one reaction x and one energy group g is defined by the relation :

$$f_{g,i,x} = \frac{\tilde{\sigma}_{g,i,x}}{\sigma^{\infty}_{g,i,x}} \qquad (1)$$

Then, by definition, self-shielding factors are lower than 1.

3- The more the isotope i contributes to the fine structure of the total macroscopic cross section, the more the self-shielding factor is small : these factors f are medium - dependent. To avoid a new calculation of the f factors for each medium, they are tabulated at once for each isotope i versus a parameter called dilution Di . That dilution characterizes the relative contribution of the isotopes of the lattice, as compared to the isotope i, to the total macroscopic cross section :

$$D_i = \frac{\sum_{j \neq i} N_j \sigma_j^T}{N_i}$$

Nj = atomic densities.

Then, for a new medium, by interpolation versus the dilution in the tabulation of the f factors and from the multigroup infinite diluted cross sections (medium-independent), the useful effective multigroup cross sections are obtained for all reactions X and isotopes i:

$$\tilde{\sigma}_{g,i,x} = f_{g,i,x} \quad \sigma^{\infty}_{g,i,x}$$

4- Calculations of tabulated self-shielding factors are performed from resonance parameters with more or less sophisticated nuclear models that will be discussed during this meeting. The temperature dependence of self-shielding factors is normally included in the tabulation, taking into account the resonance Doppler broadening in the model.

5- For example, in the CARNAVAL III system self-shielding factors are tabulated in a 25 group energy mesh from 414 ev up to 67,4 Kev ($24 \leq G \leq 10$) for a dilution variation between 0 and infinity and a 300°K to 3000°K temperature range . For 239 Pu, 238 U and 240 Pu, reaction considered are capture, total, elastic, fission (not for 238 U).

The 238 U capture self-shielding factor variation versus energy is shown on fig.1 for a normal 238 U dilution in a fast reactor (40 barns) and two temperatures 300 and 900° K.

Figure 2 presents the 238 U capture self-shielding factor variation versus dilution for the energy group 1.23 -2.04 Kev and two temperatures 300 and 900°K.

II-2 SENSITIVITY OF SELF-SHIELDING FACTORS TO RESONANCE PARAMETERS.

Sensitivity studies have been performed on the 238 U capture cross section for two energy groups located in the energy range of the largest capture rate :

450 - 750 ev	g = 19
3,3 - 5,5 Kev	g = 15

Three 238 U dilutions have been studied :

50 (usual dilution),100 and 500 barns.

Parameters considered are the averaged 238 capture cross section in the group calculated from the nuclear model $\langle \sigma_c \rangle$, the self-shielding factor f_c, the variation of the self-shielding factor versus temperature between either 300 and 900° K or 900 and 3000°K .

The present uncertainties accepted on resonance parameters for 238 U are the following ones :

± 10 % on $\Gamma\gamma$
± 10 % on Γn (swaves)
± 20 % on Γn (pwaves).

The sensitivities of the parameters previously mentionned to the maximal possible increase of these resonance parameters are presented respectively in tables I,II, and III.

The main conclusions drawn from these results are :

1- The average capture cross section variations remain large, e.g, up to 5% for a 10 % increase in $\Gamma\gamma$.

2- Self-shielding factor sensitivities to resonance parameters are small for example :

- 0,5 % for a + 10% on $\Gamma\gamma$

3- Sensitivities of self-shielding factor variations (Δf) between two temperatures are limited to $\pm$ 3% for a standard 238 U dilution.

4- For self-shielding factors the sensitivity decreases when the dilution or the energy increase.

III - INFLUENCE OF RESONANCE PARAMETERS ON DESIGN PARAMETERS

III.1. SELF-SHIELDING FACTORS VALUES

a) The self-shielding factors f averaged over the whole spectrum of several cores have been calculated for 238 U capture, 239 Pu fission and capture, 240 Pu fission and capture cross sections (Table IV).
These lattices cover the whole range of sodium-cooled fast power reactors. The results concerning metallic fuels studied in some critical experiments are also presented to put in evidence the dilution influence (fuel density variation).

From these results, it appears clearly that, in the frame of the problems considered in this meeting, only the self-shielding factor knowledge for 238 U capture is important for fast power reactors.

b) For 239 Pu fission, the self-shielding effect represents between .4 % and . 7 % of the reaction rate. Figure 4 represents the self-shielding effect on 239 Pu $\bar{\alpha}$ value versus the spectrum index r that characterizes globally the whole spectrum of a lattice : it remains small (1,3 %) and independent of the core. For 240 Pu capture cross section, it varies from 1 % for PHENIX (14 % Pu 240) up to 2,6 % for SUPER-PHENIX (20° Pu 240).

c) The variation of the parameters (1 - $\bar{f}$) for 238 capture versus the spectrum index r (fig 3), shows the strong increase of the self-shielding factor when the spectrum softens (low r values) : from 9 % of the capture rate for PHENIX inner core, up to 18 % for SUPER-PHENIX inner core.

III.2. INFLUENCE ON DESIGN PARAMETERS

a) The two parameters considered are Keff, or critical enrichments, and internal breeding gain (I B G) for the inner core of a 1200 MWe reactor at the equilibrium stage, the Pu fuel containing 20 % Pu 240.

Sensitivities of these two parameters to cross section variation have been calculated from the USACHEV generalized perturbation theory (code PERTUS) . For I B G, after a 1% cross section increase, the criticality is obtained by enrichment variation (Table V).

b) The contributions of the total self-shielding effects to these two design parameters (Table VI) confirm the only importance of 238 U capture self-shielding factors.

c) Taking into account the whole sources of uncertainties, it is admitted that the contributions of self-shielding factors uncertainties must be:

$$\frac{\Delta Keff}{Keff} = \pm 0.2 \% \quad \Delta IBG = \pm .015$$

So, from the previous results (Tables V and VI), the following requests on self-shielding factors can be made, looking either to Keff or to IBG parameters :

Reaction	$\frac{\Delta f}{\bar{f}}$ % from Keff		$\frac{\Delta f}{\bar{f}}$ % from IBG
238 U Capture	± 1.1	*	± 3.8
239 Pu Fission	± 0.4	*	±13.
239 Pu Capture	± 3.3	*	± 4.7
240 Pu Capture	±10.0	*	± 22

In all cases, the requests from Keff is more stringent (*). These requests correspond to the following relative uncertainties or the parameters ($1 - \bar{f}$) :

239 Pu fission	± 40 %
239 Pu Capture	± 180 %
240 Pu Capture	± 400 %

Looking to the small influence of resonance parameters on self-shielding factors (Table I, II, III) , these requests can be considered satisfied to day.

d) For the most sensitive cross section, 238 U capture one, the present uncertainties on $\Gamma\gamma$ and Γn (pwaves) are sufficient. (See § II and Table I and III).

Considering the energy distribution of the 238 U capture rate, it appears also that the present knowledge of Γn (swaves) parameters is sufficient. For the same 1200 MWe core, the probability of 238 U capture rate below the energy E is represented on fig 6. That probability can be characterized by the following figures :

E < 1 Kev	8 %	of the capture rate
E < 4 Kev	22 %	"
E < 10 Kev	36 %	"
E < 67 Kev	68 %	"

The main 238 U capture appears in an energy range (4 Kev- 60 Kev) where the consequence of Γn (swaves) resonance parameter uncertainties on self-shielding factors are largely lower than the requested accuracy.

e) Finally, due to the CEA philosophy in fast reactor physics, the cross section adjustment procedure allows a direct determination of effective 238 U capture cross section from systematic integral measurements of the 238 Uranium capture to 235 Uranium fission ratios. So the variation of the average 238 U capture cross section due to uncertainties on resonance parameters (see § II Table I, II, III) has no consequence. The only problem comes from the uncertainty on the transposition from integral experiments to power reactor (dilution variation).
It has been shown that this problem is sufficiently well-known.

IV - INFLUENCE OF RESONANCE PARAMETERS ON DOPPLER EFFECT

IV . 1. CONTRIBUTIONS TO THE DOPPLER

The Doppler effect is entirely due to the temperature change of resonance self-shielding, and almost entirely due to that of fertile (^{238}U, ^{240}Pu) and fissile (^{239}Pu) isotopes.

For a large fast power reactor (1200 Mwe E $\simeq$ 12 % - 20 % ^{240}Pu), the major contributor to the Doppler effect is ^{238}U isotope :

^{238}U $\geqslant$ 85 %

^{239}Pu $\simeq$ 10 %

^{240}Pu $\leqslant$ 5 %

The energy distribution of the Doppler effect in such a reactor (Fig. 5) shows that the major part comes from low energies, say below 15 Kev:

^{238}U	$\simeq$ 75 %	below 3.4 KeV	
	$\simeq$ 80 %	below 5.5 KeV	
	$\simeq$ 90 %	below 15 KeV	
^{239}Pu	$\simeq$ 60 %	below 200 eV	
	$\simeq$ 90 %	below 1 KeV	

Then, the Doppler effect is mainly due to <u>^{238}U resolved resonances</u>.

IV . 2. EFFECT OF ^{238}URANIUM RESOLVED RESONANCE PARAMETER UNCERTAINTIES

a) The ^{238}U Doppler effect is proportionnal to the following expression:

$$\Delta K \sim - \sum \phi^g \; \phi^{*g} \; \langle \sigma_c \rangle^g \; \Delta \tilde{f}_c^{\,g}$$

when : ϕ^g and $\phi^{\hat{n}g}$ are the direct and adjoint flux in energy group g.

$\langle \sigma_c \rangle^g$ is the averaged (unshielded) group capture cross section

$\Delta \hat{f}^c$ is the change, due to temperature change, of the self-shielding factor.

Uncertainties on resolved resonance parameters have a double influence :

- to modify the averaged cross sections
- to modify the self-shielding factors and their temperature variations.

b) As previously mentionned for the two design parameters, Keff and IBG (see § III),the averaged cross section variation has not to be taken into account.

For the self-shielding variation, it can be clearly seen from tables I, II, III (§ II) that :

a) A 10 % uncertainty in Γ_γ leads to a maximum variation of 2 % in the Doppler effect.

b) A 10 % uncertainty in Γ_n (s waves) results in a maximum variation of 3 % in the Doppler effect.

c) A 20 % uncertainty in Γ_n (p. waves) leads to a maximum variation of 2 % in the Doppler effect. In fact, if this uncertainty is weighted on the Doppler effect energy distribution , this variation remains lower than 1 %.

c) The combination of these uncertainties gives a maximum variation of 4 to 5 % on the Doppler effect due to the knowledge of ^{238}U resonance parameters.

This figure has to be compared :
first to the design request accuracy : ± 20 %
second to the other error sources, mainly the calculation of the flux spectrum : ± 20 to 30 %

.Then, it is concluded that the present uncertainties on resonance parameters are certainly not the major limitation of the accuracy of the Doppler effect prediction in large fast power reactors.

V - CONCLUSION

.Resonance parameters are used in fast reactor calculations through the well-known concept of self-shielding factors.

.From the calculated contributions of self-shielding effect for fertile isotopes (^{238}U, ^{240}Pu) and fissile ^{239}Pu) ones to design parameters of large power reactors, it appears clearly that only ^{238}U capture self-shielding factors play a role on critical enrichment (Keff) and internal breeding gain, even for the soften spectrum of the inner core of a 1200 MWe plant.

.For the Doppler effect, only temperature variations of self-shielding factors for ^{238}U capture cross section in the resolved resonance energy region are important.

.The following uncertainties on resonance parameters for ^{238}Uranium isotope are presently evaluated :

$\Gamma\gamma$: $\pm$ 10 % Γn (s waves) : $\pm$ 10 %

Γn (P waves) : $\pm$ 20 %

.From the sensitivity studies performed, it is concluded, at the CEA, that these uncertainties are presently largely sufficient to answer all the design requests on large fast breeder plants, many other sources of error still playing a leading part.

LIST OF TABLES

LIST OF FIGURES

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TABLE I.

Effect of a + 10 % increase in Γ_γ.

%		$\frac{\delta\langle\sigma_c\rangle}{\langle\sigma_c\rangle}$	$\delta\tilde{f}_c/\tilde{f}_c$ (300°K)	$\delta(\Delta\tilde{f}_c)/\Delta\tilde{f}_c$ (900° - 300°K)	$\delta(\Delta\tilde{f}_c)/\Delta\tilde{f}_c$ (3000 - 900°K)
group 19 450-750eV	σ_p= 50 barns		- 0.5	- 0.6	- 0.3
	100	+ 5.	- 0.4	- 0.4	- 0.1
	500		- 0.2	+ 0.1	+ 0.5
group 15 3.3-5,5 Kev	σ_p= 50 barns		- 0.4	+ 1.8	
	100	+ 5.	- 0.3	+ 2.2	
	500		- 0.1	+ 2.6	

TABLE II.

Effect of a + 10 % increase in Γ_n (Swaves)

%		$\frac{\delta\langle\sigma_c\rangle}{\langle\sigma_c\rangle}$	$\delta\tilde{f}_c/\tilde{f}_c$ (300°K)	$\delta(\Delta\tilde{f}_c)/\Delta\tilde{f}_c$ (900° - 300°K)	$\delta(\Delta\tilde{f}_c)/\Delta\tilde{f}_c$ (3000 - 900°K)
group 19 450-750eV	σ_p= 50 b.		- 3	- 1.8	+ 0.8
	100	+ 4.5	- 2.5	- 0.3	+ 2
	500		- 1.2	+ 3.	+ 4.5
3,5-5,5 Kev group 15	σ_p= 50 b.		- 0.8	+ 3.	
	100	+ 1.5	- 0.5	+ 4.	
	500		- 0.2	+ 6.	

TABLE III.

Effect of a + 20 % increase in Γn (pwaves)

%		$\frac{\delta \langle \sigma_c \rangle}{\langle \sigma_c \rangle}$	$\delta \tilde{f}_c / \tilde{f}_c$ (300° K)	$\delta(\Delta \tilde{f}_c)/\Delta \tilde{f}_c$ (900° - 300° K)
group 19		0	0	0
group 15	$\sigma_p =$ 50 b.		+ 0.5	- 2
	100	+ 6.	+ 0.3	- 3
	500		+ 0.1	- 3

TABLE IV.

Average Self-shielding factors.

	238 U	Pu 239	Pu 239	Pu 239	Pu 240	Pu 240
	Capture	Capture	Fiss.	$\alpha = \frac{\sigma_c}{\sigma_f}$	Capt.	Fiss.
METAL FUEL						
E = 25 %	.869	.963	.991	.971	.984	1
18 %	.807	.956	.987	.968	.979	1
12 %	.703	.949	.982	.966	.969	1
OXYDE FUEL						
PHENIX 2 E = 25%	.911	.983	.996	.987	.990	1
PHENIX 1 E = 18%	.858	.980	.994	.987	.985	1
1200 MWe 2 E= 19%	.855	.981	.994	.987	.978	1
1200 MWe 1 E =15%	.820	.980	.993	.987	.974	1

TABLE V.

Sensitivities of Keff and IBG to a + 1% cross section increase - 1200 MWe inner core . G R I = - 0.13

Reaction	$\delta K/K$ %	δIBG (absolute)
238 U Capture	- 0.23	+ .0049
239 Pu Capture	+ 0.55	+ .0012
239 Pu Capture	- 0.06	- .0032
240 Pu Capture	- 0.02	- .0007

TABLE VI.

Contributions of the total self-shielding effects on Keff and IBG (1200 MWe inner core)

Reaction	$(1-\bar{f})$ %	$\delta K/K$ %	δ IBG
238 U Capture	18.0	+ 4.1	- .088
239 Pu Fission	0.7	- .38	- .0008
239 Pu Capture	2.0	+ .12	+ .0064
240 Pu Capture	2.6	+ .05	- .0018

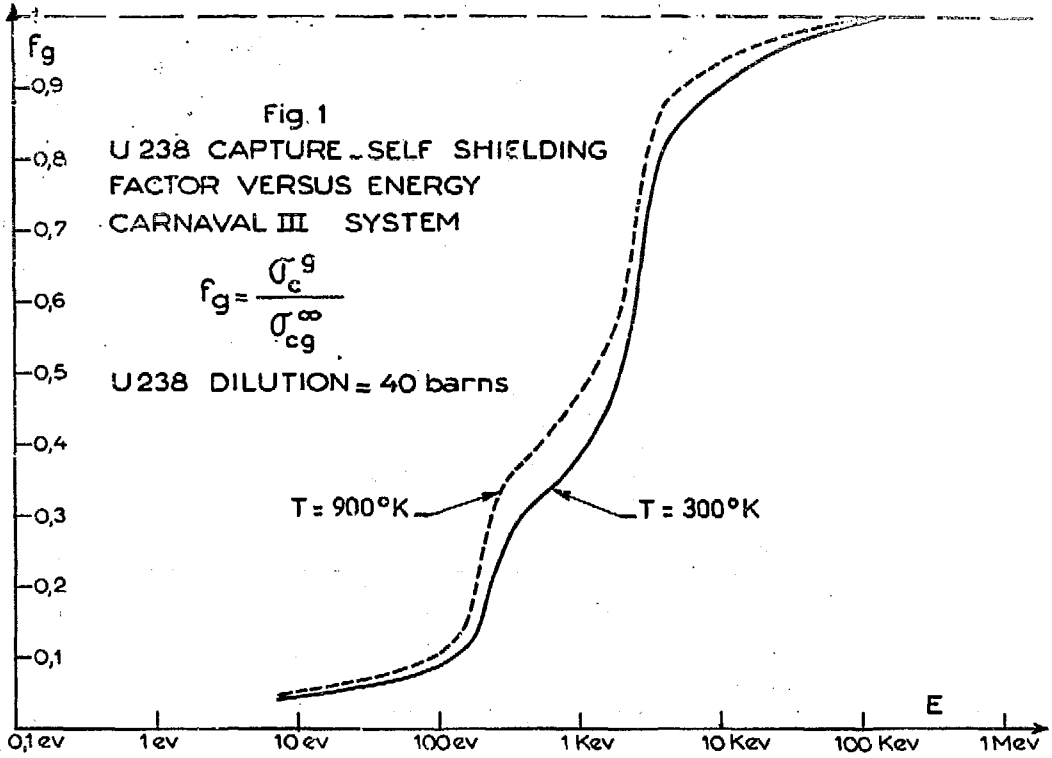


Fig. 1
U 238 CAPTURE - SELF SHIELDING
FACTOR VERSUS ENERGY
CARNAVAL III SYSTEM
$f_g = \frac{\sigma_c^g}{\sigma_{cg}^\infty}$
U238 DILUTION = 40 barns
T = 900°K
T = 300°K
f_g
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
E
0,1 ev
1 ev
10 ev
100 ev
1 Kev
10 Kev
100 Kev
1 Mev

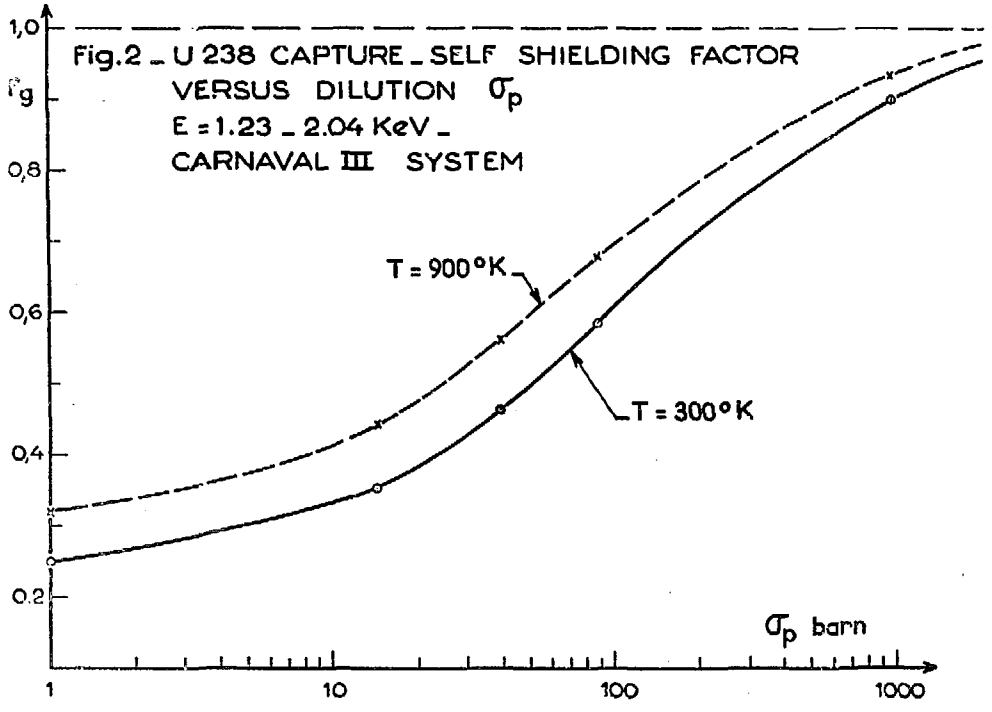


Fig.2 _ U 238 CAPTURE _ SELF SHIELDING FACTOR
VERSUS DILUTION σ_p
E = 1.23 _ 2.04 KeV _
CARNAVAL III SYSTEM
Γ_g
1,0
0,8
0,6
0,4
0.2
T = 900°K
T = 300°K
σ_p barn
1
10
100
1000

Fig.3 _ U 238 CAPTURE _ SELF SHIELDING FACTOR $\bar{f}$ VERSUS SPECTRUM

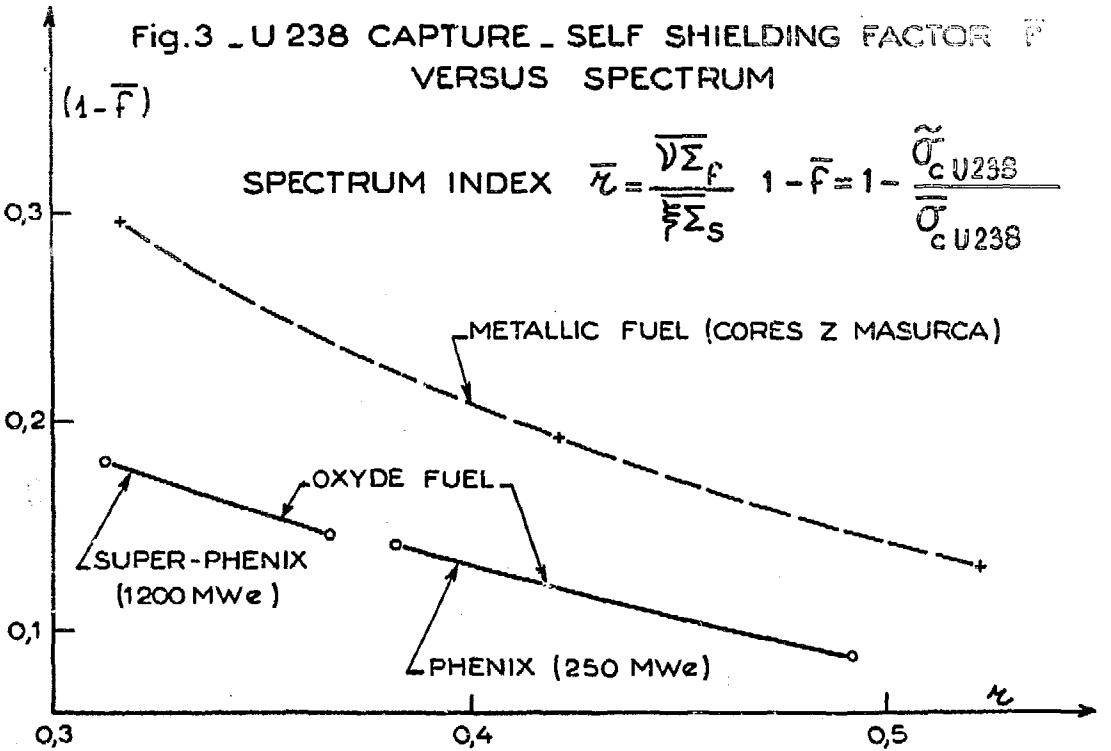


Fig. 4 _ Pu239 ALPHA _ SELF SHIELDING FACTOR $\bar{f}$ VERSUS SPECTRUM

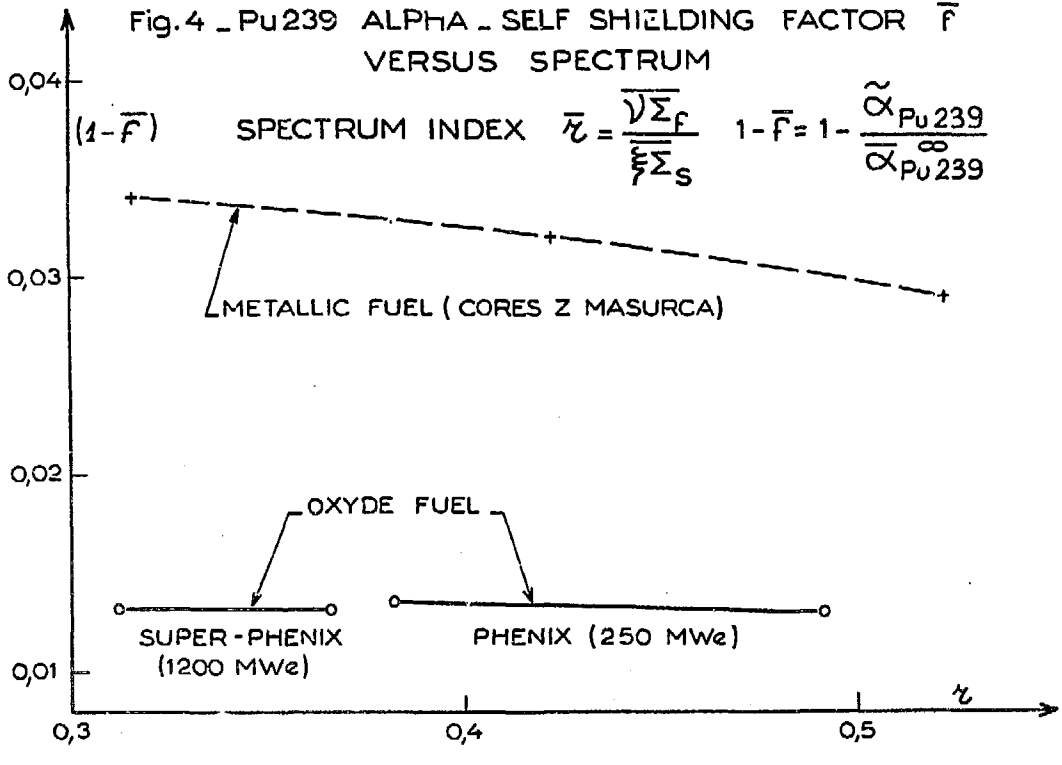
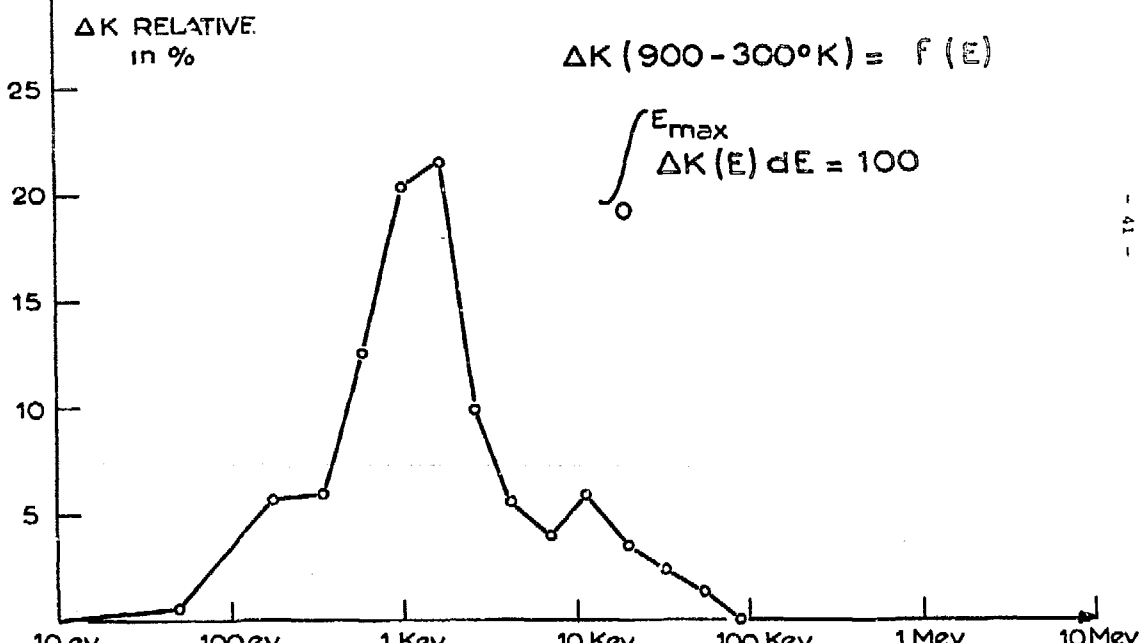


Fig.5_ENERGY DISTRIBUTION OF DOPPLER EFFECT IN A TYPICAL LARGE FAST POWER REACTOR



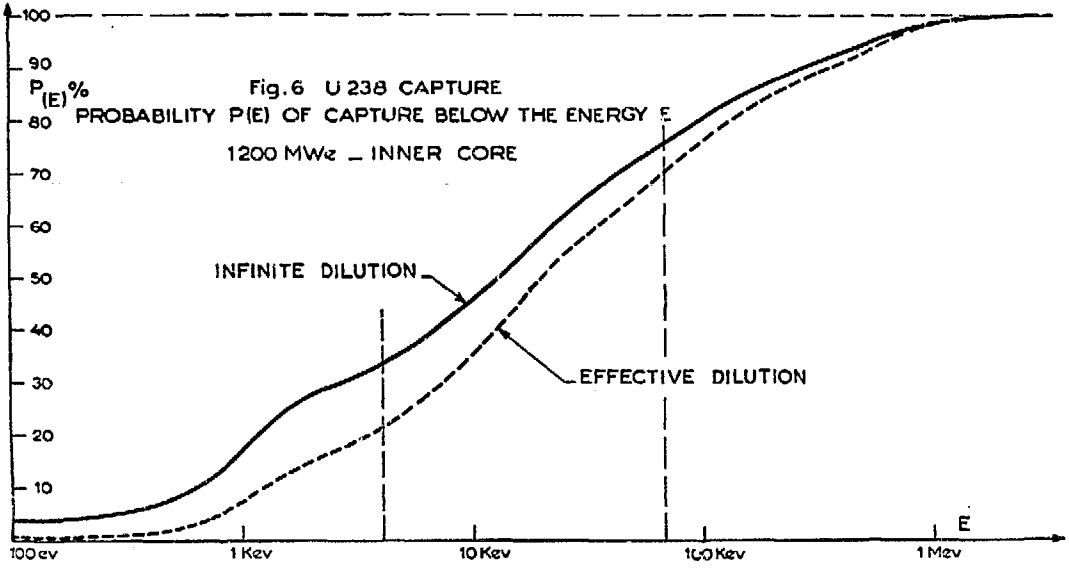


Fig. 6 U 238 CAPTURE
PROBABILITY P(E) OF CAPTURE BELOW THE ENERGY E
1200 MWe _ INNER CORE

Décembre 1974

EVALUATION OF THE THORIUM 232 CAPTURE RESONANCE INTEGRAL

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INTRODUCTION -

Before undertaking any neutronic study, it is important first of all to estimate the validity of the nuclear constants on which most of calculations are based. Such an analysis is particularly necessary for thorium 232 where fundamental data are much scarcer than in the case of uranium 238 for instance, given the comparatively recent interest created by the development of high temperature reactors (H T R).

From the view point of a reactor physicist, the most important quantity to be established for a fertile nucleus is without any doubt the resonance integral on which the conversion ratio depends in particular. We have abready studied the problem of the résonance absorption calculation (ref [1]) and proposed a set of evaluated resonance parameters, on the basis of measurements published by different laboratories. We have also carried out a comparative study in which the values of the resonance integral in infinite dilution, calculated by means of different sets of parameters, were compared with experimental values obtained from integral measurements. For this purpose, a compilation of measurements was prepared in order to determine the "best" value as reference for comparisons.

The following value was then adopted :

$$I_{\infty} = \int_{0.5\ ev}^{\infty} \sigma_c(E)\ \frac{dE}{E} = 83,7 \pm 2,5\ b \qquad (1)$$

In this work, no detailed critical study of the measurements available was attempted and the results were therefore taken simply as published.

In order to improve the estimation we have repeated this study examining each measurements in detail and adding recently published values. Before presenting this new evaluation we should point out that the definition adopted for the resonance integral is given by the formula 1, which means that the so-called "1/v" part is included.

1 - COMPILATION -

This is based on the latest version of the C I N D A reference index (ref [2]) dated October 1973 (Supplement n°1), which can be considered as an exhaustive list of references on the experiments carried out to date. We were thus able to obtain all the original articles apart from a thesis by DEKKER entitled "The local pile oscillator as a device for measuring temperature dependance in epithermal neutron absorption" mentioned in the index "Dissertation abstract" (section B, vol 30 p. 3817 - February 1970). However, it seems that the infinite dilution resonance integral is not studied in this work. It should be noted also that in

the case of reference I14 (see table I) we only have the final result which is taken from BNL 325 (ref [3]).

Fourteen measurements altogether have been collected and their characteristics are listed in table I (see end of text). This table also includes 3 other compilations for purposes of comparison (see comments on table I).

2 - GENERAL CHARACTERISTICS OF THE EVALUATION

The measurements are discussed individually in the notes on table I. From a detailed study of each measurement the validity of the result has been judged and corrections applied as necessary. There we shall merely present the choices made in order to justify our recommended values for each measurement.

2-1. Normalisation values

Generally speaking the results were renormalised using the latest values published in the BNL 325 (ref [3] bis) for the cross sections of reference nuclides. These values are essentially :

- Resonance integral of gold 197 : $I_{\infty}^{au} = 1560$ b
- Cross sections at 2200 m/s for :

  . Gold : $\sigma_o^{AU} = 98,8 \pm 0.3$ b

  . Boron : $\sigma_o^{B} = 759 \pm 2$ b

  . Thorium : $\sigma_o^{Th} = 7,4 \pm 0.08$ b.

For the error on the resonance integral of gold, the BNL 325 gives $\pm$ 40 b, which seems rather pessimistic. A recent evaluation by P. RIBON (ref [7]) confirms the BNL 325 value but with an error reduced to a more realistic figure $\pm$ 22 b. In this work we have therefore adopted the value $I_{\infty}^{AU} = 1560 \pm 22$ b.

2-2. Error calculation

All activation measurements directly involve the 3 factors σ_o^{AU}, I_o^{AU} and σ_o^{Th} (see note 1 on the measurements), which means that the relative error due to the uncertainty on these 3 values can be expressed by :

$$\frac{\Delta\sigma_o^{AU}}{\sigma_o^{AU}} + \frac{\Delta I_o^{AU}}{I_o^{AU}} + \frac{\Delta\sigma_o^{Th}}{\sigma_o^{Th}}$$

In fact it was decided to add the different errors quadratically, which gives an uncertainty of 1.8% or 1.6 b.

For the other kinds of measurement (absorption) the 3 factors are generally not involved in the same way. However it can be shown by calculating the exact error in each case that the expression of the systematic error due to these 3 normalisation values is similar in relative value to that of activation measurements.

2-3. Cut-off energy

Since the so called "cut-off" energy given by different authors is not always the same (see table I) the results are reajusted to the energy E_c = 0.5 eV, the generally accepted nominal value

2-4. "1/V" part

In case where the "1/V" part is not included, a contribution $\delta(1/V)$ = 1.46 b was added (reference [6]). It takes into account the presence of bound level below neutron binding energy in the compound nucleus of thorium 233. This problem have already been dealt with in ref [1] and we shall not return to it here, except to mention that the thermal cross section of thorium decreases faster than a 1/V law and consequently the actual contribution of this compoment is smaller than that obtained by applying the formula :

$$\delta(1/V) = \int_{0.5}^{\infty} \sigma_o^{Th} \sqrt{\frac{E}{Eo}} \frac{dE}{E} = 2 \sigma_o^{Th} \sqrt{\frac{E_o}{0,5}} = 3,33 \text{ b}$$

In the whole, the published value for the actual contribution is about 1.5 b, as given by STEEN (ref. [6], and DERRIEN (ref. [8]) . Since the study of STEEN seems to be the most accurate study on the subject, we have adopted this value. Furthermore, the value 1.46 b agrees well with those calculated from the parameters generally taken for the firt bound level.

Each measurement will now be examined briefly.

3 - ANALYSIS OF EACH MEASUREMENT

A few comments on the methods employed, will be found in the notes of table I.

reference 11 (E. STEINNES)

If we refer to the values obtained for the other isotopes studied, especially uranium 238 (I_∞ = 278 b), we can consider this as a good measurement (BNL 325 value is 275 ± 5 b). Consequently the result has merely been renormalized. However, the experimental error applied is larger than that apparently adopted by the author since many examples taken from values given for other isotopes show that the various sources of uncertainty were not accounted for systematically.

The experimental uncertainty adopted will thus be the value we can calculate directly from the error on the cadmium ratio measurement. Finally we obtain :

I_∞ = 88.6 ± 3 b (exper.)

It should be noted that the "1/V" part is included in the measurement result itself and hence there is no need to modify the measured value

Reference I2 (L. BRESTENHUBER and al.)

On original feature of this work is that absorption and activation measurements were carried out in the same sample. In addition, the reactivity variations are measured with high precision (1%) by a special technique known as D C.M ("Danger coefficient method").

Both results given by the author include a "1/V" contribution of 3.7 b, which is much too large according to our findings, although the cut off energy here is

$$Ecd = 0.4 \text{ eV and } \int_{0.4 \text{ eV}}^{0.5 \text{ eV}} \sigma_c(E) \frac{dE}{E} = 0.39 \text{ b.}$$

The result have therefore been corrected as follows

a) Renormalisation : 89,91 b (ABS) et 86,22 b (ACT)

b) "1/V" Capture : 1,46 b 1,46 b

The error calculation was repeated in detail for each measurement and led to an experimental error of ± 5.3 b for the absorption measurement and ± 1.9 b for the activation measurement, whence the values :

absorption : I_∞ = 91.4 ± 5.3 b (exper.)

activation : I_∞ = 87.7 ± 1.9 b (exper.)

Reference I3 (J. HARDY).

Many corrections are made to allow for different effects and as a result the spectrum shown to approach a 1/E form. This suggests that the measurement is carefully done. The uncertainty due to the normalisation values seems to be under estimated, but since we separate the two causes of error (experimental and "systematic") this makes no difference. The experimental error taken is that given by the author, ± 2%, whence the result after normalisation :

$$I_\infty = 83.6 \pm 1.7 \text{ b (exper.)}$$

Concerning the "1/V" contribution, the same remark applies as for reference I1.

Reference I4 (W.K FOELL and al.)

The value of the resonance integral in infinite dilution is obtained by extrapolation of reactivity measurements carried out as part of a more general study on resonance absorption in Th 232-U.238 mixtures. (W.K. FOELL : Doctoral Thesis - 1964 - Standford university).

Many theoritical and experimental corrections are applied in order to account for various effects (deviation from 1/E spectrum, energy-dependence of adjoint flux, reactivity effect of fast fissions. experimental corrections on diffusion of absorbers an diluents etc...).

According to the authors, 1 b out of the 3.4 barns total error is due to uncertainty on the resonance integral of gold. The experimental error will there fore be taken as ± 2.4 b, giving a renormalised result :

$$I_\infty = 80.3 \pm 2.4 \text{ b (exper.)}$$

It is to be noted that the authors obtain a theoritical value of 82.3 b on the basis of the BNL 325 resonance parameters (ref. [3]).

Reference I5 (R. VIDAL)

In this work all effects beable to influence the result are studied in detail, expecially the effect of the joining function for the spectrum calculation in the thermalisation range (treatement by the Horowitz and Tretiakoff formalism). It is worth noting that the result obtained for isotopes such as indium (3200 ± 70 b), hafnium (2080 ± 50 b), silver (670 ± 20 b), cobalt (50 ± 5 b) and caesium (450 ± 15 b) generally agree very well with the latest evaluation reported in the BNL 325. More over, the different sources of error are listed in especial detail. The various experimental errors have been added quadraticcaly, the result

renormalised and finally, the "1/V" contribution (1.46 b) added, giving :

I_∞ = 88.1 + 4.3 b (exper.)

The value calculated by the authors from the resonance parameters is I_∞ = 87 ± 6 b (without "1/V")

Reference I6 (M. BROSE)

The article gives relatively little information on the measurement, but we have the normalisation values adopted by the author (particularly low for the resonance integral of gold : 1461.8 b) and we can therefore renormalise the result.

The uncertainty given by the author (± 1.8 b) seems greatly underestimated if the error on the normalisation values are included. Accounting for the errors quoted on the cadmium ratio value the experimental uncertainty obtained is ± 1 b, which seems more realistic than that given by the author (0.66% or 0.6 b).

The value adopted will therefore be :

I_∞ = 87.7 + 1 b (exper.)

Note that the value calculated by the author from the resonance parameters is 96 b, which seems very high.

Reference I7 (J.B. SAMPSON and al.)

The reference value for gold are almost the same as ours (I_∞^{AU} = 1561 b, σ_0^{AU} = 98,8 b), but he thorium cross-section at 2200 m/s is taken as 7.45 b (instead of 7.4 b here). In the case of vanadium no correction are necessary, while the deviation of the thorium thermal cross section from a "1/V" law has been estimated correctly (1.5 b).

The only corrections here is therefore that applied to the thorium cross section at 2200 m/s. The experimental error seems to be about 3% which gives the result :

I_∞ = 83.4 + 2.4 b (exper.)

The authors calculate a resonance integral (without "1/V") which varies from 79.6 b to 91.8 b according to the parameters used.

Reference I8 (L.I. TIREN)

Since the report is devoted mainly to the calculation of self shielding, it contains few details on the resonance integral measurement itself. It is possible nevertheless to renormaliser the result knowing that the value adopted by the author are : I_{∞}^{AU} = 1510 b (without "1/V") and σ^{Th} = 7.45 b, giving 82.75 b for the resonant part, to which we add 1.46 b for the "1/V" contribution.

Lacking detailed information on the different sources of error we take, as experimental error, the total error reported (± 6 b) minus 2.5 b for the normalisation error contribution which gives :

I_{∞} = 84.2 ± 3.5 b (exper.)

The value calculated by the author is 82.3 b (without "1/V").

Reference I9 (R.B. TATTERSALL)

According to the authors them selves, the spectrum probably diverges appreciably from a 1/E form, although there may be some compensation du to the adjoint flux ($\Phi \times \Phi^{+} \sim 1/E$). In addition the "self screening" correction seems rather approximate, which casts doubt on the extrapolation for infinite dilution.

In view of these different sources of uncertainty it was decided to disregard this measurement, which in fact would weigh very little considering the margin of error involved (± 10 b).

Reference I10 (F.J. JOHNSTON and al.)

Of the 5 results given we concentrated on the last two, which correspond to measurements carried out on the thinnest sample. After renormalisation of each measurement the average value was taken. With regard to the range of error, account is taken of the fact that the uncertainty on the resonance integral of gold is smaller than the author suggests. From the known total error, the experimental uncertainty is estimated at ± 4 b.

The value finally taken is :

I_{∞} = 84.5 ± 4 b (exper.)

Reference I11 (V.B. KLIMENTOV and al.)

Given the abnormally low value provided by this

measurement, the results obtained for other isotopes were compared with the recommanded values in the latest BNL 325 (ref. [3]). For uranium 238 the measurement gives 224 ± 40 b, whereas the value quoted in [3] is 275 ± 5 b. Similarly for silver, we have :

measurement : 466 ± 70 b BNL 325 : 747 ± 20 b

and for indium :

measurement : 2220 ± 300 b BNL 325 : 3200 ± 50 b

etc...

This general disagreement is probably due very largely to the form of the actual spectrum, for which no correction has been applied. Therefore, this measurement has been disregarded.

Reference I12 (G.G. MYASISHCEVA and al.)

The measurements were carried out successively in 3 quite different regions of the core where the spectra are probably very far from a 1/E form. Only by knowing the form of the spectrum could be explained the disparity of the results and a conclusion reached. In the absence of such information, this measurement will be neglected.

Reference I13 (R.L. MAKLIN)

The two articles dealing with this measurement give two sightly different values : 67 b (without "1/V") and 69.8 b including a "1/V" component of 3.2 b. The value adopted here is the latter, given in the more recent publication (Progress in nuclear energy).

The article does not explicitly state the value used for the thermal cross section of thorium, but in a calculation of the "1/V" contribution the author applies formula (2), i.e an expression of the form $\sigma(1/V) = \alpha\,\sigma_0$. In principle $\alpha = 2\,\frac{E_0}{0.5} = 0.450$, but if we refer to the value calculated for gold, $(1/V) = 45$ b with $\sigma_0 = 98$ b, we find $\alpha = 0.459$ whereas author uses $\alpha = 0.44$. It finally seems that the value employed for α is 0.459, which gives for thorium ($\sigma(1/V) = 3.2$ b) : $\sigma_0^{Th} = 7$ b.

From this value and from those adopted for gold, the result can be renormalised, which gives 73.28 b. Since the cadmium cut off is 0.4 eV, the integral fraction between 0.4 eV and 0.5 eV, i.e 0.39 b, must be substracted, whence the final value :

$I_\infty = 72.9 \pm 5$ b (exper.)

The error given here is that reported by the author in the other article (J.N.E.).

Reference I14 (L. SEREN)

As mentioned above the original article concerning this measurement is not avalaible. The only information we possess comes from the BNL 325 (1965 edition), and from a comment by Macklin in the article just referred to (ref I13).

It seems that this measurement carried out in the first Chicago graphite pile (reactor CP3), is an "absolute" measurement which is therefore independant of any normalisation against another isotope.

The problem is to fix a margin of error for the result. The choice is made more difficult by the fact that the method used cannot be compared to any other. We therefore decided to take an arbitrary margin of ± 5 b, the maximum error found so far.

The value adopted is thus :

$$I_\infty = 84 + 5 \text{ b (exper.)}$$

4 - EVALUATION PROCEDURE

In view of the corrections applied, it may be considered that the experimental error assigned to the 11 remaining measurements covers the different sources of experimental uncertainty. Each measurement x_i can then be weighted by the inverse square of the experimental error x_i using the formula :

$$\bar{x} = \frac{\sum_{i=1}^{11} x_i / (\Delta x_i)^2}{\sum_{i=1}^{11} 1/(\Delta x_i)^2}$$

which gives 85.8 b.

To estimate the total uncertainty on this result, the two sources of error must now be distinguished.

a) Uncertainty on the normalisation values, which can be called the systematic error. The same value is taken for all the measurements, i.e. $d_1 \bar{x} = 1.6$ b

b) Experimental uncertainty which can be estimated by

applying the formula :

$$(\delta_2 \bar{x})^2 = \frac{\sum_{i=1}^{11} (x_i - \bar{x})^2 \times 1/(\Delta x_i)^2}{(11-1) \sum_{i=1}^{11} 1/(\Delta x_i)^2}$$

We thus find an error $\delta_2 \bar{x} = 0.9$ b.

Adding these two errors linearly, we obtain a total error of 2.5 b.

Finally our recommanded value for the resonance integral of thorium 232 is :

$$\boxed{\int_{0.5} \sigma_c(E) \frac{dE}{E} = 85.8\text{b} \pm 0.9 (\text{exper.}) \pm 1.6 (\text{norm.})}$$

TABLEAU I

ORIGINE			MESURES		CARACTERISTIQUES			EVALUATIONS				
REF.	LABO. (a)	ANNEE (b)	VALEUR I_∞	ERREUR ΔI_∞	TYPE DE MESURE (c)	NORMALIS. (d)	(e) ENERGIE COUPURE (Ec en eV)	BNL.325 (réf. [3]) (f)	DRAKE (réf. [4]) (g)	DABALL (réf. [5]) (h)	Ce travail (erreur expérimentale)	
I1	KJL	1972	83.	± 3	ACT	AU:Io=1550b	≈ 0.5				88,6±3	1
I2	CTT	1970	88.8 93.	± 4 ± 6	ACT ABS	AU:Io=1509*b AU:Io=1509*b	0.4 0.4				87,7±1,9 91,4±5,3	4 2
I3	BET	1965	82.5	± 3	ACT	AU:Io=1555 b	0.5		83,3±3		83,6±1,7	1
I4	MTR	1965	81.24	± 3.4	ABS	AU:Io=1579 b	0.5	79 ± 3	81,2±3.4	81,2±3,4	80,3±2,4	2;5
I5	FAR	1964	91.	± 4	ABS	AU:Io=1540 b	0.5	90 ± 4	85,4±4		88,1±4,3	3;5
I6	KFK	1964	82.7	± 1.8	ACT	AU:Io=1461,8b		87 ± 2	82,7±1.8	82,7±1,8	87,7±1	1;5
I7	GA	1962	84.	± 5	ACT	AU:Io=1561 b	0.52	83 ± 5			83,4±2,4	6
I8	WIN	1962	83.*	± 6	ACT	AU:Io=1510*b	0.18	86 ± 6	84,4±6		84,2±3,5	2;7
I9	LAR	1960	106.*	± 10	ABS	AU:Io=1513*b	0.67	109 ± 10	107 ±10	106±10		3;0
I10	CRL	1960	85.	±8.5	ACT	AU:Io=1565 b	≈ 0.5	83 ± 8	84 ±8.5	85,4±8,5	84,5±4	1;5
I11	CCP	1959	61.8	±12	ABS	Li(σ_o=71±1b)	0.49	62 ±12		61,8±12		2;5
I12	CCP	1957	plusieurs valeurs		ACT	AU:Io=1316*b	≈ 0.5	77 ± 8		96 ± 6		1;9
I13	CRL	1955	69.8	± 5	ACT	AU:Io=1558 b	0.4	70 ± 5	71,4	69,8* et 67±5	72,9±5	10
I14	ANL	1944	84.		ACT			84			84.0±5	

*Valeur ne comprenant pas la capture de la partie en "1/V".

COMMENTS ON TABLE I

- a) The CINDA code has been adopted for the laboratories

- KJL : INSTITUTT FOR ATOMENERGI, KJELLER NORVEGE
- GFK : GESELLSCHAFT ZUR FOERDERUNG DER KERNENERGIE, GRAZ AUTRICHE
- BET : WESTINGHOUSE : BETTIS ATOMIC POWER LAB - Pittsburgh U.S.A.
- MTR : PHILLIPS PETROLEUM COMPANY - Nat. React. testing Station (IDAHO-FALLS) U.S.A.
- FAR : Centre d'Etudes Nucléaires de Fontenay aux Roses - FRANCE
- KFK : Kernforschungszentrum - Karlsruhe - ALLEMAGNE
- G.A : General Atomic - SAN DIEGO (CALIFORNIA) U.S.A.
- WIN : AEE - Winfrith - Dorchester ANGLETERRE
- HAR : HARWELL - Atomic Energy Research Establishment ANGLETERRE
- ORL : Oak Ridge National Laboratory (Tennessee) U.S.A.
- CCP : U.R.S.S.
- ANL : Argonne National Lab. LEMONT (illinois) U.S.A.

- b) The year is that of publication

- c) Two distinct types of measurement are generally involved :

  ACT : Activation measurements which use the cadmium ratio technique

  ABS : Absorption resonance integral measurement using the technique of reactivity variation set up in a pile when an absorbant sample is introduced (see notes after theses comments).

- d) AU-Io refers to the resonance integral of gold which is usually taken as the normalisation quantity.

- e) The cut off energy only applies in the case of activation measurements which involve a cadmiun filter. For absorption measurements the energie is

merely conventional (nominal value).

- f) Evaluation ported in BNL 325 (ref [3])

$$I_\infty = 83 \pm 3 \text{ b}$$

This estimation refers to a value 1535 b for the resonance integral of gold. In the latest version of the BNL 325, the recommanded value is 85 ± 3 b.

- g) Evaluation made by Drake (ref [4]) :

$$I_\infty = 84 \pm 5 \text{ b}$$

This estimation refers to a value 1550 b for the resonance integral of gold

- h) Evaluation reported in ref. [5] , based on the choice of the "best" measurement which, according to the author is that of JOHNSTON (ref. I10) :

$$85.4 \pm 8.5 \text{ b.}$$

NOTES ON THE MEASUREMENTS

(Table I)

1 - Measurement using an activation technique, based on the comparative activities of a bare irradiated sample and the same sample irradiated under cadmium. The formula used is then :

$$I_o^{Th} = \sigma_o^{Th} \frac{(R_{cd}^{AU} - 1)\ I^{AU}}{R_{cd}^{Th} - 1)\ \sigma_o^{AU}}$$

where Rcd is the "Cadmium ratio"

2 - Measurement by absorption. The method is based on a static measurement of the reactivity variation generated by the introduction of an absorbant sample. In brief the process used is as follows :

- The constant α , which characterises the spectrum at the measurement point ($\sigma_{ef} = g\ \sigma_o + \alpha\ I_\infty$) is determined by means of a gold resonant standard

- Sample containing thorium are then measured and I_∞ obtained from the results.

The calibration value linking the reactivity variation to the reaction rates is obtained by the use of boron* . To evaluate self shielding, several measurements are carried out and the value in infinite dilution is obtained by mass linear extrapolation.

3 - Measurement of the same type as above (note 2) except that the reactivity measurement are performed by the oscillation method.

4 - Activation measurement based on the cadmium ratio technique but with a formulation slightly different from that given in note 1. The formula used is :

$$\alpha = \sqrt{\frac{4T}{\pi To}} \qquad r = \frac{g}{\frac{\sigma_r^{AU}}{\sigma_o^{AU}}\ (R_{cd}^{AU} - 1) + \frac{2g\ R_{cd}^{AU}}{\sqrt{Ecd}}}$$

* For reference III the standard is lithium.

where

. r is Wescott index (α being the spectrum index)

. g(T) Wescott's factor : g = 1.005 for gold

. $\sigma_r^{AU} = \int_0^{\infty} \left[\sigma(v) - g\,\sigma_o^{AU}\,\frac{Vo}{V}\right] \Delta \frac{2dV}{V}$ (Δ, joining function)

. Ecd = 0.55 eV (must be expressed in k T units).

From the measured ratio R_{cd}^{AU} = 2.065 it is possible to deduce α . The same formula, this time applied to thorium (g = 1), leads to :

$$\frac{\sigma_r^{Th}}{\sigma_o^{Th}} = \frac{\alpha - 0.429\ R_{cd}^{Th}}{R_{cd}^{Th} - 1} \quad \left(\frac{2}{\sqrt{Ecd}} = 0.429 \right)$$

The measurement of R_{cd}^{Th} (= 2.383 ± 1%) can then be used to deduce σ_r^{Th} , which the integral required (without "1/V" part).

5 - Measurement carried out in a U235 - H_2O pile

6 - Measurement carried out by comparison of the Th - 233, AU 198 and Vd-52 activities resulting from inadiation of Th 232, AU 197 and Vol 51 in the reflector of the reactor TRIGA (U235 - Zr Hz) then in a thermal column ("Vanadium substraction technique"). The conventional cadmium ratio method is also applied but gives poor results here.

7 - For this reference I8 the measurements are carried out in a thermal column of the reactor NESTOR (U235-H_2O) and also in the U235 - graphite reactor ZENITH.

8 - Oscillation measurements are performed at the center of a heavy water-moderated reactor (DIMPLE). The irradiations are carried out in two spectra, one of which thermal in order to measure the cross section at 2200 m/s and the g factor.

9 - Measurement carried out in a heavy water reactor.

10 - Measurement performed in a uranium - graphite reactor.

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ON THE SHAPE ANALYSIS OF VARIOUS ^{232}Th AND ^{238}U TRANSMISSION DATA

M. DERRIEN AND P. RIEON
CEN - SACLAY.

In the study of the low energy cross sections of even heavy nuclei such as ^{232}Th and ^{238}U only the elastic (n,n) and capture (n,γ) reactions have to be considered, the fission being of very little importance for reactor applications ; for each resonance these reactions are characterized by the neutron width Γ_n and the total radiative capture width Γ_γ. These parameters can be obtained by the analysis of up to 4 kinds of experimental data : transmission, self-indication, scattering and capture measurements.

The various techniques which can be utilized for the analysis of the experimental data can be shared between two groups of methods :

a) the area analysis : the widths Γ_n and Γ_γ are determined from the study of the experimental area of the resonances. Each experimental value of the area, A_E, is a function of Γ_n, Γ_γ and of the thickness n of the sample. This function, $A_E = f(\Gamma_\gamma, \Gamma_n, \ldots)$, is assumed to be known ; it is then possible to draw in the $(\Gamma_n, \Gamma_\gamma)$ plane the curve depicting Γ_n as a function of Γ_γ for each experimental data. All of these curves should go through the point $(\Gamma_{n\lambda}, \Gamma_{\gamma\lambda})$ corresponding to the true parameters $\Gamma_{n\lambda}$ and $\Gamma_{\gamma\lambda}$ of the resonance ; as a matter of fact there is a spreading of results, all of the curves do not go through the same point and the problem is to determine the best converging point. The function $f(\Gamma_\gamma, \Gamma_n, n)$ takes into account experimental effects like self screening and multiple scattering. The resolution function is not needed, but it is necessary to determine the experimental value of the total area of the resonance, including the wings ; for non isolated resonance some difficulties can arise. An other difficulty is the right estimation of the multiple scattering effect in thick samples.

b) The shape analysis : the theoretical value is calculated for each data point in the resonances and compared to the experimental value ; the theoretical curve can be adjusted to the experimental points (fitting procedure) by a least square method which provides the values of the resonance parameters. It is necessary to take into account the resolution function and the Doppler effect ; presently the memory size ant the speed of computers are great enough to allow for complicate formulations of the resonent cross sections for large number of resonances and large number of data points. This method can be easily used for transmission data for which no complicated correction have to be done. For the partial cross section, such as capture cross section, it is necessary to use experimental data corrected for self-screening and multiple scattering effects on each measured point ; if this can be done, simultaneous analysis of transmissions and partial cross sections will provide very accurate resonance parameters.

The problem of the right knowledge of the resolution and of the Doppler effect is important in the shape analysis if one want to determine accurate value of the total width. However this problem is not crucial at low energy due to the excellent resolution achieved at the present time in the time of flight experiments and to the fact that the Doppler coefficient is known with an accuracy better than a few per cent. Then accurate values of Γ_γ can be obtained for low energy resonances and consequently accurate value for the average capture width $<\Gamma_\gamma>$. At higher energy, the resolution function can be adjusted to obtain the same $<\Gamma_\gamma>$ value. Such method has been used by one of us for ^{232}Th [Ri 69] ; he obtained very good values below 300 eV ; above, the values are more scattered but coherent in their average.

All transmission data obtained up to now at the Saclay 60 MeV linac have been analysed by least square shape analysis. The codes used for these analysis have been described in detail elsewhere [Ri 64]. The theoretical transmission at the neutron energy E is calculated by a formula of the following type :

$$Tr_{exp}(E) = a + c\, e^{-n\sigma_A(E)} * R(E)$$

$\sigma_{\Delta}(E)$ is the cross section broadened by the Doppler effect (essentially a sum of ψ and φ function plus a term taking into account the interference between resonances in the neutron channel) ;

a is a term for background adjustment (equal to zero if there is no systematic error in the background determination) ;

c is the normalization coefficient (equal to one if the normalization is correct) ;

R (E) is a gaussian resolution function

Several sets of experimental data can be simultaneously analysed. The least square adjustment can be done on the resonance parameters (E, Γ_n and Γ) and, for each data set, on the corrective parameters a and c. The X^2 to be minimized has the following form :

$$X^2 = \sum_E \left[Tr_{exp} - \left(a + c e^{-n\sigma_{\Delta}(E)} * R(E) \right) \right]^2$$

For instance, the background adjustment corresponds to the solution of the following equation :

$$\frac{\partial(X^2)}{\partial a} = 0 = \sum_E 2 \left[Tr_{exp} - a - c e^{-n\sigma_{\Delta}(E)} * R(E) \right]$$

i. e. :

$$\sum_E (Tr_{exp} - a) = \sum_E c e^{-n\sigma_{\Delta}(E)} * R(E)$$

if the sum is made on an energy interval large enough compared to the resonance widths, the second member of this equation represents the theoretical total area for each resonance and is <u>independent of the resolution function</u>. So, after adjustment by least square of the parameter a, we always have :

$$\text{theoretical area} = \sum_E (Tr_{exp} - a) = \text{experimental area.}$$

Then, the least square shape analysis method gives the right value of the area, even if the resolution function is wrong, after a possible correction of the background.

In the second part of this paper, we shall examine some results obtained by shape analysis performed on some ^{232}Th and ^{238}U transmission data from Geel and Columbia.

A - RESULTS CONCERNING ^{232}Th

Table I shows the results obtained from the Columbia data in the 1450 to 1650 eV energy range. A part of these results concerns the old Columbia data (Columbia I) and has been reported already by l'Héritcau et al at the Knoxville Conference (1971) [LR 71]. Frome this table, one can draw the following conclusions :

1) The Γ_n values obtained from all the transmission data (Columbia I, Columbia II, Saclay) by our shape analysis agree within the error bar, while the values obtained by Garg et al by area analysis on the Columbia I data are lower by a factor about 2 ;

2) the shape analysis of Columbia I data brings out an important systematic error in the background (27 % for the thin sample, for instance) ; this error is probably at the origin of the discrepancy observed between Garg values and ours ;

3) the values obtained by Rahn from Columbia II agree with ours within 5 % on the average ; in fact, there is very little correction to be done on the background (less than 0.01) in this energy range for Columbia II data.

In the energy range from 2.5 keV to 2.7 keV the parameters resulting from our shape analysis of Columbia II data agree with Rahn results within 4 % on the average, but the background correction varies from 6×10^{-3} to 3×10^{-2}, i. e. is greater than in the 1.45 to 1.65 keV energy range.

Table II shows the results obtained between 3.2 keV and 3.7 keV from Columbia II data. There is a disagreement of 10 % on the average between Rahn results and ours. The disagreement on the large resonances is generally greater than 15 %. The background correction is equal to 0,036 for the 0.0034 at/b sample and 0.065 for the 0.0311 at/b sample. It seems that a systematic error in the background still exist at high energy for the Columbia II data, and is at the origin of the decreasing of the Γ_n values obtained by Rahn when the energy increases. This may be the explanation of the low value of the local strength function obtained by Rahn above 3 keV.

C - RESULTS ON ^{238}U

The Columbia II and Geel data have been analysed in the 1.40 keV to 1.80 keV energy range. The background correction is negligible on the Geel transmissions and very small for those of Columbia. Our results of the Geel and Columbia data shape analysis and the values published by Rahn are in agreement within less than 4 % on the average, while the values published by Carrero [Ca 71] are 15 % or 20 % higher. The following remarks have to be done :

1) our shape analysis of the Columbia transmissions is nearly in agreement with Rahn area analysis of the same data ;

2) our shape analysis of the Geel transmission is in disagreement with Carrero results for the same data ;

3) Carrero Γ_n values are probably overestimated ; a simultaneous shape analysis of Columbia and Geel transmissions would lead to results not far from Rahn results. This analysis method would give serious amelioration in the ^{238}U resonance parameter evaluation.

CONCLUSION

From these studies we conclude :

1) the shape analysis provide all the information resulting from the area analysis, even if the resolution function is erroneous ;

2) the shape analysis allows the detection of systematic errors on the normalization and the background determination, and their corrections ;

3) the shape analysis is particularly usefull when there are no sophisticated correction such as self-screening and multiple scattering ;

4) the origin of discrepancies between various recent transmission data is mostly linked to analysis methods (case of ^{238}U between Geel and Columbia) ; there is a problem of background determination for some old results, or at high energy for some recent data.

5) for high quality evaluations of resonance parameters it is recommended to check the analysis of experimental data in selected energy ranges ; in particular, the previous erroneous Columbia data (Columbia I) would not have been recommended ;

6) from our analysis we conclude that, for ^{238}U, below 2 keV, the Columbia II set of resonance parameters is better than the Geel's set. For ^{232}Th we conclude that, although it may be a little bit overvalued, the Saclay set of neutron widths has to be preferred to Columbia's set which presents an underestimation increasing with energy.

TABLE I.

^{232}Th Columbia Γ_n values between 1550 ev and 1680 ev.

Energy	Shape analysis of Cooley data [Bl 60]	Columbia I published values [Ga 64]	Shape analysis of Columbia I data [Lh 71]	Columbia II published values [Ra 72]	Shape analysis of Columbia II data (present work)
1580.4 eV	22.5 ± 4.5 meV	9.9 ± 1.6 meV	23.1 ± 1.7 meV	21.0 ± 1.59 meV	20.5 ± 1.0 meV
1588.7	362 ± 19	207 ± 16	325 ± 11	289.8 ± 39.87	330 ± 5.0
1601.8	55 ± 6.5	38 ± 4	49.8 ± 3.6	48.84 ± 6	46.1 ± 2
1620.3	549 ± 33	303 ± 20	501.0 ± 18	510 ± 50.1	520 ± 8
1639.8	40 ± 8	40.5 ± 6	45.7 ± 4	44.1 ± 4.86	42.0 ± 2
1660.7	132 ± 13	77.5 ± 8	110 ± 7	114.1 ± 11.82	111 ± 3.5
$\Sigma \Gamma_n$	1160	676	1055	1028	1078

In the shape analysis of Columbia I data the adjusted background parameters a were equal to :

0.015; 0.11 and 0.27 (3 samples)

In the shape analysis of Columbia II data the adjusted background parameters a were equal to :

0.009 for the 0.0934 at/b sample;
0.003 " " 0.0311 " " ;
0.001 " " 0.0052 " " .

TABLE II.

^{232}Th - Columbia Γ_n values between 3200 ev and 3620 ev.

Energy	Shape analysis of Columbia data (2 thicknesses)	Columbia published values [Rn 72]
3229.4 eV	16 ± 1 meV	17 ± 3 meV
3242.5	14 ± 1	14 ± 3
3252.7	97 ± 5	84 ± 9
3270.0	22 ± 2	26 ± 4
3295.7	461 ± 10	405 ± 44
3331.8	52 ± 3	42 ± 6
3342.9	147 ± 7	172 ± 19
3383.5	106 ± 6	74 ± 10
3409.5	10 ± 2	5 ± 2
3442.9	19 ± 2	20 ± 3
3471.9	15 ± 2	18 ± 3
3521.8	127 ± 7	107 ± 18
3574.4	14 ± 2	17 ± 3
3594.4	20 ± 2	21 ± 4
3611.6	139 ± 7	120 ± 15
$\Sigma \Gamma_n$	1259	1142

In the shape analysis of Columbia data the adjusted background parameters a were equal to :

0.037 for 0.0934 at/b sample

0.065 for 0.0311 at/b sample.

EVALUATION OF ^{232}Th RESONANCE PARAMETERS

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INTRODUCTION

In the last few years important work has been undertaken on ^{232}Th resonance parameters. The results achieved both for the individual values and the average values are frequently in disagreement. The main purpose of this work is to examine the most significant results and to propose a set of resonance parameters which seems more credible. It is obvious that the selection of a set of parameters has effects in many areas, particularly in calculating cross sections in the thermal area and high energy average cross sections ; it is also necessary to check whether the capture integral calculated as from the differential data chosen is in agreement with that evaluated as from integral determinations. Consequently the pattern of this paper will be as follows :

I - Evaluation of resonance parameters and of their average values.

II - Cross sections in the thermal range and negative resonances.

III - Calculation of the capture cross section by a statistical model and comparison with the measured values.

IV - Evaluation of the capture integral from differential data and comparison with the integral measurements.

I - EVALUATION OF RESONANCE PARAMETERS AND OF THEIR MEAN VALUES.

I - 1. Experimental data

For the choice of resonance parameters we selected seven sets of experimental data obtained, in chronological order, from the laboratories of San Diego [Ha 65], Harwell [As 66], Saclay [Ri 69], Brookhaven [Bh 67], Argonne [Bo 68], Los Alamos [Fo 71] and Columbia [Ra 72]. In the case of the Columbia data, we disregarded old publications. Different types of measurements and different methods of analysis were employed ; so that the problem of selecting the parameters may be properly determined, we shall review them for each laboratory.

1) San Diego -

The capture cross section only was measured. Three sample thicknesses were used (0.0038 ; 0.0012 and 0.0004 at/barn) ; the capture γ rays were detected by a liquid scintillator. For each resonance the experimental results were analysed by area method based on the convergence of a set of curves in the (Γ_n, $\Gamma\gamma$) plane, the capture resonance area being considered as a function of parameters Γ_n and $\Gamma\gamma$ and of the thickness n of the sample. The values of Γ_n and $\Gamma\gamma$ were determined for 11 resonances between 21.8 eV and 221.9 eV.

2) Harwell -

A varied set of techniques and sample thicknesses was employed :

a) transmission measurement using 15m, 120m and 192m flight paths with sample thicknesses varying from 0.00024 at/b. to 0.113 at/b;

b) capture cross section measurement by means of a Moxon-Rae detector with a 32.5m flight path and three sample thicknesses (0.00071 ; 0.0014 and 0.0029 at/b.) ;

c) scattering cross section measurement using a lithium glass detector with a sample thickness of 0.00014 at/barn.

The resonance parameters were established up to an energy of 866 eV by three different methods :

a) analysis of the transmission data using Lynn [Ly 60] area analysis code (intersection of curves giving the relationship between $\sigma_o k^2 a^2$ and Γ/ka) and Atta-Harvey [At 61] area method . The Γ_n and $\Gamma\gamma$ values were

obtained for resonances up to 170 eV, and Γ_n for the other resonances. A set of curves of Γ_n versus $\Gamma\gamma$ were also established for certain resonances and different sample thicknesses ;

b) simultaneous analysis of capture and scattering cross sections, by studying the convergence of several curves in the plane (Γ_n, $\Gamma\gamma$) ; the values of Γ_n and $\Gamma\gamma$ were obtained for most of the resonances ;

c) study of the convergence of all the curves in the (Γ_n, $\Gamma\gamma$) plane obtained for each resonance as from all the measurements and all the sample thicknesses ; a third set of Γ_n and $\Gamma\gamma$ values was thus obtained.

A comparative table of the parameters obtained from the three methods was given.

3) Saclay -

The set of parameters was mainly established as from the transmission measurement of a 0.120 at/barn thick sample, made with a 100m flight path with a very good resolution. The resonance parameters were determined by least square shape analysis method [Ri 66]. With this method, Γ_n can be determined in every case, and $\Gamma\gamma$ by difference between Γ and Γ_n if the Doppler effect and the width of the experimental resolution function are not too important (up to about 300 eV in this measurement). The neutron width values are given up to 3 keV.

4) Brookhaven -

The measurements concern only the 21.7 ; 23.4 ; 59.4 and 69.1 eV resonances. These transmission measurements used a 29.7m flight path with the BNL fast chopper. Five sample thicknesses were used (0.00015 ; 0.00076 ; 0.0030 ; 0.0092 and 0.028 at/barn). The Atta-Harvey method was used to obtain the resonance parameters, i.e. Γ_n and the total width Γ ; $\Gamma\gamma$ was obtained from the $\Gamma - \Gamma_n$ difference.

5) Argonne -

These also were transmission measurements, made with the ANL fast chopper, in the purpose of obtaining the parameters of the first four resonances. The preliminary results only have been published, in a progress report, without any indication as to the analysis methods used. The Γ_n and $\Gamma\gamma$ parameters of the resonances were given.

6) Los-Alamos -

The capture cross section was measured on the Physics-8 underground explosion, at a 250 m flight path, with a modified Moxon-Rae detector ; the neutron flux was measured by the ^6Li (n,α) reaction. Two sample thicknesses were

used : 0.001 at/barn and 0.05 at/barn. For the large resonances, the $\Gamma\gamma$ values were obtained from the capture areas by using Garg [Ga 64] Γ_n values up to 1 keV and Ribon's [Ri 69] from 1 keV to 2 keV. The theoretical area was calculated taking into account the contribution A_1 to the capture after a first scattering in the sample[1]; A_1 was always very small with respect to the main contribution Ao. The theoretical area was adjusted to the experimental area by a trial and error method by assuming Γ_n to be well known ; $\Gamma\gamma$ was thus obtained for 66 levels up to 2 keV. For the small resonances, the same method was used ; but $\Gamma\gamma$ = 20 meV was arbitrarily applied, the capture area then being but little sensitive to the choice of $\Gamma\gamma$; thus $g\Gamma_n$ was obtained for 124 levels up to 2 keV. The average capture cross section was also measured up to 60 keV.

7) Columbia -

Three kinds of measurement were made using the synchrocyclotron :

a) transmission measurements at 40m and 200m flight paths with sample thicknesses varying from 0.10 at/barn to 0.0011 at/barn ;

b) self indication measurement at a 40m flight path with sample thicknesses varying from 0.03 at/barn to 0.0011 at/barn ;

c) capture measurement with a Moxon-Rae detector at a 33m flight path with 0.0052 at/barn and 0.00112 at/barn thick samples.

The results were analysed by the same kind of method as those of San-Diego and Harwell, namely, for each resonance, by studying the convergence of curves in the (Γ_n, $\Gamma\gamma$) plane, obtained from different experimental areas. A shape analysis was also made for some resonances of the thick sample transmission. The resonance parameters (Γ_n and $\Gamma\gamma$) were given up to 4.5 keV.

I - 2. Examination of the results obtained for the four "s" resonances below 100 eV.

These four resonances are of particular importance in calculating the capture integral to which they contribute for about 70%. Hence the greatest care is needed in determining their parameters. Table I - 1 summarises the results obtained as from seven sets of experiments the characteristics of which have just been recalled. The dispersion of the experimental values is quite important especially concerning the resonance at 23.4 eV. However, for the three first resonances, the neutron width is small against the radiation width : the capture area being pro-

portional to $\Gamma_n \Gamma_\gamma/(\Gamma_n + \Gamma_\gamma)$, it is then important to determine Γ_n with the best accuracy, for this ratio is hardly sensitive to the error on Γ_γ ; for instance, a variation of 20% on Γ_γ induces a variation of about 2% in the capture area of the firstresonance, 3% in the second and 4% in the third.

The dispersion in the values obtained for Γ_γ can be easely understood, since, in addition to the errors of experimental origin due to the fact that the exact determination of the experimental capture area requires much adjustment (efficiency of the detectors, flux measurement, self absorption corrections and multiple scattering corrections, etc...), the area methods used in the analysis are frequently not very accurate ; the set of curves obtained in the (Γ_n, Γ_γ) plane is far from converging to a single point ; the lack of convergence may be due to a formalism defect and to systematic errors in the experimental data. The dispersion of some Γ_n values are more difficult to accept, for they should be determined with good accuracy from the transmission measurements alone which are absolute measurements free of the systematic errors encountered in capture and scattering measurements. Probably the method of analysis are at the origin of the dispersions observed. It would be desirable to apply the same shape analysis method to all the transmission experimental data. Failing such a comparison, we must make do with the critical examination of the values in table I - 1.

1) Resonance energies

In accordance with the principle itself of the shape analysis by least square method, the energies proposed by Saclay are free of the error introduced by the estimation of the "centre" position of the resonance. They agree with the other energies to within .1%, except with the Harwell values where the difference is .4% for the four resonances. Also, up to 3 keV, the energies quoted by Columbia remain in perfect agreement with those of Saclay. It therefore seems reasonable to keep the Saclay values with a possible systematic error of .1%, in other words the following values :

21.783 ± 0.022 eV

23.439 ± 0.024 eV

59.514 ± 0.060 eV

69.223 ± 0.070 eV

2) Choice of Γ_n and Γ_γ values

The values proposed by San-Diego are only based on the analysis of a capture cross section. The authors agree

TABLE I-1.

Reference	E_o	Γ_γ	Γ_n	$\frac{\Gamma_n \Gamma_\gamma}{\Gamma_n + \Gamma_\gamma}$
Ha 65	21.80 ± 0.04	21. ± 5.	2.1 ± 0.2	1.909
As 66	21.69	24.6 ± 1.2	1.88 ± 0.05	1.746
Ri 69	21.783	21.3 ± 3.7	1.96 ± 0.08	1.795
Bh 67	21.78	22.4 ± 2.4	2.61 ± 0.17	2.338
Bo 68	21.80 ± 0.04	26.5 ± 1.2	2.09 ± 0.03	1.937
Ra 72	21.78 ± 0.02	20. ± 2	1.91 ± 0.09	1.743
Ha 65	23.47 ± 0.04	22 ± 4	4.0 ± 0.3	3.385
As 66	23.35	29.9 ± 1.6	3.41 ± 0.08	3.061
Ri 69	23.439	28.2 ± 2.9	3.64 ± 0.12	3.224
Bh 67	23.45	22.0 ± 2.6	4.17 ± 0.25	3.506
Bo 68	23.47 ± 0.04	25.2 ± 1.1	11.11 ± 0.05	3.534
Ra 72	23.43 ± 0.02	25. ± 2	3.24 ± 0.24	2.868

Reference	E_o	Γ_γ	Γ_n	$\frac{\Gamma_n \Gamma_\gamma}{\Gamma_n + \Gamma_\gamma}$
Ha 65	59.5 ± 0.1	22 ± 7	4.0 ± 0.4	3.385
As 66	59.34	23.2 ± 2.0	3.34 ± 0.09	2.920
Ri 69	59.514	23.6 ± 0.7	3.93 ± 0.08	3.370
Bh 67	59.46	16.2 ± 2.3	4.41 ± 0.27	3.466
Bo 68	59.52 ± 0.07	31.7 ± 2.9	3.77 ± 0.15	3.370
Fo 71	59.5	22.7 ± 6.0	4.01 ± 0.31	3.408
Ra 72	59.48 ± 0.08	25 ± 2	3.93 ± 0.23	3.396
Ha 65	69.2 ± 0.1	24 ± 2	47. ± 15	15.89
As 66	68.95	21.2 ± 1.0	41.4 ± 1.2	14.02
Ri 69	69.223	20.5 ± 1.0	44.0 ± 0.5	13.98
Bh 67	69.13	21.5 ± 4.7	42.9 ± 2.6	14.32
Bo 68	69.25 ± 0.07	23.5 ± 1.4	42.0 ± 0.8	15.07
Fo 71	69.1	21.9 ± 2.8	42.5 ± 1.7	14.45
Ra 72	69.17 ± 0.10	25 ± 2	44.0 ± 2.0	15.91

on the fact that the area method used gives only Γ_n with precision if $\Gamma_n \ll \Gamma\gamma$, and only $\Gamma\gamma$ if $\Gamma_n > \Gamma\gamma$. Therefore the $\Gamma\gamma$ values of the first three resonances will be eliminated, as well as the Γ_n value of the fourth resonance.

Harwell's values are coherent on the whole, except for Γ_n of the third resonance where the dispersion of the values obtained by different methods is very great :

3.76 meV (transmission at 120m and 15m) ;

4.60 meV (transmission at 120m) ;

3.05 meV (capture and scattering) ;

3.34 meV (total results) ;

as this dispersion is not explained, the Γ_n value for this resonance will be eliminated.

The values of Saclay should be kept as a whole ; they were obtained by a shape analysis using the least square method ; the adaptation of the theoretical curve to the experimental transmissions is excellent. The $\Gamma\gamma$ values obtained from the $(\Gamma - \Gamma_n)$ differences are fairly accurate, for the Doppler width and the width of the resolution function are rather small at these energies.

The Γ_n values proposed by Brookhaven are systematically greater than the other values for the three first resonances. The authors pointed out that, for determining Γ_n of these resonances, the weight of ten was assigned to the transmission measurements of the thinner sample (0.000154 at/barn) and the weight of one to the other thicknesses. Now, for such a small thickness (i.e. 0.000154 at/barn) and in view of a bad resolution, the minimum of transmission at the peak of the resonances is greater than 0.95. The method is therefore surprising and justifies the elimination of the Γ_n obtained. As for the fourth resonance (69.22 eV) the parameters are very consistent with the other results ; incidentally, the authors have published the results of the analysis by the Atta-Harvey least square method, for six experimental areas ; in this case, the adaptation of the theoretical areas to the experimental areas is excellent.

The values of Argonne were published in a progress report and were considered as preliminary by the authors. There is no systematic disagreement with the other results, except for the third resonance for which $\Gamma\gamma$ is excessively great and which we shall eliminate.

The Los-Alamos results do not include the resonances at 21.8 and 23.4 eV ; for the third and fourth resonance, the authors used Garg's Γ_n values (which do not differ much from the new values of Columbia) ; so we shall only

keep the $\Gamma\gamma$ values which they propose for these two resonances.

The values of Columbia are to be kept as a whole, although the Γ_n value proposed for the second resonance is rather low ; as a fact, it contributes to the significant dispersion observed in the neutron widths of this resonance.

3) Recommended values

The recommended values are given in table I - 2. They are obtained by averaging the selected values weighted by the reciprocal of the square of the absolute error. In the last column of this table, the $\Gamma_n\ \Gamma\gamma/(\Gamma_n + \Gamma\gamma)$ ratios, calculated as from the recommended values, are indicated. These ratios are very close to those which may be calculated from the San-Diego and Los-Alamos parameters, in other words they give a good representation of the measured capture areas (San-Diego and Los-Alamos being the only laboratories to propose resonance parameters from capture measurements only).

The errors in the recommended values are not established from a strict criterion ; they attempt to reconcile the greatest number of experimental values. In particular, the error on Γ_n of the second resonance (around 10%) reflects the great dispersion on the measured values. This is the main black point of this evaluation and it would be necessary to reconsider the analysis for this resonance.

TABLE I - 2

Energy (eV)	Γ_n		Γ_γ		$\frac{\Gamma_n \Gamma_\gamma}{\Gamma_n + \Gamma_\gamma}$
	Value (meV)	Origine	Value (meV)	Origine	(meV)
21,783 ± 0,022	2,02 ± 0,06	SD, HAR SAC, ARG COL	24,5 ± 2,0	HAR, SAC ARG, COL	1,87 ± 0,06 (SD → 1,91)
23,439 ± 0,024	3,88 ± 0,40	SD, HAR, SAC BRO, ARG, COL	26,6 ± 1,5	HAR, SAC ARG, COL	3,39 ± 0,35 (SD → 3,38)
59,514 ± 0,060	3,90 ± 0,15	SD, SAC ARG, COL	23,7 ± 1,0	HAR, SAC LAL, COL	3,35 ± 0,14 (LA → 3,40) (SD → 3,38)
69,223 ± 0,070	43,2 ± 1,0	HAR, SAC BRO, ARG COL	21,9 ± 0,7	HAR, SAC BRO, ARG, LAL, COL	14,53 ± 0,70 (LA → 14,45)

SD = SAN DIEGO (Ha 65)
HAR = HARWELL (Ag 66)
SAC = SACLAY (Ri 69)
ARG = ARGONNE (Bo 68)
COL = COLUMBIA (Ra 72)
LAL = LOS-ALAMOS (Fo 71)
BRO = BROOKHAVEN (Bh 67)

I - 3. Comparative study of the resonance parameters from 0 to 3 keV.

In order to do this comparative study we selected four sets of results, those of Columbia, Saclay, Harwell and Los-Alamos. It will enable us to select a set of resonance parameters which can be used to calculate the cross sections in the resolved energy range, and a set of average parameters which can be used at higher energies. A method for testing the different experimental results consists in comparing the average parameters and their change with energy, for the purpose of finding the systematic deviations ; this comparison can be done on the reduced neutron widths, leading to the S_0 and S_1 strength functions, and on the radiation capture widths.

1) Neutron widths of the "s" resonances and S_0 strength function

Table I - 3 shows the comparison between the S_0 strength functions obtained in 0.5 keV or 1 keV energy intervals. There are no Los-Alamos values in this table, the authors having used Garg's neutron widths or Ribon's for the "s" resonances. There is excellent agreement between Columbia and Saclay in the 0 to 0.5 keV energy range ; that corresponds to a good agreement when comparing the individual resonance parameters. At higher energy there is a disagreement which increases with the energy : 3.5% from 1 keV to 2 keV and 7% between 2 keV and 3 keV.

TABLE I - 3

Energy range eV	$S_o \times 10^4$					
	Columbia		Saclay		Harwell transmission	Harwell all data
0 - 500	0.840	0.80	0.840	0.82	0.810	0.790
500 - 1000	0.760		0.800			
1000 - 1500	0.5[illegible]	[illegible]	0.573	0.91		
1500 - 2000	1.200		1.260			
2000 - 2500	0.630	0.82	0.680	0.88		
2500 - 3000	1.010		1.090			
3000 - 3500	0.670	0.56				
3500 - 4000	0.450					

A disagreement of this kind, although larger, had already been reported between the old values of Columbia and those of Saclay. In order to find the origin of this disagreement, a shape analysis using the least square method was undertaken by l'Heriteau et col. on the Columbia transmissions [Lh 71] ; this analysis showed that the disagreement vanished on condition that the background in the measurements of Columbia was revaluated. We used the same shape analysis on the new Columbia transmissions, in two energy ranges (2.48 keV to 2.76 keV and 3.2 keV to 3.7 keV) ; the detailed results of this work are given in another report [De 74]. It seems to be still necessary to revalue the background; then, in the 2.48 keV and 2.76 keV energy range the difference between the Γ_n values published by Columbia and those we obtain by the shape analysis is around 4% in the average. If this deviation is taken into account the difference with the Ribon values is only 3%. Between 3.2 keV and 3.7 keV, the deviation can be as high as 12% for the great resonances.

The S_0 strength function obtained at Harwell between 0 and 0.5 keV is consistently less than that of Columbia and Saclay by 3.5% or 7% according the results considered (analysis of the transmissions only or analysis of all the experimental data).

2) Radiation capture widths

Table I - 4 shows the average values of $\Gamma\gamma$ which can be extracted from four series of measurements (arithmetical average).

TABLE I - 4

Laboratory	Energy (eV)	$\langle \Gamma_\gamma \rangle$	Variance $(meV)^2$	Number of values
Saclay	0 - 1000	21,75 ± 0,90	10	14 (selectionned)
Columbia	0 - 2500	21,25 ± 1,20	7	87
Harwell	0 - 800	21,53 ± 0,77	5	23
Los Alamos	0 - 2000	21,29 ± 3,00	17	65

The variances given in this table are equal to $\langle \Gamma\gamma^2 \rangle - \langle \Gamma\gamma \rangle^2$; they reflect, in particular, the dispersion of the values due to errors of experimental origin. There is remarkable agreement between the mean values obtained in the various laboratories. Nevertheless we shall comment as follows :

a) few Saclay values are used in the calculation of the average value : the 14 values selected by Ribon are comprised in the energy interval up to 300 eV. The other values are very scattered and not very accurate (variance equal to 47 for 34 values between 0 and 1 keV); this is a characteristic of the shape analysis which cannot give a precise value of Γ_γ unless the Δ/Γ ratio of the Doppler width to the resonance width is relatively small ;

b) concerning the Los-Alamos results, Forman calculated the Γ_γ widths by using Garg's neutron widths between 0 and 1 keV, and those of Ribon between 1 keV and 2 keV. We revised the Γ_γ values by also using the Γ_n values of Ribon between 0 and 1 keV. The variance then decreases from 23 to 18 in this energy range ; this is due to the fact that some large values of Γ_γ obtained from Garg's Γ_n are closer to the average when Ribon's Γ_n are used (resonances at 192.6, 569.8, 590.2 and 943.4 eV) ;

c) table I - 5 shows the individual values of Γ_γ which served to establish the arithmetical average values of table I - 4. The arithmetical average of all these values equals 21.33 meV. If the average is evaluated by weighting each individual value by the reciprocal of the square of the absolute error, a value equal to (21.25 ± 0.18) meV is found. If the errors are re-adjusted to find a reasonable χ^2 for each resonance, the value of (21.66 ± 0.20) meV is found ; this illustrates the dispersion introduced by various averaging procedures upon the estimation of the mean value ;

d) table I - 6 shows some correlation coefficients obtained from individual values of Γ_γ and reduced neutron widths. Up to 900 eV, a fairly strong correlation is noticed between the different experimental series of Γ_γ, and this seems to indicate that the fluctuations noticed from resonance to resonance are partly real. On the other hand, between 0 and 2 keV, the correlation coefficient between the Los-Alamos values and those of Columbia is fairly weak ; this is due to the fact that the Los-Alamos values become increasingly less accurate towards the high energies, the fluctuations observed then are mainly due to experimental errors. The correlation coefficients between the reduced neutron widths and the different Γ_γ series are small and non significant.

TABLE E - 5. - Table of Γ_V values.

E(eV)	LASL[Fo 71] from Garg's Γ_n	LASL[Fo 71] from Ribon's Γ_n	SAC [Ri 69]	HAR [Ao 66]	COL [Ra 72]
59,5	22,7	22,8	22	23,2	25
69,2	21,9	21,5	20,5	21,2	25
113,0	21,0	17,4	20,4	20,1	20
120,0	21,0	17,3	20,7	20,7	22
129,2			16,4	21,4	18
154,3					
170,4	22,3	21,9	19,3	22,2	26
192,7	30,3	22,5	16,8	19,6	17
199,4			17,9	19,9	18
221,3	21,9	22,1	22,0	20,3	22
251,7	22,2	21,7	25,4	21,1	24
260,3	17,3	10,6	28,0	17,9	19
285,8	10,0	17,6	24,9	21,8	20
305,5	18,3	17,2	22,0	24,2	20
323,9	21,0	21,2	23,7	22,9	26
341,0	20,6	19,7	21,0	20,5	19
365,2	21,0	22,7	23,0		21
367,3	21,2	24,4	29,0		22
400,9	19,3	14,9	31,0		10
454,2					
462,5	19,3	19,0	22,0	21,5	22
480,3	17,2	17,2	19,0	19,2	10
520,2	17,4	17,9	33,0		20
567,0	33,9	26,3	25,0	19,3	19
590,3	30,0	25,6	30,0		19
618,6	18,7	16,3	24,0		20

TABLE I - 5. - Table of Γ_γ values.(continued)

E(eV)	LASL[Fo 71] from Garg's Γ_n	LASL[Fo 71] from Ribon's Γ_n	SAC [Ri 69]	HAR [As 66]	COL [Ro 72]
665,3	14,6	12,4	10,0		18
675,2	18,4	18,4	21,0		19
687,4	18,1	18,9	20,0		23
701,2	28,0				17
712,9	13,1	13,6	8,0		19
741,1	19,8	23,7	24,0	21,6	23
778,7	24,2	25,0			26
804,2	19,5	19,6	29,0	20,5	20
842,3	20,8	21,0	29,0	23,2	19
866,3	26,0	35,0	41,0		23
890,1	2[illegible],4	22,2	41,0		21
943,2	29,6	25,0	20,0		23
902,9	20,6	18,6	22,0		21
990,5	18,4	17,7	32,0		25
1010,6		20,2	34,5		20
1064,4			25,0		
1110,0		31,3	69,2		17
1130,9		23,0	1[illegible],0		19
1150,5					22
1230,0		16,1	25,[illegible]		23
1243,1					20
1249,9		22,0	36,4		15
1282,4					20
1292,2		24,1	39,4		25
1321,5		15,6	19,7		27
1334,0		18,5	8,2		26

TABLE I - 5. - Table of Γ_γ values. (end)

E(eV)	LASL(Fo 71) from Garg's Γ_n	LASL(Fo 71) from Gibbon's Γ_n	SAC [Ri 69]	HAR [As 66]	COL [Ra 72]
1378,0		21,5			24
1397,9		19,7	23,5		19
1426,6		21,2	-2		21
1433,9		26,8			16
1510,7		19,8			24
1524,3		25,2	40,0		20
1531,1		26,4			20
1569,5		23,1	15,0		24
1602,6		17,1	19,1		24
1630,9		19,2	17,0		19
1640,0		19,0	20,1		25
1651,4		24,4	45,0		25
1677,9		10,4			
1719,0					17
1746,0		19,7			23
1762,0		24,0	35,4		27
1810,9		10,0	64,0		21
1811,0		20,0	42,9		20
1821,2		20,2	54,0		10
1834,0		26,0	50,6		25
1875,0		17,6			22
1922,4					29
1951,1		10,9	24,2		30
1977,3		19,0	23,0		29

TABLE I - 6

Correlation coefficients

	Los Alamos Columbia 0 to 900 eV	Los Alamos Harwell 0 to 900 eV	Harwell Columbia 0 to 900 ev	Los Alamos Columbia 0 to 2 keV
$r(\Gamma_\gamma, \Gamma_\gamma')$	0.28	0.43	0.49	0.09

	Los Alamos	Columbia	Harwell	
$r(\Gamma_n^\circ, \Gamma_\gamma)$	- 0.12	0.13	0.15	

3) Parameters recommended for the resonances.

a) Neutron widths

The agreement between Saclay and Columbia is very good under 500 eV ; the Harwell values are 3 or 7% less on average than those of Saclay and Columbia (see table I - 3 and section I.3.1.). At higher energy, the disagreement between Columbia and Saclay increases ; the Columbia values are probably too small ; from 3 to 4 keV, particularly, the local value of S_0 according to Columbia would appear to be 33% under the average value below 3 keV, and this is rather unlikely according to the statistical distribution laws. Also, the shape analysis of the Columbia data gives values of $g\,\Gamma_n^0$ (and therefore of S_0) which are appreciably greater (see section I.3.1. and [De 74]). We conclude from this that the present Columbia results are not completely corrected for the grave defects which had falsed those of 1961, and that a tendency to under estimation of the large $g\,\Gamma_n^0$, due to an under estimation of the background, persists above about 1 keV. For these reasons, we recommend the set of Saclay neutron widths up to 3 keV.

As a consequence of this choice it is also necessary to recommend the Saclay strength function value, i.e. :

$$S_0 = (0.89 \pm 0.11)\ 10^{-4}$$

b) Radiative capture widths.

The coherence is good between the radiation capture

widths, particularly concerning the mean values. The Columbia results appear to be the most accurate ; their dispersion is less than for the other results. The knowledge of the capture area, $g\,\Gamma_n\,\Gamma\gamma/(\Gamma_n + \Gamma\gamma)$, given by a capture experiment, is improved <u>in principle</u> by the other experiments (transmission, self-indication) provided that there is no systematic error ; we concluded that this was not the case with the Columbia transmission. This is why we adopted the LASL capture areas which only come from a direct measurement of the capture and are free of other influences ; we deduced from them the individual values of $\Gamma\gamma$.

It should be observed that the influence of experiments other than the capture on $\Gamma\gamma$ is small when $g\,\Gamma_n$ is great ; it is likely that an error on $g\,\Gamma_n$ then has little effect on $\Gamma\gamma$, which can explain the absence of disagreement between the $\Gamma\gamma$ values of Columbia and the other results.

Our choice (Γ_n of Saclay and capture area of Los-Alamos) is probably not the only possible one, but it has the advantage of combining coherence, quality and simplicity.

There is no difficulty to choose a mean value of $\Gamma\gamma$; we propose the following value which is a compromise between the different ways of estimating the average of the individual values in table I - 5 (see I - 3.2.c).

$$\langle\Gamma\gamma\rangle = (21.45 \pm 0.25)\ \text{meV}$$

4) <u>Special study of the "p" resonances</u>

The Los-Alamos authors have published a comparative table of their reduced neutron widths for small resonances and those of Saclay (table I - 7). Obviously there are great differences between certain individual values but excellent agreement between the mean values obtained from 92 common resonances (0.99 ratio between the two mean values). No general disagreement is to be reported with the Columbia results (a significant error with respect to the background has little influence on the measured area of small resonances).

In order to keep our evaluation consistent, the Saclay small resonance $g\,\Gamma_n$ values can be recommended, by supplementing them with the Los-Alamos values not appearing in the Saclay results (table I - 7 mentions 92 common resonances out of the 125 values of Los-Alamos and the 120 values of Saclay between 0 and 2 keV).

Nevertheless a few remarks need to be made concerning the identification of the orbital moment of the

TABLE I - 7 $g\Gamma_n$ values (from Fo 71).

E_o (Volts)	$g\Gamma_n$ † (meV)	$\Delta g\Gamma_n$ (%)	$g\Gamma_n$ (5) (meV)	$\Delta g\Gamma_n$ (%)
0.15			0.00028	13
13.11			0.00022	16
36.9	0.00046	28	0.00103	30
38.2	0.00057	34	0.00061	40
41.0	0.00038	25	0.00032	40
43.0	0.00174	26	0.00135	30
49.8	0.00046	43	0.0006	74
54.1	0.0011	30	P	
58.8	P		0.0096	21
64.6	P		0.0003	99
92.1	0.014	50	0.007	40
97.9	0.004	28	0.005	50
103.5	0.0055	39	0.006	40
111.0	PR		0.004	99
117.8	PR		0.001	99
128.2	PR		0.073	30
145.7	0.109	23	0.091	30
147.3	0.0078	67	0.012	30
154.2	0.208	22	0.205	8
167.0	PR		0.016	65
176.7	0.025	29	0.023	30
196.4	0.13	54	0.083	13
202.7	P		0.028	25
210.9	0.016	73	0.018	35
232.0	0.013	71		
236.2	0.020	34		
242.4	0.044	54	0.049	29
258.3	PR		0.01	99
272.6	0.019	39		
274.8	0.035	65		
290.4	0.074	42	0.07	25
299.6	PR		0.042	25
307.6	PR		0.128	22
309.4	0.074	47	0.053	35
321.9	0.10	62	0.04	35
325.1	P		0.035	99
331.8	0.037	45		
362.2	P		0.20	30
380.9	0.12	29	0.115	30
391.7	P		0.176	30
403.0	0.104	40		
412.0	0.21	35	0.28	20
421.0	0.43	29	0.34	18
427.1	0.019	65		
454.3	1.07	23	1.23	13
458.9	0.07	54	0.06	60
466.6	0.10	42	P	
470.5	0.048	66	0.04	75
476.5	0.16	34	0.18	30
500.0	P		0.05	85
510.3	5.19	36	5.32	18
533.3	0.25	35	0.31	20
535.6	0.40	26	0.34	20
540.1	0.98	23	1.18	18
550.1	0.41	90		
573.8	0.60	27	0.75	20
577.8	1.8	25	2.87	18
582.7	0.085	99		
594.0	0.145	28	0.20	50
617.5	3.32	35	4.1	18
623.1	0.033	75	P	
627.7	0.055	75		
633.9	0.073	70		
644.3	0.20	48	0.09	75
655.5	0.17	68	P	
658.8	PR		0.15	75
704.1	0.21	40	0.27	75
719.7	0.093	56		
723.0	0.22	46	0.25	75
728.8	0.034	99		
738.0	0.048	94	0.24	50
764.07	0.67	76	0.82	20
770.9	0.104	79		
774.4	PR		0.05	75
786.0	0.077	80		
787.8	0.078	81		
792.3	0.063	89	P	
808.35	0.135	41	0.18	99
814.9	0.074	66	0.28	50
820.4	1.03	25	1.15	18
828.9	0.19	60	0.28	50
836.0	1.56	25	1.58	17
849.5	1.15	26	1.34	17
868.7	0.52	34	0.78	20
877.5	0.28	59		
884.6	0.30	51	0.36	22
898.8	0.082	99		
905.7	1.77	25	2.11	18
918.5	0.37	30	0.48	30
926.4	0.53	34	0.44	25
934.6	0.25	60	0.27	40
956.0	P		0.18	75
961.1	7.29	26	6.62	15
973.9	0.26	69	0.27	75
996.1	0.41	47	0.58	75
1000.9	0.21	66	0.28	40
1020.9	0.49	14	0.58	75
1039.5	0.21	33	0.33	75
1043.5	0.29	25	0.32	30
1044.5	0.16	30		
1053.6	0.34	22		
1059.3	0.26	60		
1062.9	5.1	13	6.0	20
1092.1	2.1	16	1.78	22
1114.5	P		1.70	60
1116.2	P		1.00	75
1119.2	3.74	13	3.75	17
1127.1	0.37	73	0.35	30
1132.1	0.43	60	0.40	33
1146.2	0.10	99		
1175.3	0.34	25	0.35	30
1183.9	0.1	99		
1203.7	1.9	13	2.16	23
1214.1	P		0.3	99
1216.2	0.37	30	0.6	70
1224.1			0.42	50
1233.2	0.98	20	0.70	70
1281.7	2.02	20	1.00	28
1288.4			0.28	35
1287.6	P		6.1	90
1301.5	0.35	50		
1314.5	3.51	15	3.2	20
1346.3	1.16	17	1.03	30
1359.2	4.19	15	9.0	23
1371.8	1.33	30	1.02	30
1388.4	2.79	15	2.3	25
1408.2	0.4	50	0.3	99
1418.2	0.34	30	0.6	35
1441.0	1.05	23	1.5	35
1449.1	0.28	99		
1450.6	1.22	25	1.4	30
1464.9	0.15	99		
1473.1	2.14	20	2.3	27
1483.7	0.15	99		
1501.6	0.33	50	0.8	40
1507.1	4.95	20	3.0	25
1553.9	8.07	20	6.4	32
1611.5	1.05	20	0.69	70
1623.1	0.31	60	0.3	99
1668.4	0.59	60		
1689.0	1.06	35	1.1	70
1697.8	1.60	50	2.5	40
1704.0	3.0	23	3.3	28
1724.3	1.21	30	1.50	99
1728.6	1.41	30	1.80	40
1737.0	8.8	25	6.60	20
1753.7			0.7	99
1783.9	1.72	25	2.4	35
1793.3			0.48	70
1835.7	0.9	40	1.4	60
1847.4	3.3	40	4.2	25
1887.6	0.72	50	1.1	40
1940.0	P		0.32	99

" Values of $g\Gamma_n$ † are from this work and $g\Gamma_n$ (5) are from Ribon's listing. Resonance energies are from this work, if a $g\Gamma_n$ value is reported, and estimated to be ±0.15%. The letter P in a column signifies evidence for a resonance, and PR indicates that a previously reported level could not be observed because of interference from a neighboring resonance."

small resonances. On the basis of the fact that the probability of observing Γ_n values exceeding ten times the average value is virtually nil, all the authors [Ri 69, Ra 72 and Fo 71] have assigned the orbital moment $l = 0$ to the resonances for which $\Gamma_n E^{3/2} > 10^{-7}$.

There is no reason to question these assigments. Obviously this method does not apply to those resonances at the boundary of the classification (small "s" resonances or large "p" resonances). By using a least square shape analysis with or without potential interference terms, Ribon was able to assign the orbital momentum (0 or 1) to 25 of these resonances. But in general, the assigments are based on statistical arguments. This is the case of Rahn et al [Ra 72] who made a complete classification of the resonances. This classification does not always agree with Ribon's. Let us examine it in the 1000 to 1500 eV energy interval for instance.

In this energy range, according to the Porter-Thomas law and considering Rahn's average parameters, there should be about 4 "s" resonances and 28 "p" resonances with neutron widths such that : $0.3 < g\,\Gamma_n < 3$ meV. Owing to the repulsion of levels, little or no "s" resonances will be lost (one single population) ; but, many "p" resonances may be lost (2 resonance populations and they can be hidden by large "s" resonances). According to Rahn's results, between 1000 eV and 1500 eV, there are 8 "s" resonances and 16 "p" resonances for which $g\Gamma_n$ is comprised between 0.3 meV and 3 meV, i.e. an excess of "s" resonances. If Ribon's results are accepted (which places the 1093.0 eV, 1204.4 eV and 1335 eV resonances in the group of "p" resonances) the corresponding populations are brought down to 5 "s" resonances and 19 "p" resonances, i.e. in better agreement with the statistical predictions. Finally, it seems reasonable to take Rahn's results as basis, <u>except when there is contradiction with Ribon</u>, for assigning the orbital momentum by a shape analysis is preferable to that based on statistical arguments ; this also enables the excess of small "s" resonances existing in Rahn's results to be offset.

The S_1 strenght function suggested by Ribon [Ri 69] is equal to $(1.4 \pm 0.5)\ 10^{-4}$; it was verified by studying a simulated total cross section generated by a Monte-Carlo method. This value is in agreement with 1.7×10^{-4} as given by Forman et al [Fo 71]. Rahn et al [Ra 72] studied the influence of the possible confusion between "s" and "p" resonances to establish a lower value 0.6×10^{-4} and an upper value 1.4×10^{-4} of S_1 ; they proposed an order of magnitude for S_1 equal to 0.9×10^{-4} (at the limit of the error bar given by Ribon).

Another source of information on the S_1 strenght function is the measurement of the total cross section

between 1 KeV and 1 MeV due to C.A. Uttley et col. [Ut 54]. By setting 0.80 x 10^{-4} as the value of the S_0 strenght function, they obtained the following value :

$$S_1 = (1.64 \pm 0.24)\ 10^{-4}$$

This latter value is obtained by a completely different method from those which use the resonance parameters and is consistent with the Saclay and Los Alamos values.

We therefore propose an arithmetical mean of these three values, whilst retaining a significant error of 30% to allow for the conclusions of Columbia ; this then gives :

$$S_1 = (1.58 \pm 0.50) \times 10^{-4}$$

4. Conclusion

The list of resonance parameters emerging from the critical examination we have just made is given in Appendix I. Except for the first four "s" resonances, it was established in the following manner :

a) the energies and the neutron widths are those proposed by Saclay [Ri 69] supplemented by the Los-Alamos values [Fo 71] for some small resonances not appearing in the Saclay list ;

b) the radiation capture widths were determined from the Saclay neutron widths and the capture areas measured at Los-Alamos ; the mean value 21.4 meV is assigned to the resonances for which $\Gamma\gamma$ could not be determined ;

c) the assigment of the orbital moment complies with that made at Columbia [Ra 72] except when there is contradiction with the results of Saclay [Ri 69].

The average parameters proposed are :

$$\langle D \rangle_s = 16.9 \pm 0.7 \text{ eV}$$

$$\langle D \rangle_p = 5.7 \text{ eV}$$

$$S_0 = (0.89 \pm 0.11)\ 10^{-4}$$

$$S_1 = (1.58 \pm 0.50)\ 10^{-4}$$

$$\langle \Gamma\gamma \rangle = 21.45 \pm 0.25 \text{ meV}$$

II - CROSS SECTIONS IN THE THERMAL AREA

Except for a few cases, there have been no new experimental results since 1962 ; most of them are found in the BNL N° 325, and issue, supplement N° 2, to which we would refer the reader.

II - 1. Capture cross section

The four most accurate measurements are shown in the table II - 1.

Table II - 1

Authors	Références	Méthod	Résults (barns)
CROCKER	Cr 55	Activation	7.32 ± 0.12
SMALL	Sm 55	Pile oscillation	7.57 ± 0.17
MYASISCHEVA et al	My 57	Activation	7.32 ± 0.10
HUBERT et al	Hu 57	Transmission from 10^{-3} to 2.210^{-3} eV.	7.60 ± 0.16

The weighted mean of these four values is : (7.40 ± 0.065) barns. Like BNL 325 [Bn 73] we shall adopt :

$$\sigma_{n,\gamma(2200)} = (7.40 \pm 0.08) \text{ barns}$$

The contribution of the positive energy resonances calculated from the parameters recommended in I is 0.43 barns. Therefore the contribution of negative resonances must be 6.97 barns. Several authors have proposed parameters for a negative resonance. We quote only the three series of values given in Table II - 2.

TABLE II - 2

Référence	E (eV)	Γ_n° (meV)	Γ_γ (meV)	contribution at 2200 m/s.
TIREN et JENKINS (Ti 62)	- 4.3	0.704	40	6.21
COOPER et al (Co 61)	-3.5	0.636	30	6.34
LUNDGREN (Lu 68)	-5.1±0.5	1.8±0.4	24	6.79

Probably one single negative resonance contributes significantly in the thermal area ; we propose the following parameters for this negative resonance :

$$E = -5.0 \text{ eV} \; ; \; \Gamma_n^\circ = 1.974 \text{ meV} \; ; \; \Gamma_\gamma = 21.6 \text{ eV}$$

enabling a contribution of 6.97 barns to be obtained for the capture at 2200 m/s.

The capture cross section in the thermal range can then be described by :

$$\sigma_{n,\gamma} \sqrt{E} = a + b E = 1.189 - (0.45 \pm 0.10) E \; ;$$

for Westcott's g factor, this gives :

$$g = \frac{1 + \frac{3}{2} \frac{b}{a} E_{th}}{1 + \frac{b}{a} E_{th}} \neq 1 + \frac{b}{2a} E_{th} = 0.9952 \pm 0.0010$$

II - 2. Scattering cross section and total cross section

The value of $\sigma_p = 11.70$ barns (R' = 9.65 fm) obtained by Ribon [Ri 69] from the analysis of experimental transmissions correctly normalized below 3 keV agree with several other experimental results, particularly with those of Uttley [Ut 64] who proposes $\sigma_p = 12.06 \pm 0.36$ barns as from the analysis of average high energy total cross sections

(1 keV to 1 MeV). The value σ_p = (10.41 ± 0.60) barns (R' = 9.1 ± 0.3) proposed by Rahn [Ra 72] from the analysis of resonances, is distinctly lower, as is that of 10.15 barns recommended by Leonard for ENDF - B3. Therefore there is a choice to be made between a high value close to that of Ribon, and a low value close to Rahn's. Table II - 3 shows that the high value is consistent with the total cross sections generally accepted for ^{232}Th at low energy ; the deviations between the measured cross section and the calculated cross sections are then relatively small ; they could be due to the fact that the description of the total cross section by allowing for one negative resonance only is probably insufficient. As for the low value, it is consistent with the total cross sections, apparently accurate, measured by Pattenden [Pa 65] and which constitute one of the bases of Leonard's evaluation.

For the moment we recommend the value :
σ_p = (11.70 ± 0.30) barns which agrees with a significant number of experimental data.

TABLE II - 3

Energy (MeV)	σ_R^-	σ_R^+	σ_R^T	$\sigma_T(1)$	$\sigma_T(2)$	$\sigma_T(1)-\sigma_R^T$	$\sigma_T(2)-\sigma_R^T$
0.1	5.55	- 0.58	4.97	16.1 ± 0.2		11.13	
6.0	1.08	- 0.88	0.20	11.9 ± 0.2	10.7 ± 0.04	11.70	10.58
12.0	0.67	- 1.15	- 0.48	11.5 ± 0.2	10.26 ± 0.04	11.98	10.74

σ_R^- = negative resonance contribution according to the parameters recommended in (II-1) ;

σ_R^+ = contribution of positive resonances (above 100 eV) according to the parameters recommended in (I-4)

σ_R^T = $\sigma_R^- + \sigma_R^+$;

$\sigma_T(1)$ = experimental cross sections according to [BN 58] [Ka 68] and different evaluations ; the large error bar is due to the fact that the values were taken from a graph (BN 58, Ka 68) ;

$\sigma_T(2)$ = total experimental cross sections of Pattenden [Pa 65] ;

σ_R^+ was calculated by the following relation for each resonance of energy E_λ ;

$$\sigma_R^+ = \frac{0.65658 \times 10^6}{\sqrt{E}} \; \frac{\Gamma_n^0 (\Gamma\gamma + \Gamma_n^0 \sqrt{E})}{(E-E_\lambda)^2} + 5.544 \; 10^3 \; \frac{\Gamma_n^0}{E-E_\lambda}$$

the cross sections are expressed in barns ;

III - CAPTURE CROSS SECTION BETWEEN 1 keV AND 500 keV

III - 1. Experimental data

We only considered the following recent results (less than 10 years old) :

1) the oldest results we are taking into consideration are those of Macklin and Gibbons [Ma 63], apparently known only by private communications (see Fo 71, for instance) ;

2) the results of Moxon [Mo 63] come from one of the first experiments done with the "Moxon-Rae" detector ; the cross sections obtained are 30% lower than the other values and we shall not retain them ;

3) the results of Forman et al were obtained by time-of-flight method on a nuclear explosion. The authors only published their values up to 30 keV [Fo 71] ; as we have seen these results seem to be very good in the region of resolved resonances, and there is every reason to believe that this is also the case in the 10 keV region and above ;

4) the results of Nagle et al were obtained by activation with neutrons of 100 keV to 3 MeV [Na 71] ; on figure III-1 we have only shown the results below 500 keV. The normalization was done relatively to the fission of ^{235}U given in BNL 325 (1965 issue) ; the values should be lowered by around 2% (but we did not do so). The authors state that for gold they obtain good agreement with other experimental or recommended data ;

5) the results of Stavissky, Chelnokov et al, was obtained with a slowing-down spectrometer and published in final form, in 1973 [Ch 73] . These values are shown in figure III-1 ; the error indicated by the authors is probably a systematic one. The behaviour of this capture cross section as a function of energy is very different from the other data and cannot be explained by any theoretical calculation ; so we did not take it into account.

III - 2. Description of the experimental data by statistical model

The capture cross section, calculated by means of the FISINGA code [Le 70], is shown in figure III - 1. The dotted line curve corresponds to the cross section calculated from average parameters resulting from the study of the resonances (see I - 4) and supplemented by the values $S_2 = 1.10^{-4}$ and $S_3 = 2.10^{-4}$ for the strenght functions of

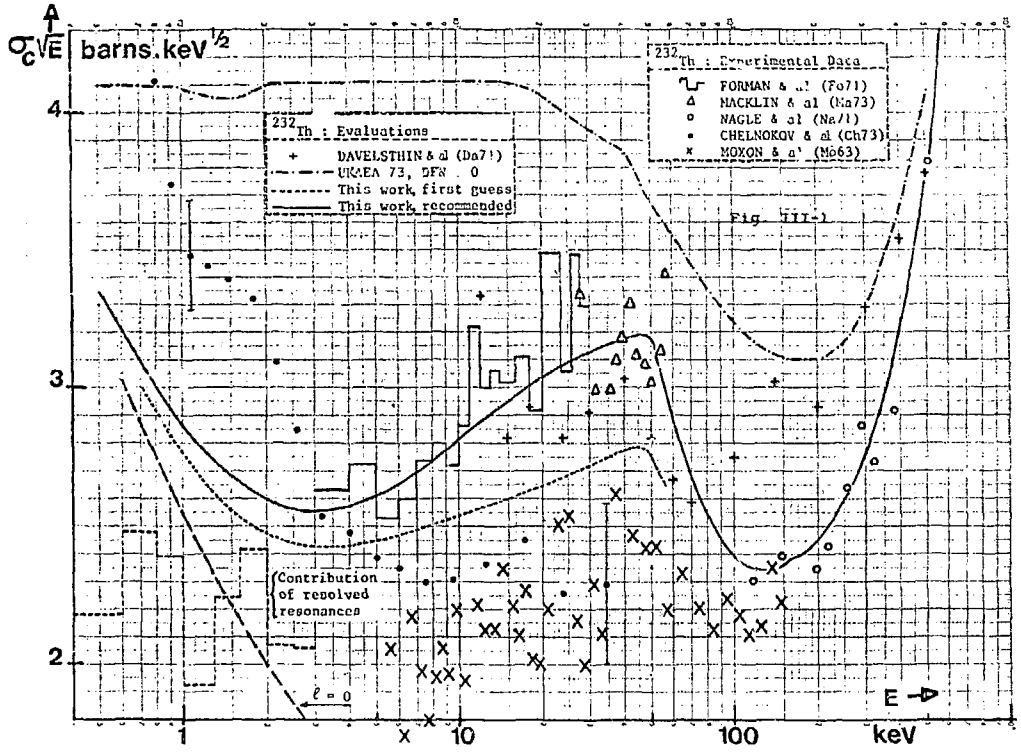
$\sigma_c\sqrt{E}$ barns.keV$^{1/2}$
4
3
2
1
10
100
keV
E
^{232}Th : Evaluations
DAVELSTHIN & al (Da71)
UKAEA 73, DFN 0
This work, first guess
This work, recommended
^{232}Th : Experimental Data
FORMAN & al (Fo71)
MACKLIN & al (Ma73)
NAGLE & al (Na71)
CHELNOKOV & al (Ch73)
MOXON & al (Mo63)
Contribution of resolved resonances
$\ell = 0$

Fig. III-1

the orbital moments $l = 2$ and $l = 3$; the mean radiative capture width was taken as being equal to 21.45 eV for all the "l" values considered. The results obtained are lower than all the experimental cross sections between 5 keV and 50 keV. In order to obtain agreement between the experimental and theoretical values, the average parameters had to be adjusted. The solid line curve corresponds to the following parameters for the strength functions :

$$S_0 = 0.93 \times 10^{-4}$$

$$S_1 = 1.80 \times 10^{-4}$$

$$S_2 = 0.65 \times 10^{-4}$$

$$S_3 = 2.7 \times 10^{-4}$$

and, at the binding energy, for average level spacings and radiative capture widths :

$$\overline{D}\ (J = 1/2^+) = 16.5 \text{ eV}$$

$$\overline{\Gamma\gamma}\ (J^+) = 21.6 \text{ meV}$$

$$\overline{\Gamma\gamma}\ (J^-) = 25.8 \text{ meV}$$

Comments on the choice of these parameters.

1) The contribution of the neutrons with orbital momentum $l = 0$ to the capture is small above 10 keV. So the corresponding parameters were only slightly modified ; we adjusted them by a quantity equal to half the error bar given in I - 4. This adjustment enables better agreement to be obtained with the experimental data below 10 keV.

2) The "p" capture (capture of neutron of orbital momentum $l = 1$) represents 2/3 of the capture between 20 keV and 50 keV. However a 10% increase on S_1 produce only a 3% increase on the total capture cross section. Hence, it seemed to us that the best way of obtaining agreement between the calculated cross section and the experimental one was to increase the average capture width of the "p" neutrons, by introducing $\Gamma\gamma$ values depending on the parity of the compound nucleus ; this can be justified by the two following arguments :

a) the fundamental of ^{233}Th is $1/2^+$ spin and parity ; it is possible, as for ^{239}Pu, that most of the levels below 0.5 MeV are also of positive parity. The direct E_1 transitions to low-lying states from negative parity

resonances would therefore be more probable, according to the selection rules, thereby producing :

$$\overline{\Gamma\gamma}\ (J^-) > \overline{\Gamma\gamma}\ (J^+)\ ;$$

b) the only "p" level for which the experimental values of $\Gamma\gamma$ has been determined, is that at 8.3 eV ; results [Pa 65], [Ri 69] give a value close to 30 meV for $\Gamma\gamma$, with, however, large error bars ; indeed, these two arguments are not quite conclusive but they do make a dependence of $\overline{\Gamma\gamma}$ with parity plausible.

We have also shown on figure III-1 the results of two recent evaluations :

- that of Davletskin et al [Da 71] which, on average, agrees with ours but gives a less marked structure towards 50-100 keV ;

- that of the British DFN 930 (1973) band which is from 20 to 30% above ours.

III - 3. Conclusion

It is therefore quite possible to describe the capture cross section of ^{232}Th up to 500 keV by a set of average parameters in very good agreement with that deduced from the study of resolved resonances. However the S_2 and S_3 values, adjusted to improve the agreement, must not be taken too seriously.

Before ending this section, we shall observe that the non elastic cross sections were also calculated by means of the FISINGA Code. They appear to be about 15% too small, which is rather satisfying since there were no adjustments on experimental non elastic cross sections. The values appearing in the evaluated data (ENDF-B format) were arbitrarily increased by 15%.

IV - RESONANCE INTEGRAL ACCORDING TO THE DIFFERENTIAL DATA.

The various contributions to the RI_c resonance integral, calculated from the differential data, are given in table IV - 1. We shall run through the methods used to obtain them.

IV - 1. Contribution of positive resolved resonances

We have indicated the individual contribution of the

main resonances below 200 eV and the total contribution of the other resonances between 0.2 keV and 1 keV, and also between 1 keV and 3 keV. The effect of a 5% variation on parameters Γ_n and Γ_γ of each resonance was also evaluated.

IV - 2. Contribution of unidentified resonances in the resolved area.

These resonances have small Γ_n values but their contribution to the capture integral is relatively significant. We simply estimated it in the following manner :

- between 1 keV and 3 keV, we took it as being equal to the difference between the result of the calculation by statistic model and the values of the mean cross sections calculated from resonances parameters ;

- we assumed that, below 600 eV, the difference between these two methods of calculation corresponded to fluctuations in the sampling, that is to say that the unidentified resonances were few (this is probably true for the "s" resonances below 500 eV [Ri 69]);

- between 600 eV and 1 keV, we used a correction equal to half the difference between the statistic model and the calculation from resonance parameters.

IV - 3. Contribution of negative resonances

This contribution may be calculated by means of the following integral :

$$RI_c^- = \int_{E_c}^{10^6} \frac{\sigma^-_{n,\gamma}(E)}{E} \, dE \; ;$$

$\sigma^-_{n,\gamma}$ is the part of $\sigma_{n,\gamma}$ due to the negative resonances ; E_c is the cut-off energy.

On the assumption that RI_c^- can be described by a single negative resonance, with $\sigma_{n,\gamma}(2200) = 6.97$ barns and the parameters indicated in II - 1 for the negative resonance, we obtain :

$$RI_c^- = 1.41 \text{ barns}$$

IV - 4. Results

The sum of the partial contributions of table IV - 1 gives :

$$RI_c = 83.7 \pm 2.7 \text{ barns}$$

The error was calculated by adding quadratically the errors in each of the contributions to RI_c. The error due to the only resonance at 23.4 eV is 2.5 barns. Without it, the error in RI_c would be around 1.1 barn. It therefore appears that learning more about RI_c as from differential data first presupposes a better knowledge of the parameters of the resonance at 23.4 eV.

A detailed review of the measured values was made by Grenèche [Gr 74]. We would refer the reader to it. He recommends the following value :

$$RI_c = 85.8 \pm 2.5 \text{ barns}$$

This value agrees with that which we obtain from differential data. A mean value of these two results can then be recommended :

$$RI_c = 84.8 \pm 1.8 \text{ barns}$$

TABLEAU - IV - 1.

Capture resonance intégral of ^{232}Th

Energy	Résonance parameters		Infinite dilution			Finite dilution p		
E	Γ_n	Γ_γ	RI_c	effect of + 5% variation		RI_c	effect of + 5% variation	
(eV)	(meV)	(meV)	barns	on Γ_n	on Γ_γ	barns	on Γ_n	on Γ_γ
8.32			0.017					
13.08			0.005					
21.75	2.02	24.5	16.31	+ 4.6 %	+ 0.4 %	3.05	+ 2.2 %	+ 2.6 %
23.41	3.88	26.6	25.55	+ 4.4 %	+ 0.7 %	3.69	+ 2.7 %	+ 2.8 %
59.48	3.90	23.7	3.91	+ 4.3 %	+ 0.7 %	0.92	+ 2.0 %	+ 2.8 %
69.19	43.8	21.9	12.62	+ 1.7 %	+ 3.4 %	1.19	- 0.2 %	+ 5.2 %
113.0	13.6	17.4	2.47			0.45	+ 1 %	+ 3.9 %
12.08	23	17.3	2.79			0.46	+ 0.4 %	+ 4. 5%
129.2	3.46	16.8	0.7			0.23	+ 2.1 %	+ 2.8 %
154.4	0.21	18.8	0.03			0.03	+ 3.9 %	+ 0.8 %
170.4	60.9	21.9	2.30			0.29	- 0.8 %	+ 5.8 %
192.7	18.1	22.5	1.12			0.19	+ 0.5 %	+ 4.4 %
199.4	10.4	17.9	0.69			0.17	+ 1.0 %	+ 3.8 %
Others resolved resonances below 1 keV 8.17			18.35	+ 2.3 %	+ 2.8 %			
Resonances between 1 and 3 keV			1.83	+ 1.9 %	+ 3.2 %			
Unresolved resonances between 0.6 and 1 keV			0.17					
between 1 and 3 keV			0.44					
Capture cross section between 3 keV and 1 MeV			3.06					
Contribution of negative resonances			1.41					
TOTAL :			83.67					

CONCLUSION

In this work, we have proposed a set of resonance parameters from a critical examination of the main experimental data available at present.

This set of parameters was not obtained by taking the mean values of all the experimental data ; a selection was made and a justification of this choice has been given. It is mostly based on the Saclay transmission measurements and the Los-Alamos capture cross section measurement. From this has resulted, a set of average parameters which is very consistent with that which is likely to represent the experimental capture cross sections up to 500 keV. Obviously other sets of parameters can be proposed ; but we consider that any other set, prepared as from other bases, would approximate closely to that we are proposing, particularly when it is a question of calculating average cross sections.

A complete evaluation of ^{232}Th is given in the ENDF-B format under number MAT 445. Our contribution concerns the data under 1 MeV ; particularly the resonance parameters and capture cross sections. The data above 1 MeV are taken from ENDF-B MAT 1296.

The author is grateful to Dr P. Ribon for his interest in this work and his help for all theoretical calculation. He is also indebted to D. Grenèche for his help in the determination of the resonance parameters below 100 eV.

APPENDIX I

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
1	8.346	0.0003	130	29.0	30	1	232	90
2	13.111	0.0002	160			1	232	90
3	21.783	2.0200	30	24.5	8	0	232	90
4	23.439	[illegible].800	30	26.6	6	0	232	90
5	36.926	0.0010	300			1	232	90
6	38.165	0.0006	400			1	232	90
7	40.925	0.0006	400			1	232	90
8	47.001	0.0014	300			1	232	90
9	49.850	0.0006	750			1	232	90
10	54.130	0.0011	500			1	232	90
11	58.780	0.0096	110			1	232	90
12	59.514	3.9000	25	23.7	4	0	232	90
13	64.580	0.0005	900			1	232	90
14	69.224	43.6000	25	21.9	4	0	232	90
15	90.098	0.00[illegible]	400			1	232	90
16	98.106	0.005[illegible]	500			(1)	232	90
17	103.646	0.0060	400			(1)	232	90
18	111.987	0.0040	900			(1)	232	90
19	113.032	13.6000	30	17.4	20	0	232	90
20	117.752	0.0020	900			1	232	90
21	120.870	23.0000	30	17.3	30	0	232	90
22	128.210	0.0730	180			(1)	232	90
23	129.190	3.4600	100	16.8	15	0	232	90
24	145.871	0.0910	100			1	232	90
25	148.074	0.0120	300			(1)	232	90
26	154.382	0.2050	80	18.8	76	0	232	90
27	167.033	0.0160	650			(1)	232	90
28	170.400	60.9000	30	21.9	10	0	232	90
29	178.931	0.0230	300			1	232	90
30	192.756	18.1000	40	22.5	21	0	232	90
31	196.315	0.0830	120			0	232	90
32	199.444	10.4000	50	17.9	16	0	232	90
33	202.668	0.0280	250			1	232	90
34	211.091	0.0160	350			1	232	90
35	219.547	0.0510	200			(1)	232	90
36	221.336	30.7000	30	22.0	15	0	232	90
37	232.020	0.0130				(1)	232	90
38	234.220	0.0200				(1)	232	90
39	242.520	0.0490	200			(1)	232	90
40	251.730	32.8000	40	21.7	15	0	232	90
41	258.287	0.0100	900			(1)	232	90
42	263.305	23.3000	40	18.6	19	0	232	90
43	272.619	0.0190				(1)	232	90
44	276.619	0.0350				(1)	232	90
45	285.797	31.2600	50	17.6	12	0	232	90
46	290.406	0.0700	250			(1)	232	90
47	299.578	0.0420	250			(1)	232	90
48	302.565	0.1280	200			(1)	232	90
49	305.501	28.8000	50	17.2	15	0	232	90
50	309.370	0.0530	350			(1)	232	90
51	321.800	0.0600	350			(1)	232	90

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
52	328.956	75.2980	60	21.2	10	0	232	90
53	335.052	0.0350	900			(1)	232	90
54	338.049	0.0500	400			(1)	232	90
55	341.831	40.0000	75	19.7	15	0	232	90
56	351.800	0.0770				(1)	232	90
57	361.202	0.1000	300			(1)	232	90
58	365.183	25.4000	100	22.7	20	0	232	90
59	369.322	26.0000	110	22.4	30	0	232	90
60	380.487	0.1150	300			(1)	232	90
61	391.697	0.1760	300			(0)	232	90
62	400.918	11.9000	100	14.9	50	0	232	90
63	403.000	0.1040				(1)	232	90
64	411.781	0.2800	200			1	232	90
65	420.853	0.5400	160			(0)	232	90
66	427.100	0.0190				(1)	232	90
67	454.218	1.2300	130			0	232	90
68	458.864	0.0600	400			(1)	232	90
69	462.541	65.5990	80	19.0	16	0	232	90
70	466.400	0.1000	420			(1)	232	90
71	470.617	0.0400	750			(1)	232	90
72	476.297	0.1000	300			(0)	232	90
73	488.775	60.1000	80	17.2	24	0	232	90
74	500.000	0.0500	850			(1)	232	90
75	510.359	5.3200	100			0	232	90
76	528.496	15.7000	100	17.9	24	0	232	90
77	533.327	0.3100	200			(1)	232	90
78	535.508	0.3400	200			(1)	232	90
79	540.208	1.1800	150			1	232	90
80	550.300	0.4100				(1)	232	90
81	569.785	28.7000	90	26.3	30	0	232	90
82	573.555	0.7500	200			(0)	232	90
83	578.093	2.9700	180			0	232	90
84	584.000	0.0850				(1)	232	90
85	594.012	0.1000	500			(1)	232	90
86	598.279	10.0990	140	26.6	40	0	232	90
87	617.838	4.0999	180			0	232	90
88	625.100	0.0530	700			(1)	232	90
89	628.000	0.0550				(1)	232	90
90	634.200	0.0730				(1)	232	90
91	644.100	0.0900	750			(1)	232	90
92	656.602	49.1000	80	16.3	18	0	232	90
93	660.700	0.2000	450			(1)	232	90
94	665.303	25.1000	90	12.4	18	0	232	90
95	675.198	210.0002	40	18.4	14	0	232	90
96	687.446	54.8000	100	18.9	17	0	232	90
97	695.800	0.1700	680			(1)	232	90
98	698.929	0.1000	750			(1)	232	90
99	701.190	10.8990	160			0	232	90
100	704.530	0.1700	750			(1)	232	90
101	712.922	29.6000	90	13.6	30	0	232	90
102	720.200	0.0930				(1)	232	90

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
103	724.10	0.1500	750			(1)	232	90
104	741.09	193.0001	45	23.7	10	0	232	90
105	749.30	0.3400				(1)	232	90
106	758.54	0.2400	500			(1)	232	90
107	764.79	0.8200	200			(0)	232	90
108	771.50	0.1040				(1)	232	90
109	774.38	0.0500	750			(1)	232	90
110	778.72	10.9990	250	25.0	19	0	232	90
111	784.60	0.0770				(1)	232	90
112	788.40	0.0780				(1)	232	90
113	793.00	0.0830	890			(1)	232	90
114	804.24	180.0001	60	19.6	12	0	232	90
115	808.40	0.1400	420			(1)	232	90
116	816.85	0.1800	500			(1)	232	90
117	821.00	1.1500	180			(0)	232	90
118	828.88	0.2800	300			(1)	232	90
119	836.87	1.5900	120			(0)	232	90
120	842.35	27.2000	90	21.0	20	0	232	90
121	846.90	0.1400	550			(1)	232	90
122	850.78	1.1400	170			(0)	232	90
123	866.33	12.8600	120	35.4	28	0	232	90
124	869.41	0.7800	200			(1)	232	90
125	878.30	0.1900				(1)	232	90
126	884.68	0.3600	220			(1)	232	90
127	890.14	37.9000	60	22.2	13	0	232	90
128	899.60	0.0820				(1)	232	90
129	906.49	2.1100	180			1	232	90
130	914.50	0.1600	750			(1)	232	90
131	919.02	0.4800	300			(1)	232	90
132	926.87	0.4400	250			(0)	232	90
133	934.28	0.2700	400			(1)	232	90
134	943.22	44.9000	60	25.8	13	0	232	90
135	955.98	0.1800	750			(1)	232	90
136	962.72	6.6200	150			0	232	90
137	974.29	0.2700	750			(1)	232	90
138	982.92	35.4000	100	18.6	17	0	232	90
139	990.53	89.8000	80	17.7	15	0	232	90
140	995.49	0.5800	750			(1)	232	90
141	1001.17	0.2800	400			(1)	232	90
142	1010.57	125.5001	80	20.2	15	0	232	90
143	1021.52	0.3800	750			(1)	232	90
144	1029.40	0.3500	750			(1)	232	90
145	1039.16	8.5600	160			0	232	90
146	1043.92	0.7000	300			(1)	232	90
147	1049.50	0.2600				(1)	232	90
148	1054.80	0.3400				(1)	232	90
149	1060.50	0.2600				(1)	232	90
150	1064.43	6.0300	200	25.0	99	0	232	90
151	1073.70	0.2000	550			(1)	232	90
152	1077.23	8.6900	180			0	232	90
153	1093.00	1.7800	220			1	232	90

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
154	1109.97	21.8000	120	31.3	30	0	232	90
155	1114.50	1.7000	400			(0)	232	90
156	1120.22	1.0000	750			(1)	232	90
157	1120.60	3.3500	170			0	232	90
158	1120.02	0.2500	300			(1)	232	90
159	1132.57	0.4000	350			(1)	232	90
160	1138.90	16.0000	140	23.0	30	0	232	90
161	1150.46	17.3000	130			0	232	90
162	1167.20	0.1000				(1)	232	90
163	1175.83	0.3500	300			(1)	232	90
164	1184.90	0.1000				(1)	232	90
165	1194.53	7.5000	150			0	232	90
166	1204.44	2.1600	230			1	232	90
167	1214.14	0.3000	900			(1)	232	90
168	1217.34	0.6000	700			(1)	232	90
169	1224.15	0.4200	500			(1)	232	90
170	1227.98	38.6000	100	16.1	25	0	232	90
171	1233.20	0.7000	700			(1)	232	90
172	1243.09	18.7000	160			0	232	90
173	1248.91	123.6000	70	22.8	17	0	232	90
174	1260.81	0.6000	350			(1)	232	90
175	1261.70	0.8000	350			(1)	232	90
176	1266.36	0.2800	750			(1)	232	90
177	1269.40	24.7000	140			0	232	90
178	1287.57	0.1000	900			(1)	232	90
179	1292.16	102.6000	80	24.1	20	0	232	90
180	1301.58	50.3000	100	15.6	24	0	232	90
181	1307.80	0.3500				(1)	232	90
182	1334.95	3.2000	200			1	232	90
183	1346.03	1.0500	300			(1)	232	90
184	1349.40	0.7000	400			(1)	232	90
185	1354.78	83.7990	100	18.5	20	0	232	90
186	1359.86	9.0000	250			0	232	90
187	1372.39	1.0000	300			(0)	232	90
188	1378.05	51.6000	100	21.5	25	0	232	90
189	1384.60	0.3000	600			(1)	232	90
190	1387.45	2.2000	250			(0)	232	90
191	1397.86	140.0001	70	19.7	20	0	232	90
192	1408.70	0.4000	500			(1)	232	90
193	1417.91	0.6000	350			(1)	232	90
194	1426.63	112.0000	90	21.2	18	0	232	90
195	1433.90	34.8000	170	26.8	19	0	232	90
196	1441.42	1.5000	300			(1)	232	90
197	1449.60	0.2800				(1)	232	90
198	1461.02	1.4000	300			(0)	232	90
199	1465.40	0.1500				(1)	232	90
200	1469.30	0.3000	600			(1)	232	90
201	1478.33	2.3000	250			(0)	232	90
202	1484.20	0.1500				(1)	232	90
203	1502.54	0.8000	400			(1)	232	90
204	1508.60	1.0000	500			(0)	232	90

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
205	1509.60	3.6000	200			(1)	232	90
206	1515.34	1.6000	740			(1)	232	90
207	1518.71	196.0002	100	19.8	15	0	232	90
208	1524.31	206.0001	80	25.2	16	0	232	90
209	1555.60	6.4000	320			0	232	90
210	1581.06	22.5000	210	26.4	32	0	232	90
211	1589.53	362.0003	60	23.1	15	0	232	90
212	1602.60	54.9000	120	27.1	22	0	232	90
213	1611.18	0.9500	700			(1)	232	90
214	1623.48	0.6000	600			(1)	232	90
215	1630.90	549.0004	60	19.2	18	0	232	90
216	1640.80	39.9000	210	19.8	20	0	232	90
217	1661.43	132.0001	100	24.4	16	0	232	90
218	1668.70	0.5000				(1)	232	90
219	1677.95	24.3000	200	18.4	38	0	232	90
220	1689.81	1.1000	700			(1)	232	90
221	1697.01	2.5000	400			(0)	232	90
222	1705.34	3.5000	280			(0)	232	90
223	1719.80	39.5000	140			0	232	90
224	1725.42	1.2000	300			(1)	232	90
225	1730.13	1.8000	400			(1)	232	90
226	1740.15	6.7999	200			(0)	232	90
227	1746.79	33.1000	140	19.7	18	0	232	90
228	1753.69	0.7000	900			(1)	232	90
229	1762.77	116.6000	70	24.6	18	0	232	90
230	1767.30	1.4000	600			(1)	232	90
231	1785.32	2.4000	350			(0)	232	90
232	1793.25	0.4800	700			(1)	232	90
233	1803.50	100.0000	110	18.0	17	0	232	90
234	1812.07	44.1000	200	28.0	22	0	232	90
235	1824.23	92.9990	100	20.2	22	0	232	90
236	1834.47	1.4000	600			(1)	232	90
237	1847.76	4.2000	250			(0)	232	90
238	1854.76	31.4000	180	24.3	33	0	232	90
239	1861.98	34.1000	180	29.6	27	0	232	90
240	1888.90	1.1000	400			(1)	232	90
241	1896.60	6.0000	740			(1)	232	90
242	1900.36	114.0000	100			0	232	90
243	1928.30	7.0000	150			(0)	232	90
244	1931.10	10.5000	150			(0)	232	90
245	1940.02	0.3200	900			(1)	232	90
246	1951.06	90.7990	110	18.9	20	0	232	90
247	1971 49	222.0001	90	19.0	22	0	232	90
248	1981.84	1.3000	999			(1)	232	90
249	1988.25	47.4000	200	24.6	99	0	232	90
250	2005.24	26.9000	280	24.1	99	0	232	90
251	2015.65	1.0000	750			(1)	232	90
252	2020.46	1.0000	750			(1)	232	90
253	2026.21	1.3000	750			(1)	232	90
254	2035.06	1.0000	750			(1)	232	90
255	2052.41	18.0000	250			0	232	90

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
256	2055.70	0.5000	600			(1)	232	90
257	2062.14	57.0000	200	24.0	99	0	232	90
258	2073.58	8.5000	700			(0)	232	90
259	2078.99	10.0000	400			0	232	90
260	2096.99	1.2000	600			(0)	232	90
261	2117.61	79.4990	150			0	232	90
262	2139.52	1.0000	700			(1)	232	90
263	2147.52	94.6990	140			0	232	90
264	2157.73	10.0000	500			(1)	232	90
265	2161.83	122.0000	130			(0)	232	90
266	2170.73	2.8000	500			(1)	232	90
267	2177.94	83.7990	130			0	232	90
268	2197.35	56.0000	150			0	232	90
269	2208.15	2.2000	400			(1)	232	90
270	2216.26	28.1000	200			0	232	90
271	2221.66	95.8990	130			0	232	90
272	2234.07	2.5000	400			(0)	232	90
273	2243.17	0.7500	999			(1)	232	90
274	2247.67	0.6000	800			(1)	232	90
275	2262.18	0.6000	700			(1)	232	90
276	2271.06	28.3000	190			0	232	90
277	2276.25	91.3990	220			0	232	90
278	2286.45	278.0002	90			0	232	90
279	2306.81	3.2000	400			(1)	232	90
280	2313.01	1.6000	400			(1)	232	90
281	2321.31	4.0000	350			(0)	232	90
282	2329.92	2.2000	500			(1)	232	90
283	2335.72	124.0000	130			0	232	90
284	2344.33	6.5999	300			(0)	232	90
285	2352.50	15.0000	200			(0)	232	90
286	2353.70	14.0000	200			(0)	232	90
287	2361.74	0.6000	800			(1)	232	90
288	2369.44	1.1000	750			(1)	232	90
289	2374.97	119.0000	130			0	232	90
290	2382.65	4.5000	400			(0)	232	90
291	2391.45	4.0000	350			(0)	232	90
292	2406.66	0.5000	750			(1)	232	90
293	2413.07	0.6000	700			(1)	232	90
294	2418.83	97.0989	120			0	232	90
295	2423.97	2.3000	750			(1)	232	90
296	2427.58	3.0000	350			(1)	232	90
297	2435.18	2.[illegible]000	350			(1)	232	90
298	2440.64	10.8000	220			(0)	232	90
299	2452.00	4.0000	700			(1)	232	90
300	2452.50	1.0000	750			(1)	232	90
301	2455.77	165.0001	120			0	232	90
302	2462.69	4.0000	700			(1)	232	90
303	2474.30	0.9000	750			(0)	232	90
304	2480.91	0.6000	750			(1)	232	90
305	2491.61	8.4000	300			(0)	232	90
306	2501.12	0.6000	700			(1)	232	90

Resonances parameters of ^{232}Th

	Energy (eV)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (eV)	ε (%)	L	A	Z
307	2508.99	357.0002	90			0	232	90
308	2526.93	52.3000	180			0	232	90
309	2535.94	2.2000	650			(1)	232	90
310	2543.84	0.4000	700			(1)	232	90
311	2548.15	0.4000	700			(1)	232	90
312	2557.15	4.9999	500			(0)	232	90
313	2563.29	328.0002	120			0	232	90
314	2569.39	71.9990	220			0	232	90
315	2582.77	1.1000	700			(1)	232	90
316	2589.77	2.0000	700			(1)	232	90
317	2595.38	0.8000	700			(1)	232	90
318	2603.18	2.4000	350			(1)	232	90
319	2612.72	97.5990	120			0	232	90
320	2624.44	10.2000	280			(0)	232	90
321	2635.30	176.0001	100			0	232	90
322	2653.16	2.5000	700			(0)	232	90
323	2663.62	209.0002	100			0	232	90
324	2677.53	11.9000	300			(0)	232	90
325	2688.64	207.0001	100			0	232	90
326	2713.18	101.9900	130			0	232	90
327	2722.76	12.0000	250			(0)	232	90
328	2733.83	410.0003	100			0	232	90
329	2748.55	14.2000	300			(0)	232	90
330	2763.28	1.8000	500			(1)	232	90
331	2773.49	72.6990	160			0	232	90
332	2782.70	2.5000	400			(1)	232	90
333	2793.09	161.0001	110			0	232	90
334	2802.41	4.9999	400			(1)	232	90
335	2810.32	0.2300	900			(1)	232	90
336	2815.62	27.0000	250			0	232	90
337	2824.33	1.4000	400			(1)	232	90
338	2833.03	54.0000	190			0	232	90
339	2839.50	1.2000	500			(0)	232	90
340	2844.44	0.7500	700			(1)	232	90
341	2852.51	216.0001	95			0	232	90
342	2861.05	6.9999	600			(1)	232	90
343	2870.56	1.9000	400			(1)	232	90
344	2884.07	5.3000	300			(0)	232	90
345	2895.37	4.0000	300			(0)	232	90
346	2907.38	2.0000	500			(1)	232	90
347	2914.49	4.9999	400			(0)	232	90
348	2922.89	1.4000	700			(1)	232	90
349	2932.15	1.8000	600			(1)	232	90
350	2939.80	1.6000	750			(1)	232	90
351	2948.13	104.0000	140			0	232	90
352	2956.68	49.2000	180			0	232	90
353	2966.45	14.2000	280			(0)	232	90
354	2979.15	9.8000	300			(0)	232	90
355	2988.58	34.4000	200			0	232	90
356	2995.84	2.3000	750			(1)	232	90
357	3006.85	2.0000	400			(0)	232	90

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Comments on Th-232 Absorption Resonance Integral, $\langle\Gamma_\gamma\rangle$, and Neutron Width Statistics

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Th-232 Resonance Integral and $\langle\Gamma_\gamma\rangle$

A coarse review was made of the Th-232 absorbtion resonance integral. Table 1 shows the results. Renormalized measured values range from 81 to 90 barns with typical error estimates of 3 barns. The higher values have been achieved in more recent years. Evaluation and review values center on 84 - 85 barns. Thus the probable range to the absorption resonance integral is estimated to be 84 < RI < 90 b.

Table 2 gives some key Th-232 radiation widths from three American evaluations and from the work of Derrien presented at this meeting. The relative importance of each resonance is indicated in the last column by its resonance integral contribution. The average for the most important resonances as well as for all the resonances considered in the reference is given in the bottom of the table. The range of average radiation widths, $\langle\Gamma_\gamma\rangle$ is seen to be about 21-26 milli ev.

Table 3 makes some comparisons between $\langle\Gamma_\gamma\rangle$ and resonance integrals. On this basis one would expect

$$25 < \langle\Gamma_\gamma\rangle < 29$$

In comparison, Derrien has recommended a value $\langle\Gamma_\gamma\rangle \approx 21^+$, based on the resonances in the range $59.5 \leq E_0 \leq 285.7$. These are shown in Table 2 under the column labelled Derrien, Table V.

However, it has been pointed out in the meeting discussion that the set $\{\Gamma_\gamma\}$ deduced depend on the set of $\{\Gamma_n\}$ assumed. Both Γ_n and Γ_γ determine the resonance integral. Thus the significance of the above disagreement is diminished somewhat.

Th-232 Neutron Width Statistics

Two independent workers have recently suggested that Th-232 neutron widths may not have a Porter-Thomas distribution (PT). To pursue this idea the Th-232 s-wave widths in BNL-325-3 were plotted as shown in Figure 1. (The bottom portion of the figure is an enlargement of the first bin in the upper portion. In each portion one can observe the change in width distribution as one includes resonances from higher neutron energies. Thus one observes a non-PT below 250 eV shifting towards a PT by ~ 1 keV. However, a non-PT remains within the first $\Gamma_n^0/\langle\Gamma_n^0\rangle$ bin as shown in Figure 2.

A similar evaluation for U-238 neutron widths from the same source, BNL-325-3 shows none of these patterns (Figure 2). Possible answers to the Th-232 behaviour could be ℓ-wave misassignments, particularly at lower energies and/or missed levels. A test for missing resonances should be made.

Table 1. Th-232 Resonance Integral

Measured Values

Year	Source	Value	Standard
1972	Steinnes	88 ± 3	
1970	GfK	90 ± 4	(1560,Au)
1965	BET	82.5± 3.0	(1555,Au)
1965	MTR	81.2± 3.4	(1579,Au)
1964	KfK	88 ± 2	(1560,Au)

Evaluation and Review Values

1974	BNL-325-3	85±3	(1560,Au)
1967	Sehgal	84	(1560,Au)
1966	Hellstrand	84	(1560,Au)
∿1966	Drake	84	

Probable Range 84 < RI < 90

Table 2. Th-232 Γ_γ

E_o (eV)	WAPD TM-378 (1970)	ENDF/B -3	BNL-325 -3	Derrien Table III	Derrien Table V		Resulting Contr. RI (ENDF/B-3)
21.8	26.3	25.9	23.0	24.5			16.2
23.4			25.0	26.6			24.6
59.5			23.2	23.7	22.0		4.0
69.1			21.9	21.9	20.5		13.9
113.0			20.1		20.4		2.7
120.8			21.0		20.7		3.2
170.3			22.4		19.3		2.6
192.6			18.0		16.8	21.7	1.1
199.3			18.5		17.9		8
221.2			20.7		22.0		1.2
251.5			21.5		25.4		.9
263.0			18.6		28.0		.7
285.7			20.8		24.9		.7
Avg. 21.8 23.4, 69.1	26.3	25.9	23.3	24.3			
Avg. All Resonances	26.3	25.9	21.2		26.6		

Table 3. TH-232 Resonance Integral and $\langle\Gamma_\gamma\rangle$

Values Calculated from Resonance Parameters or Group Constants

Source	RI(b)	$\langle\Gamma_\gamma\rangle$
Original ABBN	>100	
BNL-325-2 (65)	84.5	25.9
WAPD-TM-971 (70)	85.2	26.3
BNL-325-3 (74)	<79	21.2

Empirical Value (Malecky et al, JINR)

Predicted $\langle\Gamma_\gamma\rangle = 35 \rightarrow RI = 100$

Best Guess $25 < \langle\Gamma_\gamma\rangle < 29$

Fig. 1

Distribution of Th-232 Reduced Neutron Widths Reported in BNL 325, Third Edition

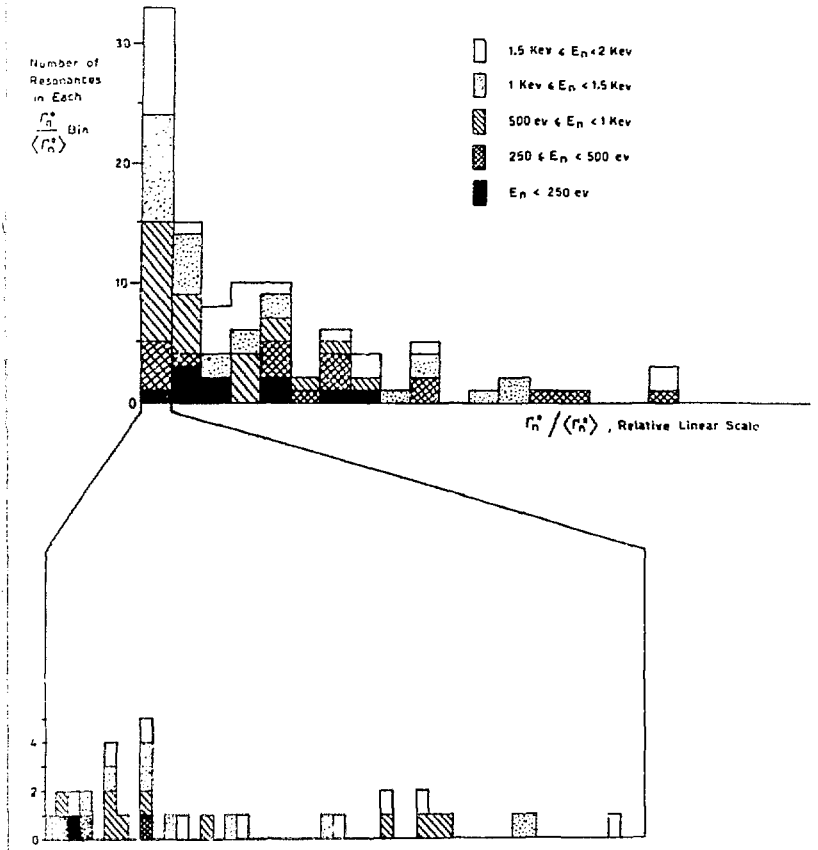
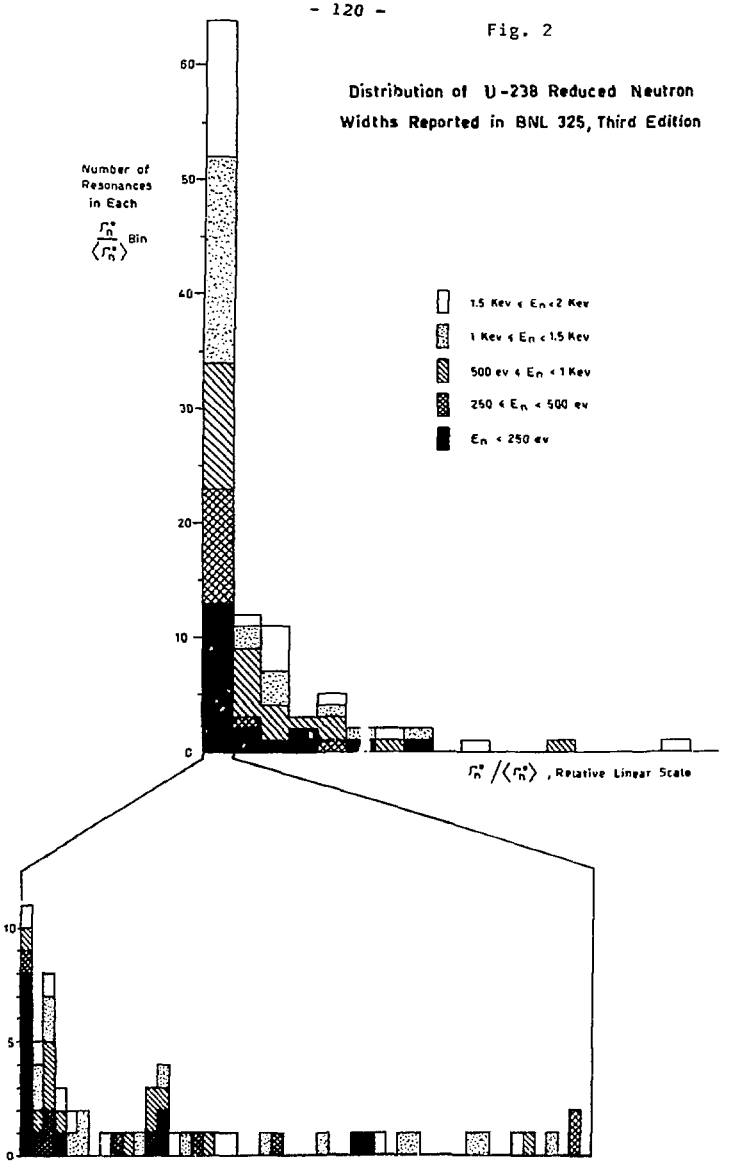


Fig. 2

Distribution of U-238 Reduced Neutron Widths Reported in BNL 325, Third Edition



NEUTRON WIDTHS FOR ^{236}U FROM HIGH RESOLUTION TRANSMISSION MEASUREMENTS AT A 100 M FLIGHTPATH

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1. EXPERIMENTAL PROCEDURE

A series of neutron transmission measurements has been performed on ^{236}U aiming at a determination of the resonance parameters and their statistical properties. (For references see (1), (2), (3), (4), (5)). The analysis range covered neutron energies from 40 eV to 4.1 keV. The experiments were carried out at ≈ 100 m flightpath of the 80 MeV electron linear accelerator of CBNM using a ^{10}Bslab-NaI detector and 2 ^{236}U-oxyde samples on loan from the USAEC (for isotopic composition see table 1). Table 2 displays the details of 6 experimental runs, 3 of which were arranged in such a way that the effect of the ^{235}U and ^{238}U impurities in the sample on the transmission was automatically compensated. For this, samples were put into the "open beam" position of the sample changer: they contained the same specific quantities of the impurities as in the ^{236}U-samples. Sample changer operation, data acquisition and storage were controlled by an IBM 1800 computer. The background was determined with the "black resonance" method.

2. DATA ANALYSIS AND RESULTS

Resonance parameters have been evaluated by means of a modified version (6) of the Atta-Harvey area analysis program (7) using up to 1.7 keV the Γ_γ values and between 1.7 keV and 4.1 keV the $\overline{\Gamma}_\gamma$ value given by Mewissen (2). The results are listed in table 3 together with those published by Carlson (1). The levels at 63.1 eV

and 243.0 eV quoted by Carlson were not observed in this experiment. Though the Γ_n values agree in the overlapping energy range of both experiments within the error limits for all resonances except two (43.92 eV and 192.89 eV resonances), the values of the present work are on the average slightly higher than those of Carlson.

In the energy range up to 1.6 keV the observed level density is almost constant. Considering also the resonances given by Carlson at 5.45 eV, 29.7 eV, 34.0 eV and 63.1 eV, we obtain for the mean level spacing the value $\overline{D} = (16.2 \pm 0.3)$ eV.

Assuming that the undetected small resonances do not influence noticeably the sum of all Γ_n^o up to 4.1 keV, the strength function turns out to be

$$S_o = \frac{\sum_{i=1}^{n} \Gamma_{n\,i}^{o}}{E_n - E_1} = (1.00 \pm 0.10) \cdot 10^{-4}$$

which includes Carlson's Γ_n^o values below 63.1 eV.
From the $\overline{D}$ value determined in the energy range $5\ \text{eV} < E_n < 1.6$ keV and the S_o value which is supposed to be valid for the total energy range $5\ \text{eV} < E_n < 4.1$ keV we deduce

$$\overline{\Gamma_n^o} = (1.61 \pm 0.16\ \text{meV}).$$

It is assumed that p-wave resonances do not play a role in these considerations.

Correcting for missed levels by the method of T. Fuketa and J. A. Harvey (8) over the entire range up to 4.1 keV we obtain

$\overline{D} = 16.2$ eV $\quad \overline{\Gamma_n^o} = 1.66$ meV $\quad$ and $\quad S_o = 1.03 \cdot 10^{-4}$.

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Table 1: Samples Composition

Isotopic composition of the two ^{236}U samples:
89% of ^{236}U; 9.2% of ^{235}U; 1.3% of ^{238}U; 0.1% of ^{234}U

	1st sample ^{236}U	2nd sample ^{236}U
Total weight of U_3O_8(gr):	41.19	57.88
Thickness (at/b):	$8.98 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$
Diameter (mm):	33.6	103.0

	Sample ^{235}U	Sample ^{238}U
Total weight of U_3O_8(gr):	2.413	0.385
Thickness (at/b):	$1.36 \cdot 10^{-4}$	$2.15 \cdot 10^{-5}$
Diameter (mm):	70.0	70.0

Table 2: Main characteristics of different runs

		1st Run	2nd Run	3rd Run	4th Run	5th Run	6th Run
Total energy range (eV)		148 - 768	390 - 1672	1559-4140	37 - 238	180 - 870	851 - 3198
Burst width		70 ns	24 ns	23 ns	22 ns	22 ns	22 ns
Repetition rate		400 Hz	600 Hz	600 Hz	400 Hz	400 Hz	400 Hz
Electron energy		65 MeV	65 MeV	65 MeV	69 MeV	69 MeV	69 MeV
Black resonances		Bi;Mn; W	Na; Bi	Al; Na	Mn; Co	Co; Bi; Mn	Bi; Na
Energy range (eV)	(a)	147.70-170.02	389.66-641.06	1558.74 - 4132.85	37.13-106.31	180.51-870.19	851.02-1874.7
	(b)	170.02-768.13	641.06-870.28		106.31-179.62		1874.7-3198.44
	(c)		870.28-1057.6		179.62-228.01		
	(d)		1057.6-1671.9		228.01-237.95		
Channel widths	(a)	0.32 μs	0.16 μs	0.02 μs	0.32 μs	0.08 μs	0.04 μs
	(b)	0.08 μs	0.08μs		0.16 μs		0.02 μs
	(c)		0.04 μs		0.08 μs		
	(d)		0.02 μs		0.04 μs		
Overlap filter		0.41gr of $^{10}BC/cm^2$	0.41gr of $^{10}B\,C/cm^2$	0.41 gr of $^{10}B\,C/cm^2$	0.41gr of $^{10}B\,C/cm^2$	0.41gr of $^{10}BC/cm^2$	0.41gr of $^{10}B_4C/cm^2$ + 0.20 gr $^{10}B/cm^2$
Sample thickness (at/b)		$8.98 \cdot 10^{-3}$	$8.98 \cdot 10^{-3}$	$8.98 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$	$1.34 \cdot 10^{-3}$

Table 3 : ^{236}U resonance parameters: neutron widths

E_o(eV)	Present work		Carlson(1)
	$g\Gamma_n$(meV)	$g\Gamma_n^o$ (meV)	Γ_n (meV)
5.45			2.16 ± .08
29.7			.585± .03
34.0			2.35 ± .13
43.92 ± .03	17.5 ± 4.0	2.64	11.8 ± .6
63.1			.034± .005
71.47 ± .06	24. ± 6.	2.84	19.0 ± 1.0
86.51 ± .07	36. ± 9.	3.87	26.0 ± 2.0
102.25 ± .14	.75± .20	.07	.8 ± .08
120.95 ± .06	57. ±11.	5.2	51.8 ± 4.0
124.88 ± .08	17. ± 2.	1.52	15.9 ± 1.9
134.57 ± .11	1.4 ± .4	.12	1.08 ± .09
137.76 ± .11	.84± .30	.07	.48 ± .1
164.72 ± .14	2.1 ± .7	.16	2.09 ± .15
192.89 ± .13	9.4 ± 1.6	.68	13.2 ± 1.3
194.35 ± .10	58. ± 6.	4.16	52.0 ±13.0
212.75 ± .11	98. ±15.	6.7	98.2 ±10.0
229.63 ± .13	2.2 ± .5	.15	2.34 ± .14
243.0			.3 ± .15
272.93 ± .12	38. ± 5.	2.30	55.0 ±15.0
288.68 ± .13	14.3 ± 1.1	.84	13.5 ± 2.0
303.15 ± .14	81. ± 6.	4.65	83.5 ±15.0
320.50 ± .20	5.5 ± 1.1	.31	5.8 ± .6
334.96 ± .22	6.4 ± 1.1	.35	6.3 ± .4
357.05 ± .30	.70± .25	.04	.64 ± .1
366.95 ± .30	.40± .30	.021	.4 ± .3
371.18 ± .18	15.8 ± 2.2	.82	13.8 ± 1.0
379.81 ± .19	115. ±24.	5.9	130.0 ± 30.0
415.39 ± .21	17.7 ± 2.0	.87	17.8 ± 2.0
430.95 ± .22	65. ± 8.	3.13	
440.63 ± .23	68. ± 9.	3.24	
465.50 ± .25	15.4 ± 2.0	.71	
478.39 ± .26	40. ± 3.	1.83	
500.41 ± .40	2.8 ± .9	.13	
507.06 ± .28	20. ± 3.	.89	
536.37 ± .31	33. ± 3.	1.43	
542.82 ± .44	12.6 ± 2.4	.54	
563.76 ± .33	81. ± 7.	3.41	
576.23 ± .34	158. ± 25.	6.6	
607.10 ± .43	13. ± 2.	.53	
617.80 ± .38	53. ± 7.	2.13	
637.77 ± .39	74. ± 8.	2.93	
647.60 ± .57	7. ± 3.	.28	
655.63 ± .41	101. ± 10.	3.95	
673.63 ± .43	59. ± 7.	2.27	
691.32 ± .44	38. ± 4.	1.45	

Table 3 : (continued)

E_o (eV)	Present work	
	$g\Gamma_n$(meV)	$g\Gamma_n^o$ (meV)
706.02 ± .45	32. ± 4.	1.20
720.58 ± .47	105. ±10.	3.91
746.25 ± .49	24. ± 3.	.88
770.65 ± .52	192. ±19.	6.92
789.43 ± .53	87. ±11.	3.10
806.56 ± .55	42. ± 6.	1.48
820.28 ± .81	8.4± 3.6	.29
827.43 ± .57	259. ±50.	9.0
849.04 ± .85	4. ± 2.	.14
864.90 ± .87	18. ± 6.	.61
888.84 ± .51	10. ± 3.	.34
900.35 ± .65	9. ± 3.	.30
930.74 ± .54	11. ± 3.	.36
948.42 ± .43	170. ±15.	5.52
955.20 ± .56	40. ± 5.	1.29
969.28 ± .44	359. ±47.	11.5
994.70 ± .46	153. ±12.	4.85
998.13 ± .60	11. ± .	.35
1013.10 ± .61	11. ± 4.	.35
1024.19 ± .48	298. ±37.	9.3
1032.10 ± .63	43. ± 5.	1.34
1064.62 ± .50	43. ± 5.	1.32
1075.71 ± .67	6. ± 3.	.18
1084.22 ± .80	2. ± 1.	.06
1098.00 ± .80	3. ± 2.	.09
1104.75 ± .53	124. ±11.	3.73
1132.10 ± .72	11. ± 5.	.33
1136.68 ± .55	116. ± 9.	3.44
1157.12 ± .57	60. ± 6.	1.76
1166.94 ± .57	11. ± 3.	.32
1184.00 ± .60	72. ± 9.	2.09
1218.64 ± .80	8.5± 4.0	.24
1254.25 ± .81	7.5± 1.5	.21
1268.83 ± .83	6.0± 1.5	.17
1281.72 ± .85	3.0± 1.5	.08
1291.66 ± .66	168. ±16.	4.68
1315.90 ± .90	4.0± 1.5	.11
1324.40 ± .90	15. ± 4.	.41
1339.53 ± .70	75. ±10.	2.05
1349.23 ± .71	69. ±10.	1.88
1363.62 ± .72	230. ±21.	6.23
1367.4 ±1.2	4. ± 2.	.11
1395.65 ± .98	21. ± 7.	.56
1405.0 ±1.0	50. ± 9.	1.33
1413.44 ± .75	275. ±22.	7.32
1426.64 ± .76	26. ± 7.	.69
1440.4 ±1.0	4. ± 2.	.11
1458.3 ±1.0	14. ± 4.	.37

Table 3 : (continued)

E_o (eV)	Present work	
	$g\Gamma_n$ (meV)	$g\Gamma_n^o$ (meV)
1470.02 ± .80	212. ±19.	5.53
1477.1 ±1.1	31. ± 6.	.81
1506.30 ± .83	145. ±16.	3.74
1535.0 ±1.1	11. ± 3.	.28
1548.03 ± .86	207. ±22.	5.26
1553.8 ±1.2	10. ± 4.	.25
1584.1 ±1.2	4. ± 2.	.10
1592.47 ± .90	110. ±11.	2.76
1609.1 ±1.2	19. ± 5.	.47
1614.3 ±1.2	8. ± 3.	.20
1659.96 ± .95	98. ±11.	2.41
1690.9 ±1.1	59. ±10.	1.44
1698.6 ±1.7	15. ± 4.	.36
1723.2 ±1.2	25. ± 6.	.60
1738.5 ±1.4	12. ± 5.	.29
1779.0 ±1.1	50. ±10.	1.19
1789.0 ±1.4	13. ± 5.	.31
1794.6 ±1.1	82. ±15.	1.94
1813.1 ±1.4	22. ± 7.	.52
1831.1 ±1.3	70. ±17.	1.64
1853.6 ±1.1	192. ±25.	4.46
1856.9 ±1.1	310. ±50.	7.2
1882.6 ±1.3	40. ±13.	.92
1895.2 ±1.2	80. ±16.	1.84
1954.5 ±1.4	84. ±11.	1.90
2010 ±1.5	82. ±20.	1.83
2017.1 ±1.5	41. ±16.	.91
2034.9 ±1.3	26. ±11.	.58
2047.5 ±1.1	89. ±16.	1.97
2063.2 ±1.3	12. ± 8.	.26
2084.7 ±1.1	37. ±15.	.81
2106.0 ±1.0	510. ±50.	11.1
2131.1 ±1.2	98. ±16.	2.12
2142.0 ±1.2	72. ±14.	1.56
2165.7 ±1.4	24. ± 8.	.52
2219.8 ±1.1	275. ±26.	5.84
2236.6 ±1.1	250. ±30.	5.29
2249.7 ±1.1	109. ±16.	2.30
2269.0 ±1.3	82. ±14.	1.72
2308.1 ±1.1	112. ±16.	2.33
2324.3 ±1.3	63. ±10.	1.31
2328.3 ±1.3	68. ±10.	1.41
2349.8 ±1.3	92. ±16.	1.90
2380.7 ±1.4	41. ±18.	.84
2389.2 ±1.6	23. ±13.	.47
2407.0 ±1.2	140. ±25.	2.85
2450.6 ±1.4	35. ±12.	.71
2459.9 ±1.4	65. ±17.	1.31

Table 3 (continued)

E_o (eV)	Present work	
	$g\Gamma_n$ (meV)	$g\Gamma_n^o$ (meV)
2480.0 ±1.5	23. ± 13.	.46
2489.8 ±1.2	165. ± 30.	3.31
2499.5 ±1.5	15. ± 8.	.30
2564.1 ±1.5	59. ± 16.	1.17
2581.2 ±1.3	135. ± 25.	2.66
2632.2 ±1.6	27. ± 15.	.53
2643.9 ±1.9*		
2660.3 ±1.6	100. ± 23.	1.94
2672.9 ±1.6	132. ± 25.	2.55
2772.7 ±1.5	330. ± 52.	6.3
2807.7 ±1.7	53. ± 15.	1.00
2822.7 ±1.8	70. ± 20.	1.32
2854.3 ±1.8	23. ± 15.	.43
2870.0 ±1.5	160. ± 32.	2.99
2880.3 ±1.7	155. ± 30.	2.89
2917.9 ±1.8	100. ± 25.	1.85
2958.9 ±2.0	30. ± 12.	.55
3015.3 ±1.6	660. ± 84.	12.0
3079.3 ±2.0	104. ± 27.	1.87
3101.1 ±2.4	40. ± 12.	.72
3131.7 ±2.0	126. ± 30.	2.25
3164.2 ±2.1	95. ± 25.	1.69
3188.4 ±2.1	100. ± 27.	1.77
3219.6 ±2.1	93. ± 25.	1.64
3245.4 ±2.1	65. ± 20.	1.14
3282.8 ±2.2	125. ± 28.	2.18
3307.2 ±2.6	26. ± 10.	.45
3365.5 ±2.3	110. ± 25.	1.90
3434.5 ±2.3	60. ± 20.	1.02
3468.4 ±2.4	116. ± 26.	1.97
3528.9 ±2.6	62. ± 20.	1.04
3560.4 ±2.5	100. ± 30.	1.68
3594.1 ±2.1	510. ± 60.	8.5
3601.1 ±2.5	115. ± 25.	1.92
3628.9 ±2.5	90. ± 20.	.49
3644.0 ±2.7	50. ± 15.	.83
3683.0 ±2.6	300. ± 70.	9
3715.2 ±2.6	310. ± 75.	.1
3737.5 ±2.6	290. ± 70.	4.7
3743.9 ±3.1*		
3758.7 ±2.7	250. ± 60.	4.08
3790.5 ±2.7	320. ± 75.	5.2
3804.9 ±2.7	105. ± 30.	1.70
3825.6 ±3.1	75. ± 30.	1.21
3871.6 ±2.8	210. ± 60.	3.38
3966.8 ±2.9	170. ± 50.	2.70

Table 3 : (continued)

E_o (eV)	Present work	
	$g\,\Gamma_n$ (meV)	$g\,\Gamma_n^o$ (meV)
3984.6 ±2.9	950. ± 120.	15.1
3994.3 ±2.9	130. ± 50.	2.06
4031.1 ±3.5	50. ± 30.	.79
4059.9 ±3.4	90. ± 35.	1.41
4106.2 ±3.0	190. ± 60.	2.97

* Levels which are uncertain

Calculated statistical properties:

$\bar{D}$ = (16.2 ± .3) eV (in the range 0 ÷ 1660 eV)

S_o = (1.00 ± .10)·10^{-4} (in the range 0 ÷ 4.1 keV)

$\bar{\Gamma}_n^o$ = (1.61 ± .16)meV (resulting from $\bar{D}$ and S_o)

NEUTRON CROSS-SECTION MEASUREMENTS ON ^{236}U BELOW 2 keV

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1. Introduction

Until now, only little information has been published on the resonance parameters of ^{236}U. Harvey et al[1] determined the neutron widths for 9 resonances from transmission measurements below 400 eV, Carlson et al[2] analysed capture and self-indication experiments up to 415 eV and the neutron widths have also been published by Harlan[3] for 14 resonances up to 376 eV.

At C.B.N.M., two types of experiments have been performed :

1) Carrero and Brusegan did high resolution transmission experiments on a 100 meter flight path up to 6 keV, using 57.8 g U_3O_8 enriched to 89.4 %. Preliminary results have already been communicated at the Budapest Conference [4].
The analysis of their experiments is now completed and the results will be published soon.
A list of the neutron widths for 185 levels up to 4.1 keV will distributed at this meeting.

2) We did capture and scattering cross-section measurements below 2 keV and also transmission experiments using the small sample (Ø 11 mm) facility on a 30 meter flight path with 5.4 grams U_3O_8, enriched to 99.7 % ^{236}U.

This report will describe the second series of experiments and discuss the results, obtained from the analysis of the scattering, capture and transmission experiments from the 30 meter flight path.

2. Experimental details

The experimental details are listed in Table 1.
The samples were prepared by settling in alcohol and canning under vacuum between two aluminium plates of a thickness of 0.5 mm[5]. The uranium oxide was on loan from the USAEC. In the partial cross-section measurements, only the thick sample run was analysed. The measurements with the thin sample (99.7 % ^{236}U) were used to identify the ^{236}U resonances.

^{3}He high pressure gaseous scintillators (LND type 800) were used as neutron detectors in the scattering and transmission experiments. The capture cross-section measurements were performed with a Moxon Rae-type detector.
The raw data from scattering are shown on Fig. 1 and from capture on Fig. 2.

3. Analysis of the data

An area analysis of the transmission data was done, using a modified version of the Atta-Harvey program [6].

The scattering cross-section was measured relative to Pt for which σ_n = 11.28 ± 0.6 barns[7]. The data were corrected for self-screening and for absorption of the scattered neutrons. For this correction, it was assumed that any second interaction was an absorption. This approximation was not valid for some strong resonances below 500 eV so that for these cases, the resonance parameters Γ_n and Γ_γ were deduced from the capture and transmission results only.

The capture experiments were performed at a 60 m flight path station. The shape of the neutron flux was measured with a ^{10}B slab viewed by a NaI crystal ; the ^{10}B (n, α) ^{7}Li reaction is assumed to vary as $E^{-1/2}$ in the energy range of interest. The absolute calibration of the product detector efficiency times neutron flux was done by observing capture in black resonances of Ag at 5.2, 16.3, 51.4 and 70.9 eV.
The resonance analysis was done with a capture area analysis program due to Fröhner and Haddad [8].

4. Results and discussion

The resonance parameters Γ_n and Γ_γ were obtained by combining the results from the area analysis of the three experiments. The neutron width Γ_n could be determined for 97 levels up to 1.8 keV and the capture width for 57 among them. The results are listed in Table 2. The error on Γ_γ which is listed in Table 2 is only the statistical error. The additional systematic error of about 5 %, mainly due to the normalization and to the uncertainty in the sample thickness is added to the error on the mean capture width.

Fig. 3 shows a plot of the number of observed levels versus energy. This figure shows that not many levels are missed below 1500 eV. The mean level spacing, calculated below 1200 eV is :

$$\bar{D} = (16.1 \pm 0.5)\text{eV} \qquad \left(\text{fractional uncertainly} = \frac{2}{n}\right)$$

If we correct for the number of missed levels, using the method of Fukota and Harvey [9] we find :

$$\bar{D}_{corr} = (15.2 \pm 0.5)\text{eV}$$

Fig. 4 shows the sum of the reduced neutron widths as a function of energy together with the strength function :

$$S_0 = \overline{\Gamma_n^0}/\bar{D} = (1.05 \pm 0.14)\ 10^{-4}$$

Fractional uncertainty = $1.4/\sqrt{n}$

n = number of levels = 95.

The most important result from these experiments is the mean capture width :

$$\overline{\Gamma_\gamma} = [23.0 \pm 0.5\ (\text{stat.}) \pm 1.0\ (\text{syst.})]\ \text{meV}.$$

This value was obtained as a weighted average for 57 capture widths, obtained below 1.7 keV.

From the comparison with the results of Carlson [2] we see that :

1º) two small levels at 243 eV and 356 eV are detected by Carlson but not in any of our experiments.

2º) For about 80 % of the levels, the Γ_n values of Carlson agree with the present results within the error limit but there is a desagreement of about 50 % in the neutron widths for two strong resonances at 272.8 eV and 379.6 eV.

3º) The mean capture width obtained by Carlson $\overline{\Gamma_\gamma}$ = (23.9 ± 1.0) meV is in good agreement with our results. Carlson does not give a systematic error and this mean value was obtained for 12 resonances.

By comparing our results with those of Carraro and Bruseqan[10] the following conclusions can be drawn :

1º) Due to the better resolutions of their experiments three more levels are detected by Carraro in the energy region below 1800 eV.

2º) The strength function value found by Carraro is (1.0 ± 0.1) 10^{-4}, obtained from 185 levels up to 4.1 keV. This is in good agreement with our result although in the energy region below 1.8 keV their neutron widths are systematically larger. In fact if one calculates the strength function from their neutron widths below 1.8 keV, one find : S_0 = (1.10 ± 0.15)10^{-4} what is approximately 12 % higher than our result. The reason for this difference is not yet explained.

Figure captions

Fig. 1. Scattering neutron yield below 1500 eV

Fig. 2. Capture yield curve below 900 eV

Fig. 3. Plot of the observed number of levels versus energy

Fig. 4. Plot of $\Sigma\Gamma_n^0$ versus energy. The slope gives the S-wave strength function.

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Table 1. Experimental Details

	transmission	capture		scattering
linac parameters				
burst width	22 ns	32 ns		32 ns
burst frequency	400 Hz	400 Hz		400 Hz
Flight path length	31.22 ± 0.02 meters	60.53 ± 0.02 meters		31.10 ± 0.02 meters
time-of-flight resolution	1.5 - 5.1 ns/m	0.7 - 6.7 ns/m		ΔE (F.W.H.M.)/E $\cong 2 \times 10^{-3}$
background filters	Na, Mn, Co, Mo, A	Al, Bi, Cu, Co, W		Na, Mn, Co, Mo, A
samples				
thickness	7.6×10^{-3} at/b	$2.15\ 10^{-4}$ at/b	$1.5\ 10^{-3}$ at/b	same as for capture
total quantity	5.4 g U_3O_8	5.4 g U_3O_8	57.8 g U_3O_8	
isotopic composition	99.7 % ^{236}U	99.7 % ^{236}U	89.4 % ^{236}U	
	0.2 % ^{235}U	0.2 % ^{235}U	0.1 % ^{234}U	
	0.1 % ^{238}U	0.1 % ^{238}U	9.2 % ^{235}U	
			1.3 % ^{238}U	

Table 2. Resonance parameters of ^{236}U

E_0 (eV)	Γ_n (meV)	$\Delta\Gamma_n$ (meV)	Γ_n^0 (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV) (stat.)
5.45 z)	2.16	0.03	0.925	24.5	1.0
29.7 z)	0.585	0.03	0.107	-	-
34.12	2.4	0.12	0.411		
43.90	15	0.7	2.26	19.2	1
64.29	0.037	0.005	0.005		
71.47	18.5	2.0	2.19	22	1
86.51	28.0	1.5	3.01	20	1
102.3	0.88	0.04	0.09		
120.8	50	2	4.55	20	1
124.9	17	0.5	1.52	19	2
134.4	1.2	0.04	0.10		
137.8	0.57	0.03	0.05		
164.6	2.1	0.08	0.16		
192.8	9.0	0.3	0.65		
194.3	44	1.3	3.16	20	1
212.7	85	4	5.83	22.8	1
229.6	2	0.12	0.13		
272.[illegible]	31	1.5	1.88	23.5	1
288.8	11.5	1	0.68	25	8
303.1	77	3	4.42	22	1
320.5	5.4	0.3	0.30		
334.9	6.2	0.4	0.34		
357					
371.2	13.5	1.5	0.70	24	4
379.8	81	4	4.67	22	1
415.4	15.7	0.8	0.77	22	4
430.9	60	2.5	2.89	22	1
440.6	62	2.5	2.95	24	1
465.5	13.9	0.7	0.64	18	6
478.4	37	2.0	1.69	21	1
500.3	2.4	0.4	0.11		
507.1	73	1	0.84	22	3

Table 2 . Continued

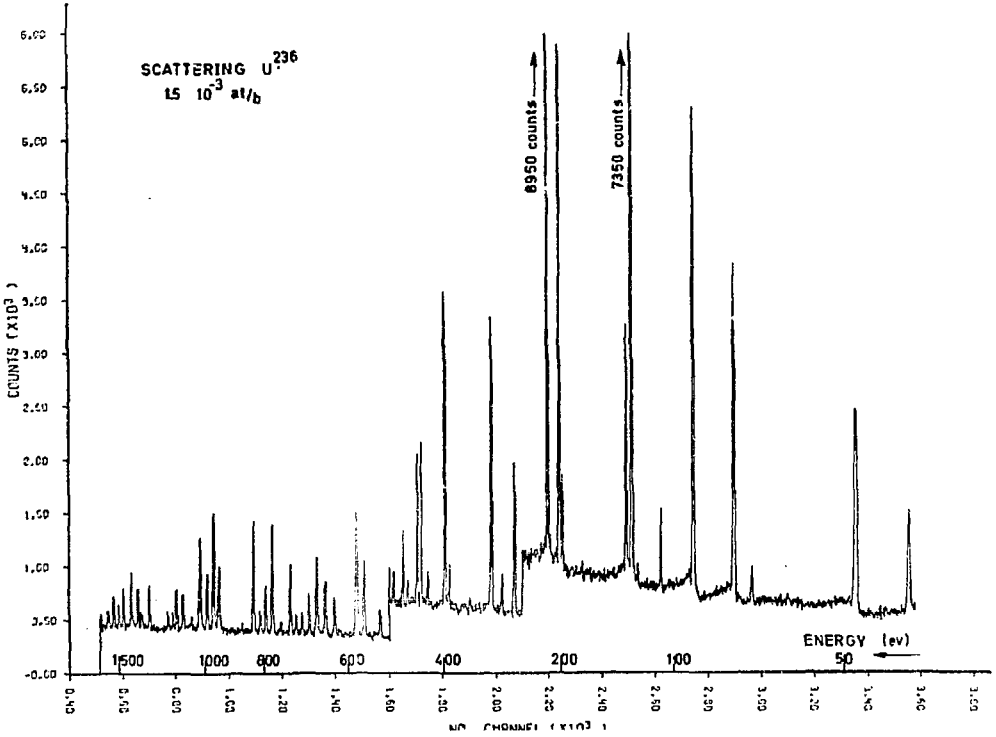
E_0 (eV)	Γ_n	$\Delta\Gamma_n$	Γ_n^0	Γ_γ	$\Delta\Gamma_\gamma$ (stat.)
536.5	30	3	1.30	22	2
542.9	10.3	0.05	0.44	30	8
563.8	80	4	3.37	22	1
576.2	142	10	5.92	26	1.3
607.0	13.3	0.7	0.54	20	8
617.8	52	5	2.09	24	1.2
637.9	78	8	3.09	24	1.2
647.1	6	1	0.24		
655.6	96	8	3.75	23	1.5
673.7	54.5	5	2.10	24	2
691.3	32	1	1.22	27	3
706.1	28.7	1	1.08	21	2
720.7	97	3	3.61	21	1
746.5	20.4	1	0.75	18	2
770.9	181	15	6.52	22	1
789.6	85	6	3.03	23	1.5
806.5	38.6	1.6	1.36	24	2
820.0	9	1	0.31		
827.4	237	20	8.24	28	1.5
848.2	2	1	0.07		
865.1	17	1	0.58	19	2
888.3	7.5	1	0.25		
900.1	4.4	1	0.15		
933.4	6	2	0.20		
948.6	162	8	5.26	24	1.5
955.2	35	5	1.13		
969.4	300	20	9.64	23	2
998					
994.7	150	15	4.76	22	1.3
1013	16	1.5	0.50		
1024	237	15	7.41	26.5	2.2
1032	29.5	6	0.92	28	8
1065	35	2	1.07	29	6

Table 2. Continued

E_0 (eV)	Γ_n	$\Delta\Gamma_n$	Γ_n^0	Γ_γ	$\Delta\Gamma\gamma$ (stat)
1075	13	3	0.40		
1084					
1098					
1104	122	15	3.67	25	2
1132	11.5	2	0.34		
1138	120	12	3.56	21.5	2
1157	63	6	1.85	26	2
1166					
1184	57	6	1.66	25	2
1219	5	1.5	0.14		
1254	7	2	0.20		
1269	5	4	0.14		
1282					
1291	162	16	4.51	30.5	4
1316					
1324	20	4	0.55		
1339	67	7	1.83	24	2.5
1349	51	5	1.39	32	5
1364	212	25	5.74	29	5
1395	12	4	0.32		
1405	35	10	0.93		
1414	300	60	7.98	21	4
1426	28	6	0.74		
1440					
1458	15	3	0.39		
1470	220	30	5.74	27	4
1477	25	5	0.68		
1506	105	15	2.71	26	4
1534	13	3	0.33		
1548	180	20	4.58	22	4
1592	91	10	2.28	26	4
1610	13	3	0.32		
1614	8	2	0.20		
1660	85	10	2.09	28	44
1690	4.	10	1.17	26	4

Table 2. Continued

E_0 (eV)	Γ_n	$\Delta\Gamma_n$	$\Gamma_n°$
1699	15	3	0.36
1723	24	5	0.58
1738	14	3	0.34
1779	45	10	1.07
1788	13	5	0.31
1794	60	15	1.42
1813	26	10	0.61


SCATTERING U236
15 10-3 at/b
8950 counts
7350 counts
COUNTS (X10³)
ENERGY (ev)
1500
1000
800
600
400
200
100
50
NO. CHANNEL (X10³)

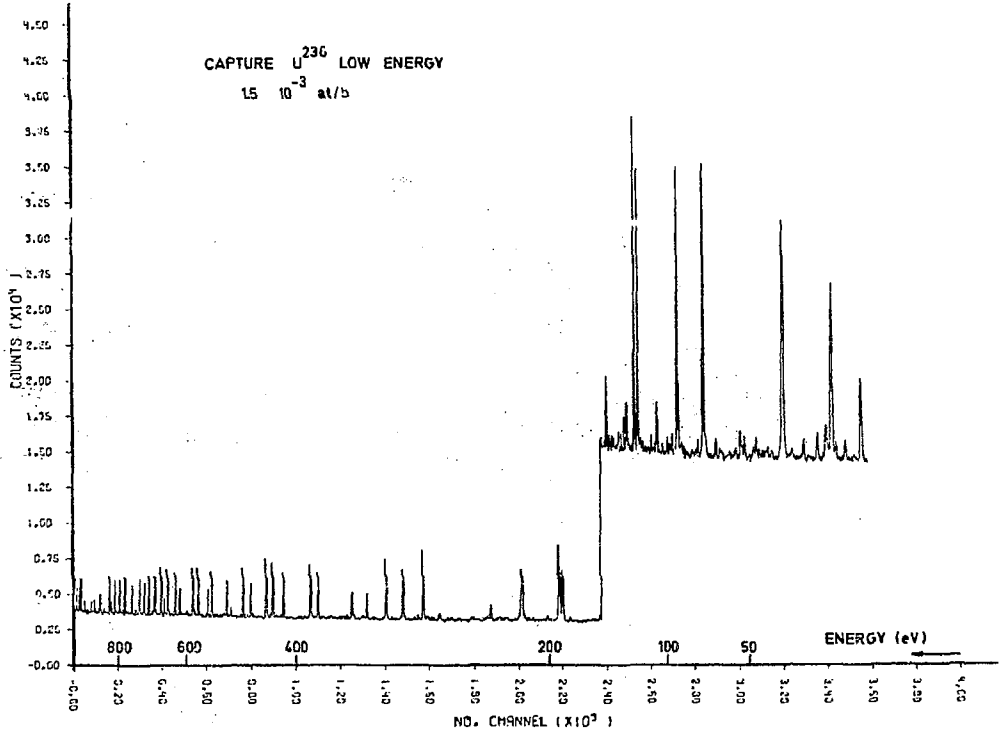
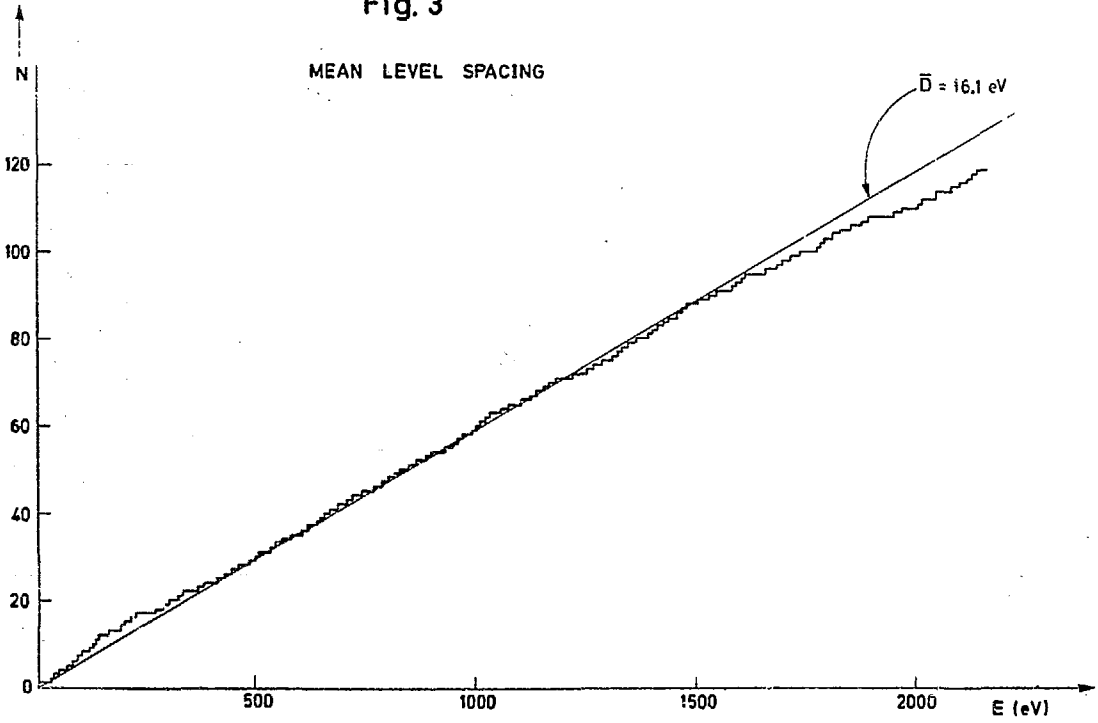

CAPTURE U236 LOW ENERGY
1.5 10-3 at/b
COUNTS (X10⁴)
ENERGY (eV)
800
600
400
200
100
50
NO. CHANNEL (X10³)

Fig. 3


MEAN LEVEL SPACING
N
$\bar{D}$ = 16.1 eV
120
100
80
60
40
20
0
500
1000
1500
2000
E (eV)

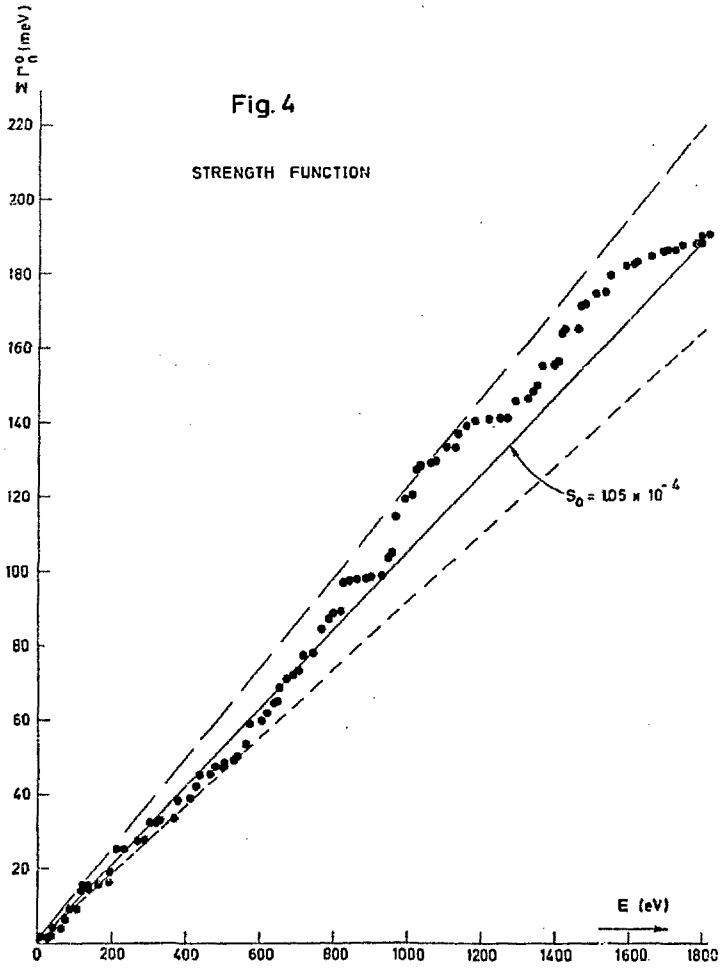


Fig. 4
STRENGTH FUNCTION
$\Sigma \Gamma_n^0$ (meV)
220
200
180
160
140
120
100
80
60
40
20
0
200
400
600
800
1000
1200
1400
1600
1800
E (eV)
$S_0 = 1.05 \times 10^{-4}$

RESONANCE SCATTERING CROSS-SECTION OF ^{238}U BELOW 220 eV*

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ABSTRACT

Results of a pilot-scale scattering experiment on ^{238}U are presented. It is shown that with thin samples reliable values for Γ_n can be obtained. In favourable cases it should be possible to combine information from scattering and transmission experiments to obtain an independant determination of Γ_γ.

INTRODUCTION

For the accurate determination of the parameters of a given neutron resonance, total cross-section measurements alone are often inadequate. An example of this is ^{238}U which has been studied repeatedly (1-5) but shows errors on the neutron and gamma widths Γ_n and Γ_γ, which are still about 15 %. To improve the situation, partial cross-section measurements are needed, preferably both capture and scattering as the sensitivity of these methods for Γ_n or Γ_γ depends very much on the ratios Γ_n/Γ_t and Γ_γ/Γ_t. The weaknesses of the capture measurements are their normalization to a suitable reference cross-section, and the variation of detector response with γ-ray energy. These difficulties do not exist with scattering experiments because Pb is available as a good standard material and detector response is uniform. Secondary interactions however can be very disturbing in both cases, and corrections for thicker samples are difficult to calculate. The purpose of this measurement is to investigate to what extent the accuracy on the partial widths of ^{238}U can be improved.

EXPERIMENTS

The experiments were performed at the electron Linac of the Central Bureau for Nuclear Measurements (CBNM), Euratom, Geel on a 30 m flight path. The samples used in these measurements consisted of metal discs of natural U alloyed to Al. The U content was about 20 % by weight, the diameter 120 mm and the thicknesses were 1.303×10^{-5} at/barn, 5.519×10^{-5} at/barn and 1.920×10^{-4} at/barn expressed in atoms of ^{236}U.

* Work performed as a joint Euratom-C.E.N./S.C.K. programma under terms of contract number 002-66-12.

The samples were prepared and assayed by the sample preparation division of CBNM. The scattering from these samples was detected by 9 ^{3}He proportional counters of 15 cm active length, 2.5 cm diameter and filled to a pressure of 10 atm. The sample was placed in an evacuated aluminium tube at right angles to the neutron beam. The detectors were mounted with their axis parallel to the incoming neutron beam and could detect neutrons scattered between 55° et 135°. The background was very low and about 10^{-3} times the counting rate obtained if all incident neutrons were scattering by the sample. A 2 mm thick pure Pb sample was used as a reference scatterer. The transmission of the samples was measured in identical resolution conditions as the scattering by observing the signal from a 14 mm thick Pb scatterer with the U-samples in transmission geometry. The data were taken with timing channel widths of 160 ns but the resolution was mainly determined by the response time and the geometry of the scattering detectors. The resolution function was assumed to be Gaussian with an experimentally determined width of $W(E) = k_1 E + k_2 E^{3/2}$ with $k_1 = 4.76 \times 10^{-3}$ and $k_2 = 6.0 \times 10^{-4}$ and E given in eV.

RESULTS

The experimental data were analysed using a shape-fitting programme. Only E_0 and Γ_n were allowed to vary however and Γ_γ was used as a parameter such that for each value of Γ_γ, the corresponding best fitting value of Γ_n was obtained. The scattering yield was calculated under the assumption that after a first scattering event in the direction of the detectors, an eventual second interaction was equal to a removal or a loss of the scattered neutron. In calculating the probability for a second interaction, the energy shift of the neutron was taken into account. The assumption of complete removal at a second interaction may seem somewhat drastic, but for samples with $n\sigma_0 \leq 0.5$ the corrections are moderate and the final influence of this assumption must be small. This can be judged from the results obtained with different sample thicknesses. Even for a predominantly scattering resonance such as the one at 190 eV, the Γ_n values obtained from the thinnest sample ($n\sigma_0 \approx 0.1$) and the thickest ($n\sigma_0 \approx 2$) are different by only 10 %. In table 1 the values of Γ_n for five resonances as obtained from the thinnest sample are given for three different assumed values of Γ_γ. In view of the difficulty to normalize the data to the Pb cross-section in an absolute way, they were normalized to $\Gamma_n = 31$ meV, $\Gamma_\gamma = 24$ meV for the 36 eV resonance.
This normalization is chosen because it is a strong low-lying resonance for which most authors agree on the parameters chosen for this normalization. Although, in principle, a combination of the results from this scattering experiment with the accurate value of Γ_n or the product $\Gamma_n\Gamma_t$ obtained from a transmission experiment would give a value for Γ_γ, we have no sufficiently accurate data to make the choice. In the most favourable cases ($\Gamma_n \approx \Gamma_\gamma$) a 10 % variation in Γ_γ introduces a shift of about 5 % in Γ_n. With careful transmission experiments, this level of accuracy could be attained.

CONCLUSIONS

The present results show that with thin samples and straightforward

correction procedures, accurate values can be obtained for Γ_n from scattering experiments. Together with capture and transmission experiments, an overdetermined set of parameters could be constructed to an accuracy of about 5 %. Thus, the distribution of the widths would become more meaningful and the existence of fluctuations more firmly established (or disproved).

ACKNOWLEDGEMENTS

The author wishes to thank Mr L. MEWISSEN for collecting the data and for valuable help during various stages of the calculations . Thanks are also due to Mr E. MIES and the electronics group for interfacing the on-line data acquisition system. The assistance in computer programming of Mrs G. DE CORTE is appreciated very much. The data gathering was greatly facilitated by the efficient help from the Linac operating group and the data handling group at CBNM.

TABLE 1

Eo (eV)	Present Results Γ_n (meV)			Ref. 1 Γ_n (meV)
	Γ_γ = 22 meV	Γ_γ = 24 meV	Γ_γ = 26 meV	
21.0	9.1 ± 0.5	9.5 ± 0.5	9.9 ± 0.5	8.7 ± 0.3
36.7	30.0	31.0*	31.9	31.15 ± 1.0
66.2	21.6 ± 1.0	22.3 ± 1.0	22.9 ± 1.0	25.2 ± 1.0
102.7	60.0 ± 3.0	61.1 ± 3.0	62.3 ± 3.0	66.0 ± 2.0
189.6	148.0 ± 7	150.2 ± 7	151.8 ± 7	150 ± 3

* taken as normalization value.

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NEUTRON SCATTERING CROSS-SECTION MEASUREMENTS ON ^{238}U IN THE RESOLVED ENERGY RANGE

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Abstract

Scattering cross-section measurements have been performed on ^{238}U below 1 keV. A part of the data has been analysed and the results are compared with previous measurements.

1. INTRODUCTION

A new series of partial and total cross-section measurements on ^{238}U are being performed or are in preparation at the linac of C.B.N.M. Geel. Scattering cross-section measurements with very thin samples have been done below 1 keV. The analysis of these data has been partly finished. Further measurements at higher energy and with thicker samples have been started. The capture cross-section measurements with the C_6F_6 detector are in preparation and transmission measurements with cooled samples will be started soon.

This report describes the scattering cross-section measurements below 1 keV and compares the resulting Γ_n values from a preliminary analysis with those from previous experiments [1-7].

The published results for the resonance parameters Γ_n and Γ_γ were in general obtained by a combination of capture, transmission and self-indication experiments. Only the Harwell results [2] were from capture and scattering experiments.

In the energy range below 1 keV, the resonances are in general well isolated, a good time-of-flight resolution is easily obtained and the flux normalization for the partial cross-section measurements is less difficult than at higher energies. In spite of these favourable experimental conditions, the discrepancies between

the existing results are still very important. This is illustrated on figs. 1-4, which show some typical results for Γn and $\Gamma\gamma$ from different groups at Harwell[2] Columbia[1,7], Los Alamos[3], Dubna[6] and Geel[4,5].

The normalization procedure of the scattering data is more easy than of the capture data. The scattering cross-section can be measured relative to Pb which is a good standard. In the case of capture measurements, the procedure is in general the following : the shape of the neutron flux is measured using for example the ^6Li (n,a) or ^{10}B (n,a) reaction and the absolute calibration of the product of detector efficiency times neutron flux is done with the "black resonance" technique. This procedure can give rise to systematic errors. For the resonances where $\Gamma n \leq \Gamma\gamma$, the parameters Γn and $\Gamma\gamma$ can also be determined by combining the results from scattering and transmission experiments. These are good examples to check eventual systematic errors on the capture experiments.

2. EXPERIMENTAL DETAILS

The experiments were performed on a 30 meter flight path. The most important factor in the time-of-flight resolution was the flight path uncertainty, due to the size of the sample so that ΔE (FWHM) / E was approximately 2×10^{-3}.

The detector system consisted of six ^3He high-pressure gaseous scintillators (LND type 800), placed at an angle of 140°.

Two very thin samples have been used (1.31 ± 0.017 10^{-5} atoms ^{238}U/b and 5.53 ± 0.01 10^{-5} atoms ^{238}U/b). It were alloys of aluminium and natural uranium. The thinnest sample contained 23 % by weight of uranium and the thickest one 17 %. The scattering yield curves are shown on figs 5 and 6.

The scattering cross-section was measured relative to Pb for which σ_n = 11.28 ± 0.06 b [8]. The Pb sample had a thickness of 6.581 ± 0.007 10^{-3} atoms/b.

3. UNCERTAINTIES IN THE MEASUREMENTS

3.1. *Systematic errors*

The major systematic error of about 2.5 % is associated with the normalization and is due to the uncertainty of the Pb cross-section (0.5 %) the error on the correction for self screening and multiple scattering in the Pb scattering experiments (< 1 %), the instability of scattering detector and monitor during the experiments (< 1.5 %) and the background subtraction in the Pb experiments (< 1 %).

The thickness of the thinnest uranium sample is known to 1.3 % and the other one to 0.2 %.

The samples were so thin that the multiple scattering corrections can be neglected. The corrections on the resonance area for self screening and for absorption of the scattered neutrons were in the worst case (36.7 eV resonance) only 7 %. For most resonances, these corrections were less than 2 %.

3.2. Statistical errors

The statistical error was less than 1 % for strong resonances and could be about 10 % for weak resonances. To obtain the area under the resonant scattering peak, we have subtracted the background and the contribution of potential scattering from uranium and aluminium. The sum of both, background and potential scattering, could be deduced from the count yield outside the resonances. The background contribution was measured separately with the black resonance technique using Mn, Co, Mo and W as black resonance filters, with Co as permanent filter.

4. RESULTS AND DISCUSSION

We have, up to now, analysed 8 resonances below 300 eV of the 1.34 10^{-5} atoms/b sample run and 5 resonances between 300 eV and 600 eV of the 5.52 10^{-5} atoms/b sample run. Figs 1-4 show the relation between Γn and $\Gamma\gamma$ obtained from an area analysis for some resonances. Also shown on these figures are the results published previously.

From this first analysis in this energy range, the following conclusions can be drawn :

The neutron widths obtained by Rahn et al[7] at Columbia University are systematically higher than our results and the Harwell results by Asgher et al[2] are systematically lower. There seems to be no systematic trend in the comparison with the other results from Columbia[1], Geel[4,5] and Dubna[6]. In table 1 are given the neutron widths Γn (for $\Gamma\gamma$ = 24 meV) for the four strongest resonances between 500 eV and 630 eV together with the previously published results. Also in this energy range, the same differences appear, but less pronounced.

The resonance parameters Γn and $\Gamma\gamma$ can be deduced by combining the results from an area analysis of partial and total cross-section measurements. So, in part, the uncertainties in $\Gamma\gamma$ are due to the uncertainties in the neutron width Γn. The mean capture width $< \Gamma\gamma >$ obtained by the Columbia group[7] is 22.9 ± 0.5 (stat) ± 3.0 (syst.) meV which is somewhat smaller than obtained at Geel[4] : $< \Gamma\gamma >$ = 24.65 ± 0.85 meV, at Dubna : $< \Gamma\gamma >$ = 24 meV and at Harwell : $< \Gamma\gamma >$ = 22.74 ± 1.09 meV. A part of the difference could eventually be explained if the Γn values obtained at Columbia should be too large.

TABLE 1

Results for Γn (meV) for the resonances at 518.5 eV, 535.5 eV, 580 eV and 595

EO	518.5 eV	535.5 eV	580 eV	595 eV
present results	42.5±3.5	41±3.5	40.5±3.5	81.5±5
Garg et al[1]	43.2±2.3	37±2.3	27 ± 0.7	82 ± 5
Asghar et al[2]	39 ± 2.2	39±2.5	37.5±2.6	71 ± 3.6
Rohr et al[4]	49 ± 1.5	43±1.4	42.5±1.6	85 ± 2.5
Carraro et al[5]	55 ± 4	45±2	44 ± 3	84 ± 5
Malétski et al[6]	42 ± 6	55±15	36 ± 6	93 ± 10
Rahn et al[7]	49 ± 5	45±5	41 ± 4	85 ± 5

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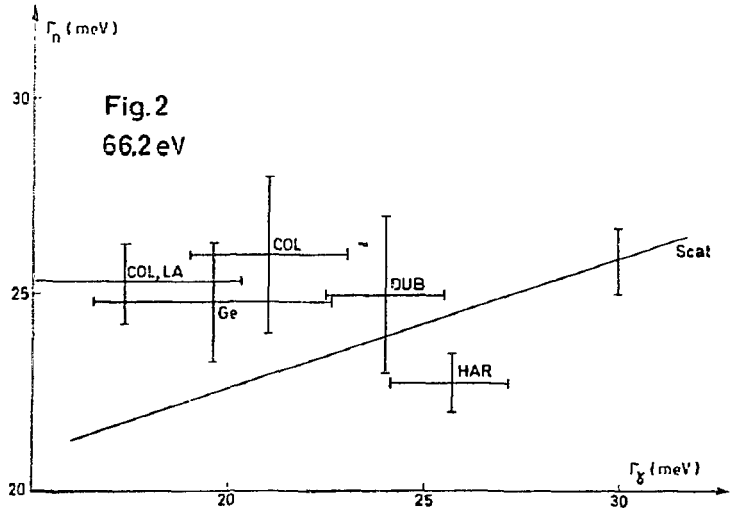
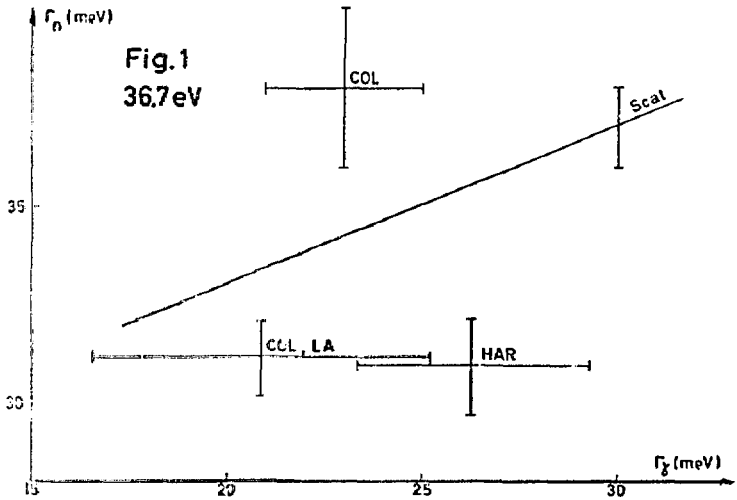
FIGURE CAPTIONS

Figs 1-4 Results from an area analysis of our scattering data (relationship between Γn and $\Gamma \gamma$). Also shown are the results obtained at Los Alamos and Columbia [1,3] (COL,LA), Harwell [2] (HAR), Geel [4] (GE), Dubna [6] (DUB) and Columbia [7] (COL).

Fig 5 Scattering yield curve with the sample of 1.31 10^{-5} atomes/b.

Fig 6 Scattering yield curve with the sample of 5.53 10^{-5} atomes/b.


Γn (meV)
Fig. 2
66.2 eV
COL
COL, LA
Ge
DUB
HAR
Scat
Γγ (meV)
30
25
20
20
25
30


Γn (meV)
Fig. 1
36.7 eV
COL
Scat
COL, LA
HAR
Γγ (meV)
35
30
20
25
30

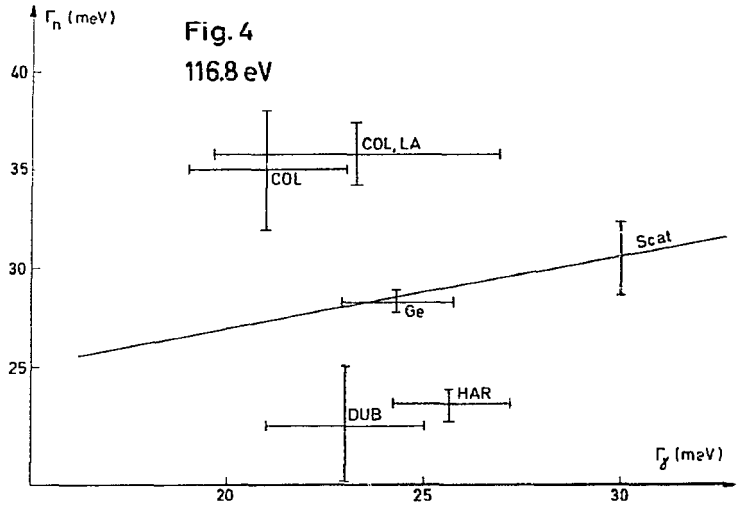


Fig. 4
116.8 eV
Γ_n (meV)
40
35
30
25
COL, LA
COL
Scat
Ge
HAR
DUB
Γ_γ (meV)
20
25
30

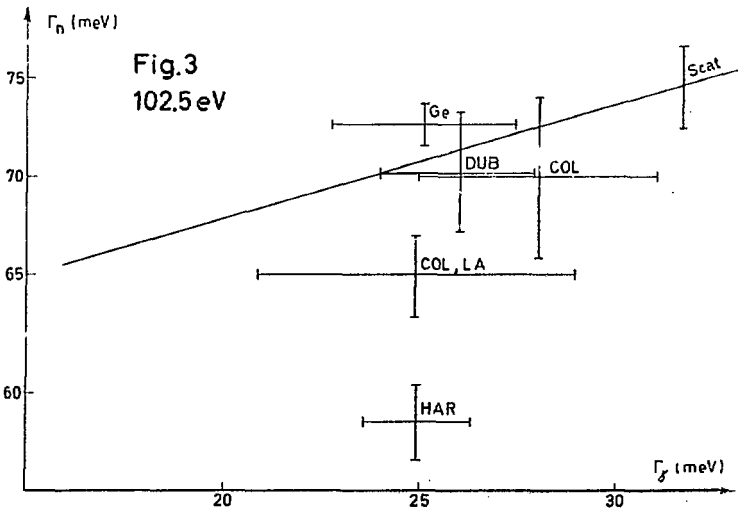


Fig.3
102.5 eV
Γ_n (meV)
75
70
65
60
Scat
Ge
DUB
COL
COL, LA
HAR
Γ_γ (meV)
20
25
30

Fig. 5

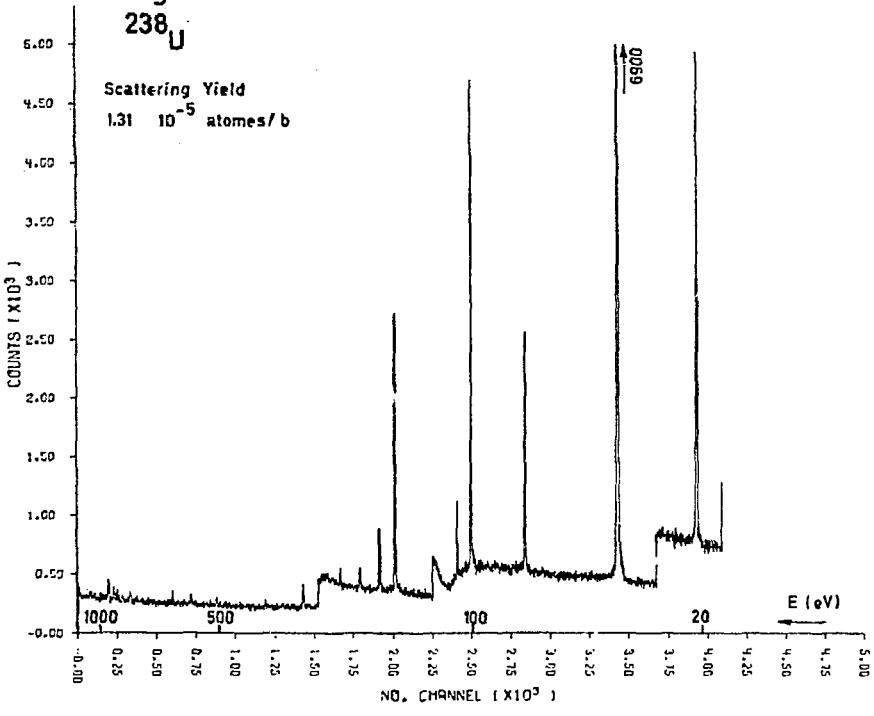
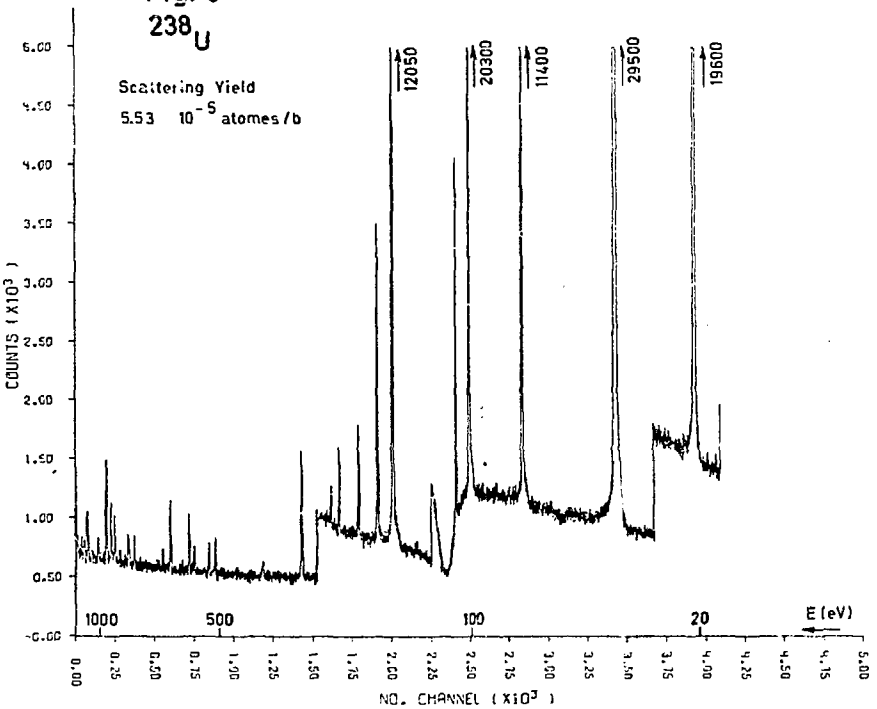

238U
Scattering Yield
1.31 10-5 atomes/b
6900
COUNTS (X10³)
NO. CHANNEL (X10³)
E (eV)
1000
500
100
20
-0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
0.25
0.75
1.25
1.75
2.25
2.75
3.25
3.75
4.25
4.75

Fig. 6


238U
Scattering Yield
5.53 10-5 atomes/b
12050
20300
11400
29500
19600
COUNTS (X10³)
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1000
500
100
20
E (eV)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
NO. CHANNEL (X10³)

Evaluation of U-238 Resonance Parameters

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The interest in this subject arises from the fact that individual resonance parameters are required in calculations of the self screening, multiple scattering and doppler effects for fast reactors. At present some evaluations of the U-238 resonance parameters are based mainly on the values given by one set of measurements, rather than any weighted mean values given by all the available data.

A list of available data is given in Table 1, together with details of the measurements and comments on the data. If no errors are quoted, then for the resonance energy it is assumed to be equivalent to three times the quoted resolution at that energy, and for the neutron and radiation width to be ±50% of the quoted value.

In this evaluation the weighted mean values for all parameters have been calculated using all the published data and are given in Table 2. Where only one measurement of the resonance parameter exists, this is quoted.

Checks were carried out to see if data from any one reference were the cause of the high values of χ^2 that were observed. Table 3 gives values of chi-squared per degree of freedom for the parameters with and without the data from the given reference. This table indicates that leaving out the data from any one reference will not significantly change the overall value of chi-squared. Thus there appears to be at present no technical reason for leaving out any of the data and the weighted mean values are probably the best ones that can be obtained at present.

(a) Resonance Energies

Weighted mean values of the resonance energies were obtained from the published data and gave the sum of χ^2 for all the resonances equal to 1369.5 for 689 degrees of freedom. Systematic differences were noticed between different measurements and as the Columbia data of Rahn et al[13] covered almost the largest energy range 6 eV to 4.6 keV it was chosen as a standard. A least squares fit was then carried out on the other sets of data to determine a flight path length and zero time correction. The values obtained are given in Table 4 and are mostly within the calculated errors. A value of 408.5 for χ^2 was then obtained from the recalculated energies. The low values of χ^2 and large errors on some of the adjusted flight path lengths and zero times are probably due to an overestimate of the errors where none have been quoted. This reduction in χ^2 suggests that the systematic differences between the sets of data have been removed and the weighted mean values given by these sets of data are taken to be the recommended values.

(b) Neutron Widths

The high value of χ^2 of 2422.1 for 679 degrees of freedom, obtained from a comparison of the neutron widths, indicates that either there are some systematic differences in the sets of data or that some of the uncertainties have been underestimated.

A dependence of χ^2 on the neutron width (which does not appear to be energy dependent) is shown in Figure 1. A possible explanation of the low values of χ^2 for small resonances could be that errors tend to be rounded up, e.g. Γ_n = 0.30±0.16 meV would be reported as Γ_n = 0.3±0.2, a reduction in the weighting of almost a factor of two. It is also possible that the statistical errors being fractionally larger for the smaller resonances tends to hide any systematic errors that may be present.

A search for systematic differences was carried out in the energy range up to

1 keV, as in this region there may be as many as nine reported values for the neutron width of a resonance. This was carried out using the fractional difference FN in Γ_n, between the data from a given reference and the weighted mean value calculated from all the other available data. Column 1 of Table 5 gives a weighted mean value of this fraction and columns 2 and 3 give a least square fit of the fraction to the form $FN = a + b \times E_r$, where a and b are determined from the data and E_r is the resonance energy. Column 4 is the correlation coefficient for this fit to the data.

Some of the sets of data, e.g. Asghar et al[3], show only a constant difference from the average values, whereas the data of Garg et al[1] give a negative correlation with neutron energy and that of Carraro et al[14] a positive one with neutron energy. Explanation of these differences could lie in the following:-

(i) the type or types of measurement
(ii) the method of analysis
(iii) doppler and resolution effects

Most of the values of Γ_n are obtained from transmission measurements or transmission combined with other types of measurements, in which the transmission data make the largest contribution in determining the value of Γ_n. There is very little that can explain these discrepancies in transmission experiments. Poor monitoring in transmission experiments will only affect the value of the potential scattering and not the resonance area as this method of analysis is insensitive to the absolute values of the transmission. The determination of the background could be a source of error but there is very little documentation on this subject and the errors associated with it.

In references 3 and 11 no transmission data are used to obtain the resonance parameters [ref. 3 is some 10% lower and 11 some 8% higher than the average values]. Asghar et al[3] use scattering and capture data to obtain the resonance parameters. In this case Γ_n is determined mainly by the capture data when $\Gamma_n \ll \Gamma_\gamma$ and by the scattering data when $\Gamma_n \gg \Gamma_\gamma$. An examination of their results would indicate that there is better agreement with the average values of Γ_n when it is smaller than Γ_γ and this would possibly indicate an error in the normalisation of the scattering data. Rosen et al[11] use self indication techniques to obtain their results. The analysis of this type of data is difficult and several problems are present that are not in the transmission measurements using a flat detector. The two most important are the effect of multiple scattering in the detector foil and the sensitivity of the γ-ray detector to scattered neutrons; neither of these are discussed in any detail in the paper.

All but one measurement (ref. 8) use some form of area analysis to obtain the resonance parameters. Problems arising from the analysis or uncertainties in the analysis are not discussed in any of the papers. Such problems can arise from correction from finite cut off to the resonance areas, long tails on the resolution function, self screening corrections, and interference effects. In self indication measurements additional problems as given above add to the difficulty of analysis of the data.

Only two papers[8,11] mention the effective temperature of the sample used in the analysis of the data. This could affect the analysis and should be given in the paper.

Possibly one or all these effects contribute to the discrepancies in the observed values of the neutron width. As transmission measurements are the simplest to perform and interpret, it should be possible to compare the measured

transmissions with a curve calculated from the final parameters, but none of the experiments using area analysis techniques even hint that such a process has been carried out.

As at present there appears to be no real explanation for these systematic differences and to take this into account, it is suggested that the quoted errors in Table 2 on the neutron widths should be at least doubled.

(c) Radiation Width

In the case of the radiation width, only 5 references (3, 11, 12, 13, 16) give values of Γ_γ for a large number of resonances. The overall value of χ^2 of 158.1 for 138 degrees of freedom indicates that the allocated errors are reasonable and that there appears to be no significant systematic differences between the reported values.

The high values of χ^2 in Table 6 for the weighted average values of Γ_γ for each reference suggest that there is a natural spread of ~2 meV but to be sure much more accurate values of Γ_γ are required. Table 6 also gives the results of a least squares fit of the values of Γ_γ to functions of Γ_n for all sets of published data. The data from Columbia[13] and Geel[16], i.e. two of the sets of data covering a large energy range, show a positive correlation for all three functions that were tried. The correlation between Γ_n and Γ_γ has no physical significance, but will be observed if there is a correlation between either Γ_γ and Γ_n^o, or Γ_γ and the scattering area. If this correlation between the radiation width and the reduced neutron width is genuine, it could have significant effects on reactor calculations, especially in the keV region when self screening corrections are large. Two sets of correlation tests were carried out on the weighted mean values of Γ_γ. The first used only the quoted mean errors and did not show any correlation between the functions of Γ_n and Γ_γ. Due to the finite number of transitions in neutron capture, fluctuations in the values of Γ_γ are to be expected; this is confirmed by the high value of χ^2 of 197 for 76 degrees of freedom, obtained for the weighted mean value of Γ_γ. To take this into account, a second correlation test was carried out using as weights for Γ_γ the inverse quadratic sum of the quoted errors + 10% of the value of Γ_γ, this gave a positive correlation between the functions of Γ_n and Γ_γ (see Figure 3). Measurements of the γ-ray spectra emitted on neutron capture in U-238 reported by John et al[17] and Thomas[18] show a variation in shape from resonance to resonance. John et al[17] conclude that there is a shift downward in the centre of gravity of the gamma ray spectra as the neutron energy increases. This effect may be enhanced by the detection of γ-rays from resonance scattered neutrons captured in the detector and surrounding equipment, as they only correct for background using the between resonance γ-ray spectra. Therefore changes in the observed radiation width could be associated with this change in the γ-ray spectra or could be due to changes in the efficiency of detecting neutron capture events as the γ-ray spectra change.

Therefore at present there appears to be very little evidence in theory or experiment to expect a physically real correlation between the radiation width and the reduced neutron width. The above statistical tests imply that the capture equipment could be more sensitive to the scattered neutrons than expected, or corrections for multiple scattering had been underestimated. In either case the measured radiation widths for resonances with large neutron widths would be increased.

(d) Recommendation

Weighted mean values of all available data given in Table 2 would appear to be the best data that can be obtained at present. As indicated in Table 3, leaving out data from any one reference will not significantly change the overall values of the parameters. These values give an infinite dilution resonance integral of 274.96±2.08 b using a radiation width of 24.14 meV when no radiation

width is given. The quoted errors on the resonance energies would appear to be realistic but the errors quoted in Table 2 on the neutron width should be increased by a factor of two to take into account the systematic discrepancies between different sets of data. The use of the weighted average radiation width for resonances in which no measured value is given, should be carried out with caution and checks carried out to see the effect of a natural spread of ~ ±2 meV in the radiation widths.

If a large fraction of the radiation width is correlated with the reduced neutron width then assumption about the energy, spin and orbital angular momentum independence of Γ_γ must be viewed with some suspicion and attempts should be made to measure some of the radiation widths of resonances with small values of Γ_n^o to either prove or disprove the presence of a correlation.

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10th May, 1974.

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Table 1 Available data on resonance parameters of U-238.

2 Recommended resonance parameters for U-238.

3 The change in χ^2 per degree of freedom with and without the data from a given reference.

4 Correction to the flight path length and zero time using reference 13 as a standard.

5 Fraction variation of Γ_n for a given reference relative to the weighted mean of all other available data in the neutron energy range up to 1 keV.

6 Weighted mean radiation width and results of least squares fits of Γ_γ to functions of Γ_n.

Figure 1 Chi-squared per degree of freedom versus the neutron width.

2 Γ_γ versus Γ_n^o from the Columbia data of Rahn et al[13].

3 Average values of Γ_γ versus Γ_n^o.

TABLE 1

Ref. No.	Authors, Year and Laboratory	Energy Range	Type of Measurement	Detector	Samples	Type of Analysis	Comments
1	J. B. Garg et al, Columbia (1964)	0.1 - 4.0 keV	TRANSMISSION using the cyclotron in conjunction with a fast chopper to reduce the background	NaI-B-10	5 samples n from 11.8 - 590 b/a	Area analysis taking into account the interference effect.	
2	F. W. K. Firk et al, Harwell (1963)	6 eV - 2 keV	TRANSMISSION using the 15 MeV electron linac	NaI-B-10	5 samples n from 5.6 x 10^{-3} - 0.13 a/b	Area analysis using interference effects developed by J. E. Lynn.	
3	M. Asghar et al, Harwell (1966)	6 eV - 830 eV	CAPTURE	Moxon-Rae capture detector	2 samples	Area analysis neglecting interference effects. Multiple scattering correction carried out in both cases using Monte Carlo techniques.	
			SCATTERING	Li-6 glass + Li-7 glass to compensate for gamma-ray detection	3 samples 1.21 x 10^{-4} - 1.59 x 10^{-3}		
4	J. S. Levin and D. J. Hughes, Brookhaven (1955)	6 eV - 40 eV	TRANSMISSION using a fast chopper	BF_3 counters	4 samples	Area analysis using single level Breit-Wigner formula.	
5	J. A. Harvey et al, Brookhaven (1955)	0 - 700 eV	TRANSMISSION using a fast chopper	BF_3 counters	4 samples	Hughes area analysis techniques.	(assumes interference effects are small)
6	R. G. Fluharty et al, Idaho (1956)	10 - 300 eV	TRANSMISSION using a fast chopper		2 samples	Shape + area analysis techniques.	
7	L. M. Bollinger et al, Argonne (1956)	4 - 350 eV	TRANSMISSION using a fast chopper	Boron loaded liquid scintillator	8 samples 0.001" to 0.7"	Mainly area analysis but some shape to help confirm Γ_n values.	

TABLE 1 (cont'd)

Ref. No.	Authors, Year and Laboratory	Energy Range	Type of Measurement	Detector	Samples	Type of Analysis	Comments
8	H. E. Jackson and J. E. Lynn, Argonne (1962)	6.5 - 6.8 eV	TRANSMISSION using a fast chopper		2 metal foils and 2 oxide samples were studied	Shape. Measurements were performed to look at solid state effects on the uranium 6.7eV resonances and were carried out at temperatures 4°K, 77°K, 239°K.	
9	L. M. Bollinger and G. E. Thomas, Argonne (1968)	0 - 200 eV	TRANSMISSION	Boron-loaded liquid scintillator	Several thick samples of pure U-238 cooled to liquid nitrogen temperature	Shape used to identify p-wave then area analysis to give $g\Gamma_n$.	
10	Yu. V. Ryabov et al, Dubna (1970)	6 - 7 eV	TRANSMISSION using the pulsed reactor	Boron loaded liquid scintillator	U-238 impurities in samples of U-235	Area analysis. (interference effects are small)	
11	J. L. Rosen et al, Columbia (1959)	90 eV - 1.3 keV	Self indication		Several foils for the detector and transmission samples	Area analysis. Assumed interference effects negligible on thin samples.	
12	H. Malecki et al, Dubna (1971)	66 eV - 600 eV	TRANSMISSION, CAPTURE using the pulsed reactor		Several samples	Area analysis.	
13	F. Rahn et al, Columbia (1972)	6 eV - 4.6 keV	TRANSMISSION CAPTURE Self indication	NaI-B-10 Moxon-Rae Plastic scintillator	Several samples used on each measurement	Mainly area analysis and some shape analysis on the thick sample transmission data.	Used as standard for resonance energy
14	G. Carraro and W. Kolar, Geel (1970)	60 eV - 5.7 keV	TRANSMISSION using Geel electron linac	NaI-B-10	1 sample	ATTA-Harvey area analysis. (includes resonance-potential interference)	

Table 1 (cont'd)

Ref. No.	Authors, Year and Laboratory	Energy range	Type of Measurement	Detector	Samples	Type of Analysis	Comments
15	J. E. Lynn and N. J. Patterson, Harwell (1969)	6 - 1.0 eV	TRANSMISSION, CAPTURE, SCATTERING using the 15 MeV electron linac		Up to 5 samples were used	Area analysis, neglecting interference effects.	
16	G. Hehr et al, Geel (1973)	50 - 1000 eV	CAPTURE	Moxon-Rae	2 samples	Area analysis.	Used in conjunction with values of Γ_n from reference 14.

TABLE 3

1	2	3	4	5		6		7		8	
	No. of values measured			reported resonance energy		recalculated energy		neutron width		radiation width	
Ref. No.	E_r	Γ_n	Γ_γ	i	ii	i	ii	i	ii	i	ii
1	221	221	0	2.665	2.155	0.454	0.538	3.041	3.939		
2	73	73	6	1.324	1.442	0.366	0.464	3.196	3.806	0.663	1.425
3	46	46	27	1.222	1.065	0.487	0.425	2.967	3.506	0.659	1.182
4	3	3	3	0.800	0.820	0.695	0.619	1.735	1.562	1.095	1.276
5	18	13	0	1.011	1.035	0.564	0.561	3.972	3.866		
6	8	8	4	0.763	0.751	0.422	0.378	5.403	5.056	1.275	1.411
7	13	15	4	0.932	0.948	0.472	0.432	4.032	3.672	1.163	1.376
8	1	1	1	0.146	0.140	0.155	0.153	0.765	1.127	0.128	0.702
9	16	16	0	2.977	2.595	2.435	1.959	0.283	0.243		
10	1	1	1	0.155	0.140	0.134	0.153	1.208	1.127	0.579	0.702
11	55	55	32	0.773	1.211	0.426	0.436	3.564	3.332	0.738	1.119
12	46	39	23	1.126	1.124	0.310	0.321	4.299	3.892	0.691	1.193
13	283	283	71	1.223	2.022	0.436	0.529	4.586	3.718	0.528	1.165
14	184	184	0	1.215	2.039	0.487	0.524	3.387	3.860		
15	7	7	6	0.558	0.586	0.397	0.345	5.322	4.998	0.900	1.404
16	28	28	28	1.243	1.084	0.266	0.240	3.539	4.185	0.556	1.170
Total χ^2 and degree of freedom				1369.5/689		403.5/689		2422.1/679		158.1/138	

Section i and ii of columns 5, 6, 7 and 8 refer to χ^2 per degree of freedom without and with the data from the given reference respectively.

TABLE 4

Ref. No.	Flight path length (m)	Corrected flight path length (m)	Corrected zero time (μsec)
1	200.0	199.9±0.27	-0.120±0.467
2	55.0	55.03±0.53	0.383±1.433
3	32.54	32.59±0.09	0.253±0.380
4	20.0	19.92±0.31	0.026±4.534
5	20.0	20.06±0.96	0.995±6.759
6	30.0	29.39±1.99	-6.148±18.00
7	58.70	58.71±5.81	-0.276±68.31
8	58.90	-	0.000±7.190
9	60.00	59.87±0.38	-0.412±3.724
10	30.00	-	-1.891±4.932
11	35.00	34.99±0.05	0.195±0.163
12	30.00	30.01±0.016	0.103±0.048
13	200.0	STANDARD	
14	100.0	100.00±0.018	0.087±0.029
15	20.00	19.98±0.75	0.150±9.695
16	60.00	60.01±0.073	0.069±0.236

TABLE 5

Ref. No.	$\bar{FN}$	Least squares fit to $FN = a + b \times E_T$		
		a	b	Correlation coefficient
1	-0.0462±0.0101	0.0267±0.0371	-0.000167±0.000071	-0.311
2	0.0244±0.0136	-0.0098±0.0429	0.000186±0.000163	0.178
3	-0.1070±0.0111	-0.1030±0.0345	-0.000017±0.000109	0.024
4	-0.0216±0.0490	0.0313±0.0508	-0.003603±0.002820	-0.788
5	0.0053±0.0260	-0.0620±0.0555	0.001383±0.000652	0.452
6	0.1598±0.0872	-0.0684±0.2255	0.002135±0.001726	0.451
7	0.0515±0.0262	0.0934±0.0268	-0.000751±0.000338	-0.546
8	0.0283±0.014[illegible]	-	-	-
9	0.0294±0.0610	-0.0276±0.1055	0.000768±0.001249	0.212
10	-0.0158±0.0212	-	-	-
11	0.0814±0.0162	-0.0243±0.0286	0.000453±0.000076	0.632
12	0.0184±0.0161	-0.0110±0.0344	0.000108±0.000100	0.181
13	0.0476±0.0129	0.0293±0.0237	0.000043±0.000044	0.117
14	0.1182±0.0106	0.0348±0.0219	0.000173±0.000040	0.511
15	-0.0746±0.0225	-0.0563±0.0318	-0.000326±0.000462	-0.301
16	0.0833±0.0072	0.1063±0.0234	-0.000068±0.000055	-0.241

TABLE 6

Ref. No.	No. of values	Weighted Mean Γ_γ	χ^2	$\Gamma_\gamma = a + b\,\Gamma_n$ a	b	χ^2	c	$\Gamma_\gamma = a + b\,\Gamma_n^0$ a	b	χ^2	c	$\Gamma_\gamma = a + b\,\Gamma_n^2/(ER \times (\Gamma_n + \Gamma_\gamma))$ a	b	χ^2	c
2	6	26.31 ± 1.23	22.01	23.65 ± 6.65	0.089 ±0.200	20.9	0.216	13.15 ± 7.16	3.40 ±1.76	11.1	0.694	16.64 ± 5.76	35.56 ±19.81	11.54	0.668
3	27	23.61 ± 0.47	38.56	24.16 ± 1.00	-0.0122 ±0.0180	37.9	-0.134	23.20 ± 1.00	0.121 ±0.241	38.2	0.100	23.05 ± 0.84	3.03 ± 3.30	37.30	0.181
4	3	24.74 ± 1.89	1.49	23.06 ± 0.66	0.60 ±0.16	0.08	0.973	21.53 ± 0.59	4.23 ±0.64	0.03	0.989	23.30 ± 0.75	59.58 ±17.34	0.11	0.960
6	4	27.60 ± 9.27	0.23	27.88 ± 4.91	-0.012 ±0.163	0.23	-0.05	28.54 ± 7.12	-0.27 ±1.87	0.23	-0.103	29.04 ± 5.70	- 6.01 ±20.10	0.22	-0.207
7	4	23.67 ± 1.76	1.53	23.99 ± 2.39	-0.038 ±0.223	1.50	-0.12	24.73 ± 2.86	-0.61 ±1.40	1.39	-0.293	24.30 ± 2.31	- 5.51 ±15.69	1.44	-0.241
11	32	24.09 ± 0.67	17.81	23.96 ± 0.67	0.009 ±0.008	16.96	0.215	23.58 ± 0.84	0.18 ±0.23	17.45	0.139	24.07 ± 0.72	0.16 ± 4.34	17.81	0.01
12	23	23.64 ± 0.49	7.47	24.58 ± 0.44	-0.015 ±0.006	5.65	-0.491	24.06 ± 0.45	-0.12 ±0.10	7.00	-0.251	23.74 ± 0.37	- 0.66 ± 1.53	7.41	-0.093
13	71	22.31 ± 0.31	84.16	21.26 ± 0.46	0.014 ±0.004	72.72	0.365	20.93 ± 0.48	0.502 ±0.131	69.12	0.419	21.71 ± 0.41	6.12 ± 2.38	76.65	0.296
15	6	24.45 ± 1.05	17.35	26.86 ± 1.96	-0.211 ±0.106	8.68	-0.704	27.07 ± 2.31	-1.503 ±1.213	12.47	-0.527	26.21 ± 2.38	-16.57 ±13.88	12.66	-0.513
16	28	24.21 ± 0.26	62.58	23.32 ± 0.56	0.013 ±0.006	53.42	0.380	23.58 ± 0.68	0.198 ±0.179	59.72	0.212	24.13 ± 0.57	0.67 ± 3.42	62.49	0.0[illegible]
Weighted values															
	76	24.14 ± 0.15	196.8	24.11 ± 0.33	0.0004 ±0.0040	196.8	0.013	24.07 ± 0.37	0.025 ±0.104	196.7	0.028	24.07 ± 0.31	0.57 ±1.74	196.5	0.038
		errors on Γ_γ increased by 10% of the value of Γ_γ													
				22.63 ± 0.41	0.0091 ±0.0040	45.4	0.258	22.28 ± 0.43	0.363 ±0.117	43.5	0.339	22.73 ± 0.36	5.554 ±2.187	45.3	0.283

c is the correlation coefficient for the fit

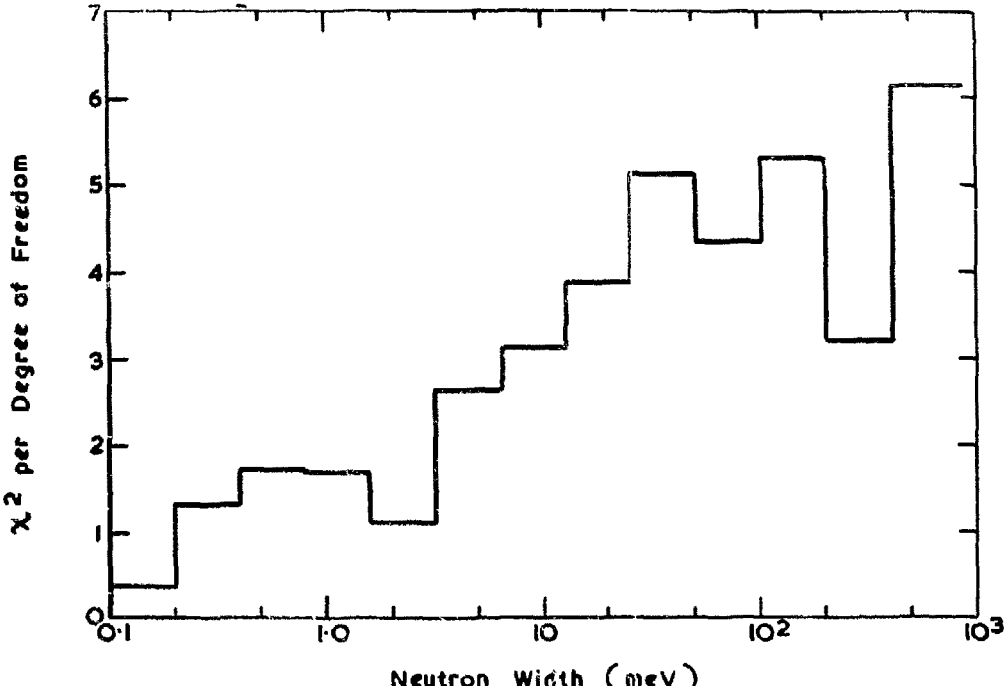
7
6
5
4
3
2
1
0
χ^2 per Degree of Freedom
0·1
1·0
10
10^2
10^3
Neutron Width (meV)

FIG.1.

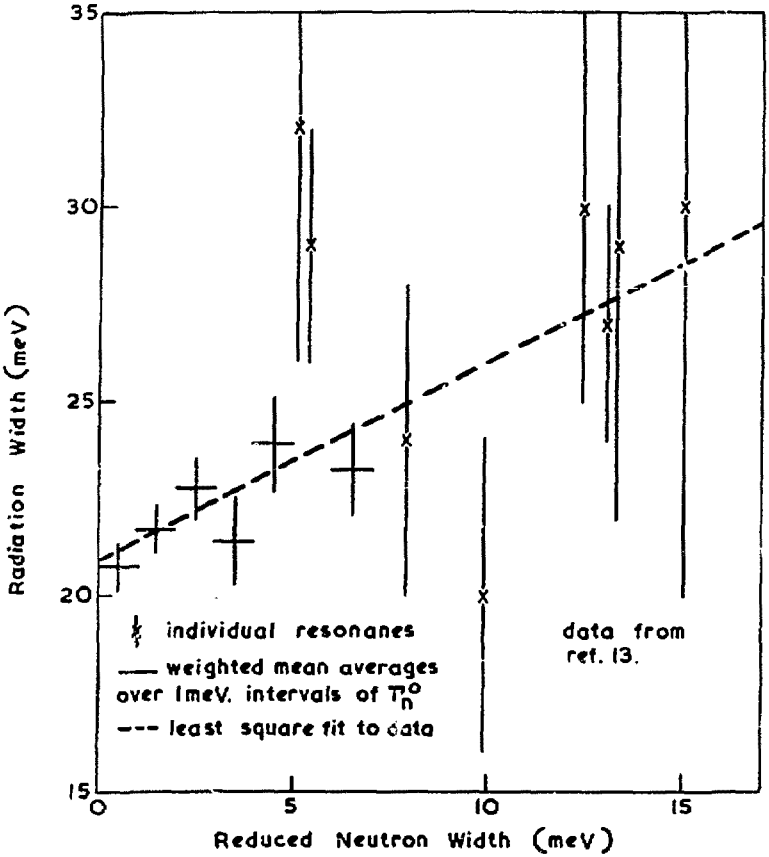
35
30
25
20
15
0
5
10
15
Radiation Width (meV)
Reduced Neutron Width (meV)
individual resonanes
weighted mean averages over 1meV. intervals of Γ_n^o
least square fit to data
data from ref. 13.

FIG. 2.

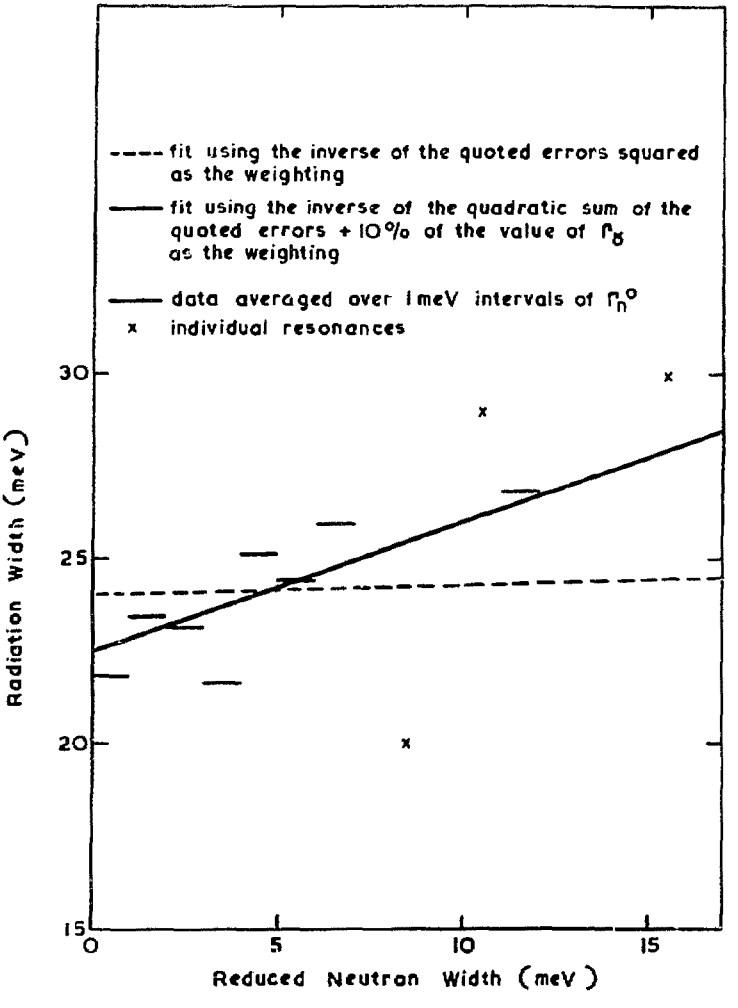
fit using the inverse of the quoted errors squared as the weighting
fit using the inverse of the quadratic sum of the quoted errors + 10% of the value of Γ_γ as the weighting
data averaged over 1 meV intervals of Γ_n^o
x individual resonances
30
25
20
15
0
5
10
15
Radiation Width (meV)
Reduced Neutron Width (meV)

FIG.3.

COLUMN NUMBER

1	+OR-	2	+OR-	3	+OR-	4	5	6	7	8	9
3.6322E+03	1.27E+00	2.9681E-01	3.35E-02			0.09	2	1.12	2		
3.7159E+03	1.28E+00	6.4769E-02	1.30E-02			0.42	2	0.23	2		
3.7331E+03	1.28E+00	1.8238E-01	3.33E-02			0.01	2	0.33	2		
3.7638E+03	1.35E+00	4.1045E-02	5.49E-03			0.11	2	7.44	2		
3.7813E+03	1.36E+00	3.1660E-01	4.30E-02			0.69	2	0.82	2		
* 3.7998E+03	3.20E+00	3.0821E-03	3.08E-03								
3.8306E+03	1.36E+00	6.4435E-03	2.38E-03			0.25	2	0.02	2		
3.8567E+03	1.37E+00	4.3421E-01	3.91E-02			0.24	2	3.68	2		
3.8720E+03	1.37E+00	1.8738E-01	4.39E-02			0.04	2	0.56	2		
* 3.8951E+03	3.30E+00	4.9928E-03	3.12E-03								
3.9018E+03	1.37E+00	2.5796E-01	5.14E-02			0.76	2	0.15	2		
* 3.9134E+03	1.50E+00	9.0082E-02	1.50E-02								
* 3.9390E+03	1.50E+00	1.2992E-01	2.01E-02								
* 3.9539E+03	1.50E+00	1.0815E-01	1.51E-02								
* 4.0404E+03	1.50E+00	6.4835E-02	1.02E-02								
* 4.0630E+03	1.50E+00	2.9959E-02	8.29E-03								
* 4.0894E+03	1.60E+00	7.2262E-02	1.47E-02								
* 4.1240E+03	1.60E+00	3.2109E-02	7.71E-03								
* 4.1678E+03	1.60E+00	1.6010E-01	3.49E-02								
* 4.1782E+03	1.70E+00	3.8137E-02	9.05E-03								
* 4.2094E+03	1.70E+00	4.0226E-02	9.08E-03								
* 4.2577E+03	1.70E+00	1.6965E-02	7.18E-03								
* 4.2990E+03	1.70E+00	1.3179E-01	1.77E-02								
* 4.3060E+03	1.70E+00	1.1485E-01	1.71E-02								
* 4.3239E+03	1.70E+00	6.1811E-02	9.86E-03								
* 4.3332E+03	1.80E+00	3.2914E-03	1.97E-03								
* 4.4350E+03	1.80E+00	1.0522E-01	2.53E-02								
* 4.4872E+03	1.80E+00	2.6795E-03	2.01E-03								
* 4.5103E+03	1.80E+00	5.0503E-01	7.99E-02								
* 4.5420E+03	1.80E+00	7.4808E-02	1.21E-02								
* 4.5672E+03	1.80E+00	3.3791E-02	8.11E-03								
* 4.5927E+03	1.90E+00	1.8298E-02	6.10E-03								

COLUMN NUMBER

1		2		3	4	5	6	7	8	9
	*OR-		*OR-	*OR-						
3.0277E+03	6.42E-01	1.4578E-01	9.62E-03		0.29	3	1.79	3		
3.0422E+03	9.17E-01	2.4819E-03	7.80E-04		0.50	2	0.12	2		
3.0586E+03	4.39E-01	2.7167E-02	2.99E-03		0.42	3	0.56	3		
* 3.0000E+03	2.35E+00	4.4406E-03	1.67E-03							
3.1090E+03	6.76E-01	1.9948E-01	1.21E-02		0.08	3	16.25	3		
3.1328E+03	6.44E-01	7.8868E-03	8.93E-04		0.07	3	1.31	3		
3.1470E+03	7.07E-01	9.4319E-02	5.91E-03		0.39	3	14.95	3		
3.1687E+03	7.00E-01	9.9092E-03	1.02E-03		0.04	3	0.72	3		
3.1778E+03	7.03E-01	8.5386E-02	5.94E-03		0.38	3	2.51	3		
3.1878E+03	7.03E-01	9.1601E-02	6.44E-03		0.45	3	11.96	3		
3.2046E+03	7.10E-01	9.0978E-02	5.80E-03		0.55	3	8.47	3		
* 3.2170E+03	1.10E+00	7.9406E-03	3.97E-03							
3.2291E+03	7.10E-01	2.5378E-02	4.00E-03		0.11	3	1.21	3		
3.2482E+03	7.11E-01	1.7124E-02	2.18E-03		0.11	3	9.96	3		
* 3.2720E+03	1.10E+00	4.0041E-03	1.72E-03							
3.2781E+03	7.11E-01	1.3856E-01	1.48E-02		0.65	3	43.09	3		
3.2954E+03	9.04E-01	5.6132E-03	1.39E-03		0.25	3	1.45	3		
3.3106E+03	7.12E-01	1.1901E-01	7.92E-03		0.11	3	9.39	3		
3.3203E+03	7.37E-01	1.0367E-01	8.14E-03		0.12	3	8.92	3		
3.3327E+03	7.79E-01	7.4922E-02	5.59E-03		0.38	3	13.80	3		
3.3545E+03	7.75E-01	1.0570E-01	7.29E-03		0.81	3	13.70	3		
* 3.3709E+03	2.65E+00	2.9030E-03	1.16E-03							
3.3887E+03	7.77E-01	1.2320E-02	1.87E-03		0.41	3	13.60	3		
3.4078E+03	8.09E-01	2.0352E-01	1.22E-02		0.23	3	15.44	3		
3.4179E+03	1.10E+00	3.5081E-03	2.07E-03		0.15	2	0.08	2		
3.4352E+03	8.11E-01	3.1166E-01	1.91E-02		0.43	3	25.87	3		
3.4566E+03	8.41E-01	5.6434E-01	3.03E-02		0.79	3	16.95	3		
* 3.4699E+03	2.80E+00	1.1781E-03	1.18E-03							
3.4841E+03	8.41E-01	1.0255E-01	7.55E-03		0.04	3	0.08	3		
3.4931E+03	8.41E-01	9.8618E-03	1.72E-03		0.21	3	0.06	3		
* 3.5119E+03	2.85E+00	2.9631E-03	1.19E-03							
3.5263E+03	1.18E+00	5.4633E-03	2.66E-03		0.02	2	0.97	2		
3.5602E+03	8.44E-01	1.9846E-01	2.53E-02		0.42	3	1.90	3		
3.5724E+03	8.44E-01	3.5968E-01	2.00E-02		0.54	3	9.10	3		
3.5931E+03	8.45E-01	2.5626E-02	3.41E-03		0.03	3	37.19	3		
* 3.6000E+03	2.95E+00	3.0000E-03	3.00E-03							
* 3.6110E+03	2.95E+00	3.0046E-03	1.20E-03							
3.6223E+03	1.19E+00	5.0443E-03	2.45E-03		0.94	2	1.35	2		
3.6286E+03	1.27E+00	2.9092E-01	3.09E-02		0.25	2	16.55	2		
* 3.6470E+03	3.00E+00	3.0195E-03	3.02E-03							
3.6722E+03	1.27E+00	4.3927E-03	2.57E-03		0.43	2	0.72	2		

COLUMN NUMBER

1		2		3	4	5	6	7	8	9
	*OR-		*OR-	*OR-						
* 2.3676E+03	6.00E-01	5.8000E-03	4.00E-03							
* 2.3841E+03	6.00E-01	2.0000E-03	7.00E-04							
2.3913E+03	4.38E-01	2.7759E-02	1.67E-03		0.37	3	14.24	3		
* 2.3989E+03	1.20E+00	3.7000E-03	5.00E-04							
* 2.4014E+03	1.20E+00	4.0000E-03	2.00E-03							
2.4105E+03	4.73E-01	4.6057E-03	5.35E-04		0.40	3	0.16	3		
2.4359E+03	4.74E-01	1.2243E-01	9.12E-03		0.12	3	12.82	3		
2.4456E+03	4.39E-01	1.5810E-01	1.10E-02		0.05	3	30.35	3		
2.4548E+03	4.74E-01	8.6734E-03	1.57E-03		0.62	3	40.03	3		
2.4885E+03	4.40E-01	7.0761E-02	4.46E-03		0.28	3	27.17	3		
2.5207E+03	5.04E-01	1.3526E-02	1.58E-03		0.07	3	6.02	3		
2.5473E+03	5.04E-01	5.1246E-01	3.65E-02		0.34	3	37.74	3		
2.5585E+03	5.04E-01	2.2978E-01	1.18E-02		0.04	3	0.31	3		
2.5801E+03	5.06E-01	3.2106E-01	1.63E-02		0.08	3	18.42	3		
2.5988E+03	5.06E-01	7.3480E-01	3.39E-02		0.83	3	3.66	3		
* 2.6036E+03	1.00E+00	2.5515E-03	2.55E-03							
2.6191E+03	5.41E-01	5.0059E-02	3.54E-03		0.42	3	0.72	3		
2.6316E+03	7.34E-01	1.5390E-03	7.25E-04		0.06	2	0.50	2		
2.6712E+03	5.70E-01	2.6564E-01	1.37E-02		0.48	3	3.28	3		
2.6954E+03	5.31E-01	2.4865E-02	2.52E-03		0.06	3	4.29	3		
2.7163E+03	5.72E-01	1.2765E-01	9.94E-03		0.10	3	21.91	3		
2.7286E+03	8.17E-01	2.2934E-03	1.43E-03		0.33	2	0.02	2		
2.7497E+03	5.73E-01	4.0337E-02	3.44E-03		0.00	3	0.45	3		
2.7616E+03	5.73E-01	1.80988[illegible]	1.85E-03		0.00	3	1.92	3		
2.7867E+03	5.73E-01	1.08[illegible]	[illegible]E-03		1.03	3	0.26	3		
2.7980E+03	7.43E-01	2.11[illegible]-03	[illegible]E-04		0.03	2	0.05	2		
2.8055E+03	8.24E-01	5.2710E-03	1.65E-03		0.04	2	0.61	2		
2.8284E+03	5.74E-01	1.2962E-02	2.04E-03		0.02	3	5.49	3		
* 2.8449E+03	2.10E+00	2.6670E-03	2.67E-03							
2.8543E+03	5.75E-01	9.1499E-02	8.82E-03		0.57	3	23.58	3		
2.8839E+03	5.75E-01	5.4608E-01	2.51E-02		0.12	3	0.18	3		
2.896[illegible]E+03	4.28E-01	1.5055E-02	4.02E-03		0.29	3	1.10	3		
2.9071E+03	7.50E-01	1.6212E-03	8.29E-04		0.27	2	0.18	2		
2.9225E+03	5.47E-01	5.7971E-03	8.74E-04		0.71	3	3.36	3		
2.9329E+03	6.00E-01	2.5290E-02	2.91E-03		1.53	3	5.31	3		
2.9559E+03	6.40E-01	1.8708E-02	3.11E-03		0.05	3	0.68	3		
2.9663E+03	6.40E-01	4.4061E-03	1.22E-03		0.47	3	2.44	3		
* 2.9737E+03	2.20E+00	2.7267E-03	2.7[illegible]-03							
2.9867E+03	6.41E-01	5.5470E-03	1.4[illegible]-03		0.25	3	0.01	3		
3.0025E+03	6.41E-01	1.2165E-01	8.8[illegible]-03		0.04	3	1.65	3		
3.0150E+03	9.14E-01	2.4047E-03	1.02[illegible]-03		0.02	2	3.45	2		

COLUMN NUMBER

1		2		3		4	5	6	7	8	9
	*OR-		*OR-		*OR-						
1.7490E+03	3.71E-01	1.7490E-03	3.59E-04			2.02	2	0.14	.		
1.7553E+03	2.98E-01	1.1429E-01	6.65E-03	2.7000E-02	4.00E-03	0.20	4	11.14	4	0.0	1
1.7821E+03	2.99E-01	5.5896E-01	3.13E-02			0.29	4	11.16	4		
1.7965E+03	2.99E-01	2.2208E+03	4.55E-04			6.68	3	1.15	3		
1.8079E+03	2.99E-01	1.6440E-02	1.60E-03	1.7000E-02	5.00E-03	0.06	3	0.44	3	0.0	1
1.8455E+03	3.37E-01	1.0866E-02	1.20E-03	1.5000E-02	5.00E-03	0.15	3	2.29	3	0.0	1
* 1.8683E+03	5.00E-01	3.0898E-03	2.16E-03								
1.9023E+03	3.38E-01	3.4011E-02	2.30E-03	1.9000E-02	4.00E-03	0.27	3	16.54	3	0.0	1
* 1.9130E+03	4.00E-01	4.9555E-04	3.10E-04								
1.9164E+03	3.38E-01	2.4472E-02	1.71E-03	1.9000E-02	5.00E-03	0.07	3	9.95	3	0.0	1
1.9532E+03	3.54E-01	3.7803E-03	4.35E-04			0.21	2	0.80	2		
1.9684E+03	3.66E-01	6.9324E-01	3.20E-02	3.0000E-02	1.00E-02	0.26	3	16.28	3	0.0	1
1.9742E+03	3.39E-01	4.4880E-01	2.79E-02			0.13	3	1.44	3		
2.0229E+03	3.67E-01	2.0329E-01	1.34E-02	2.0000E-02	4.00E-03	0.04	3	0.06	3	0.0	1
2.0299E+03	3.67E-01	5.0600E-02	4.01E-03	1.8000E-02	5.00E-03	0.31	3	0.43	3	0.0	1
* 2.0709E+03	6.00E-01	3.1055E-04	1.82E-04								
2.0886E+03	3.68E-01	1.7346E-02	1.05E-03	2.2000E-02	4.00E-03	0.03	3	7.39	3	0.0	1
2.0959E+03	3.68E-01	1.5258E-02	1.50E-03			0.01	3	19.26	3		
2.1238E+03	5.40E-01	3.5920E-03	1.19E-03			0.00	2	0.26	2		
2.1448E+03	3.69E-01	5.1967E-02	4.08E-03	1.5000E-02	5.00E-03	0.37	3	30.20	3	0.0	1
2.1522E+03	4.05E-01	2.2956E-01	1.27E-02	3.2000E-02	8.00E-03	0.01	3	16.86	3	0.0	1
2.1746E+03	4.71E-01	1.6591E-03	6.62E-04			5.52	2	0.30	2		
2.1861E+03	4.06E-01	4.0341E-01	2.59E-02	2.9000E-02	7.00E-03	0.24	3	19.44	3	0.0	1
* 2.1935E+03	1.40E+00	2.3429E-03	2.34E-03								
2.2007E+03	4.06E-01	1.1335E-01	7.82E-03	2.6000E-02	5.00E-03	0.08	3	0.01	3	0.0	1
2.2293E+03	5.54E-01	4.0679E-03	7.86E-04			0.01	2	0.31	2		
2.2351E+03	5.54E-01	4.7278E-03	8.78E-04			0.01	2	0.00	2		
* 2.2410E+03	1.45E+00	1.4203E-03	1.42E-03								
2.2588E+03	4.07E-01	7.8413E-02	5.68E-03			0.05	3	10.41	3		
2.2660E+03	4.18E-01	1.7422E-01	9.80E-03	2.0000E-02	5.00E-03	0.01	3	30.83	3	0.0	1
2.2814E+03	4.36E-01	1.2214E-01	6.42E-03	1.8000E-02	5.00E-03	0.34	3	43.90	3	0.0	1
2.2889E+03	5.57E-01	1.2004E-03	4.34E-04			0.23	2	1.95	2		
* 2.3015E+03	1.50E+00	9.5950E-04	9.60E-04								
* 2.2963E+03	1.20E+00	5.8000E-03	5.00E-04								
2.3140E+03	4.36E-01	1.9022E-02	2.12E-03			0.47	3	1.24	3		
* 2.3261E+03	7.00E-01	2.1000E-03	5.00E-04								
* 2.3316E+03	6.00E-01	1.6000E-03	2.00E-04								
2.3374E+03	4.37E-01	7.9444E-03	1.43E-03			0.98	3	2.72	3		
* 2.3456E+03	6.00E-01	3.5000E-03	1.00E-03								
2.3529E+03	4.37E-01	5.6775E-02	8.50E-03	2.8000E-02	5.00E-03	1.12	3	3.74	3	0.0	1
2.3552E+03	4.37E-01	6.6606E-02	8.50E-03	2.4000E-02	5.00E-03	0.07	3	1.68	3	0.0	1

COLUMN NUMBER

1		2		3		4	5	6	7	8	9
	+OR-		+OR-		+OR-						
1.1768E+03	2.94E-01	6.3089E-02	2.87E-03	2.2000E-02	1.66E-03	0.75	5	9.04	4	0.00	2
1.1944E+03	2.94E-01	9.0742E-02	3.75E-03	2.0400E-02	.79E-03	0.35	5	6 03	4	2.45	2
1.2105E+03	3.04E-01	7.6135E-03	5.42E-04			0.12	4	4.68	4		
* 1.2180E+03	4.00E-01	3.9367E-04	2.20E-04								
* 1.2380E+03	4.00E-01	4.0322E-04	2.10E-04								
1.2446E+03	3.04E-01	2.4282E-01	1.09E-02	2.4000E-02	2.00E-03	0.52	4	1.82	4	0.0	1
* 1.2970E+03	4.00E-01	1.9790E-04	1.48E-04								
1.2667E+03	3.23E-01	2.6973E-02	1.05E-03	2.1000E-02	2.00E-03	0.18	4	4.23	4	0.0	1
1.2727E+03	3.23E-01	2.8067E-02	1.19E-03	2.4000E-02	2.00E-03	0.01	4	0.20	4	0.0	1
* 1.2838E+03	7.79E+00	5.0000E-03	3.00E-03								
1.2982E+03	2.39E-01	3.7995E-03	7.47E-04			2.00	4	2.69	4		
* 1.3046E+03	7.97E+00	2.0000E-02	1.00E-02								
1.3165E+03	2.39E-01	3.9900E-03	4.84E-04			0.16	4	1.07	4		
1.3324E+03	4.15E-01	1.2102E-03	1.87E-04			31.50	3	0.14	3		
* 1.3402E+03	8.20E+00	5.0000E-03	5.00E-03								
1.3633E+03	5.98E-01	1.1208E-03	3.68E-04			1.83	2	0.60	2		
1.3720E+03	3.00E-01	6.3714E-04	3.16E-04			2.03	2	0.48	2		
1.3820E+03	3.00E-01	6.2152E-04	3.01E-04			2.03	2	0.49	2		
1.3931E+03	2.50E-01	1.0180E-01	9.98E-03	2.8000E-02	3.00E-03	1.03	4	10.93	4	0.0	1
1.4051E+03	2.41E-01	7.2167E-02	4.01E-03	2.5000E-02	2.00E-03	0.83	4	0.86	4	0.0	1
1.4108E+03	2.79E-01	4.2327E-04	2.31E-04			3.56	2	0.41	2		
1.4161E+03	2.53E-01	1.3763E-03	3.28E-04			0.48	3	0.82	3		
1.4193E+03	2.53E-01	9.3004E-03	9.48E-04			0.94	4	1.23	4		
1.4274E+03	3.04E-01	2.8832E-02	2.03E-03	2.6000E-02	3.00E-03	0.30	4	2.18	4	0.0	1
1.4436E+03	3.04E-01	1.8221E-02	1.99E-03	2.2000E-02	3.00E-03	0.15	4	2.68	4	0.0	1
1.4733E+03	3.07E-01	1.0622E-01	4.81E-03	2.8000E-02	3.00E-03	0.11	4	22.38	4	0.0	1
* 1.5041E+03	9.76E+00	2.0000E-02	1.00E-02								
1.5223E+03	3.18E-01	2.3749E-01	8.98E-03	3.0000E-02	7.00E-03	0.10	4	7.06	4	0.0	1
1.5321E+03	3.50E-01	7.0461E-04	3.50E-04			0.87	2	3.20	2		
1.5461E+03	3.10E-01	1.4869E-03	6.39E-04			3.28	4	8.94	4		
1.5498E+03	2.31E-01	1.3002E-03	4.29E-04			0.77	4	11.74	4		
1.5649E+03	2.68E-01	2.2725E-03	3.77E-04			0.80	4	16.86	4		
1.5975E+03	2.93E-01	3.3573E-01	1.46E-02	2.0000E-02	4.00E-03	0.08	3	1.36	3	0.0	1
1.6222E+03	2.95E-01	9.2592E-02	7.57E-03	1.9000E-02	3.00E-03	0.37	4	9.08	4	0.0	1
1.6377E+03	2.95E-01	4.9989E-02	3.20E-03	1.9000E-02	3.00E-03	0.68	3	7.85	3	0.0	1
1.6459E+03	2.85E-01	9.2016E-04	4.37E-04			1.43	2	0.03	2		
1.6620E+03	2.97E-01	1.8924E-01	1.15E-02	2.4000E-02	4.00E-03	0.41	4	10.90	4	0.0	1
1.6882E+03	2.97E-01	9.0700E-02	5.65E-03	1.9000E-02	3.00E 03	0.64	4	7.38	4	0.0	1
* 1.7032E+03	9.50E-01	8.2479E-04	8.25E-04								
1.7091E+03	3.56E-01	7.1345E-02	3.88E-03	2.8000E-02	5.00E-03	0.52	4	30.94	4	0.0	1
1.7222E+03	2.98E-01	1.4490E-02	1.08E-03			0.18	4	0.64	4		

COLUMN NUMBER

1		2		3		4	5	6	7	8	9
	*OR-		*OR-		*OR-						
8.0000E+02	3.9E-01	5.0032E-04	1.75E-04			0.01	3	1.57	3		
* 8.1500E+02	4.00E-01	1.9030E-04	1.03E-04								
8.2100E+02	2.43E-01	5.8840E-02	1.58E-03	2.3593E-02	1.10E-03	1.18	8	17.45	8	9.37	5
* 8.3240E+02	4.00E-01	2.6379E-04	1.33E-04								
8.4652E+02	2.37E-01	6.6178E-04	1.31E-04			1.83	3	1.59	2		
8.5070E+02	2.47E-01	5.7314E-02	1.90E-03	2.7548E-02	1.15E-03	0.17	7	9.87	6	9.03	3
8.5500E+02	2.47E-01	8.1643E-02	2.50E-03	2.3606E-02	1.07E-03	0.63	7	8.15	6	0.31	3
8.6713E+02	2.48E-01	3.9030E-03	3.01E-04			16.04	5	22.01	5		
8.9032E+02	2.11E-01	8.2687E-04	1.33E-04			3.11	4	1.88	4		
9.0464E+02	2.09E-01	4.7298E-02	1.19E-03	2.4919E-02	1.23E-03	1.40	7	13.17	7	5.06	4
9.0951E+02	2.19E-01	1.8833E-03	2.15E-04			0.12	3	0.73	3		
9.2463E+02	2.22E-01	9.3598E-03	4.89E-04	2.5000E-02	4.00E-03	0.53	5	22.52	5	0.0	1
9.3221E+02	2.40E-01	3.0558E-04	1.40E-04			0.26	2	0.00	2		
9.3656E+02	2.20E-01	1.3862E-01	5.81E-03	2.4117E-02	9.69E-04	0.32	7	4.45	7	0.44	4
* 9.4010E+02	3.00E-01	3.8965E-04	1.60E-04								
9.5802E+02	2.53E-01	1.7140E-01	6.69E-03	2.2311E-02	9.69E-04	0.48	7	17.18	7	0.69	4
* 9.6470E+02	3.00E-01	1.9903E-04	1.22E-04								
9.7685E+02	2.98E-01	6.4469E-04	2.02E-04			1.56	2	0.40	2		
* 9.8560E+02	3.00E-01	2.9796E-04	1.60E-04								
9.9136E+02	2.68E-01	3.5059E-01	7.98E-03	2.9895E-02	1.33E-03	0.10	7	5.42	6	1.19	4
* 9.9983E+02	4.50E-01	1.7651E-03	1.27E-03								
* 1.0079E+03	5.55E+00	6.0000E-04	4.00E-04								
1.0107E+03	2.75E-01	1.6899E-03	3.92E-04			0.43	3	0.20	3		
* 1.0140E+03	3.00E-01	1.5791E-03	3.59E-04								
1.0227E+03	2.72E-01	7.9597E-03	8.38E-04			0.61	5	9.28	5		
1.0288E+03	3.02E-01	3.0808E-03	5.63E-04			0.04	3	0.48	3		
1.0317E+03	2.35E-01	8.4255E-04	2.37E-04			16.25	4	0.43	3		
1.0538E+03	2.97E-01	8.7543E-02	4.37E-03	2.4844E-02	1.19E-03	1.10	6	7.30	6	2.20	3
* 1.0620E+03	3.00E-01	6.9250E-04	3.21E-04								
1.0676E+03	2.12E-01	7.2092E-0.	1.92E-04			4.71	3	2.18	3		
1.0707E+03	2.57E-01	3.1484E-04	1.50E-04			2.85	2	0.00	2		
1.0810E+03	2.16E-01	7.3010E-04	2.27E-04			0.62	3	1.00	3		
1.0943E+03	2.46E-01	1.0663E-03	2.44E-04			0.75	3	6.81	3		
1.0981E+03	2.62E-01	2.0154E-02	1.19E-03	2.3500E-02	2.12E-03	1.57	5	20.74	4	0.50	2
1.1025E+03	2.46E-01	1.1382E-03	2.63E-04			3.34	3	5.50	3		
1.1087E+03	2.65E-01	2.3880E-02	2.04E-03	2.4000E-02	2.00E-03	0.79	4	115.18	4	0.0	1
1.1310E+03	2.65E-01	1.0591E-03	4.30E-04			0.06	3	0.13	3		
1.1430E+03	2.69E-01	2.1915E-01	1.66E-03	2.3923E-02	1.66E-03	0.46	5	1.19	4	0.69	2
* 1.1470E+03	4.00E-01	3.0213E-04	1.58E-04								
* 1.1550E+03	4.00E-01	4.0714E-04	2.04E-04								
1.1671E+03	2.69E-01	8.2595E-02	3.16E-03	2.3000E-02	1.66E-03	0.47	5	6.69	4	0.00	2

COLUMN NUMBER

1		2		3		4	5	6	7	8	9
	+OR-		+OR-		+OR-						
3.1110E+02	8.24E-02	1.0005E-03	4.59E-05			3.78	6	2.18	6		
* 3.3720E+02	2.70E-01	5.0443E-05	2.52E-05								
3.4769E+02	9.87E-02	7.7325E-02	1.27E-03	2.2612E-02	0.90E-04	2.45	9	57.35	9	3.13	5
* 3.5180E+02	3.00E-01	0.0633E-05	3.66E-05								
* 3.5470E+02	3.10E-01	2.9602E-05	1.93E-05								
3.7673E+02	1.09E-01	1.1140E-03	5.64E-05			1.82	7	5.73	7		
3.9744E+02	1.14E-01	5.9596E-03	2.00E-04	2.4910E-02	3.79E-03	0.94	8	17.20	8	1.27	4
* 4.0769E+02	3.60E-01	0.2291E-05	4.27E-05								
4.1008E+02	1.26E-01	1.8023E-02	3.65E-04	2.1646E-02	1.05E-03	0.83	9	56.72	9	6.43	5
4.3393E+02	1.36E-01	9.2152E-03	2.65E-04	2.1541E-02	1.69E-03	0.89	8	28.91	8	2.59	4
4.3952E+02	2.79E-01	2.6222E-04	5.83E-05			0.42	2	5.92	2		
4.5338E+02	1.83E-01	3.9970E-04	4.73E-05			1.23	6	6.07	6		
4.6301E+02	1.49E-01	5.0177E-03	2.09E-04	1.8594E-02	5.44E-03	1.10	7	29.14	7	0.00	2
4.7837E+02	1.56E-01	3.3903E-03	1.85E-04	3.5000E-02	2.50E-02	10.42	7	21.24	7	0.0	1
4.8653E+02	1.66E-01	5.1115E-04	5.35E-05			3.82	6	12.04	6		
* 4.9890E+02	2.50E-01	0.2554E-05	4.54E-05								
5.1819E+02	1.46E-01	4.5731E-02	9.99E-04	2.4339E-02	8.43E-04	0.69	8	23.52	8	1.65	5
* 5.2320E+02	2.60E-01	1.9946E-04	8.87E-05								
5.3512E+02	1.55E-01	4.2230E-02	9.27E-04	2.4305E-02	8.51E-04	0.86	8	14.44	8	2.85	5
* 5.4230E+02	2.80E-01	5.1465E-05	3.74E-05								
5.5583E+02	1.73E-01	7.2955E-04	1.17E-04			0.74	6	9.63	6		
5.7983E+02	1.79E-01	3.1131E-02	8.00E-04	2.3606E-02	9.34E-04	0.57	8	122.12	8	4.82	5
5.9476E+02	1.46E-01	8.1785E-02	1.59E-03	2.2680E-02	7.58E-04	2.04	8	14.97	8	2.52	5
6.0591E+02	3.18E-01	3.1035E-04	1.03E-04			4.58	3	1.25	3		
6.1961E+02	1.59E-01	2.9489E-02	6.37E-04	2.3054E-02	1.06E-03	0.39	8	11.39	8	7.24	5
6.2363E+02	1.54E-01	6.9482E-04	8.07E-05			17.38	3	4.39	3		
6.2826E+02	1.52E-01	6.1355E-03	1.66E-04			0.91	7	39.49	7		
6.5081E+02	1.78E-01	1.2116E-01	2.20E-03	2.5372E-02	9.10E-04	0.85	8	19.59	8	4.58	5
* 6.6840E+02	3.70E-01	2.4961E-04	1.15E-04								
6.7693E+02	1.82E-01	0.4201E-04	1.11E-04			4.35	5	4.77	5		
6.9282E+02	1.02E-01	3.8114E-02	9.01E-04	2.3549E-02	9.52E-04	0.23	8	28.28	8	1.62	5
7.0794E+02	1.83E-01	2.1250E-02	8.30E-04	2.4364E-02	1.38E-03	0.85	8	3.53	8	5.94	5
* 7.1250E+02	4.00E-01	2.5358E-04	1.06E-04								
7.2121E+02	8.80E-01	1.2020E-03	1.09E-04			1.60	6	6.67	6		
7.2961E+02	1.90E-01	6.3865E-04	1.25E-04			0.43	4	2.32	4		
7.3195E+02	2.05E-01	1.4807E-03	1.09E-04			4.46	6	30.74	6		
7.4278E+02	2.40E-01	4.0306E-04	9.01E-05			1.69	2	1.93	2		
7.5582E+02	3.01E-01	4.1300E-04	1.03E-04			1.86	3	7.42	3		
7.6470E+02	2.25E-01	6.3065E-03	5.02E-04	1.7000E-02	2.00E-03	1.30	7	12.22	7	0.0	1
7.7882E+02	2.29E-01	1.4381E-03	1.01E-04			0.49	6	27.18	6		
7.9045E+02	2.24E-01	5.9364E-03	2.03E-04	1.5000E-02	1.30E-02	0.79	7	23.69	7	0.0	1

* 4.3[illegible]E+00	1.00E-02	1.1100E-07	2.00E-09									
6.6[illegible]E+00	1.06E-02	1.5145E-03	8.06E-06	2.6902E-02	3.65E-04	1.22	9	9.02	9	4.21	7	
1.0218E+01	8.74E-03	1.5601E-06	9.06E-09			0.70	5	0.40	5			
* 1.1279E+01	2.00E-02	3.5800E-07	6.00E-09									
* 1.6243E+01	4.00E-02	5.3000E-08	1.60E-08									
1.9533E+01	1.70E-02	1.0109E-06	9.85E-08			0.58	2	0.41	2			
2.0859E+01	5.90E-02	3.9609E-03	1.76E-04	2.5695E-02	1.09E-03	1.22	8	10.02	8	11.53	7	
3.6682E+01	5.20E-02	3.1595E-02	5.35E-04	2.6550E-02	1.19E-03	10.57	9	16.09	9	0.51	8	
4.5176E+01	6.61E-02	8.5608E-07	1.48E-07			0.34	2	1.36	2			
* 4.9456E+01	2.00E-01	6.8000E-07	2.70E-07									
* 5.7738E+01	3.00E-01	4.8000E-07	8.00E-08									
6.3532E+01	7.73E-02	5.6237E-06	1.30E-06			0.13	2	0.03	2			
6.6021E+01	5.50E-02	2.3990E-02	4.20E-04	2.3560E-02	7.62E-04	0.63	11	8.19	11	12.89	9	
8.0716E+01	4.12E-02	1.9610E-03	6.07E-05	2.1170E-02	8.93E-03	0.50	9	5.58	9	0.0	1	
8.3559E+01	7.84E-02	6.6627E-06	6.60E-07			0.47	2	2.09	2			
8.9326E+01	5.21E-02	8.4230E-05	3.14E-06			19.49	7	1.64	7			
* 9.2975E+01	5.00E-01	3.0000E-06	6.00E-07									
1.0252E+02	4.50E-02	7.0349E-02	4.38E-04	2.5703E-02	9.43E-04	6.05	12	75.04	12	6.59	8	
1.1683E+02	4.90E-02	2.7084E-02	3.90E-04	2.3244E-02	8.05E-04	0.92	12	100.67	12	12.42	7	
* 1.2160E+02	1.10E-01	5.9602E-06	3.48E-06									
1.2432E+02	1.18E-01	1.3972E-05	1.90E-06			0.51	2	0.14	2			
1.4563E+02	5.67E-02	0.4769E-04	2.00E-05			2.08	9	0.34	9			
1.5240E+02	1.57E-01	3.7046E-05	1.98E-06			0.01	2	0.03	2			
1.5893E+02	1.68E-01	1.0180E-05	1.26E-06			0.01	2	0.48	2			
1.6529E+02	7.78E-02	3.1904E-03	1.19E-04	1.7992E-02	4.65E-03	0.53	8	5.47	8	0.43	3	
1.7310E+02	1.87E-01	3.2449E-05	3.76E-06			0.01	2	0.48	2			
1.8962E+02	9.20E-02	1.5435E-01	1.50E-03	2.3828E-02	9.80E-04	6.27	11	54.49	11	7.14	6	
* 2.0230E+02	2.50E-01	3.9427E-05	1.60E-05									
2.0842E+02	8.48E-02	4.9696E-02	8.42E-04	2.2330E-02	5.22E-04	1.39	10	12.98	10	6.61	6	
* 2.1500E+02	2.70E-01	3.9692E-05	1.63E-05									
2.3728E+02	6.77E-02	2.6653E-02	5.25E-04	2.3117E-02	7.58E-04	15.57	10	15.99	10	9.22	5	
2.4267E+02	7.59E-02	1.5517E-04	1.82E-05			0.33	3	0.07	3			
* 2.5390E+02	1.80E-01	9.8088E-05	3.00E-05									
* 2.5540E+02	1.90E-01	6.0457E-05	2.57E-05									
* 2.5710E+02	1.90E-01	1.9851E-05	1.22E-05									
2.6377E+02	7.74E-02	2.1516E-04	1.93E-05			7.35	6	6.57	6			
2.7356E+02	7.57E-02	2.4992E-02	5.40E-04	2.3286E-02	8.12E-04	0.22	8	13.45	8	0.51	5	
* 2.7580E+02	[illegible].00E-01	7.9715E-05	3.56E-05									
* 2.8230E+02	[illegible].10E-01	6.1478E-05	2.63E-05									
2.9091E+02	9.46E-02	1.4979E-02	5.09E-04	2.2603E-02	1.05E-03	1.12	8	7.29	8	0.68	5	
* 2.9500E+02	2.20E-01	3.0023E-05	1.69E-05									

OUTPUT OF RECOMMENDED RESONANCE PARAMETERS

COLUMN 1 RESONANCE ENERGY IN EV
COLUMN 2 NEUTRON WIDTH IN EV
COLUMN 3 RADIATION WIDTH IN EV
COLUMN 4 CHI-SQUARED FOR RESONANCE ENERGY
COLUMN 5 NUMBER OF MEASUREMENTS OF THE RESONANCE ENERGY
COLUMN 6 CHI-SQUARED FOR NEUTRON WIDTH
COLUMN 7 NUMBER OF MEASUREMENTS OF THE NEUTRON WIDTH
COLUMN 8 CHI-SQUARED FOR RADIATION WIDTH
COLUMN 9 NUMBER OF MEASUREMENTS OF THE RADIATION WIDTH
RESONANCES MARKED WITH A * HAVE ONLY ONE PUBLISHED MEASUEMENT

Some comments on the evaluation of the unresolved resonance parameters of U-238

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1. Preliminary Comments

Evaluations of unresolved resonance parameters are required so that good calculations can be made of self shielding factors, the doppler temperature coefficient of reactivity and other reactor parameters which depend on resonance structure. The aim of these evaluations is to enable a set of resonances to be generated which have a similar distribution of properties as the resonances actually present. The generation of these resonances is done using various computer programmes and the formalisms used and assumptions made in these may be slightly different. The Author has made no attempt to investigate this problem but there are probably no great inconsistencies. However, because of possible differences one should take care in drawing detailed conclusions from comparisons of unresolved parameters.

Any evaluation of unresolved resonance parameters must have as its foundation the average values and distributions of the resonance parameters observed in the resolved energy range. The forms of the various distributions are of course based on resonance parameter data from many different nuclei. The evaluations are also made to be consistent with measurements of the average cross-sections in the unresolved region. For U-238 the unresolved resonance parameters are often chosen so that using a particular set of computer programmes they reproduce an evaluated capture cross-section. It is well-known that for U-238 there is considerable uncertainty about the individual resonance parameters and hence there is also uncertainty in their average values.

2. Detailed Discussion of Unresolved Region Data and Evaluations

In any evaluation the distinction between the resolved and unresolved energy ranges is very blurred because an increasing number of the smaller resonances are not analysed, owing to lack of resolution, as one gets closer to the higher energy end of the resolved energy range. The evaluator therefore has to allow for these using the "unresolved resonance parameters". For U-238 the resolved energy range extends up to ~4 keV and hence the unresolved resonance parameters are needed from $\lesssim$ 4 keV to a few tens of keV. In this energy range we have to consider s, p and d wave interactions (l = 0, 1 and 2) though the d-wave contribution is sufficiently small that we can limit discussion to the s and p-wave contributions (the value of the d-wave strength function and mean radiation width are usually assumed to be the same as the s-wave values). For s-wave the s-wave interactions form compound nuclear states with spin and parity $J^{\pi} = \frac{1}{2}^{+}$ while for p-waves the values are $\frac{1}{2}^{-}$ and $3/2^{-}$. For each of these spin states an unresolved resonance parameter evaluation must provide the following information which can vary with incident neutron energy.

(a) The mean value of the reduced neutron width (or alternatively the strength function) and the distribution function of the widths.

(b) The mean value of the total radiation width and the distribution function of the widths.

(c) The mean level spacing and the distribution of level spacings.

Other information such as the effective scattering radius and the nucleus radius [illegible] in the calculation of penetrability are also required. It is normally assumed that there is zero fission cross-section but Block et al [1] have recently

shown that there is a small amount of sub-threshold fission, which has the characteristic intermediate structure, and this will have to be included in the future.

The distribution functions for widths and spacings have been discussed extensively in the literature (see for example Lynn [2]) and there is a general concensus that

(1) the level spacing distribution is in good agreement with the Wigner form

(2) the reduced neutron width distribution is a ^{2} distribution with the number of degrees of freedom ( ) being 1 or 2 depending on whether or not the spin state can be formed for both channel spins $I + \frac{1}{2}$ and $I - \frac{1}{2}$. (For = 1 the distribution is of course the Porter-Thomas distribution).

(3) The total capture widths have a narrow distribution about their mean value (similar to a χ^2 distribution with ν very large) and it is usually assumed that the capture width is a constant.

Table 1 lists the main techniques that have been used to obtain the average resonance parameters used in evaluations of the unresolved region. A number of assumptions that have usually been made in the analysis of the results are listed below

(a) The average level spacing D_J is related to the spin J as follows

$$D_J = \frac{D_o}{2J+1} \exp\left(\frac{J[J+1]}{2\sigma^2} \right)$$

where D_o is a constant and σ is approximately 6.

(b) For a given l wave the strength function is assumed to be independent of J.

(c) The value of the radiation width Γ_γ is assumed to be independent of J and l.

Table 2 gives the average resonance parameters obtained from some typical experiments and analyses. The most striking difference is in the p-wave strength function where the analysis of transmission data gives values about 60% higher than the other techniques. However, it can also be seen that none of the parameters, except the effective potential scattering radius, are consistent within ±10% and this makes it necessary in evaluations for fast reactor purposes to select parameters which will reproduce the measured average capture cross-section.

Table 3 gives the average unresolved resonance parameters used in various evaluations. There is considerable variation in the values chosen and on the whole they are all consistent with the typical "experimental" values given in Table 2. The calculated average capture cross-sections, which are also given in 2 energy ranges, show a large spread and one would expect significant discrepancies in the calculated total cross-sections. There are some good total cross-section data available in this energy region and it would appear to be sensible to recommend evaluators to take note of these. Perhaps it is also necessary to repeat these cross-section measurements as it is desirable to have as many checks on the U-238 resonance data as reasonably possible.

It is perhaps now worth considering what other checks are possible. First, however, one should note that for reactor calculations one would like checks on the resonance parameter data at various sample temperatures so that the reactor physicists can get improved confidence in calculations of the doppler temperature coefficient of reactivity. In principle they would like to do calculations at temperatures up to 5000°K, but at the present time there are only data below ~1000°K. Two types of measurement have been done which are checks on average resonance parameter data and the changes of thick sample self screening calculations as a function of temperature. The first of these is the measurement of average transmission of neutrons by thick samples and the second is the measurement of the average self indication ratio. Measurements of the first type have been done by Vankov et al [13] and of both types by Byoun et al [14].

Table 4 gives the results obtained by Vankov et al from their data. In considering the results it should be remembered that many of the parameters obtained are effectively the result of analysing the thin and thick sample average transmissions at room temperature. Table 5 gives the best values of Byoun et al for the p-wave parameters along with the assumed s-wave data. The data in both tables are not in particularly good agreement with the evaluated data given earlier except perhaps for the second set of results of Vankov et al where $\langle\Gamma_\gamma\rangle$ and the average s-wave level spacing are kept constant.

At the present time calculations are being made at Harwell on these two types of measurements as a preliminary to performing similar experiments. The changes in thick sample transmission with sample temperature appear to be mainly due to the increased doppler broadening filling in the minima in the total cross-section caused by the resonance-potential interference produced by s-wave neutrons. The biggest effects are produced by the resonances with large Γ_n and the results are slightly sensitive to the value of Γ_γ. The calculations of the self indication ratio are not complete but in the region below 10 keV the changes as a function of temperature also appear to be sensitive to the s-wave rather than the p-wave parameters. For instance for a given set of s and p-wave Γ_n values, changing Γ_γ for the p-wave resonances by a factor 2 produces negligible changes in the average self indication ratio and its temperature dependence. However, a similar change for the s-wave resonances produces significant changes in both the self indication ratio and its temperature dependence. Around 1 keV the changes are mainly associated with the large Γ_n resonances but the situation appears more complex at higher energies and calculations are continuing. However, from this discussion it can be seen that these types of experiments should help to improve calculations of the doppler temperature coefficient of reactivity as a large part of the observed changes as a function of sample temperature arise from the large s-wave resonances which are heavily self-screened in a reactor.

3. Conclusions

In conclusion a number of points can be made

(1) The average resonance parameters in U-238 are not well known and improved data are required.

(2) Insufficient checks have been made to date to see that evaluations fit all the data that are available.

(3) In the future evaluators should check that the resolved and unresolved data on U-238 are consistent with

(a) average capture cross-section data
(b) average total cross-section data
(c) average transmission data for thick samples (including variation with sample temperature).
(d) average self indication ratio data and their variation with transmission sample temperature.

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Table 1

Methods of obtaining data on unresolved resonance parameters

Method	Assumptions	Data obtained
A Analysis of resolved resonance data	The average values of parameters in the resolved region are the same as the unresolved region when known energy dependence allowed for	s-wave strength function (S_0) s-wave level spacing and hence D_0 $\langle\Gamma\gamma\rangle$ for s-waves scattering radius R' for s-waves
B Analysis of average total cross-section data		S_0 and p and d-wave strength functions (S_1 and S_2) Dimensionless quantities for s and p-waves (R_0 and R_1^{∞}) which allows for the effect of distant levels The value of R_0^{∞} effectively gives R'
C Analysis of thick sample average transmission data	Values of D_0, $\langle\Gamma\gamma\rangle$ S_0 and distribution of s-wave neutron widths are assumed	S_1 and R'
D Analysis of average capture cross measurements	Values of S_0 and S_2 are assumed plus distribution of neutron widths	$\frac{\langle\Gamma\gamma\rangle}{D_0}$ for s-waves $\frac{\langle\Gamma\gamma\rangle}{D_0}$ for p-waves S_1 The values $\frac{\langle\Gamma\gamma\rangle}{D_0}$ for s-waves and S_1 are strongly correlated

Table 2

Data obtained from typical experiments and analyses

Experiment	Type	s-wave level spacing (eV)	S_o	Effective potential scattering radius (fm)	S_1	$\langle\Gamma_\gamma\rangle$ meV	Comment
Rahn et al[3]	A	20.8	$1.08 \pm 0.10 \times 10^{-4}$	9.6 ± 0.3	$\sim 1.4 \times 10^{-4}$	22.9 ± 0.5 (stat) ± 0.9 (syst)	Analysis to divide levels into s and p populations
Rohr et al[4]	A					24.64 $\pm$ 0.85	
Carraro and Kolar[5]	A	17.8 ± 0.9	1.13 ± 0.13				Assumes all resonances <2 keV produced by s-wave neutrons
Uttley et al[6]	B		Assumed to be 1.0×10^{-4}	Assumed to be 9.185	$2.47^{+0.16}_{-0.28} \times 10^{-4}$		
Lynn[7]	C	Assumed to be 18.0	Assumed to be 1.0×10^{-4}	9.185 ± 0.14	$2.5^{+0.4}_{-0.4} \times 10^{-4}$	Assumed to be 27	
Moxon[8]	D		1.0 ± 0.3		1.59 ± 0.45	$\langle\Gamma_\gamma\rangle/D_o = 5.7 \pm 0.9 \times 10^{-4}$ (s-wave) $= 5.8 \pm 1.2 \times 10^{-4}$ (p-wave)	If s-wave level spacing = 20.8 eV $\langle\Gamma_\gamma\rangle$ = 23.7 meV

Table 3

Comparison of Evaluations of unresolved resonance parameters

Quantity \ Evaluation	ENDF/B III[9]	James for UK SDR-GENEX evaluation [10]	Schmidt[11]	Abagyan et al[12]
S_o	1.05×10^{-4} but varied by up to 15% below 10 keV	0.93×10^{-4}	0.90×10^{-4}	0.91×10^{-4}
S_1	Variable between 1.337×10^{-4} and 1.932×10^{-4}	1.58×10^{-4}	2.5×10^{-4}	2.0×10^{-4}
s-wave level spacing	Variable decreasing from 20 to 18.59 eV from 4 to 45 keV	22.5 eV	20.8 eV	20.4 eV
p-wave level spacing J = 1/2 J = 3/2	 An s-wave Variable decreasing from 10.98 to 10.21 eV from 4 to 45 keV	 22.5 eV 11.25 eV	 20.8 eV 11.4 eV	
s-wave scattering radius (R')	9.184×10^{-13} cm	9.1843×10^{-13}	9.18×10^{-13} cm	
radius used for calculating penetrability	8.401×10^{-13} cm	8.3662×10^{-13}	9.18×10^{-13} cm	
$\langle\Gamma_\gamma\rangle$	23.5 meV	23.0 meV	24.8 meV	24.3 meV
Comment	Parameters chosen to reproduce average capture cross-section	Parameters chosen to give shielded cross-sections required to fit reactor measurements	Parameters chosen from the types of experiments listed in Table 1	Parameters chosen from resolved resonance data
Average calculated capture cross-section* 5-6 keV 10-20 keV	 0.972 0.645	 0.885 0.547	 1.138 0.736	 1.04 0.68

*Values in last column from INDC(CCP)-11/U. Otherwise data in SANDC 90 L quoted.

Table 4

Results of Vankov et al[13]

	All parameters varied	$\langle\Gamma_\gamma\rangle$ and s-wave level spacing kept constant
S_o	$0.90(\pm 0.07) \times 10^{-4}$	$0.89(\pm 0.004) \times 10^{-4}$
S_1	$1.28(\pm 0.33) \times 10^{-4}$	$1.87(\pm 0.03) \times 10^{-4}$
s-wave level spacing	25.1 ± 1.4 eV	20.8 eV (fixed)
Effective scattering radius R'	9.232×10^{-13} cm	9.053×10^{-13} cm
$\langle\Gamma_\gamma\rangle$	17.2 ± 4.6 meV	24.8 meV (fixed)

Table 5

Best p-wave data from Byoun et al[14]

	Best Fit Parameters		
	A	B	C
S_1 ($\times 10^{-4}$)	1.58 ± 0.1	$1.94^{+0.1}_{-0.2}$	$2.40^{+0.1}_{-0.2}$
Mean p-wave (eV) level spacing (both spin states)	11.3 ± 2.0	$11.3^{+3.0}_{-3.5}$	$11.3^{+3.0}_{-2.0}$
$\langle\Gamma_\gamma\rangle$ p-waves (meV)	47.5 ± 8.4	$43.8^{+11.6}_{-13.6}$	$37.0^{+9.8}_{-6.6}$
Assumed data effective scattering radius R' (fm)	9.3	9.2	9.0
Radius for penetrability (fm)	8.74	8.74	8.4
S_o ($\times 10^{-4}$)		1.0	
s-wave level spacing (eV)		20.7	
$\langle\Gamma_\gamma\rangle$ s-waves (meV)		23.0	

PRELIMINARY RESULTS OF A SHAPE MEASUREMENT OF THE ^{238}U CAPTURE CROSS SECTION IN THE NEUTRON ENERGY RANGE 20-600 keV

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Kernforschungszentrum Karlsruhe
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Presented at the specialist's meeting on
"Resonance parameters of fertile nuclei [^{232}Th, ^{238}U, ^{240}Pu] and ^{239}Pu"
Saclay, France, May 20-22, 1974

INTRODUCTION

The lack of agreement in the value and shape of the neutron capture cross section of ^{238}U below 100 keV obtained in three recent high resolution time-of-flight measurements [1-3] suggests that further measurements of this important cross section may be of value. Since all three of the above mentioned experiments were carried out using linac produced neutrons it would seem that a measurement with the pulsed Van de Graaff making use of the ^{7}Li [p,n] ^{7}Be reaction for neutron production might provide a degree of experimental independence and in that way resolve previous difficulties. For example, the Van de Graaff technique has no interfering gamma-flash and, due to the very fast time-of-flight method employed, background considerations are very different and less complex than in the previous experiments. Also since ^{10}B was chosen as a neutron flux monitor in all three linac experiments, it was decided that the present measurements would make use of the very well known ^{235}U fission cross section for this purpose.

The present measurement will be carried out in three separate stages. In the first stage, the results of which are reported here, a shape measurement was made with the 800 liter liquid scintillator tank in the neutron energy region from 20 - 550 keV relative to the ^{235}U fission cross section. As an independent check a simultaneous measurement of the ^{197}Au [n,γ] yield was made. The second stage will consist of the calibration of a Moxon-Rae detector using a pulsed, monoenergetic neutron beam of 17 meV energy at the Karlsruhe, FR 2 Reactor, and capture samples of both gold and ^{238}U. Due to possible difficulties with the small amount of ^{235}U with relatively large fission cross section in the ^{238}U sample, the gold measurement may be essential. In the final stage several measurements in the keV neutron energy region will be performed at the pulsed Van de Graaff with this calibrated system using the same samples as in stage two.

The ^{235}U fission detector will be used as a neutron monitor for both the last two stages also. This then will provide the "absolute" capture cross section to be used as a reference for the shape measurement.

^{238}U CAPTURE SHAPE

The shape measurements were carried out using a thick lithium target to produce a "white" neutron spectrum for energies below about 160 keV and thin lithium targets giving "monochromatic" neutrons at higher energies. A 1 mm thick sample of 99.76 % purity ^{238}U, a 1 mm thick gold sample and a carbon sample for background determination were cycled into the detector at intervals determined by the proton beam integrator. Flight paths for all samples were 203.3 cm. A ^{235}U, gas scintillation, fission chamber operated with a flowing mixture of 85 % Ar-15% N_2 was placed in the collimated neutron beam before the scintillator tank. This chamber was carefully adjusted so that its two ^{235}U foils covered the entire beam. The ^{235}U was electrosprayed onto thin VYNS backings [4]. Thus both fission fragments were observed in coincidence to discriminate completely against the natural α-activity of the foils. Flight paths for the two fission foils were 92.15 and 98.75 cm. For the low energy [continuous energy] run the accelerator was pulsed at a 500 kHz repetition rate, whereas for the monochromatic neutron runs a 2.5 MHz rate was used. Capture events were stored in 256 channel [time] by 12 channel [pulse height] arrays and fission events for each sample were stored into 512 time channels. The scintillator tank is optically divided into quarters so that it was possible to carry out a "Voter" coincidence whereby a routing pulse was generated if simultaneous pulses occurred in any two of the quarters. Both "Voter" and "Non-voter" events were stored separately. This system differs from that used in reference [3] where halves were run in coincidence.

The results of these measurements are presented in Figures 1-3 where they are compared to other reported values. In Figure 1 the present results for the ^{238}U capture cross section shape as computed from the gold reference sample yield is shown as points with error bars representing counting statistics [which vary from $\pm$ 2.7 % at low energies to $\pm$ 0.7 % at high energies].

Figure 1 gives the result of the continuous energy run only. The gold cross sections of Kompe [5] were used in the calculations along with the "Voter" yields for both ^{238}U and gold. The spectrum fractions required [data counts divided by total capture events] for

both ^{238}U and gold were derived from an extrapolation of the "Voter " pulse height spectra to zero gamma-ray energy below our threshold of 2 MeV. Since this extrapolation could conceivably be in error, thus resulting in a systematic error in the calculated cross section of perhaps $\pm$ 10 % these results should be considered as a shape measurement only.

Using the ^{235}U fission cross section as evaluated by Sowerby, et al., [6] a totally independent result for the ^{238}U capture shape was derived from the ^{238}U capture yield and ^{235}U fission chamber counts. These values are shown as horizontal lines in Figure 1 and include corrections for the energy dependences of the spectrum fraction, air scattering between fission chamber and sample, and self shielding plus multiple scattering. In order to achieve reasonable statistics in the fission chamber counts, channels were added together corresponding to 10 keV neutron energy intervals up to 100 keV and 20 keV intervals at higher energies. The resulting relative cross sections were normalized to the average value [210.8 mb] obtained for the present gold reference result in the region from 90 to 100 keV energy.

The shape calculated in this way is seen to be in excellent agreement with the shape obtained with the gold reference. Also shown are the decimal interval averaged results of the experiments of references [1-3]. These values were taken from Table VI of reference [3]. It may be seen that the present cross section shapes for ^{238}U capture are in excellent accord with the shape of the reference [3] results [to approx. 1 %], show some deviations from that of reference [1] and agree well with reference [2] at high energies but show a large deviation [12-15 %] at lower energies.

It should be noted that the total estimated error for the data of reference [3] are given by the length of the data bar and is somewhat representative [although not exactly so] of the total errors estimated for the data of references [1,2].

In Fig.1 a significant fine structure in the ^{238}U capture cross section as computed from the gold reference data was observed, particularly in the region below 50 keV. Figure 2 is an enlarged plot of this region showing the present results and a replot of the

high resolution results of de Saussaure, et al., [3]. The latter were averaged over the same energy intervals as the present results. It may be seen that the present results and those of reference [3] are in excellent agreement with regard to the fine structure in addition to the overall shape agreement shown previously.

Finally, in Figure 3 is shown a plot of the present results from E_n = 20 to 550 keV of the ^{238}U capture cross section shape referenced to the ^{235}U fission cross section evaluation of Sowerby et al. [6] and normalized to the value 210.8 mb at 95 keV. The large gap in the 150-300 keV region was caused by the loss of three thin target runs due to electronic difficulties and these runs will be repeated in the near future. For comparison the evaluated ^{238}U capture cross section of ref. [6] is also shown. The present results normalized to 210.8 mb at 90-100 keV lie 6-10 % higher than the evaluation in the region below 150 keV.

CONCLUSIONS

The present measurements show a very good internal consistency between the gold referenced and ^{235}U σ_f referenced capture cross section of ^{238}U. This is of utmost importance because the gold referenced measurement totally eliminates any air scattering correction and also makes negligable any shape dependence on the multiple scattering and self-shielding correction [the latter correction is virtually the same for the gold and uranium samples].

The present results represent the first good shape confirmation in recent time-of-flight measurements of the ^{238}U capture cross section in the neutron energy region below 100 keV. This agreement strongly suggests that this shape is now quite well determined and that future measurements should be primarily directed to obtaining an absolute cross section at one or more energies in the keV range. It should be pointed

out that such absolute measurements should be carried out under conditions of known neutron flux shape, preferably with relatively good energy resolution since measurements with very poor resolution can give significant errors even for a $^{1}/v$ cross section. The structure observed near 30 keV could enhance this effect.

In conclusion it should be stated clearly that the numerical results of the present experiments which will be of significance are not the cross section values used here to illustrate the fluctuations in shape, rather the cross section ratios ^{238}U capture to ^{235}U fission, ^{238}U capture to ^{197}Au capture, and ^{197}Au capture to ^{235}U fission. These ratios are currently being derived and will be reported at a later date in tabular form.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to A. Ernst, S. Liese, and D. Roller of the Van de Graaff staff for their diligent operation of the accelerator and data handling facilities. We also thank Dr. H. Beer who carried out the computations of self-protection and multiple scattering corrections for the samples used here.

Note Added in Proof

It was brought to the authors' attention by Dr. Moxon at this meeting that there exists a recent absolute measurement of the capture cross section by Ryves, et al., Journ. of Nuclear Energy, 27 (1973) 519. For the neutron energy range 157 ± 20 keV these authors give $\sigma_{CAPT.}$ (^{238}U) = 162 mb with a standard deviation of 2.4% . Averaging of our gold referenced data over this same neutron energy interval yields a value σ_{CAPT} (^{238}U) = 159 ± 0.5 mb where the error accounts for counting statistics only. Although this energy region may contain some effect due to inelastically scattered neutrons being recaptured in the samples (both ^{238}U and gold), this effect is not expected to be large. Therefore, the excellent agreement of the present data with the Ryves result would appear to show that our analysis of the Voter spectrum fractions was valid.

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3.] G. de SAUSSURE, et al., Nuclear Science and Engineering, 51 [1973] 385 and ORNL-TM-4059, Oak Ridge National Laboratory [1973].

4.] J. VERDINGH and K.F. LAUER, Nucl. Instr. Meth. 21 [1963] 161.

5.] D. KOMPE, Nucl. Phys. A 133 [1969] 513.

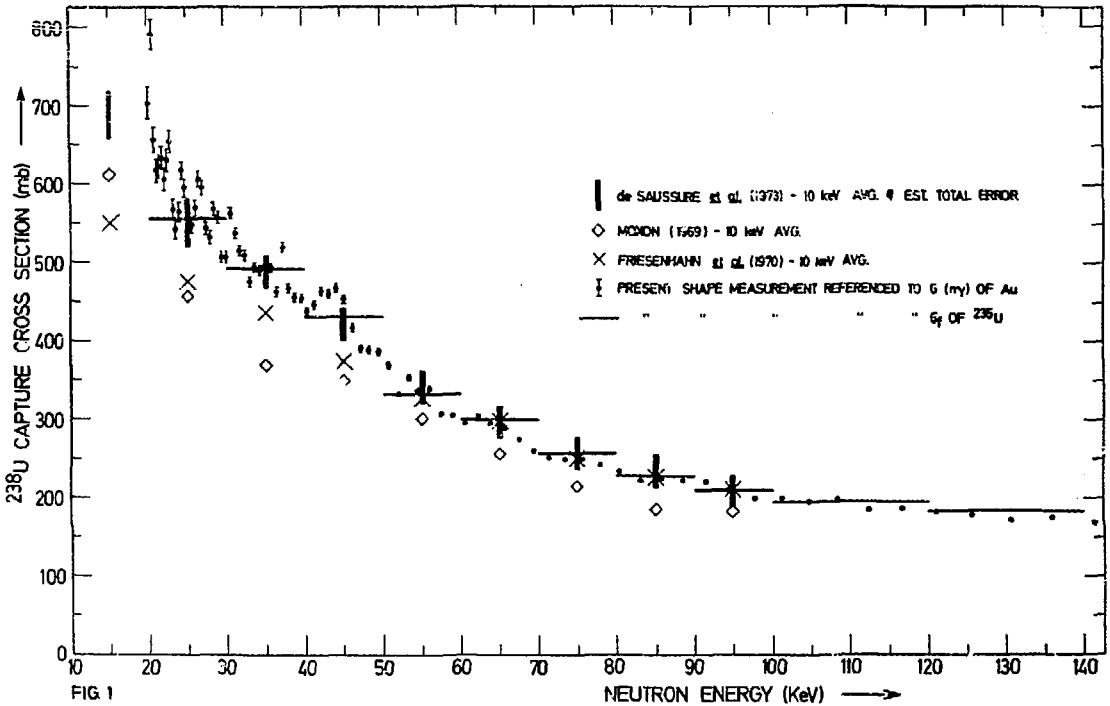
6.] M.G. SOWERBY, B.H. PATRICK and D.S. MATHER, AERE-R 7273 U.K. Atomic Energy Authority, Harwell [1973].

FIGURE CAPTIONS

Fig. 1: Present results of the shape measurement of the ^{238}U [n, γ] cross section referenced to σ [n, γ] for ^{197}Au and to $\sigma_{fission}$ for ^{235}U compared with three other recent time-of-flight measurements. Error bars on the ^{197}Au referenced result demonstrate counting statistics only.

Fig. 2: Comparison of the detailed structure of the present ^{238}U [n, γ] cross section [referenced to σ [n, γ] for ^{197}Au] with the very high resolution data of reference [3] averaged to give the present energy resolution. Errors bars represent counting statistics only.

Fig. 3: Comparison of the present result for the ^{238}U [n, γ] cross section [referenced to $\sigma_{fission}$ for ^{235}U and normalized to 210.8 mb at 95 $\pm$ 5 keV] with the evaluation of ref. [6].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200
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40
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60
70
80
90
100
110
120
130
140
238U CAPTURE CROSS SECTION (mb)
NEUTRON ENERGY (KeV)
de SAUSSURE et al. (1973) - 10 keV AVG. & EST. TOTAL ERROR
MOXON (1969) - 10 keV AVG.
FRIESENHAHN et al. (1970) - 10 keV AVG.
PRESENT SHAPE MEASUREMENT REFERENCED TO σ (n,γ) OF Au
" " " " " σf OF 235U

FIG. 1

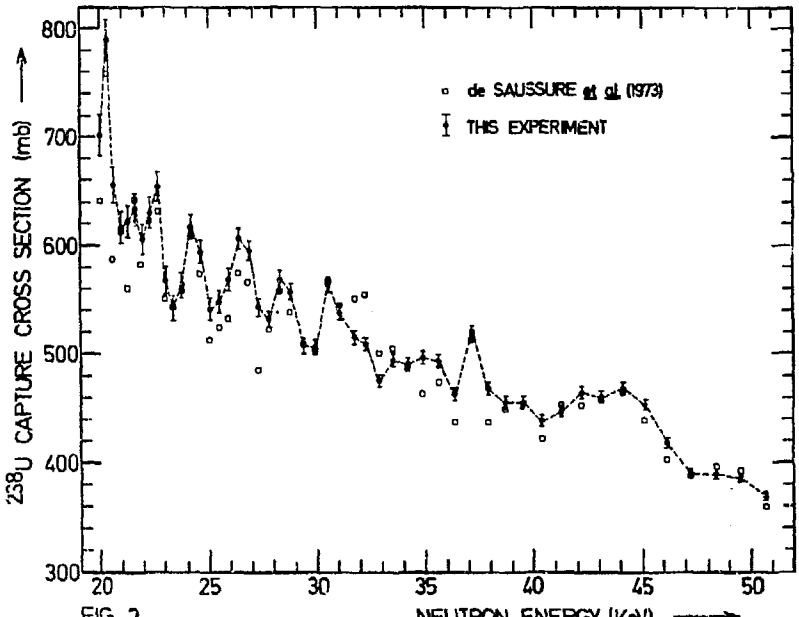
800
700
600
500
400
300
^{238}U CAPTURE CROSS SECTION (mb)
20
25
30
35
40
45
50
NEUTRON ENERGY (KeV)
de SAUSSURE et al. (1973)
THIS EXPERIMENT

FIG. 2

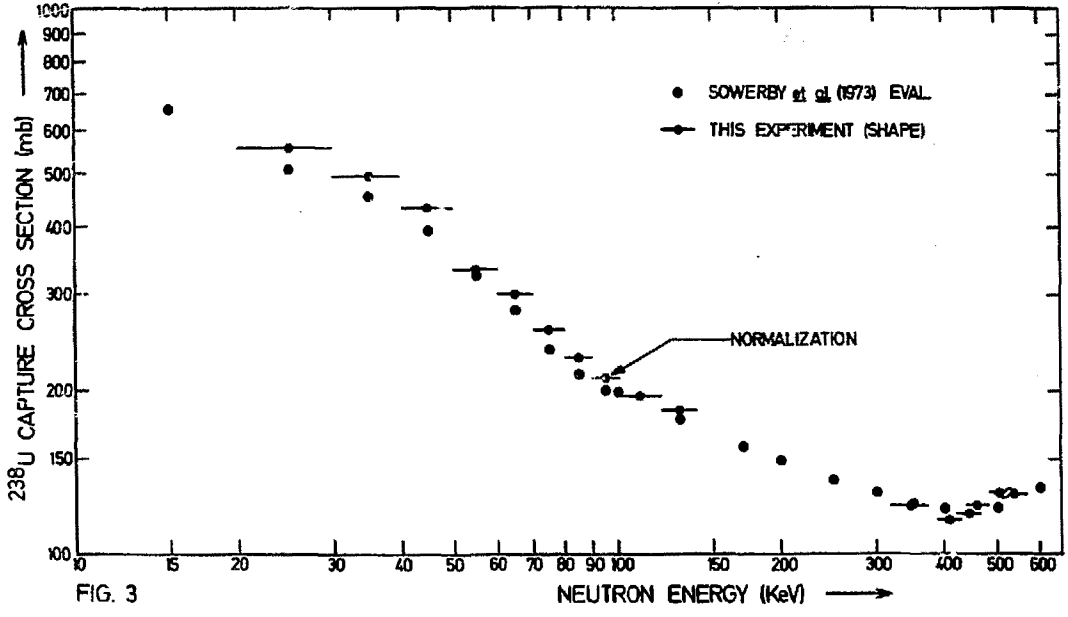
1000
900
800
700
600
500
400
300
200
150
100
238U CAPTURE CROSS SECTION (mb)
10
15
20
30
40
50
60
70
80
90
100
150
200
300
400
500
600
NEUTRON ENERGY (KeV)
SOWERBY et al. (1973) EVAL.
THIS EXPERIMENT (SHAPE)
NORMALIZATION

FIG. 3

RECENT MEASUREMENTS ON 238 U AT ORNL

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In 1972, Perez, Silver and I completed a series of measurements of the capture cross section of U-238 in the range 5 eV to 100 keV, using a large liquid scintillator. These measurements have been discussed in detail in ORNL-TM-4059 and in Nucl. Sci. and Eng.

We have compared our data to the two previous sets of data obtained by the time-of-flight technique, those of Moxon (Harwell) and Friesenhahn et al. (G.G.A.). The three sets of data show systematic discrepancies which are larger than the known uncertainties of the measurements.

To attempt to resolve these discrepancies, Perez, Macklin, Halperin and I have started a new series of measurements with a detector entirely different from that used in 1972. We hope that a comparison of the results obtained between the two different systems will help in identifying the reasons for the discrepancies.

We have not yet reduced the data obtained in this last series of measurements to the point where we can say with which previous measurement they agree, if any.

I shall briefly describe the experimental techniques used in the two series of ORNL measurements, then I will discuss some of our 72 results, in the resolved range.

Fig. 1 (68-10873R) shows the large liquid scintillator detector. It contains 3000 ℓ of NE-224 poisoned with trimethylborate, and is viewed by 32 photomultipliers. An aluminized mylar foil, not shown, separates the tank in two halves. Coincidence signals between these two halves and singles are stored separately. The U-238

sample, a disk of about 8-cm diameter, was placed in the center of the tank and decoupled from the scintillator by a ^{6}LiH liner, 2.5 cm thick.

We stored separately the coincidences and singles as well as two pulse-height groups, but we did not observe significant systematic changes in the ratio of coincidences to singles or in the PH distribution, either with energy, or from level to level in the resolved range.

Fig. 2 (69-1344R) illustrates that the signal to background ratio is about eight times better in the coincidences than in the singles and that the ratio of singles to coincidences remains constant from level to level, within our accuracy of approximately 5%.

Fig. 3 (70-11350) illustrates how the background was determined. The level of the background is obtained in the notches of a set of resonance filters. Inbetween these notches the shape of the background is obtained from a run where the uranium is replaced by lead (with minor corrections for the capture in lead). This background shape is mostly determined by the lifetime of the scattered neutrons in the tank and is not a sensitive function of the thickness of lead used.

From the runs with the notch filters we determined the net counts per incident neutron away from the notches. From a second set of runs without notch filters we then obtain the net count rate over the regions with notches.

Fig. 4 (70-7209) illustrates the incident neutron spectrum with and without the notch filters. This spectrum was measured with a BF_3 ionization chamber and with a 1-mm thick ^{6}Li glass. The two measurements agreed within 3% over decimal intervals up to 100 keV. The structure above 20 keV is caused by the filtering of the beam by a 20-mm aluminum housing surrounding the ORELA moderator. This housing was later replaced by beryllium and the spectrum became much smoother. The neutron spectrum decreases at low energies due to a ^{10}B overlap filter.

Fig. 5 (71-2354R2) illustrates the normalization of the data by the saturated resonance technique. The solid line was obtained by a Monte Carlo calculation, which is insensitive to the exact value of the resonance parameters. It is difficult to see how this normalization could be in error by more than 2%.

In order to obtain average capture cross sections, the data must be corrected for multiple scattering and resonance self-shielding. Above 4 keV this correction is less than 4% for the two sample thicknesses used and we have evaluated it by a method due to Dresner and coded by R. L. Macklin. Below 4 keV and particularly over the 100 eV wide intervals, the statistical approach breaks down and we have used the ENDF/B-III resonance parameters (which are in fair agreement with our data) to compute the RSP and MS corrections by a Monte Carlo technique. For the thick samples used in the measurement (.0028 at/b) the correction becomes as large as 300%; for the thin sample (.0004 at/b) it is always smaller than 40%.

Before discussing discrepancies between measurements I like to describe briefly the detector used in our new series of measurements. This detector was designed by Macklin and is illustrated in Fig. 6 (69-14021).

The rectangular sample, perpendicular to the neutron beam, is placed between a pair of non-hydrogeneous scintillator cells (NE-226) viewed by photomultipliers. On line pulse-height weighting insures that the capture detection efficiency is independent of multiplicity and function only of the total energy released (binding energy). The BF_3 and proton recoil monitors shown in the figure have now been replaced by a .5-mm ^6Li glass monitor. The normalization is done by the saturated resonance technique. The scattering background is obtained by replacing the uranium sample by a lead sample and is normalized to the main run by the ratio of the monitor counts.

Turning now to the discrepancies among measurements, Fig. 7 (72-12634R) illustrates three data sets averaged over decimal intervals in the range .5-100 keV. Our data agree, more or less within errors, with Moxon's up to 10 keV and with Friesenhahn's above 50 keV. From 10 to 50 the three sets of data are inconsistent and over most of the range .5-100 keV at least one set of data is inconsistent with the others. Note also that in the interval .9 to 1 keV our capture is 25% larger than that of Moxon.

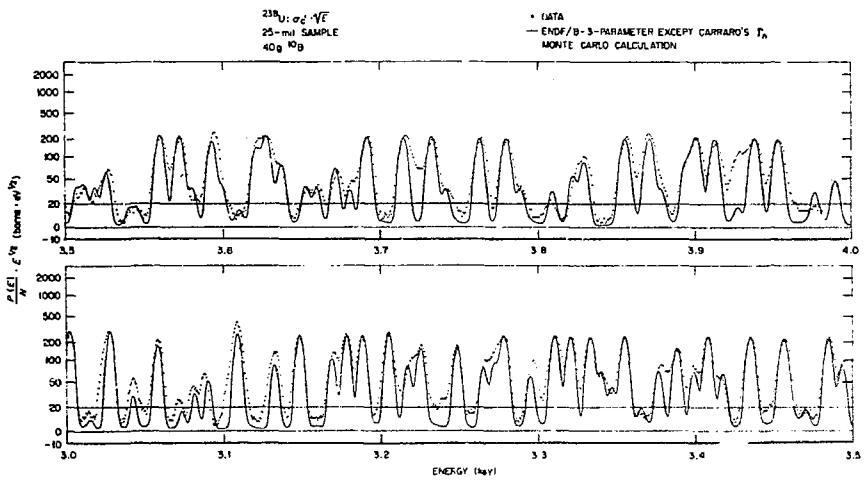
In Fig. 8 (72-12954) we compare our data averaged over 50 eV intervals (solid line) with data obtained with Van de Graaff's and other monoenergetic sources. Within the rather large uncertainties of these earlier data, and the large fluctuations of the cross section, the various sets of data are consistent with ours. Probably a comparison of the recent time-of-flight data on a scale that shows these fluctuations could help in identifying sources of discrepancies such as errors in energy scale or in backgrounds.

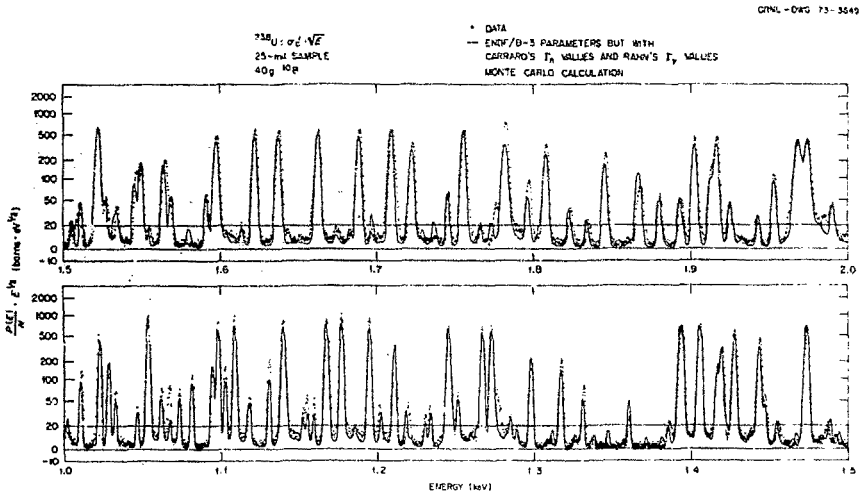
Fig. 9 (72-12306) illustrates a comparison between our results and a calculation based on ENDF/B-III. The discrepancies are mostly in the area and peak values of particular levels, such as those near 1100 eV and some small levels at lower energies. In the range .9 to 1 keV our value of the average capture is 27 $beV^{1/2}$ higher than that of Moxon. The figure seems to rule out that the discrepancy could be due to an under-estimate of the background.

Fig. 10 (73-3649) and 11 (73-4917) show comparisons between our data and calculations based on the neutron widths published by Carrara. Again our data indicate more capture than predicted by the resonance parameters, and the discrepancy is not systematic but concentrated on a few levels.

In conclusion, we are still puzzled by the discreapncies between different measurements. We are attempting to better identify the source of these discrepancies by new measurements using different techniques and followed by detail comparisons of the data from the different measurements. We shall also shortly do some transmission experiments and analyze our low energy data for resonance parameters.

ORNL - DWG 73-4917




^{238}U: $\sigma_c^2 \cdot \sqrt{E}$
25-ml SAMPLE
40g ^{10}B
* DATA
— ENDF/B-3 PARAMETERS BUT WITH
CARRARO'S Γ_n VALUES AND RAHN'S Γ_γ VALUES
MONTE CARLO CALCULATION
$\frac{\rho(E)}{N} \cdot E^{1/2}$ (barns · eV$^{1/2}$)
2000
1000
500
200
100
50
20
0
-10
1.5
1.6
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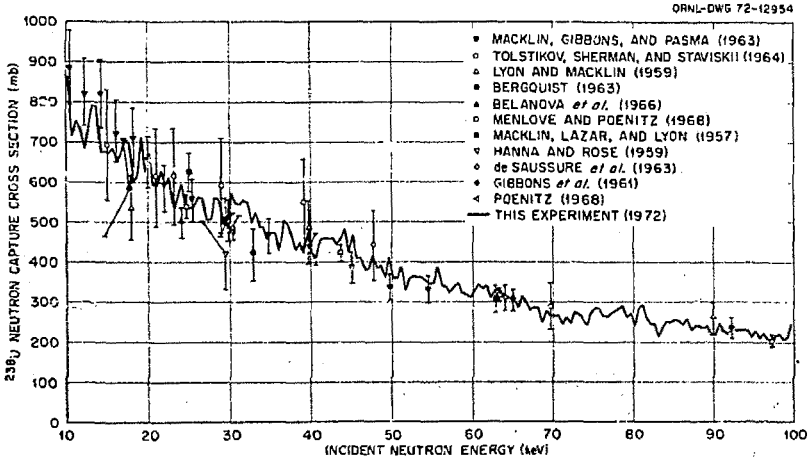
1.3
1.4
1.5
ENERGY (keV)


ORNL-DWG 72-12954
MACKLIN, GIBBONS, AND PASMA (1963)
TOLSTIKOV, SHERMAN, AND STAVISKII (1964)
LYON AND MACKLIN (1959)
BERGQUIST (1963)
BELANOVA et al. (1966)
MENLOVE AND POENITZ (1968)
MACKLIN, LAZAR, AND LYON (1957)
HANNA AND ROSE (1959)
de SAUSSURE et al. (1963)
GIBBONS et al. (1961)
POENITZ (1968)
THIS EXPERIMENT (1972)
238U NEUTRON CAPTURE CROSS SECTION (mb)
INCIDENT NEUTRON ENERGY (keV)
0
100
200
300
400
500
600
700
800
900
1000
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20
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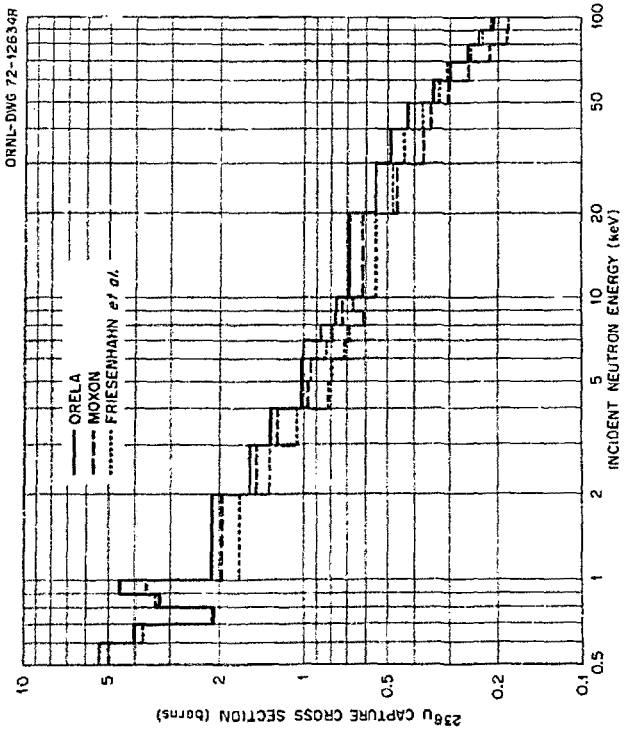
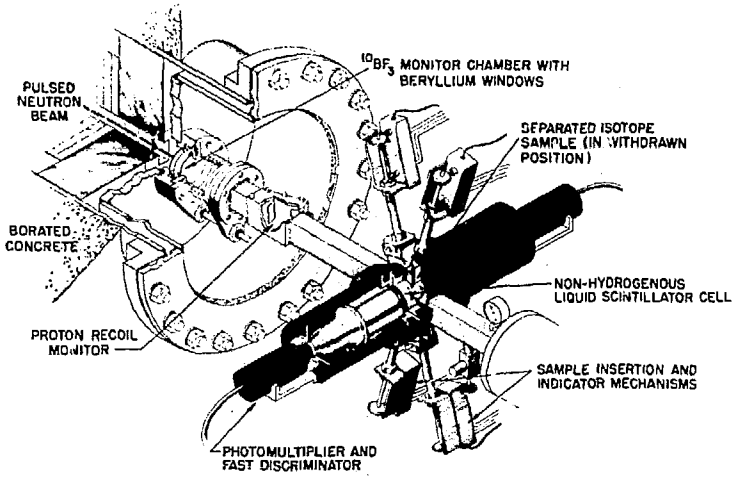
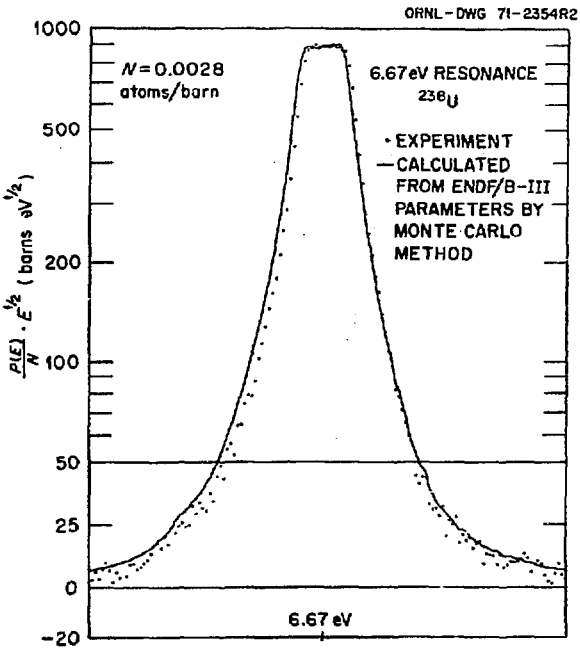
80
90
100


ORNL-DWG 72-12634R
ORELA
MOXON
FRIESENHAHN et al.
^{238}U CAPTURE CROSS SECTION (barns)
10
5
2
1
0.5
0.2
0.1
0.5
1
2
5
10
20
50
100
INCIDENT NEUTRON ENERGY (keV)

ORNL DWG 69-14021



ORELA Neutron Capture Cross Section Experiment (FP 7, 40m)


ORNL-DWG 71-2354R2
N = 0.0028
atoms/barn
6.67eV RESONANCE
238U
• EXPERIMENT
— CALCULATED FROM ENDF/B-III PARAMETERS BY MONTE CARLO METHOD
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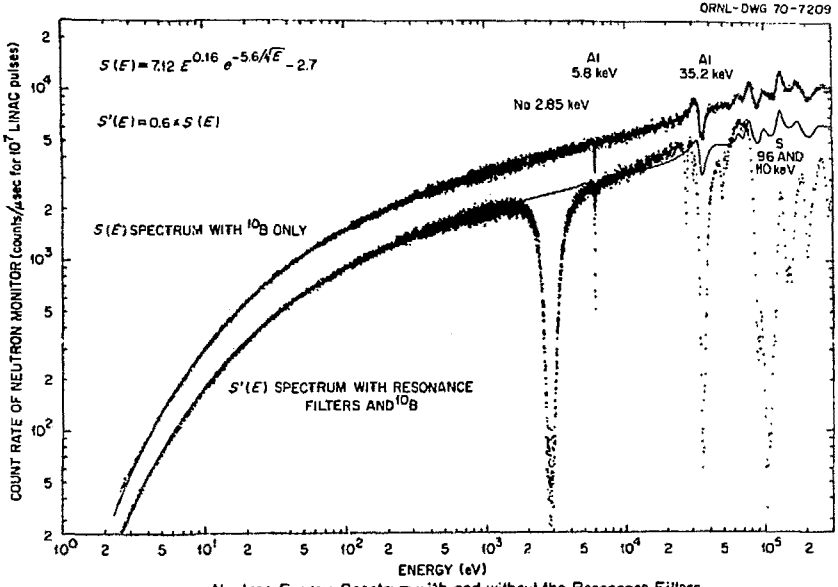
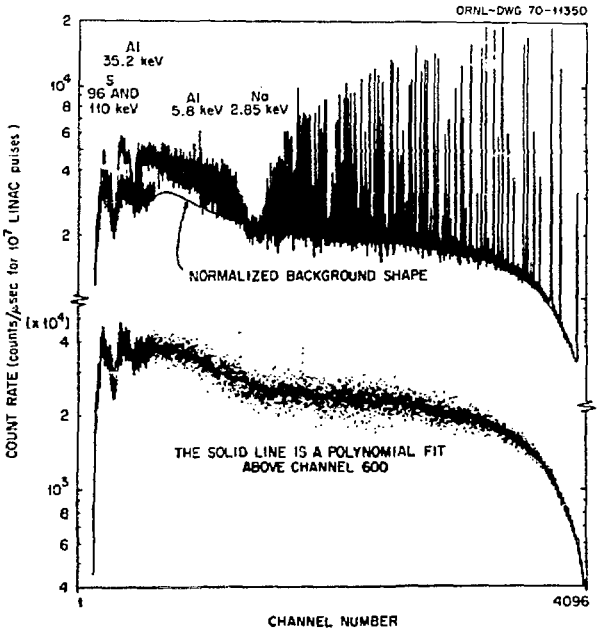
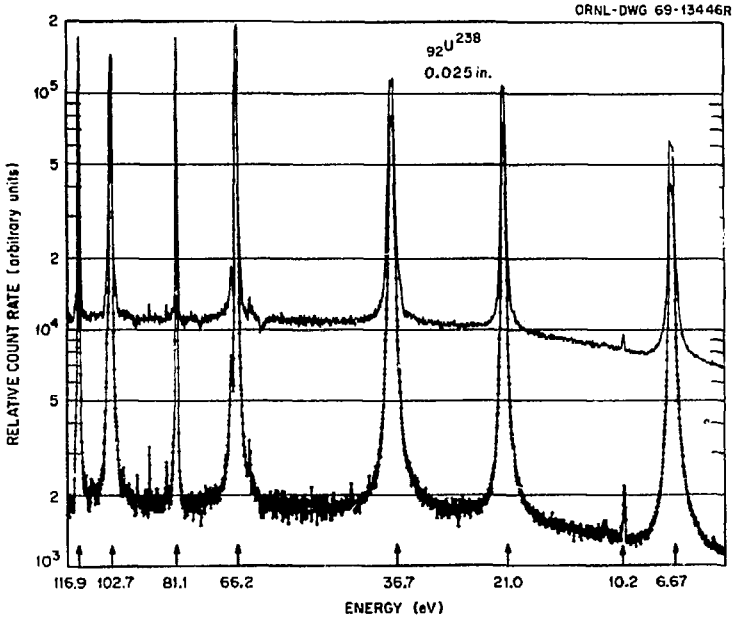
200
100
50
25
0
-20
6.67 eV
P(E)/N · E^1/2 (barns eV^1/2)



Neutron Energy Spectrum with and without the Resonance Filters.



Shape of Background—Measured with a 0.003-in. Pb Sample.


ORNL-DWG 69-13446R
$_{92}U^{238}$
0.025 in.
RELATIVE COUNT RATE (arbitrary units)
2
10^5
5
2
10^4
5
2
10^3
116.9
102.7
81.1
66.2
36.7
21.0
10.2
6.67
ENERGY (eV)

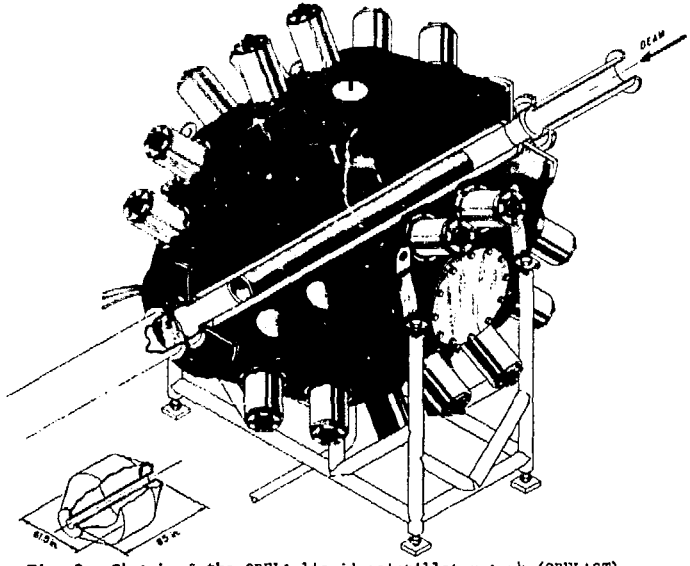


Fig. 3. Sketch of the ORELA liquid scintillator tank (ORELAST). The tank is viewed by thirty-two 5-in.-diameter RCA 4522 photomultipliers; it was separated into two equal halves with an aluminum reflector located in the vertical plane containing the beam axis. This separation is not shown on the figure.

AN EVALUATION OF ^{240}Pu RESONANCE PARAMETERS

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ABSTRACT

The status of data on ^{240}Pu resonance parameters is reviewed. Some statistical tests are performed on the data and recommendations are given, particularly with respect to the average parameters.

I. Introduction

There have been several extensive evaluations of the neutron cross-sections of ^{240}Pu, including its resonance parameters[1-3]. Since the most recent one[3] had appeared, there have been important changes in the experimental data, particularly what concerns the parameters of resolved resonances[4, 5], and new data have become available[6]. In the following we will give a survey of the present status of our knowledge about the resonance parameters and some related properties of cross-sections of ^{240}Pu: In section II we will discuss the cross-sections in the thermal region and the parameters of the first strong resonance at 1.056 eV neutron energy; in section III we will compare the available data on the parameters of resolved resonances and discuss, in section IV, their statistical properties; finally, in section V, some information on average resonance parameters will be obtained from the cross-sections in the unresolved resonance region.

II. Cross-sections in the thermal energy range and parameters of the first resonance at 1.056 eV

Various evaluations have been made for the resonance parameters of the first resonance. These evaluations were based on results of transmission measurements in this resonance, performed with crystal spectrometers or fast choppers in the period 1955 - 1959. In general, the parameters were adjusted in order to get a thermal cross-section value consistant with the measured results.

In the last evaluation done by L'Heriteau and Ribon[3], the following parameters are recommended:

$$E_o = 1.056 \pm 0.002 \text{ eV} \qquad \Gamma_n = 2.30 \pm 0.15 \text{ meV} \qquad \Gamma_\gamma = 32.2 \pm 2 \text{ meV}$$

The value of Γ_γ has been adjusted to get a thermal capture cross section $\sigma_{c\,2200} = 281 \pm 5$ barns.

Since 1970, two new measurements have been performed:
1) Ramakrishna and Navalkar[7] did transmission measurements in the first resonance using a crystal spectrometer and obtained the following results:

from a shape analysis:

$\Gamma_\gamma = 28.8 \pm 3$ meV $\qquad \Gamma_n = 2.18 \pm 0.1$ meV

from an area analysis:

$\Gamma_\gamma = 28.7 \pm 2$ meV $\qquad \Gamma_n = 2.15 \pm 0.10$ meV

These results disagree with the previously published values and are inconsistent with a thermal cross-section value $\sigma_\gamma = 281$ barns. It must be noted however that their experiments were performed with a very bad neutron energy resolution and with a sample containing only 9.24% of ^{240}Pu.

2) Lounsbury et al.[8] have obtained a very precise value for the thermal capture cross-sections:

$$\sigma_c = 289.5 \pm 1.4 \text{ b.}$$

i.e. about 3% higher than the value to which the parameters of the first resonance had been adjusted in ref.[3]. On the other hand, we estimate a contribution of about 2 barns to the thermal cross-section from the higher energy resonances. Allowing for a similar contribution from bound states as well, we estimate that the 1.056 eV resonance may contribute about 286 barns to the thermal cross-section. Thus we adjust the parameters of the first resonance to

$E_o = 1.056 \pm 0.002$ eV $\quad \Gamma_n = 2.34 \pm 0.15$ meV $\quad \Gamma_\gamma = 32.2 \pm 2$ meV

III. Parameters of resolved resonances

a) General

As far as the parameters of resolved resonances are concerned, the evaluation of L'Heriteau and Ribon[3] was based on two sets

of data available in 1970, from measurements at Geel and Harwell. The Geel data included a measurement [9] of the total cross section up to 5.7 keV neutron energy and measurements of the capture [10] and, for a few resonances, elastic scattering cross section [11], up to 820 eV. The Harwell data [12] include all three types of measurements too, but go up to only 1 keV neutron energy, also for the total cross-section, and resonance parameters were available only up to 287 eV. In both cases, the capture data were normalized to the capture rate at the 20 eV resonance.
The two data sets showed internal inconsistancies and systematic discrepancies which were extensively discussed in ref. [3].
More recently, it has been shown [4] that essentially all of the difficulties were due to wrong parameters used in ref. [10], [12] for the 20 eV normalization resonance. New, very careful measurements of this resonance performed at Harwell [4] which apply normalization to the capture rate at the 1.056 eV resonance, yielded Γ_n = 2.65 meV and Γ_γ = 32.2 meV for the 20 eV resonance, i.e. larger than assumed before by 29% and 58%, respectively.
Both, the Harwell and Geel capture data have been re-analysed with the improved normalization due to these parameters, and the renormalized Geel set has been published [5]. Already before, a new set of resonance parameters from total and capture cross section measurements at RPI had been published [6]. In this case, the capture data were normalized by comparison of the measured capture area of the 92.5 eV resonance to the area calculated with the aid of the resonance parameters as obtained from the simultaneous transmission experiment. This normalization was checked to another one based on the 20 eV resonance and a cross normalization to Au.
The parameters of ^{240}Pu resonances up to 665 eV neutron energies as given by these three experiments are listed in table 1. Only the neutron widths from the Geel transmission data extend above this energy (up to 5.7 keV).

b) Neutron widths

By far the most extensive set of neutron widths of ^{240}Pu resonances is due to the total cross-section data from Geel [9].
In this set, the values obtained for a few strong resonances at very low neutron energies were influenced by the low value assumed for Γ_γ. These resonances have therefore been re-analysed and the results are given in table 2.

Table 2: Results from a re-analysis of the Geel transmission data [9]

Resonance energy (eV)	Neutron width (meV)
(20.45)	(2.65 ± 0.07)
38.32	17.0 ± 1.0
41.62	15.5 ± 1.0
66.62	52.0 ± 2.0
72.78	21.0 ± 1.0
105.00	43.0 ± 2.0
121.6	14.5 ± 1.0
287.1	132 ± 7
405.0	108 ± 5
665.1	195 ± 8

For the 20 eV resonance, we have adopted the Harwell-value [4].
With two exceptions, the above improved neutron widths are identical to those given in ref. [5] as resulting from a combined analysis of the Geel transmission, capture and scattering data; the two exceptions are the very strong resonances at 66.62 eV and 287.1 eV, where the scattering data are probably less accurate due to larger multiple scattering effects. With the above changements applied, the neutron widths of ref. [illegible] in the range of overlap, i.e. below 500 eV neutron energy, in very good agreement with the two other sets. We finally recommend the revised Geel set of neutron widths because of the following reasons:
First of all, the Geel transmission measurements are by far the most extensive ones, both with respect to the energy range covered as well as with respect to the number of individual runs with

different sample thicknesses. Secondly, in combining this set with the set of recommended Γ_γ -values of the next paragraph, one obtains a set of quantities $\Gamma_n \Gamma_\gamma / \Gamma$; they may be compared to the corresponding quantities from the three different laboratories: For all of the 6 resonances where Γ_γ is given by all three laboratories, the "recommended" $\Gamma_n \Gamma_\gamma / \Gamma$ differs from the average over the three individual values by less than 1%. Finally, the difference between the three sets of neutron widths are usually very small, with in most cases the Geel value lying in between the two others. Remarkable differences occur essentially for reronances which are either particularly large or particularly small; but it is in these cases that measurements with strongly different sample thicknesses are most important.

The recommended neutrons widths are listed in table 3.

c) Radiative widths

There are three extended sets of radiative widths for ^{240}Pu resonances, from the measurements at RPI [6], and the renormalized sets from Harwell [4] and Geel [5]. They differ systematically, in the sense that the Geel values are on the average, about 8% larger than those of RPI, with the Harwell data lying in between, although the difference is inside the combined experimental errors which are mainly due to normalization uncertainties. In all cases, the radiative widths have essentially been obtained from combining the capture cross-section measurement with a transmission experiment which practically determines the neutron widths.
Under this circumstance and as long as not always $\Gamma_n > \Gamma_\gamma$ an error in the normalization of the capture measurement which is an error on the quantities $\Gamma_n \Gamma_\gamma / \Gamma$, causes an error on Γ_γ which is the larger, the smaller Γ_n. Also a systematic error in the transmission measurement (Γ_n -values) has a similar effect.
Therefore, the correlation coefficients corr $\{\Gamma_n, \Gamma_\gamma\}$ between neutron and radiative widths have been calculated for the three

sets of data, and are given below:

Laboratory	RPI	Harwell	Geel
corr$\{\Gamma_n \Gamma_\gamma\}$	0.35 ± 0.23	-0.07 ± 0.25	-0.13 ± 0.26

where the errors are given by $(1 - \mathrm{corr}^2)/\sqrt{n}$, and indicate the uncertainty of the correlation coefficient due to the limited size n of the sample. The figure for the Harwell set changes drasticaliy if one omits the last resonance (with by far the largest Γ_n) at 267.1 eV, namely to corr $\{\Gamma_n \Gamma_\gamma\} = +0.44 \pm 0.21$.
Principally, a positive correlation between neutron and radiative widths could also arise from an insufficient treatment of multiple scattering corrections or a sensitivity of the capture γ-ray detector for scattered neutrons. However, for the case of ^{240}Pu we exclude this possibility, because the same methods as used in ref. [6] have successfully been applied by the same authors to much more critical cases (larger ratios Γ_n/Γ_γ) like structural materials. Although they are at the limit of being significant, the above correlation coefficients indicate that for the RPI (Geel) data set the radiative widths are the smaller (larger), the smaller Γ_n. According to the above discussion, this may be explained by a too low (too high) normalization of the capture cross-section data (however, as mentioned above, it might also be due to systematic errors in the transmission data). In fact, comparing values of $\Gamma_n \Gamma_\gamma/\Gamma$ from the three different laboratories, it turns out that the Geel values are, on the average, 3% higher than those from RPI, with again the Harwell ones lying in between.
All of this would explain the systematic difference in the three sets of radiative widths and indicate that the correct values should lie in between the two extreme ones.

One may further ask the question whether the scatter of individual Γ_γ-values around their average as observed in the experimental data, is physically real, or just an expression of the experimental uncertainties. To answer this question, we have calculated the

correlation coefficients corr$\{\Gamma_\gamma(1), \Gamma_\gamma(2)\}$, where (1) and (2) stand for any two of the three data sets:

(1) - (2)	RPI-Geel	Harwell-Geel	RPI-Harwell
corr$\{\Gamma_\gamma(1), \Gamma_\gamma(2)\}$	0.45 ± 0.28	0.44 ± 0.31	-0.17 ± 0.29

At first sight, the situation seems confusing. However, one has to recognize that the three correlation coefficients are calculated from different subsets of the data corresponding to different energy intervals. The fact that for two out of the three combinations the correlation coefficient is positive, seems to indicate, to our opinion, that most of the scatter may be regarded as physically real.

In table 3 we give a final set of recommended radiative widths. They have been obtained in the following way: First of all, each individual set of radiative widths has been renormalized by multiplication with a factor $f = 30.6\ \text{meV}/\bar{\Gamma}_\gamma$, where $\bar{\Gamma}_\gamma$ is the average radiative width as given by the respective laboratory (see next section) and the value of 30.6 meV is the average of the three $\bar{\Gamma}_\gamma$-values. Then, for resonances where more than one Γ_γ-value is available, the average of these is taken.

d) Fission widths

The fission widths of ^{240}Pu resonances are characterized by the well-known intermediate structure. Many intermediate structure peaks have been observed, but only in the first one at ~ 780 eV neutron energy the experimental resolution of the data of ref.[13] is sufficient to unambiguously determine the fission widths of the individual resonances. They are included as recommended values in table 3. An analysis of this intermediate structure group with the maximum likelihood method described in ref.[14] yields the parameters

$E_{II} = 778\ eV \quad \Gamma^{\uparrow} = 12.5\ eV \quad \Gamma^{\downarrow} = 0.16\ eV$ (assuming $\Gamma^{\uparrow} \gg \Gamma^{\downarrow}$)

in reasonable agreement with more rough estimates made before.

Besides of the resonances within the 780 eV intermediate structure peak, individual fission widths are known for the first three resonances. The fission widths recommended in ref. [1,3] for the 20.46 eV and 38.32 eV resonances have to be changed, because they are based on measured ratios Γ_γ/Γ_f and a low assumed value of Γ_γ. The revised values are also included in table 3.

IV. Average Resonance Parameters and Statistical Properties

a) Level spacing and s-wave strength function

Following ref. [9], in the discussion of statistical properties of neutron widths we limit ourselves to the neutron energies from thermal to 1.5 keV, because in this range the number of missed levels is still small. The distribution of experimental neutron widths (ref. [3,9]) shows that all observed levels may be regarded as s-wave.

Application of a missed level analysis using a Fortran program similar to that as has been used by Fuketa and Harvey [15], which takes into account the experimental bias ($\delta = 4.1 \cdot 10^{-9}\, E^{1.4}$) for the detection of weak resonances, yields the following parameters which we recommend:

$$D(l = 0) = (12.7 \pm 0.3)\ \text{eV}; \qquad S_o = (1.04\ ^{+0.14}_{-0.12}) \cdot 10^{-4}$$

The error on S_o is obtained according to the prescriptions of Liou and Rainwater [17], whereas the error on $D(l = 0)$ includes an estimate of the uncertainty in determining the number of missed levels ($\pm$ 3 out of 117).

The values given here differ slightly from those of ref. [3]; for $D(l = 0)$ this is due to the different method of analysis, whereas the difference in S_o is due to the changes in the neutron widths for a few low energy resonances as discussed in section III b.

b) Average radiative widths

For the average radiative widths, there are 3 experimental values. Additionally, a statistical model estimate is given in

ref.[16]. These data are compared in table 4.

Table 4: Average radiative widths for ^{240}Pu resonances

Laboratory	Source	$\bar{\Gamma}_\gamma$ (meV)	Quoted error %
RPI [6]	experiment	29.5	5
Harwell [4]	experiment	30.2	not given
Geel [5]	experiment	32	8
Geel [16]	stat. model	32	25

The (small) difference between the experimental values has been discussed in section III c); from this discussion, we expect the true value to lie approximately half way between the extreme figures and finally recommend the average of the individual recommended radiative widths of table 3:

$$< \Gamma_\gamma > = (30.8 \pm 1) \text{ meV}$$

c) Fission widths

The problem of the statistical properties of the fission widths of ^{240}Pu is more complex than that of neutron and radiative widths.

First of all, one has the intermediate structure peaks. For the average parameters characterizing their properties, only rough estimates may be given. From ref. [6, 13] we estimate the average spacing of the intermediate structure groups to be

$$D_{II} = (650 \pm 100) \text{ eV}$$

For the parameters $\Gamma^\uparrow$ and $\Gamma^\downarrow$ (again we assume $\Gamma^\uparrow \gg \Gamma^\downarrow$), we have the figures obtained above for the 780 eV group and some further, although less precise, information from the groups at 1405 eV and 1920 eV. Taking into account the bias introduced in determining the expectation value of a Porter-Thomas distribution from a small number (3) of individual quantities [17], we adopt as averages

$$\bar{\Gamma}^\uparrow = 30 \text{ eV} \qquad \text{and} \qquad \bar{\Gamma}^\downarrow = 0.16 \text{ eV}$$

For an estimate of the average (over all resonances) of the fission width, we have to take into account two contributions: 1) the "background" fission width due to tunneling through both peaks of the double-humped fission barrier without amplification by any class II state, and 2) the average fission width obtained if the fission strength within the intermediate structure groups is thought to be smeared out over all resonances; the latter contribution is a meaningful quantity only at higher energies where the position of intermediate structures is no longer of practical importance.

1) The "background" fission width may be estimated as

$$\Gamma_f \text{ (backgr.)} = \frac{D_I}{2\pi} P^{(2)}_{min}$$

where $P^{(2)}_{min}$ is the minimum transmission through the double-humped barrier which according to Ignatynk et al.[18] is given by

$$P^{(2)}_{min} = \frac{1}{4} P_A P_B$$

and the transmission factors P_A and P_B through the first and second barrier may be obtained from the above quantities $\Gamma^{\downarrow}$ and $\Gamma^{\uparrow}$ according to $\overline{\Gamma}^{\downarrow} = \frac{D_{II}}{2\pi} P_A$, $\overline{\Gamma}^{\uparrow} = \frac{D_{II}}{2\pi} P_B$;

with the above figures we get Γ_f (backgr.) = 0.23 meV in rough agreement with the experimental fission widths of the resonances at 20.46 eV and 38.32 eV. The fact that the fission width of the 1.056 eV resonance is so much smaller, may be explained as being due to Porter-Thomas fluctuations.

2) The second of the above contributions to the average fission width would simply be given by

$$\overline{\Gamma}_f \text{ (i. s.)} = \overline{\Gamma}^{\downarrow} \frac{D_I}{D_{II}} = 3.1 \text{ meV}$$

Altogether

$$\overline{\Gamma}_f = \Gamma_f\,(\text{backgr.}) + \overline{\Gamma}_f\,(\text{i. s.}) = 3.3 \text{ meV at low energies,}$$

where both terms contain P_A and thus increase with energy approximately as $\exp(6\ \text{MeV}^{-1}.\,E)$ (Γ_f(backgr.) also contains P_B, but as it contributes only little to $\overline{\Gamma}_f$, we neglect its variation with P_B).

Thus, at 25 keV $\overline{\Gamma_f}$ = 3.8 meV, at 100 keV $\overline{\Gamma_f}$ = 6.0 meV i.e. smaller than Γ_γ by a factor of 8.1 and 5.1, respectively. Assuming no correlations between fission and neutron widths, this average fission width would lead to an average fission cross-section which is smaller than the average capture cross section by roughly the same factors. Actually in the case $\Gamma^\uparrow \gg \Gamma^\downarrow$ there is a third contribution to the average fission cross-section which is due to the direct population of the class II states and which is not contained in the above estimate. This contribution is however, only of the order of 1%. The assumption of no correlation which is equivalent to the assumption that $\Gamma^\uparrow \gg \Gamma^\downarrow$, is not assured (for a more detailed discussion see ref.[19]). In the opposite case, $\Gamma^\uparrow \ll \Gamma^\downarrow$, a strong anti-correlation between fission and neutron widths is to be expected which could easily reduce the average fission cross-section by a factor of 2 against the above estimate. All of the rest of the above discussion remains valid also in the case $\Gamma^\uparrow \ll \Gamma^\downarrow$, with only $\Gamma^\downarrow$ and P_A interchanged with $\Gamma^\uparrow$ and P_B, respectively.

Experimentally[6], the average fission cross-section is approximately 20% of the capture cross-section in the region from 20 to 30 keV, i.e. even larger, by a factor of 1.6 than the first estimate. This could mean an additional support for the assumption $\Gamma^\uparrow \gg \Gamma^\downarrow$ in ^{240}Pu.

V. Data from the unresolved resonance region and p-wave strength function

There have been several approaches to a calculation of the average cross-sections of ^{240}Pu in the unresolved resonance region from resonance parameters. Prince[20], Yiftah et al.[21] as well as Caner and Yiftah[2] have employed the optical model and Hauser-Feshbach calculations to determine average cross-sections; here, resonance parameters which could not be determined from resolved resonance data, as the p-wave strength function, were obtained from the optical model. On the other hand, Dyos[22] has used the method of Monte-Carlo generation of ladders of resonances to determine the average cross-sections. In all these cases, the calculations aimed in predicting the cross-sections on which no experi· ental information was available. To day, essentially the only experimental data on average cross-sections in the keV region are those of Hockenbury et al.[6]. These authors compare their average capture data to the calculations of Yiftah et al[21] and of Dyos[22] as well as to an own calculation on the basis of the isolated resonance approximation of the statistical model. As the results of this last calculation depend on assumptions made about the correction factor for width fluctuations (no information is given on this point), we have repeated a Dyos-type analysis in order to determine the p-wave strength function from a comparison to the experimental data of Hockenbury et al.

In this analysis the average capture cross-section is given by

$$\bar{\sigma}_{n\gamma} = \frac{1}{\Delta E}\, 2\pi^2 \left(1 + \frac{1}{A}\right)^2 \sum_i \lambda_i^2 g_i \frac{\Gamma_{ni}\Gamma_{\gamma i}}{\Gamma_i} \qquad \Gamma_{ni} = \Gamma_{ni}^{(l)}(J)\, v_l(E_i)\sqrt{E_i}$$

$$v_l(E) = \begin{cases} 1 & \text{s-waves} \\ \dfrac{\rho_i^2}{1+\rho_i^2};\ \rho_i = k_i \cdot R & \text{p-waves} \end{cases} \quad \text{for}$$

where $R = 9.1 \cdot 10^{-13}$ cm and the $\Gamma_{ni}^{(l)}(J)$ are sampled from Porter Thomas distributions with the average $\bar{\Gamma}_n^{(l)}(J) = S_l \cdot D(J)$, and the positions of resonances are sampled from Wigner distributions with average spacing

$$D(J) = \frac{D_o}{2J+1} \left(\frac{U+E}{U} \right)^{5/4} \exp\{2\sqrt{a}\,(\sqrt{U+E} - \sqrt{U})\} \exp\left(-\frac{J(J+1)}{2\sigma^2}\right)$$

with U = 4.8 MeV (effective binding energy)

$a = 25.10^{-6}$ MeV^{-1}

$\sigma = 4$

and D_o = 24.85 eV in accord with the observed spacing of resolved s-wave resonances.

For each energy interval the computation is repeated a sufficient number of times such that the average of results is statistically precise to better than 1%. S_o and Γ_γ are chosen according to the above discussion as $S_o = 1.04 \cdot 10^{-4}$, Γ_γ = 31 meV; and the cross-section calculated for the best choice of the p-wave strength function, $S_1 = 2.2 \cdot 10^{-4}$, is compared to the experimental data of Hockenbury et al. in fig. 1.

Table 5 gives values for the p-wave strength function as proposed by several authors.

Table 5: Data for the p-wave strength function of ^{240}Pu

Authors	Caner and Yiftah[2]	Prince[20]	Hockenbury et al.[6]	Present report
S_1 [10^{-4}]	1.95	1.98	2.8	2.2

Of these, only the last two are based on (the same) experimental data. The difference between them is not only due to the different methods of calculation, but also to the different figures used for the other parameters like, e.g. the level spacing.

We recommend $S_1 = (2.2 \pm 0.2) \cdot 10^{-4}$

both, because most up to date values of D_1, S_o and $\bar{\Gamma}_\gamma$ have been used, and because in the Monte Carlo sampling method width fluctuations are automatically taken into account in a correct way.

V. Conclusion

Since the latest extensive evaluation by L'Heriteau and Ribon[3] the experimental situation in the resolved resonance region has been improved very much due to the new measurements of RPI[6] and the renormalization of the capture data of Harwell[4] and Geel[5].

However, there are still discrepancies: The average capture widths from Geel and RPI still differ by about 8% and parameters of individual resonances differ sometimes up to 20%. As discussed before, there are arguments for the assumption that the true parameters lie in between the extreme experimental ones, and we expect the recommended parameters quoted in this paper to be accurate within 5 to 10% (3% for $\langle\Gamma_\gamma\rangle$). However, in order to check on this expectation and to resolve the cases of particularly large discrepancies, additional measurements are desirable, also in the light of requests for, e.g., the capture cross section in the resonance region which demand accuracies down to 3%. It is unsatisfactory also, that above 500 eV neutron widths are available from only a single measurement.

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Table 1: Resonance Parameters of ^{240}Pu up to 665 eV, as measured at Geel, RPI and Harwell.

Laboratory	Geel[5,9]		RPI[6]		Harwell[4]	
E_0 [eV][9]	Γ_n	Γ_γ	Γ_n	Γ_γ	Γ_n	Γ_γ
20.45±0.01	2.7±0.3	---	2.2±0.6	---	2.65±0.09	32.2 ±3.5
38.32±0.02	19.2±0.9	30 ±2	17.0±0.5	25.5±0.8	17.16±0.50	29.4 ±2.8
41.62±0.02	16.8±0.9	33 ±2	14.2±0.5	32.8±1.0	17.64±0.31	27.36±0.93
66.62±0.05	55.9±2.2	31 ±2	53.2±1.0	27.4±0.6	54.48±0.72	32.74±0.89
72.78±0.05	22.0±1.0	32 ±2	21.5±0.5	27.0±0.6	20.7 ±1.0	29.5 ±2.5
90.77±0.06	13.5±0.6	---	12.7±0.3	39.5±1.0[x)]	12.8 ±0.75	27.5 ±3.0
92.51±0.06	3.0±0.2	---	3.3±0.1	---	2.96±0.10	---
105.00±0.07	45.5±2.5	35.5±2	47.5±1.5	37.5±1.0[x)]	42.0 ±1.5	34.0 ±2.5
121.6 ±0.0	14.5±0.9	---	15.0±0.5	---	13.8 ±0.7	31.0 ±4.0
130.7 ±0.15	0.15±0.06	---	0.19±0.03	---	---	---
135.3 ±0.10	18.5±1.1	---	20.6±0.5	---	17.0 ±2.0	31.5 ±2.5
151.9 ±0.12	14.2±1.0	---	13.8±0.5	29.5±1.1	14.5 ±0.7	27.7 ±2.0
162.7 ±0.13	8.6±1.0	---	9.0±0.3	27.5±0.9	18.0 ±2.0	27.0 ±3.5
170.1 ±0.14	13.7±1.2	---	17.5±0.5	27.3±0.9	14.5 ±1.5	30.0 ±5.0
185.8 ±0.16	16.3±1.2	---	18.8±0.5	28.8±0.9	15.5 ±1.5	32.7 ±5.0
192.0 ±0.20	0.20±0.12	---	0.3±0.94	---	---	---
199.6 ±0.17	0.94±0.1	---	1.0±0.1	---	---	---
239.2 ±0.15	12.2±0.7	---	13.8±0.6	27.7±1.0	12.2 ±2.5	29 ±6
260.5 ±0.15	23.2±1.2	32 ±3	25.0±0.9	30.5±1.0	23.5 ±2.5	34 ±7
287.1 ±0.17	138.2±7.0	30 ±2	137.0±0.4	33.0±1.1	142 ±15	28 ±4
304.9 ±0.20	7.2±0.7	---	7.4±0.2	---	---	---
318.3 ±0.15	5.2±0.5	---	6.0±0.3	---	---	---
320.7 ±0.15	19.3±1.0	---	20.0±0.6	---	---	---

Table 1 (continued)

Laboratory	Geel[5,9]		RPI[6]		Harwell[4]	
E_o [eV][9]	Γ_n	Γ_γ	Γ_n	Γ_γ	Γ_n	Γ_γ
338.4±0.15	5.7 ±0.6	---	7.4±0.3			
346.0±0.15	16.5 ±0.7	---	17.7±0.5			
363.7±0.15	32.5 ±1.3	35±3	30.4±1.5	32.8±1.7		
372.0±0.17	13.8 ±0.8	---	16.0±1.5	27.5±0.3		
405.0±0.20	108.5 ±5.0	30±2	102.6±6.0	30.0±0.2		
419.0±0.20	6.1 ±0.7	---	6.2±0.3			
445.8±0.30	1.6 ±0.3	---	2.2±0.2			
449.8±0.20	16.5 ±1.2	---	18.7±3.5			
466.5±0.22	3.1 ±0.6	---	2.4±0.2			
473.3±0.22	4.2 ±0.5	---	4.3±0.3			
493.9±0.22	5.8 ±1.1	---	6.4±0.3			
499.3±0.25	19.3 ±1.4	---	17.0±2.2	33.5±1.5		
514.3±0.25	21.5 ±1.5					
526.1±0.40	0.91±0.5					
530.8±0.40	0.70±0.4					
546.4±0.25	31.0 ±2.2	36±4				
553.2±0.25	18.5 ±1.5					
566.3±0.30	31.5 ±1.7	29.5±2				
584.1±0.45	1.14±0.6					
596.8±0.20	57.5 ±2.5	33.5±2				
608.1±0.20	22.8 ±1.4	31.5±3				
632.5±0.20	13.3 ±1.2					
637.5±0.20	11.7 ±1.2					
665.1±0.20	197.0 ±8.0	33±2				

Table 3: Recommended Parameters of ^{240}Pu Resonances

E_o (eV)	Γ_n (meV)	Γ_γ (meV)	Γ_f (meV)
1.056±0.002	2.34±0.15	32.2±2	0.006
20.45 ±0.01	2.65±0.07	32.2±3.5	0.23
38.32 ±0.02	17.0 ±1.0	28.5±2	0.11
41.62 ±0.02	15.5 ±1.0	31 ±2	
66.62 ±0.05	52.0 ±2.0	30.5±2	
72.78 ±0.05	21.0 ±1.0	29.5±2	
90.77 ±0.06	13.5 ±0.6	28 ±3	
92.51 ±0.06	3.0 ±0.2		
105.00 ±0.07	43.0 ±2.0	34 ±2	
121.6 ±0.10	14.5 ±1.0	31.5±4	
130.7 ±0.15	0.15±0.06		
135.3 ±0.10	18.5 ±1.1	32 ±2.5	
151.9 ±0.12	14.2 ±1.0	29.5±2	
162.7 ±0.13	8.6 ±1.0	28 ±2	
170.1 ±0.14	13.7 ±1.2	29.5±2	
185.8 ±0.16	16.3 ±1.2	31.5±2	
192.0 ±0.20	0.20±0.12		
199.6 ±0.17	0.94±0.1		
239.2 ±0.15	12.2 ±0.7	29 ±2	
260.5 ±0.15	23.2 ±1.2	32 ±2	
287.1 ±0.17	132 ±7	30.5±2	
304.9 ±0.20	7.2 ±0.7		
318.3 ±0.15	5.2 ±0.5		
320.7 ±0.15	19.3 ±1.0		
338.4 ±0.15	5.7 ±0.6		
346.0 ±0.15	16.5 ±0.7		
363.7 ±0.15	32.5 ±1.3	34 ±2	
372.0 ±0.17	13.8 ±0.8	28.5±2	
405.0 ±0.20	108 ±5	30 ±2	
419.0 ±0.20	6.1 ±0.7		
445.8 ±0.30	[illegible].6 ±0.3		
449.8 ±0.20	16.5 ±1.2		
466.5 ±0.22	3.1 ±0.6		
473.3 ±0.22	4.2 ±0.5		
493.9 ±0.22	5.8 ±1.1		
499.3 ±0.25	19.3 ±1.4	34.5±3	
514.3 ±0.25	21.5 ±1.5		
526.1 ±0.40	0.91±0.5		
530.8 ±0.40	0.70±0.4		
546.4 ±0.25	31.0 ±2.2	34.5±4	
553.2 ±0.25	18.5 ±1.5		
566.3 ±0.30	31.5 ±1.7	26 ±2	
584.1 ±0.45	1.14±0.6		
596.8 ±0.20	57.5 ±2.5	32 ±2	
608.1 ±0.20	22.8 ±1.4	30 ±3	
632.5 ±0.20	13.3 ±1.2		
637.5 ±0.20	11.7 ±1.2		
665.1 ±0.20	195 ±8	31.5±2	
678.6 ±0.20	26.0 ±1.8		

Table 3: (continued)

E_o (eV)	Γ_n (meV)	Γ_γ (meV)	Γ_f (meV)
712.1±0.30	1.3± 0.6		
743.3±0.30	1.0± 0.7		
750.0±0.24	68.2± 3.4		7.8±1.0
758.9±0.25	6.0± 0.9		
778.3±0.30	1.2± 0.8		
782.2±0.30	2.8± 1.0		> 45
791.0±0.25	23.9± 1.4		12.9±1.7
810.5±0.25	213.0±10		9.6±1.2
819.9±0.26	110.0± 5.5		1.0±0.1

Table 3 : continued (change in arrangement of table)

E_o (eV)	Γ_n (meV)	E_o (eV)	Γ_n (meV)
845.6±0.27	10.3± 1.0	1362.9±0.6	7.4± 3.0
854.9±0.27	48.0± 2.5	1377.0±0.5	64.7± 4.5
876.5±0.27	13.9± 1.3	1389.0±0.6	14.2± 2.8
891.5±0.27	94.5± 4.5	1401.2±0.6	5.2± 3.1
903.9±0.28	21.8± 1.5	1408.6±0.6	10.9± 2.5
908.9±0.28	79.1± 4.0	1426.1±0.5	36.7± 3.7
915.3±0.28	36.1± 2.2	1429.0±0.5	15.0± 3.0
943.5±0.30	122.8± 5.5	1450.2±0.5	64.6± 5.2
958.4±0.30	71.5± 3.5	1462.9±0.5	21.0± 3.3
971.3±0.30	80.4± 4.0	1481.2±0.7	9.4± 3.0
979.2±0.32	7.3± 1.5	1540.7±0.5	101.0± 6.1
1001.8±0.32	98.2± 5.0	1549.5±0.5	156.7± 8.6
1024.1±0.42	5.0± 1.5	1563.7±0.5	114.7± 8.0
1041.6±0.35	12.7± 1.9	1575.3±0.5	126.2± 7.6
1045.7±0.35	4.0± 1.6	1609.6±0.6	34.8± 3.9
1072.6±0.35	109.3± 5.5	1621.4±0.6	28.6± 3.7
1099.8±0.35	84.1± 8.5	1643.0±0.6	107.1± 7.0
1115.7±0.5	2.6± 1.6	1662.6±0.6	63.9± 5.2
1128.8±0.4	50.1± 3.0	1687.9±0.6	32.7± 4.3
1133.8±0.4	6.7± 2.0	1724.1±0.6	83.5± 6.7
1142.7±0.4	40.4± 2.8	1741.6±0.6	24.9± 4.3
1159.6±0.4	22.1± 2.2	1763.7±0.6	51.7± 4.8
1185.5±0.4	157.5± 8.0	1771.4±0.8	9.8± 5.0
1190.8±0.4	114.8± 6.0	1779.0±0.6	491 ±25
1208.9±0.4	62.9± 3.8	1841.2±0.7	125.8± 9.0
1228.0±0.4	10.0± 2.0	1852.7±0.7	34.4± 5.5
1236.5±0.4	11.4± 2.2	1872.7±0.7	77.4± 7.0
1254.7±0.4	76.8± 4.6	1901.6±0.7	209 ±12.5
1281.4±0.4	4.3± 2.1	1916.6±0.7	35.9± 6.1
1300.3±0.4	245 ±12.5	1943.3±0.9	8.0± 5.0
1328.1±0.4	369 ±18.5	1949.1±0.7	82.5± 7.6
1345.6±0.5	26.1± 3.1	1956.2±0.7	261 ±16.0
1350.9±0.6	8.3± 2.5	1973.1±0.7	68.1± 7.5

Table 3 : (continued)

E_o(eV)	Γ_n(meV)	E_o(eV)	Γ_n (meV)
1991.5±0.7	114.5± 9.5	3029.0±1.2	21.0±11.0
1998.3±0.7	5.6± 4.0	3054.7±1.2	47 ±15.0
2016.7±0.7	52.5± 7.5	3077.4±1.2	128 ±19
2022.9±0.7	55.5± 7.5	3088.0±1.2	35 ±17.0
2033.4±0.7	101.5± 9.5	3112.7±1.2	38.5±14.0
2055.6±0.8	68.5± 7.5	3172.5±1.3	225 ±23
2082.8±0.8	98.8± 9.5	3192.5±1.3	349 ±35
2110.7±1.0	13.7± 5.5	3237.5±1.3	72 ±15.0
2154.0±1.1	14.3± 7.0	3268.5±1.3	134 ±20
2182.0±0.8	85.6± 8.5	3332.0±1.3	14.5±10
2198.2±0.8	130 ±10.5	3423.0±1.4	34.5±12.0
2240.6±0.8	34.1± 7.5	3458.0±1.4	68 ±13.5
2256.6±0.8	134.5±11	3465.5±1.4	344 ±35
2277.9±0.8	427 ±26	3493.5±1.4	65 ±13.5
2290.7±0.9	208.5±17	3555.0±1.4	91 ±15.5
2303.3±1.2	17.2± 7.0	3567.5±1.4	162 ±20
2334.4±0.9	36.6± 7.5	3595.0±1.4	28.5±13.5
2350.9±0.9	31.6± 8.0	3657 ±1.5	293 ±30
2365.8±0.9	241 ±17	3665 ±1.5	54.5±19
2373.4±0.9	---	3702 ±1.5	51 ±17
2386.1±0.9	18.7± 7.5	3723 ±1.5	60 ±20
2405.0±0.9	25.1± 7.5	3800 ±1.6	101 ±23
2416.0±0.9	64.9± 9.0	3844 ±1.6	76 ±20
2434.3±0.9	205 ±15	3852 ±1.6	98 ±20
2459.4±0.9	25.6± 8.5	3872 ±1.6	46 ±19
2470.8±0.9	45.5± 8.0	3900 ±1.6	209 ±27
2485.3±0.9	21.2± 8.5	3917 ±1.6	163 ±23
2521.0±1.0	109.5±11	3954 ±1.6	92 ±21
2538.6±1.0	287.5±20	3975 ±1.7	102 ±22
2549.2±1.0	79.7±12.0	3990 ±1.7	29 ±18
2575.3±1.0	47.5± 9.5	4031 ±1.7	109 ±21
2639.5±1.0	426 ±42	4084 ±1.7	120 ±23
2652.4±1.0	36.3± 8.0	4100 ±1.7	257 ±28
2692.8±1.0	345 ±26	4122 ±1.7	497 ±40
2717.7±1.0	40.7±10.0	4134 ±1.7	67 ±23
2739.2±1.0	177 ±18	4149 ±1.7	265 ±29
2748.4±1.0	102 ±13	4161 ±1.7	89 ±24
2817.5±1.1	41.2±10.0	4203 ±1.8	438 ±43
2843.5±1.1	157 ±16	4221 ±1.8	68 ±21
2859.7±1.1	27 ±11	4270 ±1.8	159 ±27
2882.0±1.1	30 ±12	4288 ±1.8	316 ±41
2895.6±1.1	60 ±12	4329 ±1.8	302 ±35
2905.0±1.1	115 ±14	4376 ±1.8	82 ±30
2938.0±1.1	132 ±15	4386 ±1.8	32 ±24
2968.6±1.1	85 ±13.5	4398 ±1.9	78 ±25
2980.5±1.2	108 ±20	4422 ±1.9	61 ±24
2986.2±1.2	12.5± 8.0	4433 ±1.9	47 ±22
2994.7±1.2	56 ±11.5	4458 ±1.9	102 ±27
3004.0±1.2	76.5±13	4570 ±1.9	220 ±45
3018.0±1.2	117 ±18	4588 ±1.9	526 ±60

Table 3: (continued)

E_o (eV)	Γ_n (meV)	E_o (eV)	Γ_n (meV)
4599 ± 1.9	75 ± 30	5194 ± 2.2	313 ± 55
4615 ± 2.0	262 ± 63	5215 ± 2.3	163 ± 40
4646 ± 2.0	149 ± 45	5249 ± 2.3	524 ± 70
4721 ± 2.0	510 ± 75	5279 ± 2.3	140 ± 45
4745 ± 2.0	245 ± 50	5299 ± 2.3	270 ± 45
4755 ± 2.0	56 ± 28	5334 ± 2.3	203 ± 50
4766 ± 2.0	15 ± 15	5350 ± 2.3	153 ± 50
4771 ± 2.0	22 ± 20	5367 ± 2.3	70 ± 40
4779 ± 2.0	34 ± 25	5393 ± 2.4	84 ± 42
4792 ± 2.0	133 ± 34	5417 ± 2.4	255 ± 50
4812 ± 2.1	172 ± 35	5489 ± 2.4	50 ± 40
4823 ± 2.1	63 ± 25	5499 ± 2.4	87 ± 40
4894 ± 2.1	59 ± 27	5510 ± 2.4	355 ± 70
4958 ± 2.1	291 ± 55	5522 ± 2.5	172 ± 45
4969 ± 2.1	158 ± 50	5544 ± 2.5	582 ± 90
4993 ± 2.2	92 ± 35	5574 ± 2.5	758 ± 90
5072 ± 2.2	509 ± 50	5592 ± 2.5	207 ± 60
5113 ± 2.2	93 ± 35	5615 ± 2.5	62 ± 50
5134 ± 2.2	42 ± 30	5681 ± 2.5	106 ± 50
5148 ± 2.2	50 ± 35	5692 ± 2.5	91 ± 46
5162 ± 2.2	40 ± 30		

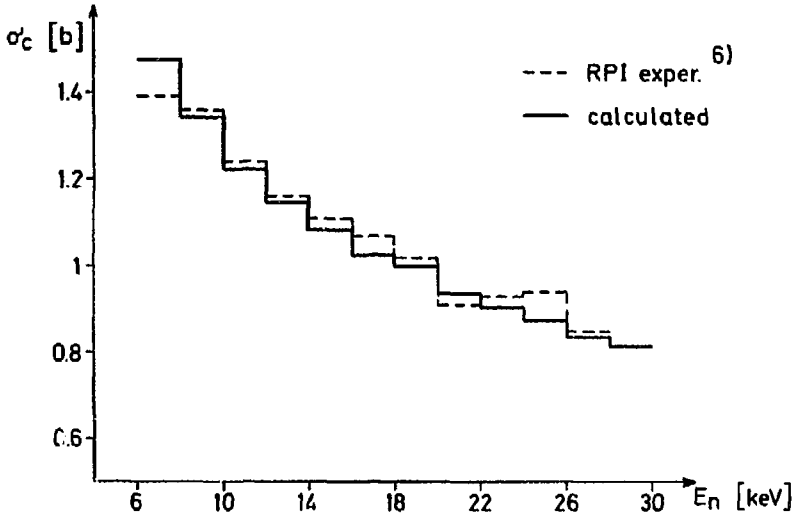

Fig.1 Comparison of calculated σ_c of ^{240}Pu to RPI - data

PLUTONIUM 239 RESONANCE PARAMETERS

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I - INTRODUCTION

When examining Pu 239 resonance parameters, two kinds of information must be taken into account : (a) the experimental data and the corresponding analysis, and (b) the various evaluations made so far.

A - Experimental data

The oldest to be taken into account are L. Bollinger's concerning the total cross section and the fission cross section up to around 50 eV (Bo 58). These data have been analysed with a one level formalism and E. Vogt also proposed a multi-level analysis up to 10 eV (Vo 60).

The total cross section and the scattering cross section have been measured and analysed at Harwell, the former by C.A. Uttley (Ut 65) who proposed a set of resonance parameters in the 100 eV to 300 eV neutron energy range and the latter by M. Asghar (As 67) who also attributed a certain number of spin up to 300 eV.

G. de Saussure, R. Gwin et al (Gw 71) made simultaneous measurements of the fission cross section and the capture cross section at ORNL-RPI in order to determine α. But no reconance parameters has been proposed from these measurements.

The Saclay results are the largest and most complete set of data in the resonance field (Bl 70, De 70, Tr 70, De 73a). The transmission measurements used five sample thicknesses cooled at liquid nitrogen temperature, with 50 and 100 m flight paths ; the fission cross section was also measured at liquid nitrogen temperature (up to around 30 KeV) with a 50 m flight path. The scattering measurement was done with a 50 m flight path, thus providing a resolution comparable to that of the transmission and the fission. A complete set of parameters was obtained up to 660 eV by a single level analysis and up to 205 eV by a multi-level analysis.

The fission cross section was measured at Los Alamos (Sh 65) on an underground nuclear explosion and was analysed by J.A. Farrell with a multi-level formalism between 20 and 80 eV (Fa 68).

B - The evaluations

We shall retain two evaluations : the first by P. Ribon and G. Le Coq (Ri 71) based on the set of Saclay experimental parameters and the second by O.D. Simpson and F.B. Simpson (Si 72) who tried to match the Saclay and O.R.N.L. experimental data ; comments about the latter evaluation have been previously done (De 73b).

What are the problems arising on the resonance parameters of Pu 239 and their use for reactor calculation ? First, there is the problem of interferences due to the wide resonances of the 0^+ spin state. The single level analysis cannot provide a set of parameters correctly describing the cross sections in these resonances. We are therefore obliged to compare two sets of parameters due to two different kinds of analysis, namely the one level analysis and the multi-level analysis. Sophisticated computation codes are required when using multi-level parameters. Then, it can be wondered if the problem of interferences is really important for calculating reactors and, if so, how can these calculations be simplified. A second problem, which could also be important, is that of the intermediate structure obvious in the fission cross section due to the 1^+ spin state (De 73a) : what is its importance in calculating the average cross section at high energy and must the variations of $\langle \Gamma_f \rangle_{1^+}$ due to the coupling between the class I and class II states be taken into account ?

These various problems could be examined at this session. I shall merely examine the set of parameters that Saclay proposes, and compare this set with other results. Incidentally, two sources of significant disagreements can be eliminated right from the start :

1) the anomalies mentioned by O.D. Simpson and F.B. Simpson (Si 72) concerning the narrow resonances disappear quite naturally when the spin of the resonances is taken into account in calculating the scattering cross section. This is a common place observation sufficient enough to warrant this evaluation being disregarded ;

2) J.A. Farrell's (Fa 68) multi-level analysis leads to parameters that are far from reproducing the total cross section (De 73a), since it is quite impossible to determine all the parameters of the 1^+ resonances only from the fission, even by multi-level formalism : a theoretical interpretation of the distribution of fission widths obtained by Farrell, such as was done recently (Va 73), leads to wrong conclusions as to the number of exit channels and that of missed resonances. In this analysis just the resonance areas can be kept, but not the Γ_n, Γ_f and Γ_γ values which, particularly, lead to aberrant α values.

II - EXAMINATION OF THE SACLAY PARAMETERS AND COMPARISON WITH THE PARTIAL RESULTS FROM OTHER LABORATORIES.

A - Single level parameters

All the results concerning the definitive analysis of Saclay's experimental data will be found in reference (De 73a). They comprise :

1) the energies and the neutron widths of 254 identified resonances up to 660 eV neutron energy ;

2) the fission widths of 212 resonances ;

3) the capture widths of 107 resonances ;

4) the attribution of 164 spins by direct or indirect methods : 63 resonances in the 0^+ state and 101 in the 1^+ state ;

5) the attribution of spin 1^+ to the resonances for which no direct or indirect spin assignment method could be used, i.e. to the 90 remaining resonances, in agreement with the (2 J + 1) law for the level spacings; the risk of including a few 0^+ resonances in this group is of no consequence for the evaluation, since the $2\,g\Gamma_n$ values of this resonances are generally very weak.

The table of the experimental parameter set has already been published (De 73a) ; this table is also reproduced in reference (Ri 71).

The table I shows the mean values of the parameters per spin state :

TABLE I

J^π	g	$\langle D \rangle$ eV	$\langle 2g\Gamma_n^\circ \rangle$ meV	$S^\circ \times 10^4$	$\langle \Gamma_f \rangle$ meV	$\langle \Gamma_\gamma \rangle$ meV
0^+	1/4	$9{,}60^{+0{,}70}_{-0{,}84}$	0,72±0,13	1,56±0,28	2145±390	39,5±4,0
1^+	3/4	$3{,}20^{+0{,}13}_{-0{,}20}$	0,54±0,06	1,13±0,12	33,5±4,0	42,2±1,4

The main difficulties of the single level analysis come from the wide 0^+ resonances, which interfer strongly and, owing to this, are very far from the single level Breit-Wigner form. Four particularly difficult cases should be considered :

a) the 11.5 eV resonance considered as 0^+ which is only used to mask the interference effect between the 10.93 and 11.89 eV 1^+ levels (one of the rare cases of significant interference between narrow resonances) ;

b) the group between 55 eV and 66 eV in which three wide 0^+ resonances were introduced, whereas the multi-level analysis will show that there are in fact only two large and highly interfering resonances ;

c) the group between 80 and 86 eV also containing three large resonances against two in the multi-level analysis ;

d) between 300 and 400 eV the parameters resulting from the single level analysis do not reproduce the total and fission cross sections, unless a very high residual cross section is introduced. This led P. Ribon and G. Le Coq to introduce two extra very wide levels at 320 and 364 eV.

These difficulties being due to the interference effect the fact of introducing extra symmetrical resonances is obviously only a makeshift ; the use of Adler formalism shows that the true cross-section is the sum of symmetrical (pseudo Breit-Wigner) and asymmetrical functions, and that, in no case, can an extra symmetrical resonance account for the destructive part of the asymmetrical function, unless it is of negative area. This fact is at the source of the introduction of a smooth file in the ENDF-B format to allow for these effects, when a single level set of parameters is used.

Comparison with other single level analysis

L. Bollinger et al. published the parameters of 20 resonances up to 53 eV (Bo 58), obtained from the single level analysis of a total cross section and fission cross section. We are only mentioning them here to draw attention to the overall good agreement existing between their results and those of Saclay. C.A. Uttley gave the values of $g\,\Gamma_n$ and Γ for 63 resonances between 100 and 300 eV ; his $g\,\Gamma_n$ values are, on average, 6% smaller than ours. The local strenght functions deduced from the Saclay measurements and those deduced from the Harwell measurements are compared in the table II.

TABLE II

Energy in eV	I	a	II	a	III	a	b
0 - 100					1.56	0.02	0.34
100 - 200	1.15	0.03	1.04	0.02	1.13	0.01	0.25
200 - 300	1.54	0.02	1.27	0.04	1.51	0.02	0.33
300 - 400	1.02	0.02			0.84	0.01	0.19
400 - 500	0.76	0.02			0.75	0.01	0.17
500 - 600	1.71	0.02			1.77	0.03	0.39

I : $S_o \times 10^4$ according to C.A. Uttley's average cross sections ;

II : $S_o \times 10^4$ according to C.A. Uttley's resonance parameters ;

III : $S_o \times 10^4$ according to the resonance parameters (De 73a) ;

a : experimental statistical error.

b : sampling error.

Excellent agreement is found between the local strengh functions obtained from the Saclay resonance parameters and those deduced from the average values of Uttley's total cross sections ; the difference between the figures in columns II and III is due to two causes :

a) Uttley probably underestimated the $2g\,\Gamma_n$ values ;

b) he did not allow for the wide resonances in his analysis.

The comparison between the spin assignment due to M. Asghar and those due to J. Trochon was also made (Tr 70) ; out of 47 possible comparisons, there are only 6 disagreements, all the explanations for which were favourable to the Saclay assignment.

As for the ORNL-RPI measurements, it is not possible to establish a comparison on the resonance parameters ; the only analysis made on these results is due to O.D. Simpson and F.B. Simpson, on the Saclay and ORNL-RPI data simultaneously. According to what we said at the beginning of this report, the results of this analysis are not an improvement compared with the Saclay analysis.

B - Multi-level parameters

The multi-level analysis carried out at Saclay is given in detail in reference (De 73a). It is a least square analysis simultaneously made on the total cross section and the fission cross section, between 4 eV and 205 eV. It uses the Reich-Moore formalism and is founded on three main assumptions :

1) the resonance spin assignments have been correctly done by the single level analysis ;

2) there is only one fission channel, partly open, for the 1^+ transition states ;

3) there are two, open or partly open, fission channels for the 0^+ transition states.

The following conclusions may be drawn from this multi-level analysis :

1) the base assumptions were confirmed and enabled the theoretical cross section to be adapted very satisfactorily to the experimental data ;

2) the 1^+ resonance parameters are almost unchanged in relation to the single level analysis ; the few changes made are due to three causes :

a) a few rare cases of interference ;

b) a better accuracy on the determination of the parameters is achieved by the simultaneous analysis of two cross sections ;

c) the analysis of the narrow resonances was made easier, since the shape of the wide resonances, playing the role of "background noise" in relation to the narrow resonances, was well reproduced ;

3) the individual 0^+ resonance parameters are generally very different from those obtained in the single level analysis but there is no significant change in the average values, as it is shown in the table III.

TABLE III

	Number of resonances	$\langle D \rangle_{0^+}$ (eV)	$\langle \Gamma_n^0 \rangle_{0^+}$ (eV)	$S^0_{0^+}$	$\langle \Gamma_f \rangle_{0^+}$ (eV)
one level analysis	24	8,85	$1,52 \times 10^{-3}$	1,71	1,47
multilevel analysis	22	9,70	$1,66 \times 10^{-3}$	1,71	1,59

4) the two 0^+ fission channels are respectively characterised by the mean fission widths :

$$\langle \Gamma_{f1} \rangle_{0^+} = 1.305 \text{ eV (open channel)}$$

$$\langle \Gamma_{f2} \rangle_{0^+} = 0.276 \text{ eV (partly open channel)}$$

The results of the multi-level analysis are given in table IV.

Comparison with other multi-level analysis

The fragmentary analysis made by E. Vogt (Vo 60) and C.D. James (Ja 68), can hardly be considered for this comparison. The first was made from 0.1 to 10 eV and can be used to calculate the total cross section and the fission cross section in the thermal région. It allows for a negative resonance but is not in agreement with the spin assignment at present accepted for the 15.34 eV resonance. The second concerns the wide resonances in the energy range from 80 to 85 eV ; it was only done to show that the number of open, or partly open, 0^+ fission channels is at least equal to 2.

There remains J.A. Farrell's 20 eV to 78 eV analysis. In the introduction to this report we explained why it should be excluded. As for the work undertaken by D.D. Adler and F.B. Adler on the Pu 239 cross sections, the comparison with our results can only be made through the transformation which diagonalises the level matrix

(Ad 68) ; there is no doubt that identical results are obtained if the analysis is carried out on the same cross sections and starting from the same bases.

C - The role of multi-level analysis in evaluating resonance parameters and calculating cross sections.

In order to define this role correctly, it would be necessary to know the effect of the interferences in the calculation of the cross sections in the non-resolved domain. As was said at the beginning of this report, we shall not go into this problem in detail, but simply recall that G. de Saussure and R.B. Perez (Sa 73a) studied it in the particular case of U 235. They showed that pratically no difference existed between the statistical properties of the cross sections achieved by multi-level formalism and that obtained by single level formalism ; these différences are too small, particularly towards the high temperatures (> 300° K), to have any effect on the reactor calculations, this conclusion being still more true for Pu 239 than for U 235.

Efforts are also being made in the United States, still by G. de Saussure and R.B. Perez, to develop simple calculation methods allowing multi-level parameter sets to be employed in the resolved region (Sa 73b). These methods transform multi-level sets into sets composed of pseudo Breit-Wigner parameters and parameters defining a smooth background ; the calculations are then done only by means of the conventional Ψ and φ functions. In such a case the set of multi-level parameters we are proposing can prove useful.

Where we are concerned, we shall only keep, from the multi-level analysis, the extra accuracy it gives to the parameters of the 1^+ resonances and the fact that the mean parameters of the 0^+ resonances vary but little irrespective of the kind of analysis used.

TABLE IV

Energy (eV)	Γ_n (meV)	Channel 1^+ Γ_f (eV)	Channel 0^+ Γ_{f1} (eV)	Γ_{f2} (eV)	J (a)	J (b)
0,296	0,24			0,0600	0	
7,800	0,77	-0,0470			1	
10,910	1,65	-0,1200			1	
11,870	0,98	0,0210			1	
14,307	0,66	0,0610			1	
14,660	1,92	0,0370			1	
15,405	1,73		-0,4420	0,0994	0	
17,633	1,83	-0,0405			1	
22,234	2,59	-0,0640			1	
23,876	0,09	0,0300				1*
26,223	1,52	0,0440			1	
27,233	0,15	-0,0050				1*
32,265	0,84			-0,1140	0	
35,422	0,25	0,0053			1	
41,373	3,79	-0,0036			1	
43,623	1,38	0,0434				1*
44,435	5,83	-0,0050			1	
47,494	5,25		0,2810	-0,0700	0	
49,446	3,44		-0,7860	-0,0610	0	
50,033	2,97	-0,0125			1	
52,533	10,02	0,0090			1	
55,582	1,51	0,0220			1	
57,003	14,47		-1,5500	0,0280	0	
59,153	4,80	0,1020			1	
61,866	26,25		7,1020	0,0200	0	
63,018	0,70	0,0800				1*
65,497	13,06		0,2380	0,1510		0*
65,711	9,17	0,0285			1	
74,053	3,37	-0,0260			1	
74,937	22,70	-0,0870			1	
78,969	0,04	0,0020				1
80,915	4,95		0,9630	0,5820	0	
82,666	0,39	0,0100				1
85,490	7,45	0,0094			1	
85,534	53,41		- 2,0100	0,0550	0	
90,711	11,86	0,0030			1	
92,953	0,70	0,0090				1
95,374	1,90	- 0,0250			1	
96,332	20,86		0,8420	1,8160	0	
101,751	9,05		- 4,8230	0,0250	0	
103,010	1,61	0,0100			1	
105,301	4,78	- 0,0060			1	
106,670	8,93	- 0,0260			1	
110,410	0,44	0,0130				1
114,602	2,50		- 1,6540	- 0,0170	0	

Energy (eV)	Γ_n (meV)	Channel 1^+	Channel 0^+		J	
		Γ_E (eV)	Γ_{f1} (eV)	Γ_{f2} (eV)	(a)	(b)
115,185	0,21	0,1600				1
116,075	11,75		- 0,1170	- 0,1390	0	
118,831	16,85	- 0,0340			1	
121,006	2,38	0,0360				1
123,467	0,51	- 0,0390				1
126,226	1,93	- 0,0200				1
127,557	0,51	0,0250				1
132,321	35,06		3,9910	- 0,0350	0	
133,784	5,59	- 0,0060			1	
136,770	10,24			- 0,0840	0	
139,340	0,10	0,1200			1	
142,963	3,24	0,0820			1	
143,470	4,08	0,0310			1	
146,250	7,05	0,0130			1	
147,496	3,53		1,4990	0,0860	0	
148,242	0,44	0,1020				1
149,442	1,69	0,0500				1
157,009	32,55		0,0290	0,4730	0	
161,988	0,11	0,003				1
164,568	28,00	- 0,008			1	
167,128	5,83	0,069			1	
170,529	0,57	0,120				
171,150	3,14		- 0,208	1,606	0	
176,012	2,09	0,031				1
177,253	3,57	0,006			1	
178,924	1,22	0,014			1	
183,673	1,68	0,028				1
185,167	16,93		- 1,422	0,499	0	
188,305	0,61	0,009				1
190,677	1,67	0,013				1
195,399	57,73		- 0,411	0,012	0	
196,742	4,01	0,025			1	
199,434	8,93	0,065			1	
203,473	2,26	0,036				1
203,980	59,39		0,343	0,038	0	

a) Spins previously assigned;

b) Spins arbitrarly assigned; (the probalities for a correct assignment is great); values with " can be considered as resulting from multilevel analysis.

III - SET OF RECOMMENDED PARAMETERS

This set is based on the results of the Saclay single level analysis of the 4 eV to 660 eV neutron energy range. Obviously some of the parameters cannot be measured ; particularly some of the Γ_f values cannot be determined experimentally, for they correspond to resonances which have too small neutron widths or fission widths. The evaluation made by P. RIBON and G. Le Coq enables the parameter table to be completed according to a certain number of coherence criteria with the measured cross sections.

Table V shows how the cross section, calculated as from measured or evaluated parameters, compares with the Saclay experimental cross section. This comparison highlights the local deviations due to the interference effects in the 0^+ resonances. However there is a compensating effect, and the sum $\sum_{E1}^{E2} \frac{\pi}{2} \sigma_o \Gamma_f$ obtained between 40 and 600 eV (by introducing two additional large resonances between 300 and 500 eV) differs very little from the fission integral calculated from the experimental fission cross section :

$$\sum_{40\ eV}^{600\ eV} \frac{\pi}{2} \sigma_o \Gamma_f = 10\ 513 \text{ barns-eV}$$

$$\int_{40\ eV}^{600\ eV} \sigma_f(E)_{exp.}\, dE = 10\ 488 \text{ barns-eV}$$

The difference between these values is only 0.2%.

The one level resonance parameters recommended by Ribon and Le Coq are given in table VI (Ri 71).

TABLE V

Energy Intervals (eV)	$\int_{E1}^{E2} \sigma_f(E)dE$ from $\sigma_f(E)$ experimental values [B1 70] (barns eV)	$\sum_{E1}^{E2} \frac{\pi}{2} \sigma_o \Gamma_f$ from $\sigma_o \Gamma_f$ experimental values [B1 70] (barns eV)	$\sum_{E1}^{E2} \frac{\pi}{2} \sigma_o \Gamma_f$ from [Ri 71] evaluation (barns eV)
40 - 50	293.5	286	287.7
50 - 60	777.1	727	732.8
60 - 70	571	661	663.4
70 - 80	655.7	578	579.2
80 - 90	690.2	751	818.5
90 -100	317.4	219	221
40 -100	3305	3222	3303
100 -200	1918	1837	1885
200 -300	1802.5	1737	1772
300 -400	904	739	933
400 -500	985	911	946
500 -600	1574	1652	1674
40 -600	10488.5	10097	10513

TABLE VI

^{239}Pu evaluated resonance parameters

	E (eV)	Γ_t (meV)	ε (%)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (meV)	ε (%)	Γ_f (meV)	ε (%)	J
1	0.297	98.8		0.0600		38.2		60.4		0
2	7.820	87.8	5	0.5998	33	40.0	6	47.0	6	1
3	10.930	199.8	10	1.4077	53	55.0	17	143.0	11	1
4	11.500	51.8		0.0744		41.5		10.0		0
5	11.890	67.0	10	0.7634	65	42.0	11	24.0	13	1
6	14.310	101.6	8	0.4511	52	34.0	16	67.0	11	1
7	14.680	69.9	10	1.4177	17	38.0	10	30.0	10	1
8	15.460	699.9	7	0.4858	80	42.0	99	656.0	15	0
9	17.660	74.8	11	1.3582	18	39.0	11	34.0	11	1
10	22.290	108.6	9	1.9828	25	44.0	11	62.0	10	1
11	23.940	70.1	17	0.0644	76	32.0	35	38.0	31	
12	26.240	83.4	12	1.0905	68	38.0	16	44.0	15	1
13	27.240	42.2	19	0.1041	83	37.0	20	5.0	54	
14	32.310	151.8	13	0.2082	48	41.0	19	110.0	14	0
15	34.600	91.5		0.0099		41.5		50.0		
16	35.500	47.3	19	0.2131	46	43.0	19	4.0	54	1
17	41.420	52.1	16	3.0733	29	44.0	17	4.0	26	1
18	41.660	106.0	16	1.0013	124	58.0	22	46.0	25	
19	44.480	58.6	12	4.9421	20	47.0	13	5.0	13	1
20	47.600	311.6	8	1.4177	52	58.0	26	248.0	10	0
21	49.710	800.3	25	1.0905	92	50.0	99	746.0	27	0
22	50.080	57.0	24	2.2554	44	41.0	25	13.0	26	1
23	52.600	60.4	14	7.7824	95	49.0	16	9.0	17	1
24	55.630	58.4	50	1.0905	55	36.0	52	21.0	27	1
25	57.440	499.8	50	3.2220	500	42.0	99	445.0	40	0
26	58.840	1099.0	50	2.7263	500	42.0	99	1047.0	50	0
27	59.220	180.4	8	4.0647	55	52.0	19	123.0	11	1
28	60.940	6797.0	50	4.9570	35	42.0	99	6736.0	40	0
29	63.080	155.1	11	0.5948	210	43.0	80	111.0	33	
30	65.360	92.0		0.2677		41.5		50.0		
31	65.710	137.0	10	9.0316	26	54.0	13	71.0	11	1
32	74.050	71.1	11	2.3545	42	36.0	13	32.0	13	1
33	74.950	146.9	10	10.4570	45	41.0	16	84.0	11	1
34	78.950	91.7		0.0800		41.5		50.0		
35	81.760	2047.0	50	2.4785	500	42.0	99	1996.0	40	0
36	82.680	70.7		0.3718		40.0		30.0		
37	83.520	1750.0	50	0.9948	500	42.0	99	1706.0	40	0
38	85.320	2098.0	50	13.0000	143	42.0	99	2002.0	40	0
39	85.480	74.8	12	5.8492	31	51.0	21	16.0	52	1
40	90.750	59.8	17	9.1456	23	39.0	22	8.6	19	1
41	92.970	57.0	9	0.5205	40	47.0	13	9.0	51	
42	95.361	98.1	10	1.5614	47	66.0	11	30.0	15	1
43	96.491	1700.0	20	3.3112	39	42.0	99	1645.0	23	0
44	100.250	6000.0	50	2.7759	500	42.0	99	5947.0	40	0
45	102.990	47.6	10	1.1995	33	36.0	12	10.0	27	1
46	105.300	48.0	15	3.4500	57	38.0	16	5.4	19	1
47	106.670	75.6	5	6.9199	42	40.0	6	26.4	7	1
48	110.380	43.6	37	0.3272	106	30.0	40	13.0	50	
49	114.440	1499.0	50	0.3470	500	42.0	99	1456.0	50	
50	115.100	205.3		0.1586		40.0		165.0		

TABLE VI (continued)

^{239}Pu evaluated resonance parameters

	E (eV)	Γ_t (meV)	ε (%)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (meV)	ε (%)	Γ_f (meV)	ε (%)	J
51	116.030	267.7	6	2.6817	24	39.0	38	218.0	9	0
52	118.830	102.1	6	12.8480	23	43.0	9	42.0	8	1
53	120.990	78.3	15	1.8340	41	32.0	21	39.0	18	0
54	123.440	63.7	22	0.3470	110	24.0	86	39.0	56	
55	126.200	95.9	11	1.4672	40	70.0	18	20.0	51	(0)
56	127.510	64.8	19	0.3817	120	40.0	28	24.0	40	
57	131.750	3799.0	6	8.9226	65	42.0	99	3722.0	10	0
58	133.780	55.5	10	4.1539	36	44.0	13	6.0	51	1
59	136.750	126.1	8	2.5379	30	32.0	25	84.0	12	0
60	139.280	321.6		0.0892		41.5		280.0		
61	142.920	137.2	15	2.4091	44	52.0	26	82.0	20	1
62	143.470	83.0	14	3.0336	24	48.0	15	31.0	16	1
63	146.250	70.0	10	5.2445	30	50.5	11	12.5	12	1
64	147.440	1000.0	50	0.5948	500	42.0	99	956.0	50	0
65	148.210	149.6	50	0.3470	140	47.0	58	102.0	50	
66	149.420	119.5	17	1.2987	46	67.0	22	50.0	26	
67	157.080	621.6	8	8.4000	23	48.0	47	540.0	9	0
68	160.800	141.7		0.1041		41.5		100.0		
69	161.960	150.2		0.1041		40.0		110.0		
70	164.540	78.7	12	20.8190	72	43.0	20	8.0	15	1
71	167.100	111.7	7	4.3373	46	37.0	15	69.0	10	1
72	170.490	158.8	38	0.4263	23	38.0	99	120.0	48	
73	171.080	999.7	50	0.4412	34	42.0	93	956.0	35	0
74	174.560	241.5		0.0297		41.5		200.0		
75	175.980	73.1	7	1.5564	32	39.0	17	31.0	21	
76	177.220	51.5	12	2.6569	33	41.5	13	6.5	24	1
77	178.900	58.2	5	0.9071	33	43.0	9	14.0	26	(1)
78	183.640	72.3	50	1.1351	52	42.0	62	28.0	71	
79	184.870	2098.0	10	4.6595	200	42.0	99	2030.0	30	0
80	188.270	52.9	19	0.4560	75	43.0	22	9.0	54	
81	190.640	67.0	13	1.2442	36	49.0	19	13.0	52	(0)
82	195.360	446.4	9	14.8710	40	52.0	52	335.0	12	0
83	196.690	111.6	16	3.4897	60	53.0	21	54.0	20	1
84	199.390	132.5	10	7.1826	52	43.0	16	80.0	12	1
85	203.460	72.4		2.9742		41.5		25.0		
86	203.930	440.6	50	13.4000	38	42.0	99	345.0	52	0
87	207.370	56.9	9	5.2048	40	44.0	10	6.0	18	1
88	211.090	789.7	50	0.6940	500	42.0	99	745.0	50	0
89	212.020	1500.0	50	0.5948	500	42.0	99	1456.0	50	0
90	213.280	199.6	30	0.3470	280	42.0	99	157.0	65	
91	216.530	67.2	10	4.6595	42	50.0	13	11.0	32	1
92	219.490	70.5	14	2.6569	50	41.0	24	26.0	33	1
93	220.220	52.4	18	5.5220	44	34.0	23	11.0	35	1
94	223.160	59.4	10	2.5379	28	47.0	14	9.0	51	1
95	224.390	85.5	20	1.2689	56	58.0	30	25.0	54	
96	227.770	8095.0		7.6337	500	41.5		8024.0	50	0
97	227.890	66.7	15	1.2590	56	33.0	29	32.0	30	(1)
98	231.400	53.8	18	8.8234	56	37.0	23	5.0	27	1
99	232.630	120.6	50	0.3272	220	40.0	66	80.0		
100	234.320	74.1	12	7.6089	40	49.0	14	15.0	17	1

TABLE VI (continued)

^{239}Pu evaluated resonance parameters

	E (eV)	Γ_t (meV)	ε (%)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (meV)	ε (%)	Γ_f (meV)	ε (%)	J
101	239.040	72.4	12	4.0399	50	51.0	13	16.0	19	1
102	240.600	241.5		0.0248		41.5		200.0		
103	242.880	96.5	6	4.9173	45	34.0	14	56.0	10	1
104	247.500	280.3	20	0.6741	140	45.0	99	234.0	39	
105	248.860	61.6	10	10.9690	40	42.0	13	5.0	16	1
106	251.230	82.2	6	20.4220	30	43.0	10	12.0	10	1
107	254.500	54.8	18	2.0819	70	27.0	24	25.0	24	(1)
108	256.110	91.3	17	4.7091	50	53.0	20	32.0	22	1
109	259.000	241.8		0.1983		41.5		200.0		
110	262.370	6299.0	50	24.7850	500	42.0	99	6158.0	30	0
111	262.740	59.6	17	1.8043	124	46.0	20	10.0	45	
112	264.230	341.7		0.1239		41.5		300.0		
113	269.110	130.0	50	1.0409	400	42.0	95	86.0	56	
114	269.540	71.8	28	2.8750	120	40.0	33	28.0	34	1
115	272.620	91.6	11	20.7200	36	33.0	20	31.0	13	1
116	274.800	791.8	50	6.9398	140	42.0	99	736.0	40	
117	275.570	149.1	20	17.3990	43	54.0	37	72.0	27	1
118	277.230	5299.0	50	4.4613	500	42.0	99	5240.0	50	0
119	279.590	111.0	7	5.2742	30	34.0	20	56.0	13	0
120	282.920	85.0	7	18.7370	73	49.0	10	11.0	14	1
121	285.730	341.5		0.0496		41.5		300.0		
122	288.000	6498.0	50	7.1380	500	42.0	99	6428.0	87	0
123	288.300	341.5		0.0397		41.5		300.0		
124	292.330	114.5	10	2.8849	41	31.0	34	72.0	17	(0)
125	296.460	81.2	15	2.4239	40	48.0	34	30.0	52	(1)
126	298.590	73.4	10	7.8320	39	43.0	15	20.0	23	1
127	301.810	108.0	6	13.5320	37	42.0	19	48.0	17	1
128	308.200	150.3	20	2.1810	62	49.0	85	98.0	45	
129	309.010	84.9	14	10.4590	35	47.0	18	24.0	18	1
130	311.120	82.2		0.3619		41.5		40.0		
131	313.620	61.5	10	10.1120	35	38.0	13	10.0	15	1
132	316.660	73.1	14	3.8416	400	43.0	25	25.0	45	1
133	320.000	5061.0		10.0000		41.5		5000.0		
134	321.750	341.6		0.0991		41.5		300.0		
135	323.360	159.8	10	14.9700	39	53.0	24	47.0	18	(0)
136	325.300	104.4	10	6.3449	40	50.0	25	46.0	27	1
137	329.650	1999.0	50	2.6767	500	42.0	99	1947.0	40	0
138	333.910	67.4	10	4.0845	36	52.0	14	10.0	51	1
139	335.930	82.6	7	13.1850	26	47.0	11	18.0	17	1
140	337.950	74.0	10	5.9930	35	55.0	12	11.0	32	1
141	339.240	80.7	15	2.4388	40	37.0	33	34.0	34	0
142	343.180	74.6	80	11.7430	33	41.0	99	18.0	16	1
143	346.560	1200.0	50	2.5776	118	42.0	99	1148.0	55	0
144	350.300	97.3	6	15.9860	28	41.0	11	35.0	10	1
145	352.820	68.8	19	2.8948	40	48.0	21	17.0	28	(1)
146	354.890	79.1		0.2974		41.5		37.0		
147	357.870	5999.0	50	2.2306	500	42.0	99	5949.0	50	0
148	359.990	113.6	20	0.8229	110	32.0	99	80.0	55	
149	361.280	341.8		0.1636		41.5		300.0		
150	364.000	3051.0		5.0000		41.5		3000.0		

TABLE VI (continued)

^{239}Pu evaluated resonance parameters

	E (eV)	Γ_t (meV)	ε (%)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (meV)	ε (%)	Γ_f (meV)	ε (%)	J
151	366.000	4999.0	50	2.6767	500	42.0	99	4947.0	50	0
152	368.330	162.0		0.2974		41.5		120.0		
153	370.310	89.9	20	1.9332	61	57.0	46	29.0	83	
154	371.720	3399.0	50	5.7005	500	42.0	99	3335.0	50	0
155	375.020	42.9	28	1.9828	75	29.0	36	6.0	42	0
156	377.100	99.9	20	1.4771	100	58.0	29	39.0	37	
157	378.040	224.3		0.9319		41.5		181.0		
158	382.430	129.6	50	0.3123	240	43.0	99	86.0	75	
159	384.260	108.6	30	4.2382	58	28.0	55	75.0	34	1
160	385.900	999.7	50	0.6940	500	42.0	99	955.0	50	0
161	389.510	74.1	19	1.0360	90	51.0	31	21.0	64	
162	391.520	124.8	19	0.9369	100	55.0	65	68.0	54	
163	394.430	106.4	13	4.8479	30	48.0	22	52.0	20	1
164	396.910	108.1	20	1.5713	64	44.0	36	61.0	29	
165	401.560	219.2	10	14.4240	40	46.0	39	154.0	15	1
166	404.240	155.0	15	17.2500	37	56.0	24	76.0	18	1
167	406.030	321.2		1.3532		41.5		277.0		
168	406.950	331.4	50	0.7237	410	30.0	99	300.0	50	
169	408.710	114.9	50	0.9616	150	55.0	53	58.0	50	
170	412.310	144.8	10	6.6473	47	66.0	20	70.0	19	1
171	415.660	61.8	20	2.4239	74	50.0	23	7.0	54	
172	417.600	230.3	24	1.1896	140	50.0	99	178.0	57	
173	419.850	139.0	18	4.5158	50	59.0	32	74.0	27	1
174	425.670	341.8		0.1983		41.5		300.0		
175	426.370	6996.0	50	7.3363		42.0	84	6925.0	50	0
176	429.640	779.6	50	2.8056	140	42.0	99	732.0	30	
177	431.290	3490.0		3.4699		41.5		3443.0	50	
178	432.730	341.0		0.7634		41.5		298.0		
179	437.760	61.7	25	2.0026	74	49.0	28	10.0	56	(1)
180	438.720	60.9		2.1612		55.0		3.0	90	1
181	440.070	341.9		0.2082		41.5		300.0		
182	442.410	411.8	13	5.2048	50	44.0	87	347.0	17	0
183	449.50	133.4		0.9914	100	41.5		90.0	55	
184	451.350	59.1		10.4590	50	41.5		3.7	47	1
185	454.450	402.1		0.3470		41.5		360.0		
186	455.730	615.2		19.6790	60	41.5		495.0	32	0
187	457.330	170.5		5.5022	60	41.5		118.0	35	
188	458.800	79.1		3.4203	80	41.5		33.0	40	1
189	461.260	97.4		1.7349	100	41.5		52.4	46	
190	462.640	128.2		0.3966	300	41.5		86.0	85	
191	468.200	2092.0		3.2220	150	41.5		2045.0	30	
192	470.000	5085.0		7.4355	300	41.5		5030.0	50	
193	473.100	55.6		3.0733	60	41.5		10.0	57	1
194	475.310	582.0		2.7759	150	41.5		535.0	30	
195	476.900	1993.0		1.3383	400	41.5		1950.0	50	
196	479.240	201.6		0.0991		41.5		160.0		
197	484.150	59.9		1.9332	80	41.5		14.5	90	
198	487.290	224.7		1.6358		41.5		180.0		
199	487.810	226.6		2.5776		41.5		180.0		
200	490.650	2280.0		9.9140	60	41.5		2220.0	30	

TABLE VI (end)

^{239}Pu evaluated resonance parameters

	E (eV)	Γ_t (meV)	ε (%)	$g\Gamma_n$ (meV)	ε (%)	Γ_γ (meV)	ε (%)	Γ_f (meV)	ε (%)	J
201	494.100	116.0		3.4203	60	41.5		70.0	41	1
202	495.630	202.6		0.5948		41.5		160.0		
203	500.500	76.9		2.5200	180	41.5		32.0	65	(1)
204	502.860	85.3		8.8234	100	41.5		32.0	43	1
205	505.780	442.3		0.4461		41.5		400.0		
206	508.220	692.1		0.3470		41.5		650.0		
207	509.740	260.1		38.7630	160	41.5		167.0	46	1
208	511.520	3353.0		6.3945	500	41.5		3300.0	50	
209	515.160	482.4		0.4957		41.5		440.0		
210	516.570	321.7		0.1487		41.5		200.0		
211	517.980	362.1		0.3470		41.5		320.0		
212	520.220	99.3		11.1030	130	41.5		43.0	38	(1)
213	524.210	91.8		22.7520	200	41.5		20.0	40	1
214	525.400	10650.0		59.9790		41.5		10500.0	50	
215	526.000	94.0		0.7435	500	41.5		51.0	90	
216	527.300	59.0		0.7435	600	41.5		16.0	90	
217	530.520	243.0		31.6250	200	41.5		75.0	60	0
218	539.170	55.2		8.4764	150	41.5		2.4	66	1
219	540.710	85.5		1.9328		41.5		40.0		
220	541.650	89.4		3.96[illegible]5		41.5		40.0		
221	543.080	58.1		8.7243	150	41.5		5.0	46	1
222	545.850	1178.0		8.6747	90	41.5		1120.0	30	
223	547.140	843.2		0.8923	600	41.5		800.0	50	
224	549.670	60.2		8.7738	70	41.5		7.0	49	1
225	553.500	61.3		8.4269	170	41.5		3.0	50	
226	554.130	1232.0		25.8750	60	41.5		1140.0	50	
227	555.720	446.3		2.4289	500	41.5		400.0	50	
228	559.160	89.5		20.2240	60	41.5		21.0	36	1
229	562.840	274.6		26.5690	60	41.5		180.0	50	
230	564.030	52.2		4.8578	120	41.5		2.0	53	
231	565.810	60.6		7.0389	70	41.5		5.0	38	
232	571.110	83.0		6.3945	70	41.5		33.0	38	(1)
233	574.000	419.1		39.4080	60	41.5		220.0	38	(0)
234	575.770	88.9		29.5930	80	41.5		8.0	40	1
235	578.000	80.0		1.2392	300	41.5		36.0	90	
236	579.040	55.3		5.1057	85	41.5		7.0	39	1
237	584.810	322.1		0.3470		41.5		280.0		
238	588.090	62.7		8.3773	65	41.5		10.0	38	(1)
239	589.940	441.9		0.2478		41.5		400.0		
240	593.520	48.7		1.5862	150	41.5		4.0	99	
241	597.350	55.0		6.3945	150	41.5		5.0	66	1
242	598.040	5976.0		10.4090	200	41.5		5915.0	50	
243	604.010	69.0		18.6380	100	41.5		3.5	44	1
244	607.640	50.8		7.2372	60	41.5		7.7	39	1
245	609.290	63.7		11.6980	75	41.5		6.6	41	1
246	612.820	64.2		4.3621	65	41.5		14.0	39	
247	620.640	50.7		8.8234	60	41.5		5.4	40	1
248	622.590	61.0		7.2867	60	41.5		9.8	39	1
249	625.170	56.8		5.8492	65	41.5		7.5	45	(1)
250	628.210	52.7		1.0905	120	41.5		9.0	85	
251	632.970	3874.0		16.8530	90	41.5		3800.0	30	
252	636.470	65.4		3.9655	110	41.5		16.0	65	
253	639.280	56.7		6.8902	60	41.5		6.0	47	1
254	641.420	522.1		0.3470		41.5		480.0		
255	644.940	50.3		4.3621	70	41.5		3.0	99	1
256	646.650	242.9		0.7435		41.5		200.0		
257	658.290	141.1		60.4750	100	41.5		19.0	45	1

IV - CONCLUSION

In this paper we have examined a set of parameters that may be used for calculating Pu 239 cross sections from 4 eV to 660 eV by the single level formalism. We have also proposed the Saclay multi-level parameter set between 4 eV and 205 eV in the case it should be found necessary to allow for the interferences in wide resonances. There are probably other problems needing to be examined, particularly the inter normalization of the various cross sections existing in the literature. It is obvious, for instance, that a normalization of a fission cross section will lead to a change in the corresponding fission widths, namely, to a change in the α values. This is why an evaluation of the kind carried out by O.D. Simpson and F.B. Simpson is worthy of further consideration, taking into account several total, fission and capture cross sections and the fact that the resonance spins are known.

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THE MULTILEVEL BREIT-WIGNER FORMALISM WITH DOPPLER BROADENING APPLIED TO THE Pu^{239} RESONANCES

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1. INTRODUCTION

A two step procedure is required in order to prepare the neutron cross sections in the resonance region, to be utilized by the reactor physicists:

i) the analysis of experimental data

ii) the calculation of the cross section profile functions.

In the first step, a good fit of the experimental data implies the use of an adequate formalism based on a theory of the nuclear resonances.

For consistency, the same formalism must be used in the second step.

It is well known that many difficulties are encountered to carry out the full procedure, the main of which are:

i) the complexity of the exact theoretical expressions which implies the use of some approximations;

ii) the great number of free parameters entering the formulas not linearly;

iii) the uncertainties in the experimental data which generally make unuseful to adopt a sophisticated formalism.

For these reasons, simplified formulas are used, which are a good compromise between the most rigorous formalism and practical exigencies of reactor physicists.

The formalisms currently utilized for the representation of the resolved resonances are:

1) Breit-Wigner single-level formula (SL)

2) Breit-Wigner multilevel formula (ML)

3) Reich-Moore formalism (RM)

4) Adler-Adler formalism (AA).

A critical review of the advantages and disadvantages of such formalisms has already been presented in a previous meeting on neutron nuclear data evaluation /1,2/. The conclusions are still actual and we want to recall the main observations there reported, useful to justify the present work.

1. The SL formalism is a too poor approximation for all the cases where the ratio $\overline{\Gamma}/\overline{D}>0.1$. Then, it does not work properly for fissile nuclei and for light nuclei (Fe, Ni, Cr, ...) in the ten keV range . As advantage, the Doppler broadening is performed quite easily through the analytical functions ψ and χ , so that the formalism is used as a first guess in nearly all cases.

2. The ML formalism is sometimes used also for non-fissile nuclei, taking into account only the resonance scattering interferences /3/, /4/, or it is used for the fission cross section calculations in the Sailor version /5/, which was deduced from the Feshbach et al. approximation /6/. The formalism would be very convenient, because it uses the physically meaningful R-matrix parameters. The following disadvantages can be attributed to the method:

   a) It may not yield an accurate description of the cross sections in the region where the widths are larger than the spacings /6/, /7/.
   Nevertheless, under this regard, it can be observed that, in applications, the approximate ML version of the interference term between two resonances, has been found to differ from the Lane-Thomas full approximation /8/ by less than the experimental error /5/, /9/.

   b) The formalism is settled down for the most commonly used approximation in which a great number of levels but few channels are considered. It does not seem to be feasible if the approximation is needed in which few levels but a great number of channels are considered /10/.

   c) In our information, a generalized analytical Doppler broadening formalism has not been given for all the reactions. The problem has been solved for the one-channel fission reaction by Cook /9/. A corresponding procedure for the elastic reaction, including both resonance to potential and resonance to resonance interference terms, has not been found in the literature.

3. The RM formalism is convenient for the analysis and calculation of the fission cross section. The R-matrix parameters are used. Starting from the Wigner-Eisenbud formalism /11/ the order of the level matrix to be inverted is reduced to the number of retained interfering channels by using the simplification coming from the

stacistical hypothesis for the radiation widths. In our opinion, the main disadvantage of the formalism lies on the fact that numerical Doppler broadening is needed, because the analytical convolution with the maxwellian could not be done till now.

4. The AA formalism, by means of a previous diagonalization of the A level matrix, has the property that the Doppler broadening can be performed analytically through the usual ψ and χ functions. But the R-matrix real parameters are lost and any conversion to these ones from the new complex and energy dependent parameters is quite difficult. Moreover the assessment of interfering levels cannot be guessed "a priori".

The above picture on the status of the formalism seems to indicate as convenient, in many cases, the use of the ML formalism which may be a good compromise between the exigency of simplicity for reactor calculations and the requested accuracy of the fit which would be, as remarked above, generally better than experimental precision.

For these reasons, the Authors were interested in the arrangement of the formalism in order to obtain analytical Doppler broadening for all the reactions.

In fact, the main disadvantage of the numerical broadening is that it may be quite easily wrong if not sufficiently fine tabular description of the resonant cross section is given. The fine tabulation is hard to be carried out, due to the same nature of the resonance function which requires a high number of points to be well described.

The arrangement started from a reduction of the existing formula in matrix form. The main advantage of such a representation is a cross section factorization in which:

- one factor is an energy independent matrix with the elements containing the products of the reduced widths γ's ;
- another factor is an energy dependent matrix which does not contain the reduced widths.

As a consequence we have:

i) The role of the interference is more evident and easily assigned;

ii) the sign attribution to the reduced widths, in all the possible permutations, is more easily generated /12/.

The first version of the formalism so assessed has been presented at the Karlsruhe Meeting on structural materials /13/. Any reaction and both interference type were included (i.e. for elastic reaction, the resonance to potential and the resonance to resonance interference terms).

In the last version, which will be described by us in a separate report /14/ , an analytical expression has been obtained for the ML Doppler broadened cross sections which make use of the well known ψ and χ functions.

Here we want now to describe some results of the application of the ML formalism to the multilevel R-matrix parameters of Pu^{239}.

The Farrell set /15/ , with two open fission channels in the interval between 14 to 90 eV, has been used. It consists of 47 resonances of which 32 have been assigned to the 1^+ spin state and the remaining 15 to the 0^+ state.

The fission width of each resonance was put entirely in one channel or in the other one, as justified by the Author. This fact made possible to use our ML code, essentially prepared for the case of one open fission channel, which can be easily adapted to the two-channel calculation, in this special case.

Our choice of parameters does not involve any judgement on their validity with respect to other discussed sets (e.g. /16/,/17/ and references there reported) which could not be used with our code, in absence of the condition of only one open fission channel, at each level.

The aim of application was to solve some questions arising when the ML formalism is used.

The questions are the following:

i) The sensitivity of the fission cross section, at different energies, due to any selected sequence of signs for the reduced width products.

ii) The variability with the temperature of the SL and ML cross section profile functions.

iii) The dependence upon dilution and temperature of the group SL and ML cross sections.

Let us examine such problems in some detail.

i) Cross section dependence upon the set of the reduced width signs

According to Bethe's assumption (see /8/ , pag. 302), when a large number of levels must be treated, the average cross section, within a finite energy interval, can be obtained assuming random signs for the reduced width amplitudes.

On the other hand, the consequence of a random choice of the signs on the cross section values at any given energy, till now were not examined by calculations. With respect to the random choice of signs, it will therefore be interesting to calculate:

a) the amount of uncertainty in the cross section values and its variability as a function of the neutron energy;

b) the difference between the arithmetic means of the cross section values at fixed energies and the corresponding SL values, which does not depend upon the γ signs;

c) the search for the distribution density of the cross section values at any fixed energy point.

In order to solve these questions, it has been calculated - at four energies - the frequency distributions of the cross section within the range determined by a sample of 1000 different permutations of the γ signs (the total number of permutations is 2^{46} for 47 resonances /12/).

The frequency hystograms are shown in figs. 1 to 4.

The main statistical quantities of such distributions are given in table 1.

The following comments can be made:

a) The choice of signs of the reduced width amplitudes may have a great influence upon the results. If the choice is random, the cross section uncertainty is largely variable with the energy. The dispersion coefficient ranges, in our examples, from 1.75% at a resonance energy to a maximum of 93.13% in the energy interval between two resonance peaks.
Of course, only the experimental values lying within the uncertainty band can be satisfactorily approximated by means of a proper choice of the signs. In the other cases, it seems reasonable to change the resonance parameters.

b) The mean value of the frequency distribution always resulted to be equal to the SL value, at each energy and temperature. It has been previously observed that, if the interference terms "contribute constructively at one energy, they will contribute destructively - in roughly equal measure - at some other energy" /10/, /12/. From the present result, one can infer that a similar full compensation exists, with regard to the change of signs, at each fixed energy and for any temperature.

ii) Temperature dependence of the ML and SL cross sections

The Pu^{239} fission, elastic and capture cross sections have been calculated from the Farrell's parameters in the range 14-90 eV at 0 , 300 , 900 and 2100 °K temperature degrees.

Following a previous work concerning calculations of elastic cross section at 0°K temperature for structural materials /13/ , both ML and SL formalism have been used again for the fission and elastic cross sections, in order to estimate the error arising from the application of the SL formalism to ML parameters for different temperatures.

In the figures at the end of the paper the differences ML-SL are plotted.

Looking at the results, some relevant local differences between ML and SL curves can be observed. However, a remarkable absolute reduction and smoothing of such differences were obtained with the increasing of the temperature. Moreover, the difference in the mean, over energy intervals including many resonances, tends to diminish and reduces here to the relative value 2.63% over an interval including all the resonances (10÷100 eV). By considering the Farrell set of γ signs as a random one, theBethe's assumption means that, by the random choice, a convergence to the SL results is obtained in the mean for an increasing number of resonances.

iii) Temperature and dilution dependence of the ML and SL group cross sections

It may be important for reactor calculations to compare the change, with dilution and temperature, of both the SL and ML group cross sections.

The formalism commonly adopted by reactor physicists is the single level one, sometimes corrected with a background term /4/.

In order to verify the hypothesis that a temperature independent background can be retained when large groups are considered, in the present work this term has been assumed to be equal to the difference ML-SL at 0°K degrees.

The comparison among ML, SL and SL+ "background" (SL+Bg) fission and total group cross sections in the Russian library (ABBN) schema, is shown in tables 2 and 4 respectively, as a function of the dilution (σ_o) and temperature (T) values therein considered.

As expected, because of the self-shielding effect, the relative differences between ML and SL cross sections decrease with the increasing of the temperature and, more appreciably, of the dilution. In table 3 the percent differences, for the fission cross section, are given. The same behaviour has been observed for the total cross section, with regard to the dilution parameter σ_o, while the temperature dependence becomes unsignificant.

It can be seen in tables 2 and 4 that, by the addition of the background term to the SL cross section, the relative differences [(SL+Bg)-ML]/ML becomes negligible.

In any case, with the Fa[illegible]l parameters, the SL formalism gives rise to an overestimate of [illegible]e group cross sections.

CONCLUSIONS

The ML formalism, set up with the analytical Doppler broadening, can be considered to be suitable, in a large number of cases, for reactor calculations. In our opinion, the fission cross section can also be treated successfully, if no more than one or two partial fission widths are assumed for such reaction.

The [illegible]lication of the formalism to the Pu^{239} resonances has shown, preliminarly, some important results, the main of which are:

1) The great variability of the fission, and consequently of the total cross section, with the choice of the γ signs. An investigation to find the distribution law vs. energy, empirically found with the histograms of figs. 1-4, would probably be very useful for the cross section fits.

2) Significant variability of the microscopic differences ML-SL with the temperature was observed, in the present calculations. Then, with the above defined "background" term, the assumption:

$$SL + Bg \simeq ML \quad ,$$

may introduce non-negligible errors, whenever microscopic or fine group cross sections are required (e.g. Monte Carlo, MC^2 calculations, etc..).

3) The variability of the differences ML-SL are reduced in the mean, if large group cross sections are considered, as in the ABBN schema. Then the condition $SL+Bg \simeq ML$ is satisfied in ABBN group calculations with the assumed Pu^{239} parameters. If generally confirmed, this result might be of great practical importance in the applications.

ACKNOWLEDGMENT

The authors are greatly indebted to Mr. T. Martinelli for his contribution to this work in programming the machine codes.

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TABLE 1

STATISTICAL QUANTITIES OF THE FISSION CROSS SECTION DISTRIBUTION AS A FUNCTION OF SIGNS OF THE REDUCED WIDTHS. THE CROSS SECTION IS DOPPLER BROADENED AT 300°K

Energy (eV)	Range (barns)	A Mean (barns)	B Mode (barns)	C Standard deviation (barns)	Skewness (A-B)/C	Dispersion coefficient (%) C/A	Nearest resonances (eV)	Farrell's value (barns)
36.75	4.96	0.99	0.1627	0.88	0.87	93.13	35.47 ; 37.25	0.233
41.50	45.20	86.4	71.9974*	13.83	1.04*	16.00	41.43 ; 41.72	97.35
44.51	10.00	119.9	118.4485	2.10	0.69	1.75	resonance level	118.368
65.10	124.70	110.6	77.1202*	30.03	1.11*	27.15	63.16 ; 65.40	109.04

* Non-unimodal distributions; the modes have been assumed to be in the maximum peak (see figs. 2 and 4).

TABLE 2

FISSION GROUP CROSS SECTION OF Pu^{239} IN THE RESOLVED REGION
(ABBN WEIGHTING FLUX AND REF./15/PARAMETERS) DOPPLER BROADENED

BARN UNITS

E lower (eV)	E upper (eV)	T (°K) \ σ_o (b)	0	10	10^2	10^3	∞	FORMULA	GROUP No
10.	21.5	300	7.48 5.20 5.23	9.70 7.31 7.34	18.97 16.31 16.31	37.99 35.08 35.08	50.98 48.58 48.48	SL ML SL+Bg	20
		900	7.65 5.38 5.42	9.97 7.59 7.64	19.80 17.16 17.21	39.50 36.77 36.72	51.56 49.14 49.01	SL ML SL+Bg	
		2100	7.90 5.64 5.70	10.38 8.03 8.10	20.95 18.37 18.38	41.06 38.81 38.19	51.87 49.45 49.27	SL ML SL+Bg	
21.5	46.4	300	3.69 2.71 2.73	4.61 3.70 3.72	8.28 7.51 7.52	16.27 15.25 15.27	21.67 21.01 21.03	SL ML SL+Bg	19
		900	4.04 3.05 3.07	5.15 4.22 4.23	9.44 8.64 8.62	17.69 16.74 16.72	22.21 21.54 21.54	SL ML SL+Bg	
		2100	4.46 3.43 3.45	5.76 4.78 4.80	10.72 9.86 9.87	18.92 18.13 18.13	22.50 21.83 21.91	SL ML SL+Bg	
46.4	100.	300	18.73 15.03 15.02	22.33 18.95 18.94	36.33 34.16 34.13	62.27 61.55 61.59	89.31 88.77 88.85	SL ML SL+Bg	18
		900	19.38 15.73 15.71	23.31 19.89 19.87	38.07 35.93 35.90	64.55 64.02 63.95	89.53 89.01 89.09	SL ML SL+Bg	
		2100	20.38 16.81 16.80	24.63 21.26 21.24	40.33 38.15 38.16	67.15 66.80 66.55	89.72 89.21 89.29	SL ML SL+Bg	

Bg - Background, i.e. the difference ML-SL calculated at 0°K temperature degree.
SL - Single level.
ML - Multilevel.

TABLE 3

PERCENT RELATIVE DIFFERENCES (SL-ML)/ML FOR THE GROUP FISSION CROSS SECTION FROM TABLE 2

E lower (eV)	E upper (eV)	σ_0(b) / T (°K)	0	10	10^2	10^3	∞	ABBN Group No.
10	21.5	300	43.8	32.7	16.3	3.3	4.9	20
		900	42.2	31.4	15.4	7.4	4.9	
		2100	40.1	29.3	14.0	5.8	4.9	
21.5	46.4	300	36.2	24.6	10.3	6.7	3.1	19
		900	32.5	22.0	9.3	5.7	3.1	
		2100	30.0	20.5	8.7	4.4	3.1	
46.4	100	300	24.6	17.3	6.4	1.2	0.6	18
		900	23.2	17.2	6.0	0.8	0.6	
		2100	21.2	15.9	5.7	0.7	0.6	

TABLE 4

TAL (ABBN-type) GROUP CROSS SECTION IN THE RESOLVED REGION FOR Pu^{239} (ABBN WEIGHTING FLUX AND REF./15/PARAMETERS)

BARN UNITS

E lower (eV)	E upper (eV)	T (°K) \ σ_o (b)	0	10	10^2	10^3	∞	FORMULA	GROUP No
10.	21.5	300	13.57 11.99 12.00	15.27 13.51 13.51	23.89 21.65 21.68	52.32 50.23 50.28	85.32 82.98 82.88	SL ML SL+Bg	20
		900	13.62 12.03 12.04	15.39 13.62 13.64	24.36 22.18 22.25	55.75 53.04 52.91	86.31 83.95 83.82	SL ML SL+Bg	
		2100	13.64 12.05 12.08	15.51 13.75 13.79	25.27 22.78 22.91	58.81 56.52 55.96	86.82 84.46 84.28	SL ML SL+Bg	
21.5	46.4	300	13.19 12.15 12.16	14.46 13.46 13.47	20.23 19.37 19.38	35.72 35.02 35.02	53.47 52.80 52.82	SL ML SL+Bg	19
		900	13.36 12.31 12.32	14.90 13.88 13.90	22.38 21.54 21.54	36.53 35.80 35.32	54.81 54.13 54.14	SL ML SL+Bg	
		2100	13.54 12.51 12.54	15.30 14.28 14.31	24.24 23.49 23.57	43.79 43.04 43.06	55.51 54.78 54.81	SL ML SL+Bg	
46.4	100	300	21.31 18.55 18.55	24.45 21.36 21.36	38.63 35.92 35.90	71.47 70.20 70.17	114.67 114.13 114.21	SL ML SL+Bg	18
		900	21.42 18.79 18.78	24.78 21.80 21.79	40.36 37.67 37.62	72.75 71.33 72.24	115.12 114.61 114.68	SL ML SL+Bg	
		2100	21.69 19.26 19.25	25.40 22.02 22.06	42.71 40.02 39.96	78.45 77.17 77.31	115.41 114.91 114.99	SL ML SL+Bg	

Bg = Background, i.e. the difference ML-SL calculated at 0°K temperature degree.
SL = Single level.
ML = Multilevel.

FIGURE CAPTIONS

Frequency histograms of the Pu^{239} fission cross section at different energies, obtained by 1000 random permutations of signs (±) of the reduced widths. The absolute values of Farrell's parameters /15/ were used.

FIG. 1 - neutron energy E=36.75 eV
FIG. 2 - " " E=41.50 eV
FIG. 3 - " " E=44.51 eV
FIG. 4 - " " E=65.30 eV

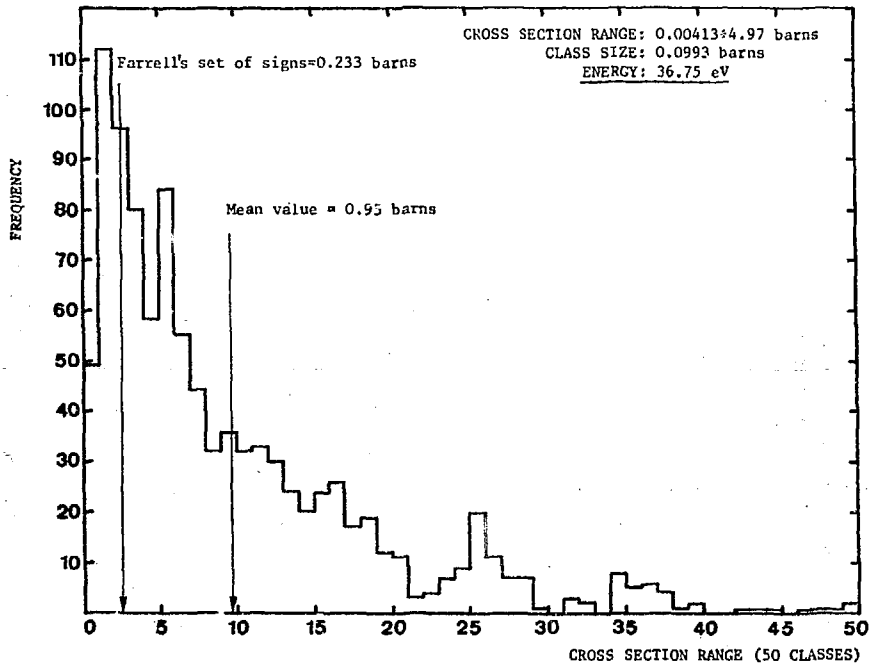

CROSS SECTION RANGE: 0.00413÷4.97 barns
CLASS SIZE: 0.0993 barns
ENERGY: 36.75 eV
Farrell's set of signs=0.233 barns
Mean value = 0.95 barns
FREQUENCY
110
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
45
50
CROSS SECTION RANGE (50 CLASSES)

FIG. 1

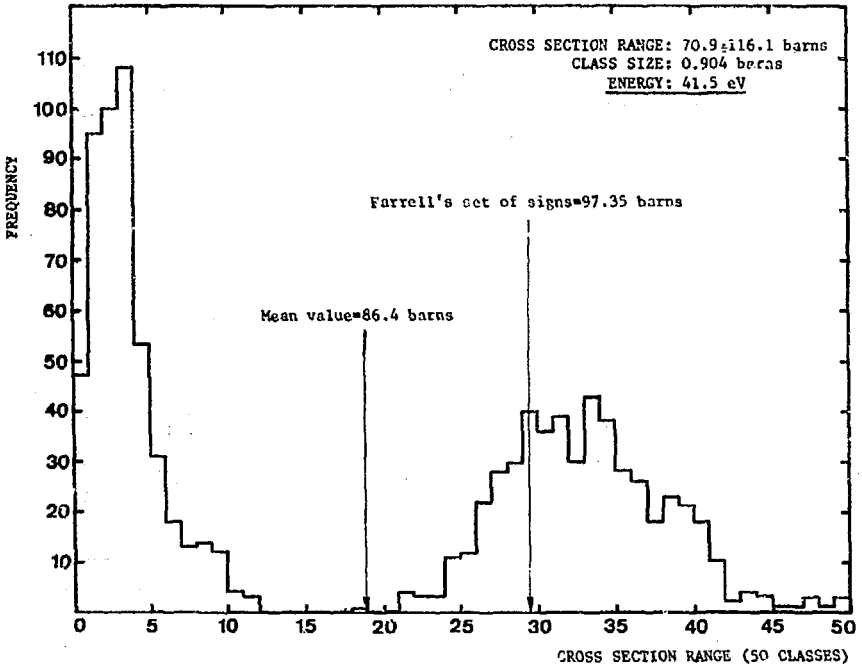

CROSS SECTION RANGE: 70.9÷116.1 barns
CLASS SIZE: 0.904 barns
ENERGY: 41.5 eV
Farrell's set of signs=97.35 barns
Mean value=86.4 barns
FREQUENCY
110
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
45
50
CROSS SECTION RANGE (50 CLASSES)

FIG. 2

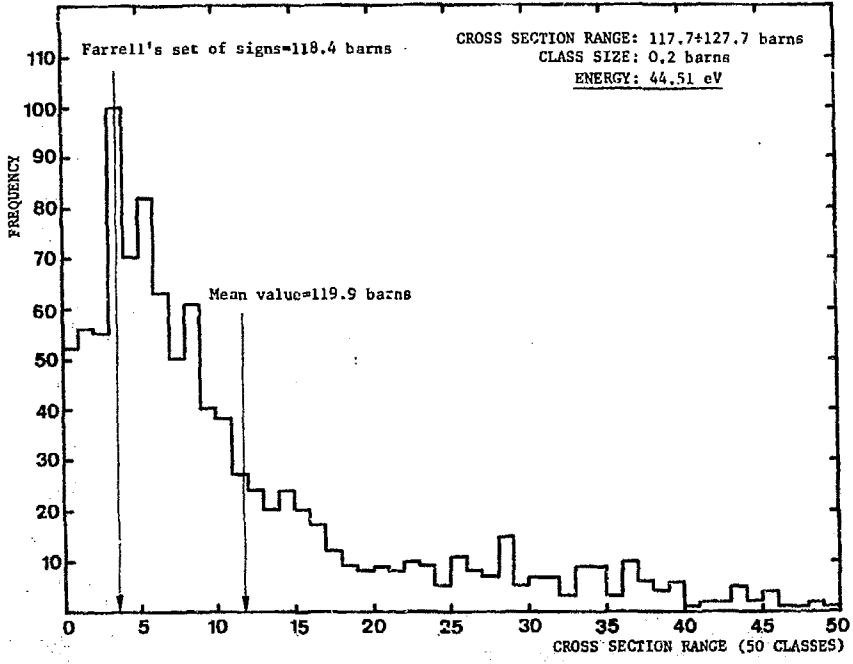

Farrell's set of signs=118.4 barns
CROSS SECTION RANGE: 117.7÷127.7 barns
CLASS SIZE: 0,2 barns
ENERGY: 44.51 eV
Mean value=119.9 barns
FREQUENCY
110
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
45
50
CROSS SECTION RANGE (50 CLASSES)

FIG. 3

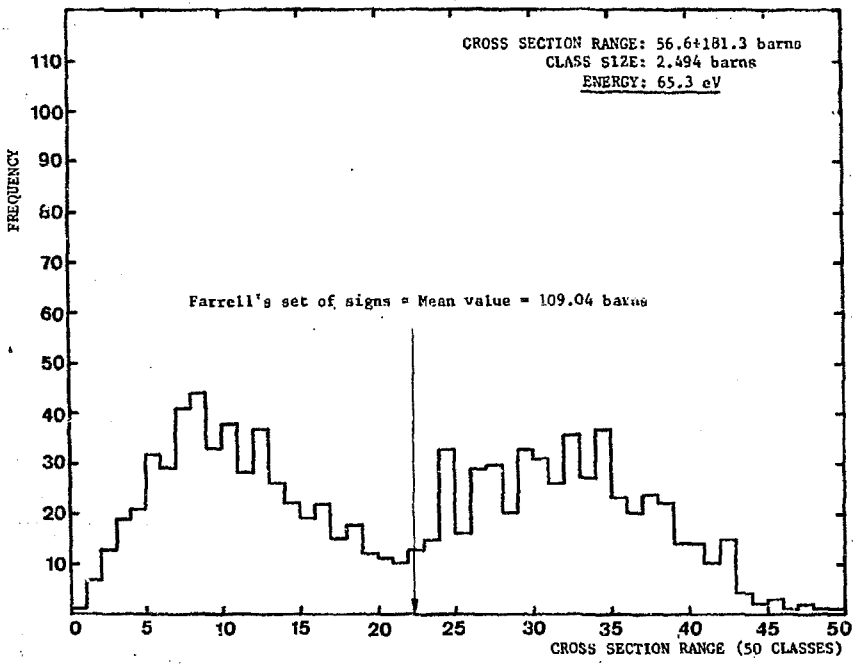
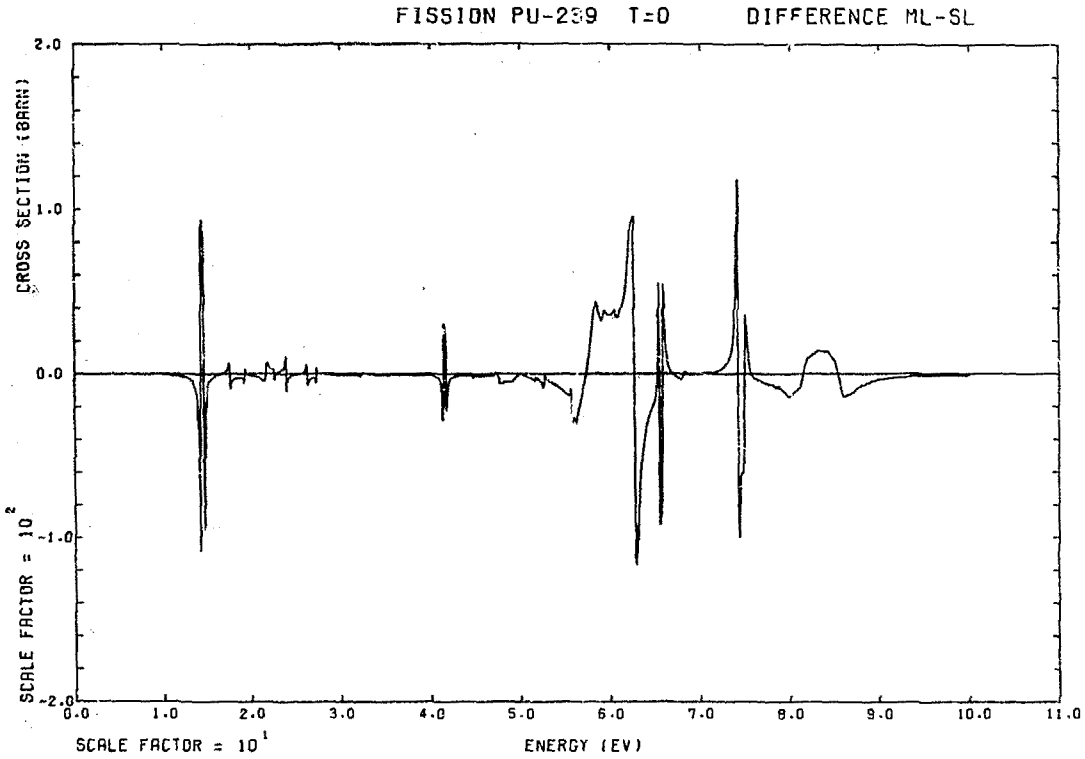
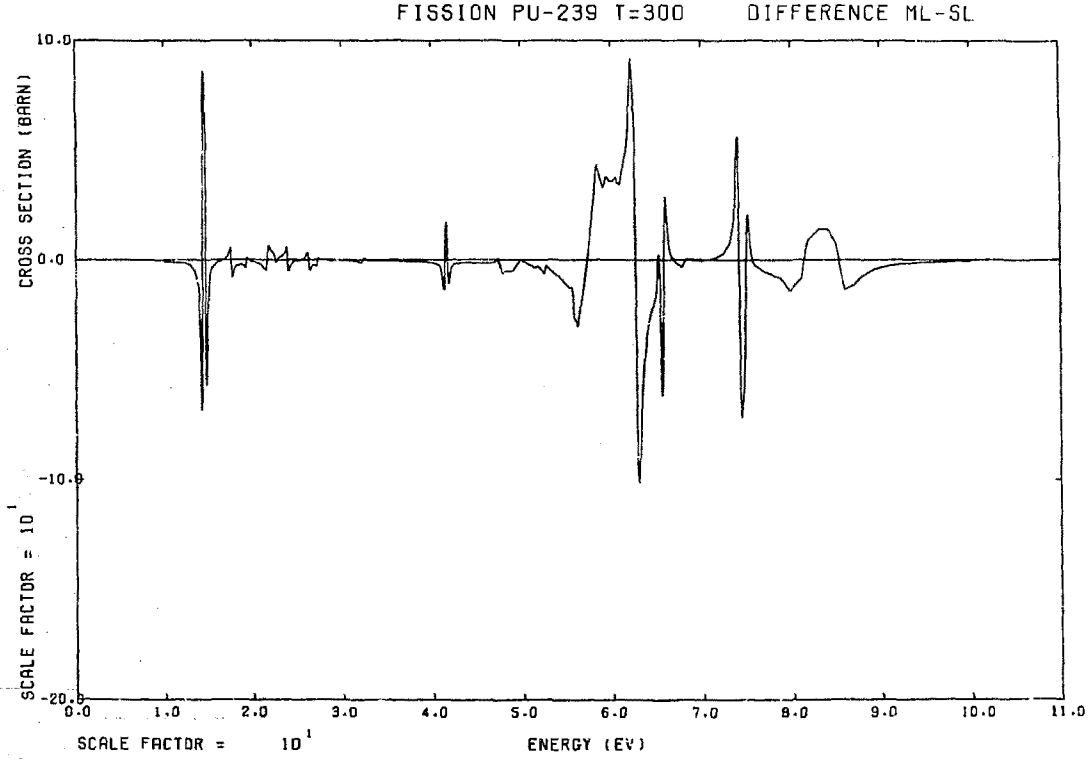

CROSS SECTION RANGE: 56.6÷181.3 barns
CLASS SIZE: 2.494 barns
ENERGY: 65.3 eV
Farrell's set of signs = Mean value = 109.04 barns
FREQUENCY
110
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
45
50
CROSS SECTION RANGE (50 CLASSES)

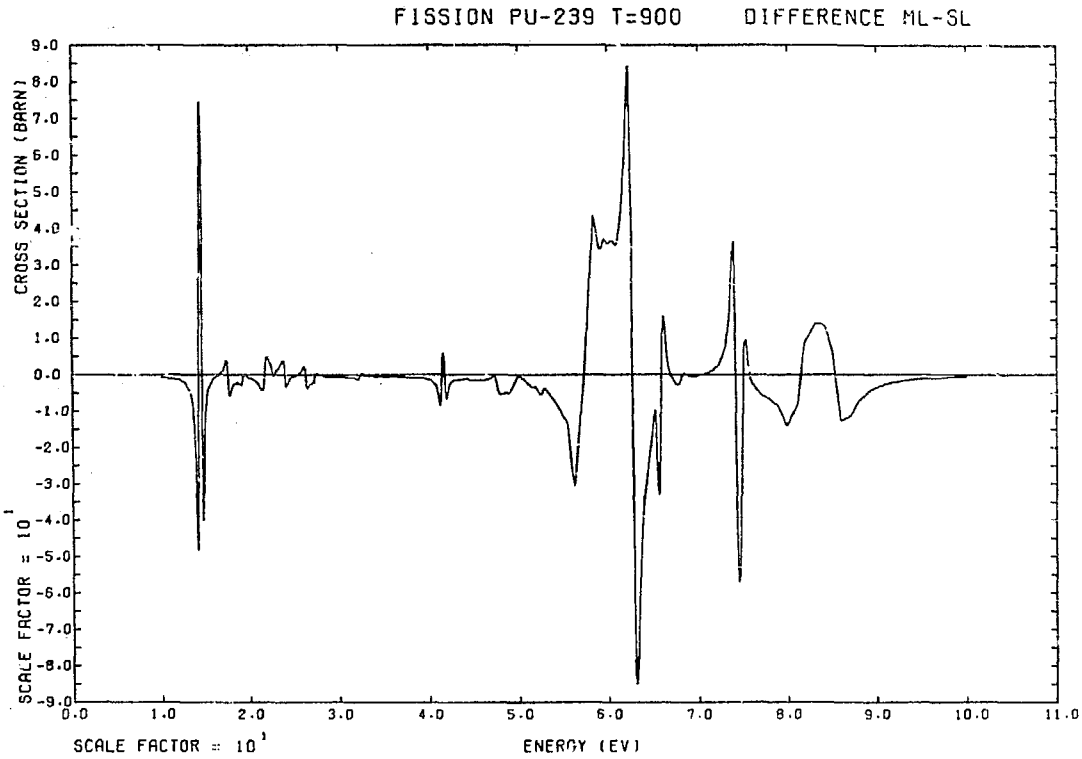
FIG. 4

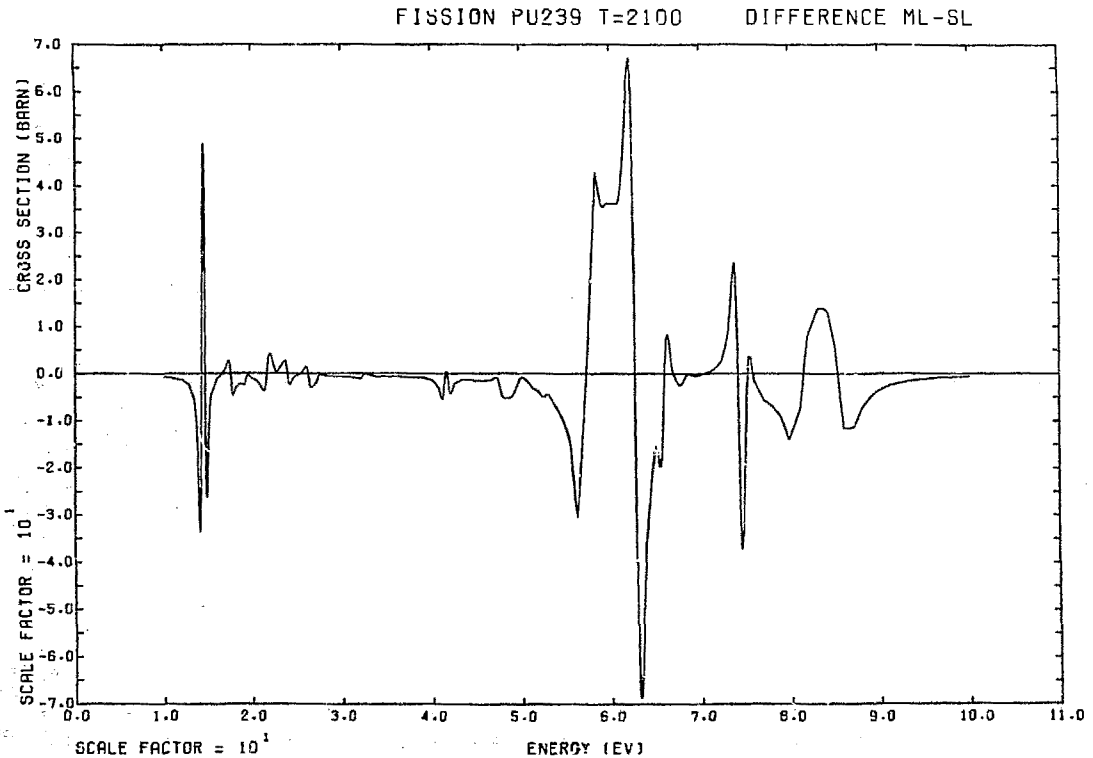
CROSS SECTIONS

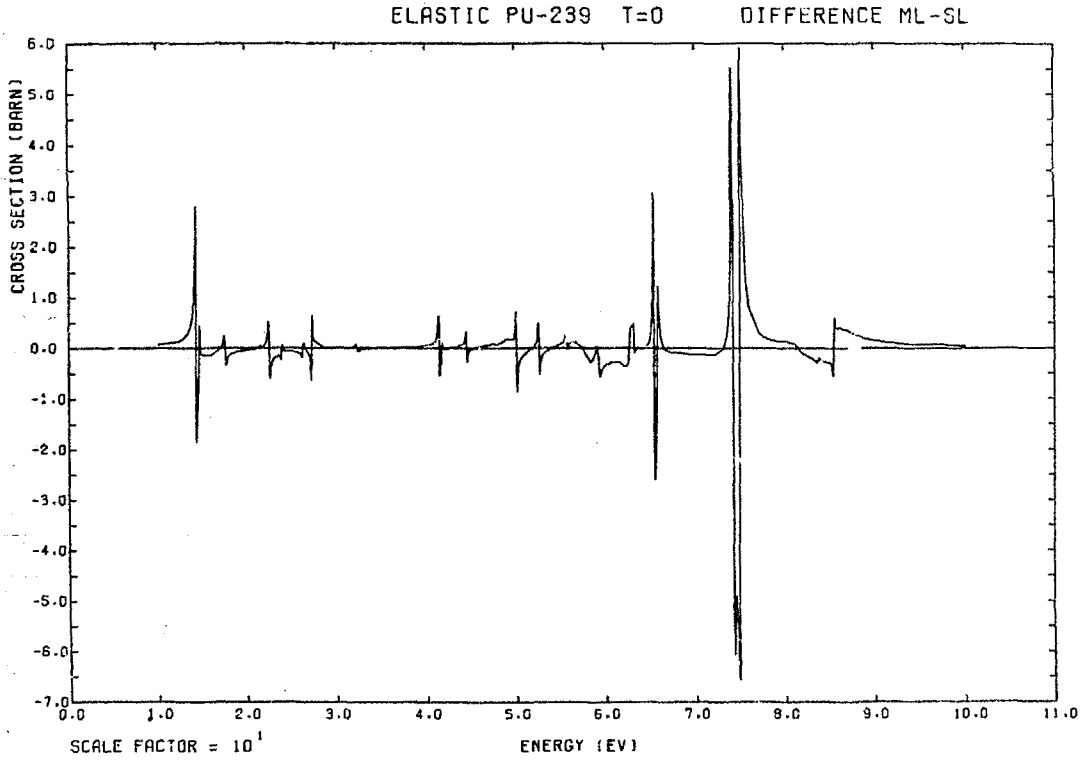
ML-SL differences of Pu-239 fission and elastic cross sections from Farrell's parameters /15/ in the interval 10÷100 eV at different temperatures.

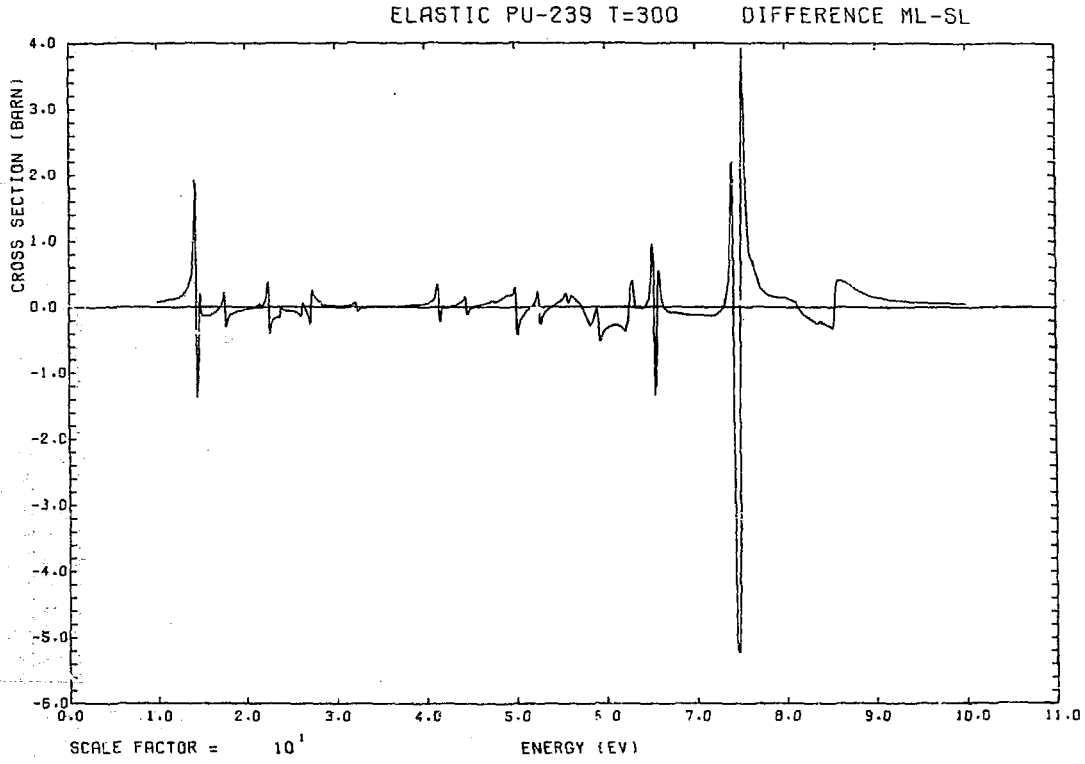

FISSION PU-239 T=0 DIFFERENCE ML-SL
CROSS SECTION (BARN)
SCALE FACTOR = 10^2
2.0
1.0
0.0
-1.0
-2.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)

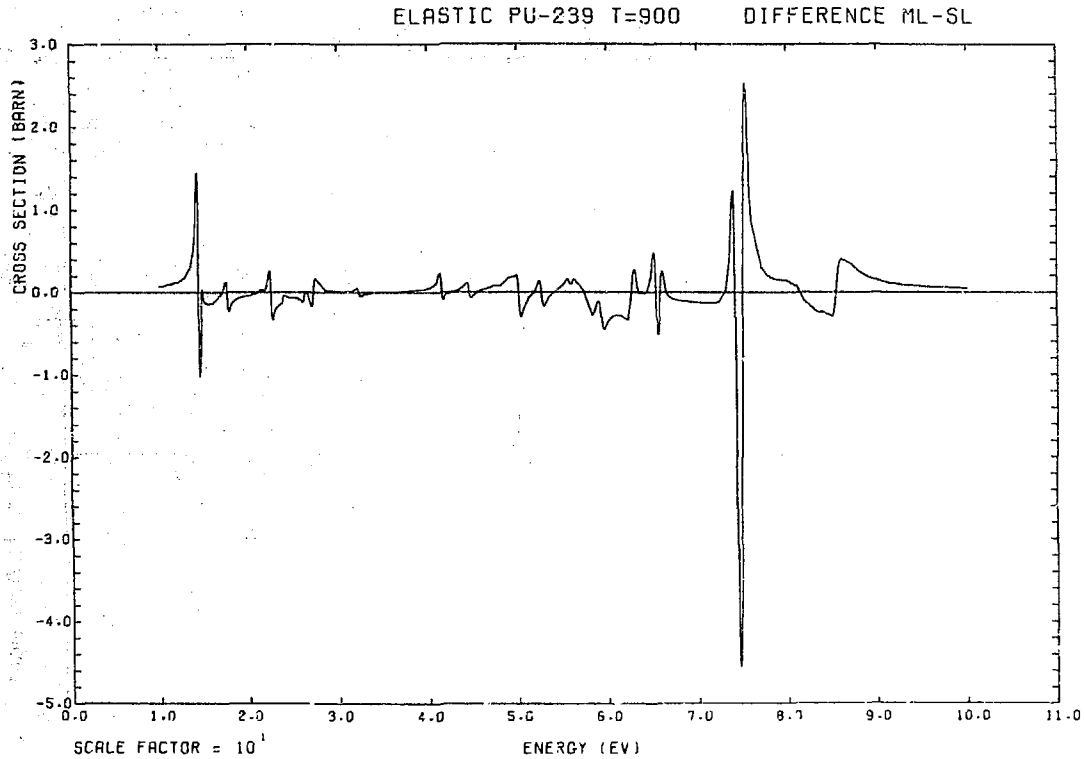

FISSION PU-239 T=300 DIFFERENCE ML-SL
CROSS SECTION (BARN)
10.0
0.0
-10.0
-20.0
SCALE FACTOR = 10 1
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10 1
ENERGY (EV)

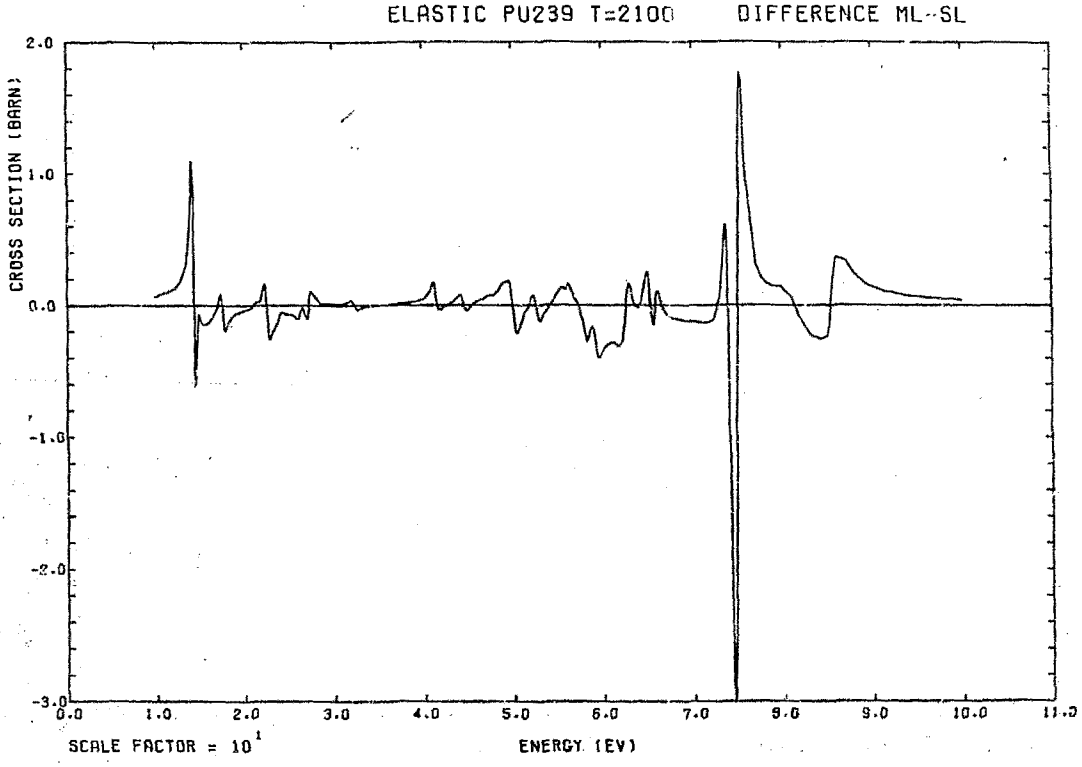

FISSION PU-239 T=900 DIFFERENCE ML-SL
CROSS SECTION (BARN)
SCALE FACTOR = 10^1
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)


FISSION PU239 T=2100 DIFFERENCE ML-SL
CROSS SECTION (BARN)
SCALE FACTOR = 10^1
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)


ELASTIC PU-239 T=0 DIFFERENCE ML-SL
CROSS SECTION (BARN)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)


ELASTIC PU-239 T=300 DIFFERENCE ML-SL
CROSS SECTION (BARN)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)


ELASTIC PU-239 T=900 DIFFERENCE ML-SL
CROSS SECTION (BARN)
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)


ELASTIC PU239 T=2100 DIFFERENCE ML-SL
CROSS SECTION (BARN)
2.0
1.0
0.0
-1.0
-2.0
-3.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
SCALE FACTOR = 10^1
ENERGY (EV)

THE TEMPERATURE COEFFICIENTS IN THE THERMAL REACTORS

G. LE COQ et P. REUSS

The temperature coefficient of a reactor is defined as the logarithmic derivative of the multiplication factor k with respect to the temperature :

$$\alpha = \frac{1}{k}\frac{\partial k}{\partial T}$$

It is generaly expressed in "pcm per degree".

Experiment-calculation comparisons

Some comparisons have been made for graphite or water moderated lattices : it appears a discrepancy of about 2 pcm/° (calculation < experiment) at room temperature. This difference decreases at higher temperature. Notice that sometimes the measurements can be made with a precision of ± 0.5 pcm/°.

Doppler effect

An error on the Doppler effect cannot explain such a deviation. Indeed the order of magnitude of this effect is - 2 pcm/° : so it would be necessary to cancel this effect to nullify the deviation.

Origin of the temperature coefficient in the thermal range

When the temperature increases, the thermal neutron spectrum moves towards the higher energies. If all the cross-sections had the same law with energy, this shift would not produce any effect on the multiplication factor which is a quotient of reaction rates. It is because that is not the case that the temperature coefficient does exist.

Reference law for the cross-sections

It is practical to chose the "$\frac{1}{v}$ - law" as the reference law for the cross-sections. Then one can say that the temperature coefficient is due to the deviation of the cross-sections from this $\frac{1}{v}$ - law. At the first order the deviation can be characterize by a λ parameter such that :

$$(1) \qquad \sigma(E) \simeq \frac{a}{\sqrt{E}} (1 + \lambda E) \qquad (a : \text{constant})$$

(if the Breit and Wigner formula can be used one can see that $\lambda = 2/E_r$ where E_r is the energy of the resonance). One can also characterize the deviation by the difference between the Westcott's g-factor and 1. A simple calculation shows that :

$$(2) \qquad g - 1 \simeq \frac{1}{2} \lambda E_0 \qquad (E_0 = 0.0253 \text{ eV})$$

Incertainties on the calculation of the temperature coefficient

An approximate calculation of α is sufficient to estimate the incertainties. Let us consider the contribution of the reaction rate R to α. It can be written :

$$\frac{\partial k/k}{\partial R/R} \cdot \frac{\partial R/R}{\partial T}$$

The first factor, h, can be deduced of the neutronic balance. The second one is :

$$\frac{1}{1 + \lambda \overline{E}} \cdot \frac{\partial(1 + \lambda \overline{E})}{\partial T} = \frac{\lambda}{1 + \lambda \overline{E}} \cdot \frac{\partial \overline{E}}{\partial T} \simeq \lambda \frac{\partial \overline{E}}{\partial T}$$

since R is proportionnal to $a(1 + \lambda \overline{E})$ ($\overline{E}$: average energy of the thermal neutrons) as shown by (1). Finally one can approximatively take :

$$\frac{\partial \overline{E}}{\partial T} = \frac{3}{2} k \qquad \text{(k : Boltzmann's constant)}$$

i.e. suppose that the derivative of $\overline{E}$ is the same than the derivative of the average energy of the Maxwell's spectrum. Therefore this contribution is :

$$h \lambda \frac{3}{2} k$$

and the incertainty on this contribution due to the incertainty on λ :

$$\Delta \alpha = \frac{3}{2} k h \Delta \lambda = 13 h \Delta \lambda \qquad (3)$$

($\Delta \alpha$: pcm/° ; $\Delta \lambda$: eV^{-1})

Applications

The table below gives some numerical examples of these incertainties.

- For the fissile nuclides λ and $\Delta \lambda$ have been evaluated by (2) from g and Δg of [1].
- For ^{238}U we have taken $\Delta \lambda = \lambda$ because a precise measurement of the slope of $\sigma\sqrt{E}$ has never been made [we had studied in [2] the implications of a possible p-wave resonance in the thermal range for this isotope : the effect on α would be small and increase the discripancy with experiment].
- For ^{240}Pu we have taken the same $\Delta \lambda$ than for ^{239}Pu fission.

Nuclide		^{235}U Fission	^{235}U Capture	^{238}U	^{239}Pu Fission	^{239}Pu Capture	^{240}Pu	^{241}Pu Fission	^{241}Pu Capture	Quadratic Sum
	g - 1	- 0.024	0.04		0.057	0.15		0.042	0.04	
	Δg	0.002	0.02		0.003	0.02		0.006	0.02	
λ	% per eV	- 190	320	10	450	1200		330	320	
Δ λ	% per eV	20	150	10	20	150	20	50	150	
h	NUGG	0.54	- 0.08	- 0.32						
	HTR	0.39	- 0.12	- 0.09						
	D_2O	0.56	- 0.08	- 0.30						
	PWR	0.35	- 0.11	- 0.10						
	PWR-Pu	0.03	- 0.01	- 0.03	0.38	- 0.20	- 0.19	0.09	- 0.03	
Δ α pcmy°	NUGG	1.4	1.6	0.4						2.2
	HTR	1.0	2.3	0.1						2.5
	D_2O	1.5	1.6	0.4						2.2
	PWR	0.9	2.1	0.1						2.3
	PWR-Pu	0.1	0.2	0.0	1.2	3.9	0.5	0.6	0.6	4.3

Conclusions

- The incertainties on α appear rather big : the discripancy between calculation and experiment is not a priori surprising.

- For a great part the total incertainty comes from the incertainty of the capture cross-section of the fissile nuclides.

- The integral measurement of α can be precise enough to bring an useful informations for the knowledge of these cross-sections in the thermal range (slopes of $\sigma\sqrt{E}$).

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THE LOW-ENERGY NEUTRON INDUCED FISSION CROSS-SECTION OF ^{239}Pu AND THE TEMPERATURE DEPENDENCE OF THE WESTCOTT g_f - FACTOR

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Introduction

The neutron induced fission cross-section of ^{239}Pu was determined in an absolute way at the slow chopper facility of the BR2 high-flux reactor of S.C.K./C.E.N., Mol in the energy region 0.005 eV to 0.1 eV [1]. From this measurement an absolute value of the thermal fission cross-section σ_f^0 = (741.9 ± 3.4) barn was calculated. A complementary measurement was performed at a well collimated short flight path of the CBNM Linac [2]. Here we determined the relative fission cross-section from 0.01 eV to 30 eV. The large region of overlap with the above mentioned BR2 measurement permitted a direct normalization to the absolute σ_f^0 value obtained there.

Both measurements were performed with Si (Au) surface barrier detectors. The ^{239}Pu (n, fission) rate and the $^{10}B(n, \alpha)^7Li$ rate were compared directly at the same position in the neutron beam, using the 1/v - behaviour of the $^{10}B(n, \alpha)^7Li$ reaction cross-section. For a detailed description of the apparatus, the experimental procedure and the treatment of data we refer to [1] [2].

In this paper we examine the most important σ_f (E) measurements in the energy region considered and we look for the origins of the discrepancies between them. We further use our differential cross-section data to calculate the Westcott g_f - factor in function of the temperature of the Maxwellian neutron distribution.

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The neutron induced fission cross-section data and the importance of a proper normalization procedure

Figure 1 shows the ^{239}Pu neutron induced fission cross-section σ_f (E) in function of the neutron energy from 0.008 eV to 10 eV. The data below 0.02 eV are obtained at the BR2 reactor ; those above 0.02 eV are the Linac results. Figure 2 covers the same energy region but here all the BR2 data are used (0.008 - 0.0717 eV) and completed with the Linac results from 0.0717 - 10 eV. Figure 3 shows σ_f (E) versus E from 1 eV to 30 eV.

The Linac results are normalized to the integral

$$\int_{0.02081\ eV}^{0.06001\ eV} \sigma_f\ (E)\ dE = (75.15 \pm 0.13)\ \text{barn. eV}$$

obtained at the BR2. This normalization method is more accurate than a simple no-malization of the relative cross-section at thermal energy to the 2200 m/s reference cross-section.

DERUYTTER and BECKER[1] explain indeed that with one single set of absolute σ_f-data one can obtain different σ_f^0-values in function of the fitting procedure applied. So they obtained σ_f^0 = (742.5 ± 3.3) barn when applying a straight line fit through the data points in the region around 0.0253 eV. With a fit of more physical nature, i.e. a formula taking into account interference between four 1^+ levels (-0.53 eV ; 0.30 eV ; 7.9L eV and 11.0 eV) with the usual Breit-Wigner terms added, and when minimizing the sum of the squares of the deviations between the experimental points and the fit in a small region around 0.0253 eV, they obtained σ_f^0 = (740.7 ± 3.3) barn.

Because of the small sensitivity of the obtained σ_f^0 - value to the fitting procedure used they then calculated fits of the type $\sigma_f\sqrt{E} = \sum_{i=1}^{N} C_i E^{i-1}$ for N going from 2 to 8. From this series of fits they feel that an error of 0.10 % has to be added to the total error, due to the curve fitting procedure in the neighbourhood of 2200 m/s. The final value accepted in their work is the average value of all fits : $\sigma_f^0\sqrt{E}$ = 118.00 barn$eV^{1/2}$ leading to σ_f^0 =(741.9 ± 3.4)b.

The same fitting problem reappears when one needs to determine the relative σ_f-value at 0.0253 eV. This small but not negligible "fitting effect" can be avoided by using fission integral as we did.

The great advantage of this set of data is that the Linac results as well as the data used for normalization are obtained with the same basic detection techniques by the same group of physicists.

To compare these data with previous results obtained with other detection techniques or by other ways of normalization, we examined the results of several authors.

In Table 1 the most relevent fission integrals $\int_{E_1}^{E_2} \sigma_f\ (E)dE$ are given.

The integrals in the lower part of this Table (E>6 eV) were obtained from an integration by the N.E.A. Neutron Data Compilation Centre,

Saclay (France) of the differential data retrieved from their files ; the low-energy integrals given in the upper part (borrowed from GWIN et al.[3]) are in good agreement. The lower part of this table reveals differences up to more than a factor of two between the different integrals. The same differences are found back when calculating the resonance integrals

$$\int_{E_1}^{E_2} \sigma_f\ (E)\ \frac{dE}{E}\ .$$

To determine the reasons for these differences we first of all examined the normalization methods applied in the different measurements. Table 2 shows that they are nearly all different. Only half of the measurements are directly normalized to σ_f^0 but different numerical values are used. All the other normalization methods are indirect and hence more liable to systematic errors.

So we wanted to check up to what extent the differences in normalization procedures were responsible for the discrepant fission integral values. Therefore we looked for a convenient fission integral which could be used to renormalize the different measurements in the same way. Such an integral must have a sufficiently high counting rate, thus contain one or more large resonances. Furthermore its numerical value should nearly not be affected by timing errors, which implies that the cross-sections at its limits must be very small. Finally it should cover an energy region easily attainable by most experiments.
We found that the fission integrals

$$\int_{9.0\ eV}^{20.0\ eV} \sigma_f\ (E)\ dE = (1226.3 \pm 12.2)\ \text{barn eV}$$

and $$\int_{9.0\ eV}^{20.0\ eV} \sigma_f\ (E)\ dE = (1046.6 \pm 10.4)\ \text{barn eV}$$

obtained from our measurement would be very convenient. The indicated errors are composed of the error on the primary normalization integral (obtained at the BR2) and the error on the relative cross-section experiment (interconnection of the different runs, fitting of the neutron spectrum, background correction, statistical errors).

Before renormalizing the σ_f - measurements mentioned in Table 1, we verified their relative behaviour with respect to our σ_f - curve. Therefore we calculated the ratio of our fission integrals in the most interesting energy intervals to the corresponding integrals obtained from the other measurements. These results are given in Table 3.

They clearly show that the ratios are constant within the precision of the experiments for the data of GWIN et al.[3][4] and BLONS et al.[5] In the case of GWIN[3][4] the ratios are about equal to 1 which means that their normalization yields about the same result as ours. This nearly constant ratio means that the four σ_f - measurements considered have a very similar shape and that the differences are mainly a normalization effect. The same can be said with respect to the integrals obtained from the ENDF/BIII file.

In the case of BOLLINGER et al.[6] the ratios fluctuate significantly but within reasonable limits. The same can be said about IGNATIEV'S[7] results although the fluctuations become important. The ratio for the energy interval 9 eV - 20 eV (which is indeed the renormalization factor) is about the mean value of the extreme ratios as well for BOLLINGER as for IGNATIEV. This could be an indication that the integral considered is well chosen for normalization purposes.

Finally with the data of RYABOV et al.[8] the ratios fluctuate very strongly. It is clear that such strong discrepancies can only to a minor extent be explained by normalization effects ; they are probably due to systematical errors or experimental effects. Since the normalization of one cross-section to another is only valuable and accurate if the normalization factor does not change with the energy, it has no sense to renormalize RYABOV'S data which should in fact be rejected.

In Table 4 we summarize the numerical values of the fission integrals of Gwin, Blons Bollinger and Ignatiev after renormalization to our integral

$$\int_{9\ eV}^{20\ eV} \sigma_f\ (E)\ dE = (1045.6 \pm 10.4)\ \text{barn eV}$$

The original discrepancies are considerably reduced, in such a way that our results and those of Gwin and Blons are in good agreement now over the whole energy range covered. Recently BLONS[9] renormalized his data in the way proposed by us. Compared with the ENDF/B III results the agreement is good except from 350 eV to 650 eV. Also the data of Bollinger agree rather well. The results of Ignatiev are in better agreement now but there remains clearly a slope in his data.

These results together with the preceding considerations stress once more the need for a reliable common normalization method of all relative fission cross-section curves.

The Westcott g_f - factor in function of the temperature

The general expression for the reaction rate per atom for a neutron induced reaction is

$$R = \int_0^\infty n(v).\sigma(v).v.dv \qquad (1)$$

with n(v) the neutron density distribution in the velocity interval (v,v + dv) and σ(v) the reaction cross-section.

WESTCOTT [10] defined a so-called effective cross-section $\hat{\sigma}(T)$ and a g(T) factor for a pure Maxwellian distribution with absolute temperature T in the following way :

$$\hat{\sigma}(T) = \sigma_0 \cdot g(T)$$

$$R = n.v_0.\hat{\sigma} = n.v_0.\sigma_0.g(T) \qquad (2)$$

with $n = \int_0^\infty n(v)dv$, $v_0 = 2200$ m/s and $\sigma_0 = \sigma(v=v_0)$.

From (1) and (2) following expression for g(T) is deduced :

$$g(T) = \frac{\int_0^\infty n(v).\ \sigma(v).\ v.\ dv}{\sigma_0.\ v_0.\ \int_0^\infty n(v).dv}$$

which gives in function of the energy

$$g(T) = \frac{1}{\sigma_0\ \sqrt{E_0}} \int_0^\infty \sigma(E).\sqrt{E}.n(E).dE \qquad (3)$$

with $\int_0^\infty n(E)dE = 1$

$$n(E) = \frac{2\pi\sqrt{E}}{(\pi kT)^{3/2}} \exp\left[-E/kT\right]$$

k = the Boltzmann constant

E_0 = 0.0253 eV .

In the case of a fission reaction the explicit temperature dependance $g_f(T)$ is derived from eq. (3) :

$$g_f(T) = \frac{1}{\sigma_f^0\ \sqrt{E_0}} \int_0^\infty \frac{2\pi}{(\pi kT)^{3/2}} \exp\left[-E/kT\right]\sigma_f(E)EdE$$

$$\text{or} \quad g_f(T) = \frac{2}{\sigma_0\sqrt{\pi E_0}.(kT)^{3/2}} \int_0 \exp\left(-E/kT\right)\sqrt{E}\,\sigma_f(E)\sqrt{E}\,dE \qquad (4)$$

So the g-factor is a function of temperature and can be calculated from the cross-section curve $\sigma(E)$ in the low-energy region. Especially for the fissile nuclides the g_f - factor is of considerable importance for the physics of thermal reactors. From equation (3) it follows that $g(T) = 1$ for cross-sections with a 1/v-law. So the g(T)-factor is *measure for the deviation from the 1/v-law.* It should be stressed that g(T) depends only on the shape of the cross-section and not on its absolute value.

For the calculation of $g_f(T)$ we had to extrapolate our $\sigma_f(E)$ data from 0 eV to 0.0086 eV (i.e. our first differential data point). Therefore we fitted our $\sigma_f(E)\sqrt{E}$ curve from 0.0086 eV to 0.0717 eV with a polynomial function $\sigma_f(E)\sqrt{E} = \sum_{i=1}^{3} c_i E^{i-1}$. By extrapolation this polynomial function yields the missing part of the $\sigma_f(E)\sqrt{E}$ curve.

Based on expression (4) we calculated $g_f(T)$ in three steps with a program written by H. DE PUYOT [11] :

$$g_f(T) = A.\int_{0\ eV}^{0.0086\ eV} \exp\left[-E/kT\right]\sqrt{E}\,.\left[\sum_{i=1}^{3} c_i E^{i-1}\right]dE$$

$$+ A.\sum_{E_1=0.0086\ Ev}^{E_1=E_1} \exp\left[-E_1/kT\right].\sigma_f(E_1).E_1.\Delta E_1$$

$$+ A\sum_{E_1=E_1}^{E_1=10eV} \exp\left[-E_1/kT\right].\sigma_f(E_1).E_1.\Delta E_1 \quad \text{with } A = \frac{2}{\sigma_0\sqrt{\pi E_0}.(kT)^{3/2}}. \qquad (5)$$

Thanks to the very small energy distance between the differential data points, the part of the integral (4) between 0.0086 eV and infinity can in very good approximation be replaced by the second and third terms in eq (5). The energy limit E_1 is introduced as a variable, and determines the part of the differential data that in fact determines g_f.

With expression (5) we first calculated g_f for T = 20.44 °C with the σ_f (E) data given in Fig. 1 which are mainly Linac - results.
This yielded g_f (20.44 °C) = 1.0522. The Linac data contribute for 67 % this value.

The same calculations were redone with the data given in Fig. 2 (mainly BR2 data). So we obtained $g_f(20.44\ °C) = 1.0534$. The BR2 data contribute for 86% to this value.

From both results we deduce a final value of

$$g_f(20.44\ °C) = 1.053 \pm 0.003$$

which supersedes the values given in [1][2].

The error is to a large extent due to the extrapolation to zero energy, for which we adopted very conservative errors. The first term from (5) (extrapolated term) indeed contributes for about 11 % to g_f (at 20.44 °C). Its magnitude decreases considerably at higher temperatures : from 5 % at 200 °C to 0.5 % at 1000 °C. From 0.35 eV on the contribution is negligible at 20.44 °C. This result for g_f (20.44 °C) is in perfect agreement with IAEA recommended value [12]

$$g_f(20.44\ °C) = 1.0548 \pm 0.0030$$

and with WESTCOTT's "best value"

$$g_f(20.44\ °C) = 1.0522 \pm 0.00348.$$

Furthermore we calculated the temperature dependence of the g_f - factor. Therefore we varied T in eq. (5) from 0 °C to 1000 °C in steps of 10 °C.
Based on the σ_f (E) data from Fig. 1 we obtained the g_f (T) curve from 0 °C to 1000 °C which is shown in Fig. 4. The numerical values are given in Table 5. With the σ_f (E) data from fig. 2 we obtain quite similar results which are given in Table 6. Both results are slightly higher than the tabulated g_f (T) - values of WESTCOTT [14].

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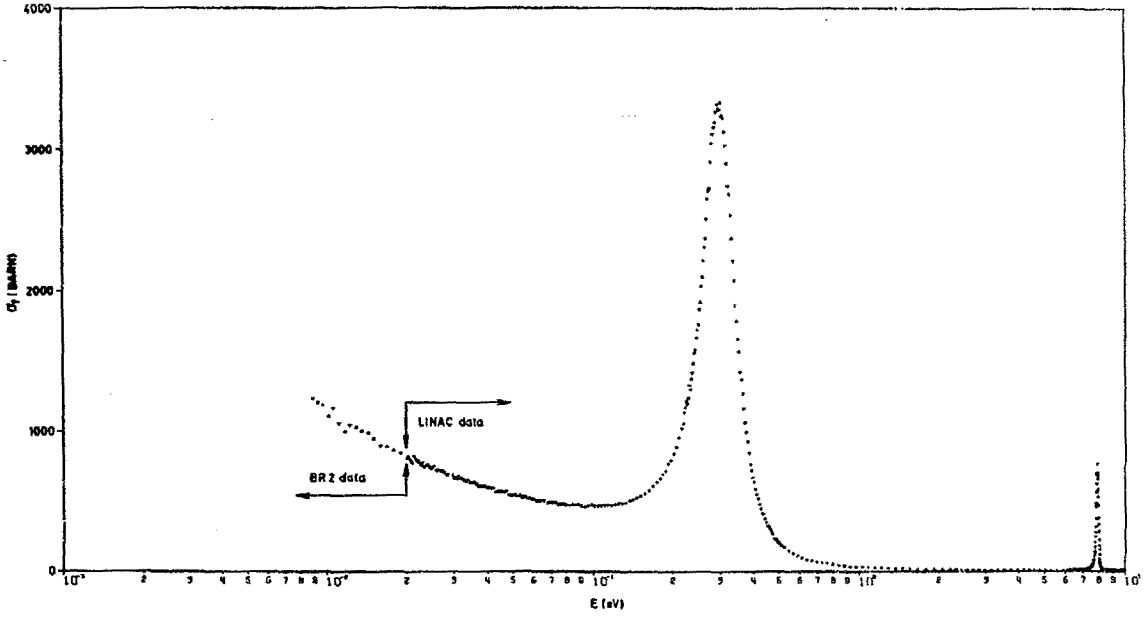

Figure 1: Fission cross-section from 0.008 eV to 10 eV for ^{239}Pu (mainly Linac data)

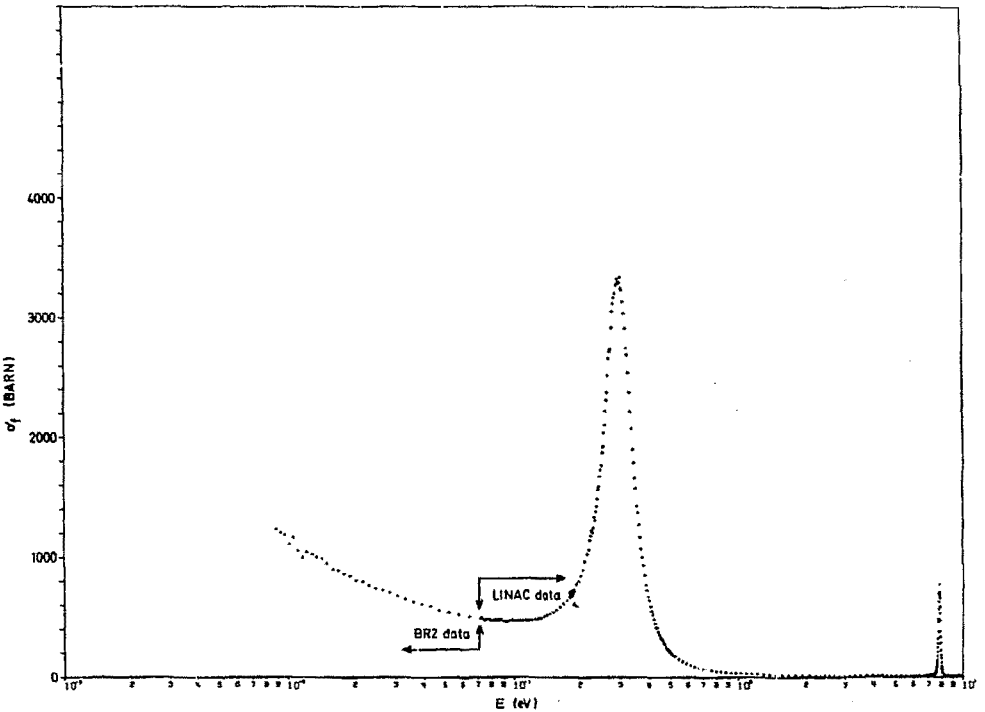

Figure 2: Fission cross-section from 0.008 eV to 10 eV for ^{239}Pu (mainly BR2 data)

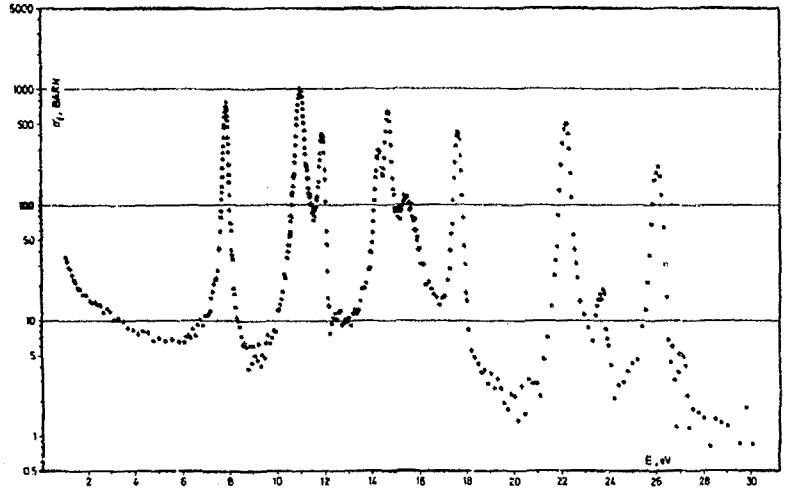

Figure 3: Fission Cross-Section from 1 eV to 30 eV for ^{239}Pu

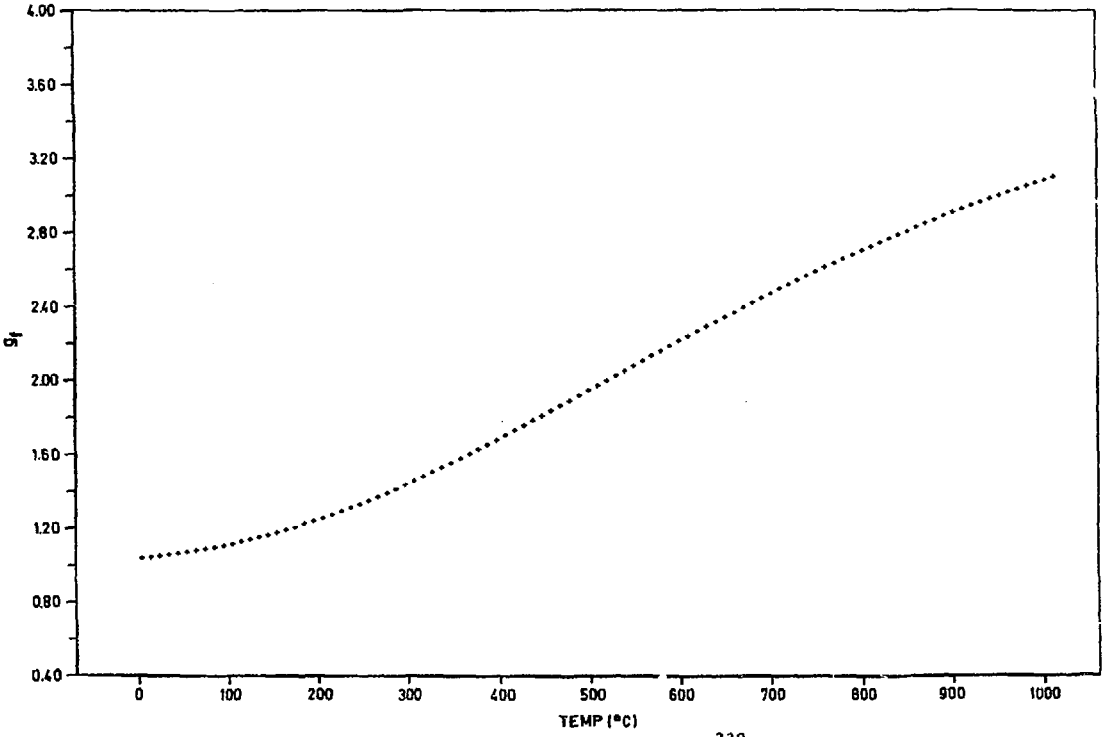

Figure 4: The Westcott g_f-factor in function of the temperature for ^{239}Pu

Table 1: ^{239}Pu fission integrals $\int_{E_1}^{E_2} \sigma_f(E)dE$ (Barn. eV) without renormalization

Energy interval (eV)	This measurement	ENDF/B III	Gwin (1971)	Gwin (1969)	Blons (1971)	Bollinger (1958)	Ryabov (1968)	Ignatiev (1964)
0.02-0.03	7.53	7.50	7.49	7.52				
0.03-0.04	6.42	6.43	6.44	6.47				
0.04-0.06	11.21	11.11	11.17	11.25				
0.06-0.010	19.51	19.39	19.53	19.68				
6.0-9.0	179.7	181.4	180.8	181.0	182.7	173.0	107.0	159.0
9.0-12.6	502.8	505.2	494.8	497	512.7	516.9	348.3	412.9
12.6-20.0	543.8	554.2	547.5	546.5	558.0	538.4	479.5	443.2
20.0-24.7	223.2	226.7	224.3	223	224.5	221.4	192.5	171.8
24.7-30.0	100.3	103.7	100.7	100.5	103.2	105.5	46.8	83.7
30-54		429	421	425	466		250	324
54-78		1734	1719	1750	1850		939	1070
78-92		748	735	746	785		529	435
92-109		412	405	417	441		323	
109-152		827	818	839	852		635	
152-172		332	329	338	355		205	
172-350		2639	2718	2780	2830		1860	
350-415		662	583	596	640		283	
415-650		2742	2458	2510	2540		1710	
650-1000		2185	2145	2180	2220		2600	

Table 2: Comparison of the normalization methods applied in the different σ_f measurements of ^{239}Pu

Bollinger et al. (1958)	σ_f normalized at 0.0253 eV to σ_f^o = 730 barn. This value is about 2% too low.
Ignatiev et al. (1964)	σ_f normalized to the value Γ/Γ_γ = 0.465 for the 7.8 eV resonance. Estimated normalization error ≤ 5%.
James (1965)	σ_f normalized to the integrated fission cross-section from 4 eV to 16 eV of Bollinger.
De Saussure et al. (1967)	σ_f normalized at 0.0253 eV to σ_f^o = (741.6 ± 3.1) barn.
Blons et al. (1966)	σ_f normalized to the value $\sigma_o\Gamma_f$ = 108.2 barn. eV for the 7.8 eV resonance as given by Bollinger.
Blons et al. (1968)	σ_f normalized to the $\sigma_o\Gamma_f$ -values for the 44.5 eV, 47.6 eV, 52.6 eV and 74.95 eV resonances from Blons (1966).
Patrick et al. (1968)	σ_f normalized at 10.95 eV to η = 2.041 assuming $\bar{\nu}_p$ = 2.864.
Ryabov et al. (1968)	σ_f normalized at 0.0253 eV to σ_f^o = (740 ± 4) barn. Lowest data point given by the author is 5 eV.
Gwin et al. (1969) (1971)	σ_f normalized at 0.0253 eV to σ_f^o = (741.6 ± 3.1) barn.
This measurement	σ_f normalized to the absolute integral $\int_{0.02001\ eV}^{0.06001\ eV} \sigma_f(E)dE$ = 25.15 ± 0.13 barn. eV corresponding to a σ_f^o -value of (741.9 ± 3.4) barn
Blons (1973)	σ_f normalized to our integral $\int_{6\ eV}^{20\ eV} \sigma_f(E)dE$ = (1226.3 ± 12.2)barn. eV.

Table 3: Ratio of our fission integrals $\int_{E_1}^{E_2} \sigma_f(E)dE$ to the corresponding integrals obtained from other measurements

Energy interval (eV)	ENDF/B III	Gwin (1971)	Gwin (1969)	Blons (1971)	Bollinger (1958)	Ryabov (1968)	Ignatiev (1964)
6.0- 9.0	0.991	0.994	0.993	0.984	1.039	1.679	1.130
9.0-12.6	0.995	1.016	1.012	0.981	0.973	1.444	1.218
12.6-20.0	0.981	0.993	0.995	0.975	1.010	1.134	1.227
20.0-24.7	0.984	0.995	1.001	0.994	1.008	1.159	1.299
24.7-30.0	0.967	0.996	0.998	0.972	0.951	2.143	1.198
9.0-20.0	0.988	1.004	1.001	0.976	0.999	1.262	1.220

Table 4: ^{239}Pu fission integrals (barn. eV) renormalized via our integral $\int_{9\ eV}^{20\ eV} \sigma_f(E)dE = 1046.6$ barn. eV

Energy interval (eV)	This measurement	ENDF/B III	Gwin (1971)	Gwin (1969)	Blons (1971)	Bollinger (1958)	Ignatiev (1964)
6.0- 9.0	179.7	179.2	181.5	181.5	178.6	171.6	194.4
9.0- 20.0	1046.6	1046.6	1046.6	1046.6	1046.6	1046.6	1046.4
20.0- 24.7	223.2	224.0	225.2	223.7	219.4	219.6	210.0
24.7- 30.0	100.3	102.4	101.1	100.8	100.9	104.6	102.3
30 - 54		424	423	426	455		396
54 - 78		1713	1726	1755	1808		1308
78 - 92		739	738	748	767		532
92 -109		407	407	418	431		
109 -152		817	821	842	833		
152 -172		328	330	339	347		
172 -350		2607	2729	2788	2766		
350 -415		654	585	598	626		
415 -650		2709	2468	2517	2483		
650 -1000		2159	2154	2187	2170		

Table 5: The Westcott g_f-factor in function of the temperature (based on $\sigma_f(E)$ data from fig. 1)

T(°C)	g_f	T(°C)	g_f	T(°C)	g_f	T(°C)	g_f
0	1.04003	250	1.35107	500	1.97256	750	2.61394
10	1.04577	260	1.37152	510	1.99968	760	2.63691
20	1.05192	270	1.39251	520	2.02678	770	2.65961
30	1.05850	280	1.41403	530	2.05384	780	2.68204
40	1.06555	290	1.43606	540	2.08086	790	2.70420
50	1.07308	300	1.45856	550	2.10781	800	2.72607
60	1.08113	310	1.48152	560	2.13467	810	2.74767
70	1.08971	320	1.50492	570	2.16145	820	2.76898
80	1.09886	330	1.52872	580	2.18811	830	2.79001
90	1.10859	340	1.55291	590	2.21464	840	2.81075
100	1.11892	350	1.57746	600	2.24105	850	2.83121
110	1.12986	360	1.60235	610	2.26730	860	2.85137
120	1.14145	370	1.62754	620	2.29340	870	2.87124
130	1.15367	380	1.65303	630	2.31932	880	2.89083
140	1.16655	390	1.67877	640	2.34506	890	2.91012
150	1.18008	400	1.70475	650	2.37062	900	2.92912
160	1.19428	410	1.73095	660	2.39597	910	2.94782
170	1.20914	420	1.75733	670	2.42112	920	2.96624
180	1.22466	430	1.78388	680	2.44605	930	2.98436
190	1.24083	440	1.81057	690	2.47076	940	3.00219
200	1.25763	450	1.83739	700	2.49523	950	3.01973
210	1.27509	460	1.86431	710	2.51947	960	3.03698
220	1.29317	470	1.89130	720	2.54347	970	3.05394
230	1.31188	480	1.91835	730	2.56721	980	3.07061
240	1.33118	490	1.94545	740	2.59070	990	3.08699
						1000	3.10309

Table 6 : The Westcott g_f-factor in function of the temperature (based on $\sigma_f(E)$ data from fig. 2)

T(°C)	g_f	T(°C)	g_f	T(°C)	g_f	T(°C)	g_f
0	1.04137	250	1.35139	500	1.97262	750	2.61392
10	1.04705	260	1.37182	510	1.99973	760	2.63689
20	1.05313	270	1.39279	520	2.02683	770	2.65959
30	1.05965	280	1.41430	530	2.05389	780	2.68202
40	1.06664	290	1.43631	540	2.08090	790	2.70418
50	1.07411	300	1.45880	550	2.10784	800	2.72605
60	1.08210	310	1.48174	560	2.13470	810	2.74765
70	1.09063	320	1.50513	570	2.16147	820	2.76896
80	1.09972	330	1.52892	580	2.18813	830	2.78999
90	1.10940	340	1.55310	590	2.21467	840	2.81073
100	1.11969	350	1.57764	600	2.24107	850	2.83118
110	1.13059	360	1.60251	610	2.26731	860	2.85135
120	1.14213	370	1.62769	620	2.29341	870	2.87122
130	1.15432	380	1.65317	630	2.31933	880	2.89080
140	1.16716	390	1.67890	640	2.34507	890	2.91009
150	1.18066	400	1.70487	650	2.37062	900	2.92909
160	1.19482	410	1.73106	660	2.39597	910	2.94779
170	1.20965	420	1.75743	670	2.42112	920	2.96621
180	1.22514	430	1.78398	680	2.44605	930	2.98433
190	1.24129	440	1.81067	690	2.47075	940	3.00216
200	1.25806	450	1.83748	700	2.49523	950	3.01970
210	1.27549	460	1.86439	710	2.51946	960	3.03695
220	1.29356	470	1.89137	720	2.54346	970	3.05391
230	1.31224	480	1.91842	730	2.56720	980	3.07058
240	1.33151	490	1.94551	740	2.59069	990	3.08696
						1000	3.10306

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