Average Total Neutron Cross Section OF ^{233}U, ^{235}U AND ^{239}Pu from ORELA Transmission Measurements and Statistical Analysis of the Data

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The average total neutron cross sections of ^{233}U, ^{235}U, and ^{239}Pu were obtained from transmission measurements in the unresolved resonance region up to several hundred keV neutron energy. The method used for the calculation of the self-shielding effect is described. A statistical model analysis of the results was performed and the s-, p- and d-wave neutron strength functions were obtained.

KEYWORDS: total cross section, statistical model, strength function, uranium 233, uranium 235, plutonium 239

I. Introduction

Total neutron cross section data for actinide nuclei are scarce and not reliable in the unresolved resonance region. High resolution neutron transmission measurements of ^{233}U, ^{235}U and ^{239}Pu were performed in the neutron energy range 0.5 eV to 500 keV using the Oak Ridge Electron Linear Accelerator(ORELA) as a pulsed neutron source.[1)2)] The low energy part of the data was analysed with the code SAMMY[3)] in order to obtain the Reich Moore resonance parameters.[4)5)6)] The aim of the present work is to obtain from these transmission measurements accurate average total cross sections in the energy range from 1 keV to several hundred keV. The results should be considered as the complement of the work of Poenitz *et al.*[7)] performed in the energy range above 40 keV.

In section II the method used to obtain the average total cross sections from the transmission data is described and the results are compared to Poenitz data in the energy range above 40 keV. In section III a statistical model analysis of the cross sections is proposed and the neutron strength functions are obtained.

II. Average Total Cross Sections

The neutron total cross section σ(E) is related to the neutron transmission Tr(E) of a sample of thickness n by

$$Tr(E) = \exp\{-n\sigma(E)\}, \quad (1)$$

where the cross section σ(E) is given in barns (b) and n in atom/barn (at/b). However, the transmission of neutrons through the sample cannot be measured at the precise energy E of the neutrons, but instead is averaged over the width of the experimental resolution function. The quantity which is really measured is:

$$Tr(E) = \int \exp\{-n\sigma_\Delta(E')\}R(E-E')dE' , \quad (2)$$

where R is the experimental resolution function and $\sigma_\Delta(E')$ is the Doppler-broadened cross section at energy E'.

The quantity which can be obtained directly by the inversion of an equation similar to (1) is the so-called effective average total cross section, σ_{eff} (E), given by:

$$\sigma_{eff}(E) = -(1/n)\ln(Tr(E)) ; \quad (3)$$

σ_{eff}(E) is smaller than the true average total cross section σ(E). The difference is due to the resonance structure of the data and is important for thick samples; it is the resonance self-shielding effect in the transmission measurements. The effect is negligible if n is small because exp{-nσ(E)} will be close to 1-nσ(E). However, using thin samples will give large experimental errors on the cross section; usually, large n values are used in the transmission measurements, which makes the self-shielding corrections unavoidable. The thicknesses of the samples used in the transmission experiments were 0.0297 at/b, 0.0330 at/b and 0.0747 at/b for ^{233}U, ^{235}U and ^{239}Pu, respectively.

Direct calculation of the self-shielding correction for thick samples in the unresolved resonance region is hardly feasible. The only way to evaluate the correction is to simulate the data from resonance parameters obtained by Monte-Carlo sampling, or obtained directly from the sample of parameters of the resolved energy range[4,5,6)] shifted to the unresolved energy range. From these parameters, average values of the true total cross sections were first calculated (using SAMMY) in selected energy ranges of the unresolved region. Next, the experimental conditions of the transmission experiment were used to calculate the effective cross section as follows: the(unaveraged) true total cross sections were Doppler-broadened, converted to transmission, and averaged. From these simulated values of transmission, the effective average total cross section was extracted using Eq. (3). The self-shielding corrections were then obtained by comparing the calculated effective with the calculated true total cross sections. Results obtained for the self-shielding corrections with the experimental conditions of the^{235}U measurement are shown in **Fig. 1**; the correction varies from 2.5% at 2 keV to 0.18% at 20 keV. The variation of the correction versus neutron energy shows linear behaviour in the

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log-log scale. Similar results were obtained for ^{233}U and ^{239}Pu. The correction was 3% at 1 keV and 1% at 50 keV for ^{239}Pu, and 1.5% at 1 keV and 0.2% at 20 keV for ^{233}U. In each case, the variation of the correction versus energy could be approximated by the following relation:

$$k(E) = A \exp(-B \ln E) , \qquad (4)$$

where k(E) is given in % and the parameters A and B were obtained from the linear behaviour of the correction versus energy in the log-log scale. The accuracy of the correction was about 20%, due to the method of calculation. More details on the method are found in other publications.[8,9]

Average values of the true total cross sections obtained from the effective experimental cross sections corrected for self-shielding are displayed in **Fig. 2-4**. Accuracies better than 2% were achieved at all energies. The agreement with Poenitz data in the energy range above 40 keV is excellent. The data are available from the authors on request.

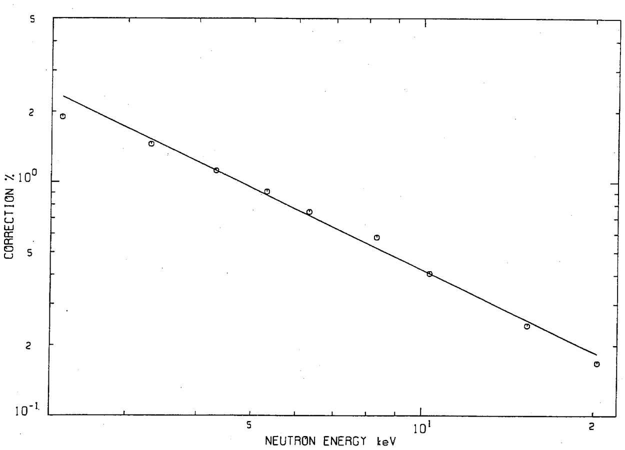

Fig. 1 The ^{235}U self-shielding correction in the experimental conditions of the neutron transmission measurement.

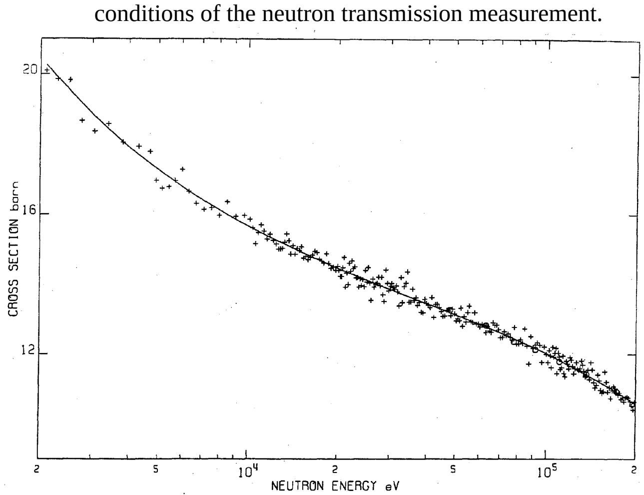

Fig. 2 ^{235}U average total cross section in the energy range 2 keV to 200 keV: present results(+) and Poenitz results(o). The solid line is the result of the SAMMY/FITACS fit.

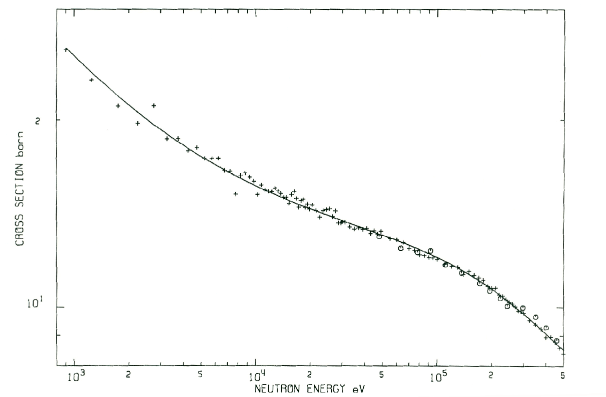

Fig. 3 ^{239}Pu average total cross section in the energy range 1 keV to 500 keV: present results(+) and Poenitz results(o). The solid line represents the result of the SAMMY/FITACS fit.

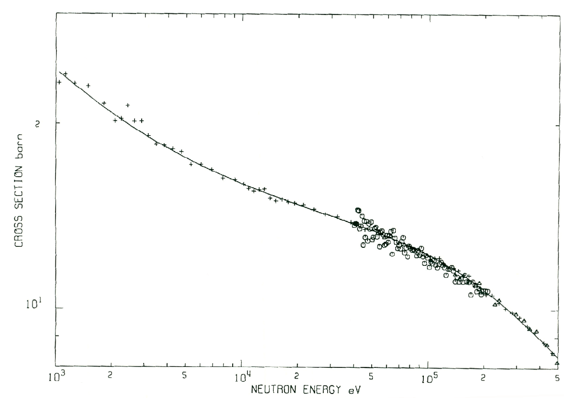

Fig. 4 Average total cross section of ^{233}U in the energy range 0.6 keV to 800 keV: present results(+), Poenitz results (o,Δ). The solid line represents the results of the fit.

III. Statistical Analysis of the Data

1. The Code SAMMY/URR

A statistical model analysis of the experimental data was performed using the code SAMMY[3] which recently incorporated the Bayesian Hauser-Feshbach statistical model code FITACS of Froehner.[10] Improvements were made in the SAMMY implementation of FITACS, particularly the possibility of using several independent experimental total or partial cross sections as input. The input parameters for the calculation of the theoretical cross sections are mainly the neutron strength functions, the average level density, the average partial widths at low energy, the distant level parameters, the energy, spin and parity of the low-lying levels of the target nucleus, and the fission barrier parameters. The energy dependence of the average resonance parameters is obtained from the Bethe formula for the level density, from the Hill-Wheeler fission barrier penetration for the fission widths, and from the giant dipole model resonance for the capture widths. The effective scattering radius R' is related to the distant level parameter R^∞ by $R' = r(1-R^\infty)$ where r is the nuclear radius ($1.23A^{1/3}+0.8$) fm.

A consistent fit of the experimental cross sections is obtained by solving Bayes equations for the parameters to be varied.

The experimental data of Poenitz *et al.* were added to the present data in the experimental data base.

2. ^{235}U Results

Results of the fit to the ^{235}U experimental data are displayed in Fig. 2. The s-wave input parameters were those obtained from the analysis of the resonance region in **Ref. 5**. The p- and d-wave input parameters were those obtained by Uttley from a similar statistical analysis of the experimental total cross section measured at Harwell.[11] The neutron strength functions S_l, the distant level parameter R^∞ and the effective scattering radius R' obtained in the present work for the neutron angular momentum l=0,1,2 are shown in **Table 1**.

Table 1 Parameters obtained by fitting the experimental total cross sections of ^{235}U

l	0	1	2
10^4 S_l	0.945±0.009	1.695±0.034	1.048±0.243
R^∞	-0.149±0.002	0.124±0.017	-0.048±0.050
R' fm	9.640±0.017	7.182±0.298	8.557±0.334

The s-wave neutron strength function agrees with the value of (0.88±0.09)10^{-4} obtained from the resonance parameters in the well-resolved energy range.[5] However, the present value has a much better accuracy. The p-wave strength function agrees with the Uttley value of (1.76±0.25)10^{-4}, but again a much better accuracy is achieved. The d-wave strength function is much larger than the Uttley value of (0.60±0.50)10^{-4}; note the present accuracy of 23% and the accuracy of 83% given by Uttley. The s-wave effective scattering radius is very close to the value of 9.602 fm obtained in the analysis of the resolved resonance region.[5]

3. ^{239}Pu Results

The s-wave input parameters for ^{239}Pu were those obtained in the analysis of the resolved resonance region in **Ref. 6**. The p- and d-wave input parameters were estimated. Results of the fit are shown in Fig. 3 and the parameters obtained are displayed in **Table 2**. The s-wave srength function agrees with the value of (1.14±0.10) obtained in the resolved resonance region;[6] but the accuracy is improved. The p-wave strength function agrees with the values expected for nuclei in this mass region. The d-wave strength function has an unexpected small value of about half the s-wave value. The s-wave effective scattering radius agrees with the value of 9.42 fm obtained in the resolved resonance region.[6]

Table 2 Parameters obtained by fitting the experimental total cross sections of ^{239}Pu.

l	0	1	2
10^4 S_l	1.099±0.037	2.206±0.108	0.575±0.161
R^∞	-0.105±0.007	0.061±0.010	-0.084±0.049
R' fm	9.294±0.072	7.868±0.084	9.025±0.481

4. ^{233}U Results

The s-wave input parameters for ^{233}U were those obtained in the analysis of the resolved energy range in **Ref. 4**. The p- and d-waves input parameters were estimated. Results of the fit are shown in Fig. 4 and the corresponding parameters are displayed in **Table 3**. The s-wave strength function agrees with the recommended value of (0.895 ±0.047)10^{-4} obtained in the resolved energy range,[4] with an improved accuracy. The p-wave strength function is twice the s-wave value, and the d-wave value is close to the s-wave value.

Table 3 Parameters obtained from the statistical model fit of the average total cross sections of ^{233}U.

l	0	1	2
10^4 S_l	0.946±0.021	1.767±0.068	0.725±0.210
R^∞	-0.162±0.007	0.076±0.029	-0.032±0.098
R' fm	9.728±0.081	7.680±0.280	8.601 ±0.870

IV. Conclusion

Average total cross section of ^{233}U, ^{235}U and ^{239}Pu were obtained in the neutron energy range from the resolved energy region to several hundred keV with an accuracy of 1-2%, from ORELA high resolution transmission measurements of thick samples. Accurate values of the self-shielding correction were calculated by using samples of resonances parameters deduced from those obtained in earlier works by a SAMMY analysis of the low energy part of the data. The results fill the gap of accurate data in the unresolved energy range and are in good agreement with Poenitz results in the energy range above 40 keV. Statistical analyses of the data were performed with the SAMMY/FITACS code and improved accuracy was obtained for average values of the resonance parameters.

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References

1) J. A. Harvey, N. W. Hill, F. G. Perey, G. L. Tweed, and L. C. Leal, *Proc. Int. Conf. On Nuclear Data for Science and Technology*, Mito, Japan (May 30- June 3, 1988).

2) K. H. Guber, R. R. Spencer, L. C. Leal, P. E. Koehler, J. A. Harvey, R. O. Sayer, H. Derrien, T. E. Valentine, D. E. Pierce, V. M. Cauley, and T. A. Lewis, *Nucl. Sci. Eng.* **139**, 1 (2001).

3) N. M. Larson, *Updated User's Guide for SAMMY; Multilevel R-matrix Fits to Neutron Data Using Bayes' Equations*,ORNL/TM-9179/R5, Oak Ridge National Laboratory, Oak Ridge, TN (November, 2000).

4) L. C. Leal, H. Derrien, K. H. Guber, J. A. Harvey, and N. M. Larson, *Evaluation of the ^{233}U Neutron Cross Section in the Resolved Resonance Energy Range*, Paper 148 this Conference.

5) L. C. Leal, H. Derrien, N. M. Larson, and R. Q. Wright, *Nucl. Sci. Eng.* **131**, 230 (1999).

6) H. Derrien, G. De Saussure, R. B. Perez, *Nucl. Sci. Eng.*, **106**, 434 (1990).

7) W. P. Poenitz, J. F. Hallen, A. B. Smith, *Nucl. Sci. Eng.*, **78**, 333 (1981).

8) H. Derrien, *J. Nucl. Sci. Technol.*, **29**, 794 (1992).

9) H. Derrien, J. A. Harvey, N. M. Larson, L. C. Leal, and R. Q. Wright, *Neutron Total Cross Section of ^{235}U from transmission measurements in the energy range 2 keV to 300 keV and statistical analysis of the data*, ORNL/TM-2000/129 (2000).

10) F. H. Froehner, *Nucl. Sci. Eng.* **103**, 119 (1989).

11) C. A.Uttley, *Nuclear Data for Reactors Conf.*, Vol. 1, page 165, Paris 1966.