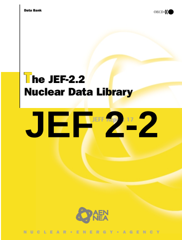

JEF/DOC - 708

An evaluation of the ^{235}U resonance parameters using the program REFIT

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12 Dec 1997

(1) Introduction

Simultaneous fits to transmission, fission yield, absorbtion yield and fission neutron yield measurements has been carried out using the latest version of REFIT [1] over the neutron energy range from 0.01 eV to 120 eV. The program REFIT has been amended since a visit to Oak Ridge to be all in double precision and in the Doppler broadening routines the simple gaussian type ideal gas model has been replaced with the full ideal gas model equation. At the same time the latest values of the nuclear and mathematical constants where put into the program.

In the fits as well as the nuclear parameters, many of the experimental parameters were adjusted eg flight path length, the start of the time of flight scaler, some of the resolution parameters, efective sample temperature, normalisation, efficiencies for detecting either fission or capture events, abundance of minor isotopes etc.

Good fits to all the data were obtained using a fitted constant value of the radiation width for all the resonances over the energy range 0.01 eV to 120 eV. Fits to the range below 25 eV indicate that the spread in the radiation width is small i.e. less than 1 meV. Above 25 eV the uncertainties on the fitted values of the radiation width are larger and it was not possible to determine an accurate value of the natural spread in the radiation widths.

The fitted resonance parameters from this report can be used to extrapolate from zero to 10 meV. For the energy region from 120eV to 2250 eV the resonance parameters given in the evaluation by Leal et al [2] are to be used. In the unresolved region above 2250 eV it is thought that the ENDF-B evaluation meets most of the requirements but the magnitude of the capture cross-section in the region above 10 keV may be too low by 5 to 15 % and is still under investigation.

(2) Data used in the evaluation

The following sets of data were used in this evaluation. There are many more measurements of the ^{235}U cross-section, some of which could have been used, the choice was one of availability and suitability for input into the shape fitting programs. Much of the data in the neutron energy region especially below 1 eV is averaged over various energy regions and its use with the fitting program would require substantial additions to the program to accommodate both the input of the data and the calculation of the averaged "cross-sections".

(a) Transmission

The original data from the transmission measurements on three samples of ^{235}U at liquid nitrogen temperatures carried out by Harvey et al [3] at Oak Ridge were used in the evaluation over the whole energy range above 0.4 eV. There were two measurements on the eighty meter flight path and three measurements using the eighteen meter flight path. Two of the uranium samples used in the measurements were found to contained ~0.3% of tantalum as well as small amounts of other uranium isotopes. Resonance parameters for ^{181}Ta were found from fits to transmission measurements carried out at Oak Ridge on two samples of tantalum at normal temperatures. These parameters were used in the analysis of the uranium data to account the tantalum impurity.

In talks with Dr. Harvey it was mentioned, that although the background was small (≤ 5% of the open beam count rate), three types of background were subtracted from the original counts, (i) a constant, independent of the time of flight, (ii) a time of flight dependent background that decreased with increasing time and (iii) a background that was proportional to the count rate in the time interval just prior to it. This showed up as a decrease in the background count rate with increasing time in the bottom of "black" resonances.

$$B_3(t) = \alpha \int_0^t C(x)\ e^{-\beta(t)\ (t-x)}\ \delta x$$

Where α and $\beta(t)$ were found in fits to the data and C(x) is the neutron count rate at time x. The subtraction of this third type of background will alter the shape of the resonances and hence, if in error, could have an effect on the resonance parameters obtained in fitting this transmission data.

The transmission measurement by Spencer et al [4] on a single thin sample of ^{235}U were include in the evaluation covering the energy range from 10 meV to 10 eV. Signal to background ratios larger than 400 to 1 were observed in the neutron energy region below 7 eV. Detector and time of flight scaler dead time corrections were at most a few tenths of a percent. The corrections to the sample out data due to neutron from previous cycles at an energy of 25 meV were ~0.8% for the 25 Hz runs and ~1.5% for the 35 Hz runs. Overlap correction were negligible for the sample in data. The total cross-section obtained at 0.0253 eV from this measurement increased from 690±5 b, given by the authors, to 694±5.5 b due to the change in the ^{236}U content and to taking into account the extension of the flight path length at neutron energies below 0.5 eV.

Also included in the neutron energy range below 2 eV were two transmission measurements carried out at Harwell [5] on the same sample. The data were to be used in the analysis of the eta measurement. These measurements were carried out on the same flight path at distances of ~3.6 m and ~5.5 m from the tantalum electron target. The neutron detectors were ^{10}B ion chamber, with the boron coated on single thin aluminum plates. Count loss correction were at most 1%. The corrections due to neutrons from previous cycles were at most 2% at 25 meV and determined from a fit to the shape to a Maxwellian over the energy range from ~10 to ~100 meV, taking into account the transmission of the samples/filter in the neutron beam. The eta measurement had to be moved to Oak Ridge when the tantalum electron target was replaced by a depleted uranium electron target. This gave a factor of about two in the neutron flux but the delayed neutrons from the ^{238}U(γ,f) reaction increased the background to signal ratio by over a factor of twenty in the neutron energy region below 25 meV.

(b) Fission

The high cross-sections observed in the minima between resonances in most fission fragment measurements was assumed to be due scattering in the aluminum backing of the foils. If there was no information about the backing its thickness could be adjusted in the fit to the data.

The fission fragment measurements carried out by Weston et. al. [6] at Oak Ridge using an 18.9 metre flight path were included. There is no mention of any correction for the backing of the fission foil or the structure of the fission chamber. In talks with Weston, he was able to recall some details about the measurements. He mentioned that the errors on each data point included the uncertainty in the normalisation of about 3%. This explained the low values of chi-squared obtained in the fits to this data.

The fission fragment measurements carried out by Schrack. [7] at the National Bureau of Standards electron LINAC facility have been included, despite having had no contacted with him. He used a nominal 8.367 ± 0.004 metre flight path with an ion chamber containing foils of ^{235}U and ^{10}B. The neutron energy range was from 20 meV up to 1 keV. The incident neutron spectrum was measured with the ^{10}B foil. The flight path length was determined by matching the structure in the data to fission cross-section given in the ENDF/B-V files. There is no mention in the paper of any correction for the backing of the fission foil or the structure of the fission chamber.

Two statements in the report require some explanation. It is stated that only one count per linac pulse was accepted and that the average count rate was 0.25 counts per pulse. At the end of the time cycle this corresponds to a correction of least a factor of 4/3, this does not correspond to a previous sentence that stated the count loss correction was negligible. If the count rate from both foils are recorded simultaneously and the backgrounds negligible then the count loss corrections cancel out when the ratio of the counts is formed.

$$\begin{aligned} R(t) &= \left(\frac{C_u(t)\, f(t) - B_u(t))}{C_{10}(t)\, f(t) - B_{10}(t)} \right) \\ &\simeq \left(\frac{C_u(t)}{C_{10}(t)} \right) - \left(\frac{B_u(t)}{C_{10}(t)\, f(t)} - \frac{B_{10}(t)}{C_{10}(t)\, f(t)} \right) \end{aligned} \qquad (2)$$

Here R(t) is the ratio at time t, $C_u(t)$, $B_u(t)$ and $C_{10}(t)$, $B_{10}(t)$ the observed count and background rates from the uranium and boron foils respectively. f(t) is the single shot count loss correction factor for the total count rate of $C_u(t)+C_{10}(t)$.

The other statement is that only the ambient background was subtracted from the observed counts and that other backgrounds were assumed to be yield dependent and occurred in both detectors and cancelled out in the measurement process. As can be seen equation 2 this is only true if the background counts from both foils are small and very similar in magnitude.

(c) Fission and capture

Measurements were carried out at Rensselaer Polytechnic Institute (RPI). by deSaussure et al [8] using a multi-plate fission chamber mounted in the centre of a large liquid scintillator and data were collected in coincidence and anti-coincidence between the two detectors. Correction to the data for the presence of the structure of the fission chamber was measured with a dummy fission chamber. The data stored at the data bank consists of separate fission and capture cross-sections corrected, by the authors, for self screening and the effects of neutrons scattered by the aluminum backing foils using the "observed" cross-sections .

DeSaussure et al describe in great detail how they arrived at the "measured" cross-section values from the observed count rates. The program REFIT requires as input a yield uncorrected for self screening and multiple scattering as these depend on the true neutron cross-sections of the sample. Using the parameters and equations given in their Oak Ridge publication it was possible to calculate the observed fission yield and "absorbtion" yield together with their errors, from the reported fission and capture cross-section values. The contribution due to ^{234}U, ^{236}U and ^{238}U in the capture cross-section had been calculated and subtracted by the authors. In the program REFIT it is possible to determine either the "abundance" of isotopes or, in the case of a yield measurement the efficiency for detecting capture events in the isotopes from the regions around resonances in the isotope. (All three minor isotopes have large resonances in the neutron energy region from about 4 to 8 eV.) The normalisation for both sets of data and the ratio of the capture to fission efficiency for the absorbtion data gave values within the errors quoted by deSaussure et al. The efficiencies for ^{236}U and ^{238}U showed that the original subtraction was correct but for ^{234}U the product of the efficiency and the abundance had been over estimated by 26%.

The measurements carried out by Perez et al [9] used a multi-plate fission chamber mounted in the centre of a large liquid scintillator. The counts were collected in coincidence and anti-coincidence between the two detectors. Correction to the data for the presence of the structure of the fission chamber was measured with a dummy fission chamber. Dr. Gwin provided more details about the ^{235}U foils and their backings used in this measurement. As with the measurements of deSaussure et al, the published cross-sections were converted back into "observed" fission and absorbtion yields using the parameters and equations given in the references [8, 9].

Using the fact that a fission event has, on average, a higher γ-multiplicity than a capture event, Ingle et al [11] determined a fission and an absorbtion cross-section from measurements on two metallic samples of ^{235}U surrounded by 12 BaF_2 scintillation detectors, covering the neutron energy range below 50 eV. They also provided sets of unnormalised yield data, some of which where used in this evaluation. The yield data consists of the ratio of the counts from the ^{235}U sample minus the background due to the incident neutron spectrum. An almost pure fission yield is given by the sum of the data sets for multiplicities greater than seven and the absorbtion yield (capture plus fission) by sum of the data sets for multiplicities between one and twelve.

(d) Eta

These measurements were carried out at Oak Ridge by Moxon et al [5] to determine the neutron energy dependence of eta below 1 eV. The data covered the neutron energy range from 1 meV up to several keV. The fast neutron and gamma-ray yield from a thick metallic sample of ^{235}U was measured as a function of the incident neutron time of flight. The detector consisted of a liquid scintillator, 100 mm in diameter and 10 mm thick, using pulse shape discrimination to separate the signals due to neutron and gamma-rays. The incident neutron spectrum was measured with a thick sample of ^{10}B oxide, detecting the gamma-rays from the $^{10}B(n,\alpha\text{-}\gamma)^7Li$ reaction with the same detector. The fast neutron counts were divided by the incident neutron spectrum and the resultant curve was normalised to the fission yield calculated from the ENDF-B evaluated cross-sections in the thermal region.

Correction had to be applied to the calculation of the fast neutron yield to take into account the attenuation of the emitted fission neutrons as a function of the product of the sample thickness and the total cross-section ($n\sigma_T$). This correction depends on the position of the neutron detector relative to the position of the incident neutron beam on the sample. In the case of the Oak Ridge measurement it decreases from unity for small values of $n\sigma_T \leq 0.1$ to a value of 0.97 for $n\sigma_T \geq 4$. A similar correction has to be used to determine the incident neutron spectrum from the observed counts in the $^{10}B(n,\alpha\gamma)^7Li$ reaction, but because of the simple 1/V dependence of the cross-section this could be incorporated in the program used to calculate the neutron spectrum.

(e) Coherent scattering

Using interferometry techniques it is possible to measure very precisely the bound coherent scattering length in the neutron energy region form ~10 meV to ~100 meV. In reference [12] a thermal value 10.47±0.04 is quoted for ^{235}U. The seven data points from the measurements of Kaiser et al [13] and Arif et al [14], covering the energy range from 30 to 90 meV were included in the fits to the energy region below 4.5 eV. In the 10's of meV energy region the capture cross-section is essentially determined from the total cross-section minus the fission and scattering cross-sections. Prior to the inclusion of the coherent scattering length, the scattering cross-section had to be calculated using the fitted parameters.

(f) Recommended thermal values

The recommended thermal values of the fission and capture cross-sections of 584.24±1.1 b and 98.96±0.74 b respectively were included in the fits to the energy range below 4.5 eV.

(4) Conclusions from the initial calculations

The initial calculations where carried out for all the data sets, comparing the values calculated from the evaluation of Leal et al [2] to the measured values over the neutron energy range up to 100 eV. The variables could include were possible the abundance of the minor isotopes ^{234}U, ^{236}U, ^{238}U and impurities ^{181}Ta, ^{27}Al, the effective temperature for each measurement, the normalisation and an adjustment of the background for transmission measurements containing resonances that have zero transmission and initially all the yield measurements. As the flight path length and the start of the first time of flight channel are defined differently in REFIT and SAMMY it was necessary to adjust these values using the evaluated resonance energies and the data given in the region from ~4 eV to ~20 eV where possible.

(a) Cross-section

The calculations indicated that the resonance parameters derived from the Leal et al [2] evaluation reproduce both the data from the fission and transmission measurements in the neutron energy region under investigation around the peaks of the resonances but did not reproduce the observed minima in the cross-section. The parameters do however reproduce the absorbtion cross-section to within the given uncertainties. The smooth structure observed in the residual from some of the measurements, although mostly inside the limits of ± two standard deviation, indicates that there may be some problems with the parameters.

The residuals from the initial calculations in the neutron energy region around the 2 and 4.2 eV show that the solid state effects are contributing to the shape of the low energy resonances. In the region above about ~30 eV and ~100 eV the neutron resolution starts to contribute to the observed width of the narrower peaks for the data measured at under 18 m and 80 m respectively.

(b) Doppler effect

The temperature of each sample was determined in the fits to the data in the neutron energy region above ~8 eV, if possible. The variation of the effective temperature of the transmission samples from the expected liquid nitrogen temperature was possibly due to poor thermal contact between the samples and the liquid nitrogen bath. In most neutron cross-section measurements the sample temperature is not mentioned in the reports.

If the total width of a resonance is less than or comparable with the Doppler width Δ, then the shape of the peak, within the range of $\pm 4\Delta$ about the resonance energy, depends more on the shape of the Doppler functions than the resonance parameters. Therefore, the shape fitting program requires accurate data outside these limits of $\sim \pm 4\ \Delta$ in order to determine accurate values of the total and partial width of the resonances from the shape. The determination of the resonance width above ~ 35 eV becomes more difficult because at this energy four times the Doppler width at normal temperatures is comparable with the resonance spacing of ^{235}U.

(c) Neutron energy resolution

The neutron resolution has very little effect on any of the measurements in the neutron energy region below a few 10's of eV. Calculations of the shape of the cross-sections above a neutron energy of 50 eV showed that the shape of the neutron resolution function was correct down to the few percent level of the peak height. All the measurements also showed that the resolution function in this energy region was dominated by the effect of the moderator used to produce the slow neutrons from the initial short burst of fast neutrons. The full width at half maximum for the moderator component of the resolution function at an incident neutron energy E is $\sim 1.6/\sqrt{E}$ μ secs. The shape and the neutron energy dependence of the moderator component of the resolution function is well understood and has been checked by other measurements carried out at Oak Ridge, Geel and Harwell over the neutron energy range from 1 eV up to 100 keV. The neutron energy dependence and shape of the total resolution function used in REFIT is calculated by numerically, folding together up to seven separate components. The shape and neutron energy dependence of each component is calculated using physically meaningful parameters. Some of these parameters can be adjusted in the fits to the data.

In the neutron energy region below 1 eV there is an additional component in the moderator part of the resolution function, this is described by Ikeda and Carpenter [15]. This component not only increases the width of the low energy resolution function but also gives an apparent increase in the flight path length of up to 60 mm. This was checked and found to be correct at Oak Ridge by looking at the time of flight for the Bragg edges in the eta measurements (see reference 5).

(5) The results of fits using the program REFIT

(5a) Fit to Tantalum transmission data

Before trying a full analysis of the ^{235}U data, a fit to the two sets of ^{181}Ta transmission data supplied by Harvey et al [3] was carried out to check the neutron and radiation widths given in by Mughabghab in reference [17]. The fits were carried out in two energy ranges from 1.3 to 285 eV and from 285 to 475 eV to determine the resonances energies and neutron widths and some of the experimental parameters. The experimental parameters included the effective temperature of each sample and a time dependent background correction factor for the thicker sample. Chi-squared per degree of freedom for the range 1.3 to 285 eV was 0.8706 for 14657 data points and 181 variables, which was lower than the expected value of unity. From these data it was only possible to determine an average radiation width of 52.14 ± 0.66 meV for all the resonances.

The fit gave an ideal gas model effective temperatures in good agreement with the value of 26.16 meV calculated using a Debye temperature of 210°K and an actual temperature of 294°K. The neutron mean free path in the moderator used for both samples was 6.37 ± 3.74 mm, in agreement with the expected value of 5.86 mm. Because the resonances in tantalum are narrower and more widely spaced then for ^{235}U, it was possible to check the resolution function. This showed that the resolution function only started to affect the resonance shape in the region above an energy of $\sim$100eV and $\sim$200 eV for the 18 m and 80 m data respectively.

(5b) Fit to the ^{235}U data

The experimental parameters found in the initial fits to the individual measurements were not adjusted at first in the simultaneous fits to determine the nuclear parameters unless the residual from the fit indicated some problems. In the neutron energy range below 4 eV and above 22 eV the abundance of the minor uranium isotopes or the tantalum content of the samples could not be checked and was taken to be that determined in the fit to the data region from 4 to 10 eV. The normalisation of all partial cross-sections measurements were adjusted in these fits.

In the case of the transmission measurements the background adjustment was only possible in the case of the measurements on the thickest sample and required a determination of a constant plus a time dependent term. It was possible for the program to normalise some of the partial cross-section measurements to the recommended thermal values while fitting the negative and low energy resonance parameters and then moving up in energy, effectively normalise the other data when fitting the resonance parameters. In the calculation for the fragment yield data the deep minima between resonances, observed in some fragment and the eta measurements, was filled in by the scattering effect of an aluminum backing and explains the differeneces between the fragment measurements and those using thicker samples.

The fits to the simultaneous measurements showed that an additional component to the resolution function was required for the fission and captures cross-sections measured by deSaussure et al [8]. The addition of an exponentially decaying tail with an amplitude of 0.1234 ± 0.008 of the initial pulse and a half life of 1.411 ± 0.045 μsec, improved the fit to the data. Within the limits of the errors both parameters were found to be independent of the incident neutron energy in the range up to 150 eV. Dr Block at RPI thought that this additional component of the resolution function was possibly due to the lead shield used around the electron target of the RPI electron linear accelerator.

In the neutron energy range from ~ 0 to ~ 100 eV there are listed 222 resonances. As there are five parameters per resonance i.e. the resonance energy, the radiation width, the neutron width and the width of each fission channel, this would require the program to fit at least 1110 parameters! The parameters of some negative energy levels have to be included and some of the experimental parameters; then the number of parameters will exceed 1150. As the program REFIT can determine a maximum of 200 variables, the energy range was divided into 8 regions. Each region containing about the same number of resonances, the start and finish coinciding with minima in the cross-sections. The time required to carry out a fit to a region was between 5 and 10 days using an Alpha computer.

(i) Neutron energy range 4 to 22 eV

There were two main simultaneous fits to the neutron energy range 4 to 22 eV. The first was used to check values of the flight path length, the start time of the first channel, the effective temperatures, the abundance of the minor uranium isotopes and the tantalum, as well as determining the efficiency for detection of fission/capture events in the yield measurements and the parameters for each individual resonance, i.e. the energy, the neutron width, the fission widths for each channel. In the first fit an average radiation width for all the resonances and the effective nuclear radius for both s-wave spins in ^{235}U were also determined. The second fit was carried out after the completion of the fit to the neutron energy region below 10 eV and above 22 eV. This second fit (see figures 1, 2 and 3) used the efficiencies for capture and fission for measurements that extended down to the thermal energy found in the fit to the region below 4.5 eV i.e. these yield measurements were effectively normalised to the recommended values of the fission and capture cross-sections at 0.0253 eV.

A spread from 26 to 55 meV was observed in the fits carried out in the energy region 4.5 to 22 eV to determine the radiation widths of individual resonances. This is similar to the spread observed by Leal et al [2] of 23 to 63 meV. The weighted average radiation width was 37.9±0.3 meV. The more accurate values coming from the resonances with small fission widths, which dominated the weighted average. The uncertainty in the value of the individual radiation width for resonances with small peak cross-sections i.e. those with large fission widths often exceedes their values and in most cases there was a large correlation coefficient with the parameter used to adjust the underlying background level. The final values from the fit, gave an overall chi-squared per degree of freedom of 0.80. The fitted value of the average radiation width for this energy range was 38.17±0.17 meV this value was used in the final fits to the energy regions above 22 eV. The fitted value of the radiation width is slightly lower than that given by Leal et al [2].

(ii) The neutron energy range from 22 to 57 eV

This range was divided into two regions 22 to 47 eV and 47 to 57 eV fitting 12236 data points with 226 variables and 6205 data points and 126 variables respectively. The fitted values of the effective temperatures for both regions were in agreement with the ones found in the fit to the 4 eV to 22 eV region. The overall values of chi-squared per degree of freedom were 0.86 and 0.78 for the 22 to 47 eV and 47 to 57 eV regions respectively. These values of chi-squared per degree of freedom indicate that the fitted parameters reproduce the data well inside the quoted errors.

The uncertainty in the widths of the individual fission channels above ~45 eV increased and is thought to be a reflection of the large correlation coefficients between the individual fission channels for a resonance and there are also a large correlation coefficients between the fission widths and the sample temperatures.

(iii) The neutron range 57 to 100 eV

For most resonances above an energy of about 50 eV, only the total fission widths could be found due to the effects of Doppler and resolution broadening in the data. The values of the individual fission channels were obtained from the total fission width by assuming they had the same ratio to the total fission width as given by Leal et al [2].

This neutron energy range was divided into three regions 57 eV to 72 eV, 72 eV to 87 eV, and 87 eV to 102 eV. The overall value of chi-squared per degree of freedom of 0.97, 1.01 and 1.15 indicate good fits, but remembering that the values of chi-squared per degree of freedom for the lower energy regions were all less than unity, shows that the parameters may not represent the data to the same accuracy as for the lower regions.

(iv) The neutron region below 4.5 eV

This neutron energy region was fitted after the regions above 4 eV so as to able to use were possible the experimental parameters determined in those regions, as the data was not very sensitive to the experimental parameters The recommended thermal values for the fission of 584.25 b and capture cross-sections of 98.96 b and the coherent scattering lengths were included in the fit to this region.

In the final fit to this region the values of 101 parameters were found and included energies and widths of the two negative energy resonances in each spin. The ideal gas model was used in the final fits for the Doppler broadening, with the effective temperatures for each measurement being fixed at the value found in the region from 4.5 to 22 eV. The use of the ideal gas model was to make the nuclear parameters compatible with the use of the proccessing codes such as NJOY [16], which at present can only use the ideal gas model for the Doppler broadening. In figures 4 and 5 the residual on either side to the two resonances at 2.03 and 4.28 eV show the oscillation that indicates neglect of the solid state effects in the calculation of the Doppler broadening. The radiation width was fixed at a value of 38.17 meV in the final fits. The inclusion of the recommended thermal cross-sections enable the program to re-normalize the measured fission cross-sections of Schrack [7], Gwin et al [10], the fission neutron yield (eta) measurements of Moxon et al [5] and some of the fission and absorbtion data from the measurements of Ingle et al [11].

The fits to some of the data are shown in figures 6, to 10. A value of chi-squared per degree of freedom was 0.909 for 8484 data points and 101 parameters. The energy of the first negative resonance with spin J=4 was changed to +70.99±32.18 meV. The addition of a small resonance at 1.3 eV improved the fit to the fission data of Schrack [7] and the fission neutron yield data of Moxon et al [5]. It also improved the fit to the thick sample transmission data of Harvey et al [3] but there is still some structure left in the residual that suggests either the presence of small quantities of impurities (^{193}Ir, ^{103}Rh or ^{152}Eu) or that the resonance is much wider and the program is only fitting the interference effects in the fission cross-section.

In figures 9 and 10 it can be seen that there is a good fit to shape of the fission cross-section of Schrack [7] and the fission neutron yield of Moxon et al [5] in the neutron energy region below 100 meV. The fitted values of the fission cross-section and the capture cross-section are 581.7b and 98.23 b are compared to the presently recommended values of 584.24±1.11 and 98.96±0.74. It must be noted that essentially the capture cross-section is obtained from the total cross-section minus the fission and scattering cross-section.

5 Comments and conclusions on fit carried out using REFIT

The main result of the REFIT analysis of the ^{235}U cross-section measurements is that a constant radiation width for all the resonances up to an energy of 120 eV can be found that simultaneously fits the total, eta, fission and absorbtion data to within their published accuracy. The resonances that initially appeared to have smaller radiation widths than the average could be fitted with this average value when the fission and absorbtion data were renormalised and relative efficiencies adjusted. The quality of the fit can be judged by low values of chi-squared compared to the number of data points and the comparison of the measured and calculated areas given in the table in the Appendix.

The smooth variation of the residual may indicate the presence of additional resonances although these variation are well inside the expected values of ±4 standard deviation. These minor discrepancies could not be followed through due to a lack of time on the computer. It takes several days to carry out a re-fit to the 30 to 40 resonances that will be affected by the added resonances causing additional interference effects.

The spread in the residual for the fits to the 80 m and 18 m thickest transmission data are not as good as expected and show that there may be some problems with the data. The only consequence of leaving these data out of the analysis was that the neutron widths of the resonances with small peak cross-sections have much larger error. The low value of chi-squared for the thin sample transmission data may also point to some over estimate of the statistical error calculation in the processing of Harvey et al [3] transmission data. Similarly the low values of chi-squared for the fission data of Weston et al [6] and the capture and fission data of Perez et al [9] indicates that the published uncertainty on each data point includes a systematic uncertainty that is larger than the statistical error. The effect of this increase in the uncertainty is that the fitting program does not take these data into as much consideration as the quality of the data warrants.

In the neutron energy region from 120 to 2250 eV the use of the parameters determined by Leal et al [2] is recommended. These parameters are a recipe that reproduces the cooled transmission data of Harvey et al [3] and the fission data of deSaussure et al [8] and Perez et al [5]. They also reproduce the observed "absorbtion" yield from the later two measurements. Any changes to the resonance parameters outside the range form 0 to 120 eV will affect the cross-section in that range. These changes to the cross-section are in general small and can be reduced by adjusting två parameters of the resonances included above 2250 eV and below -10 eV.

The nuclear parameters for ^{235}U have been sent to the Data bank in Paris for processing. The errors are those given by the program and are determined from the quality of the fits, but do not take into account any uncertainty in the experimental parameters that are not adjusted in the different energy regions. Errors in the resonance energy vary from less than 1 meV in the lower energy region to 10's of meV in the highest energy region. In the case of the neutron width the errors are generally small and reflect the high quality of the data used in the fits. The errors on the fission widths vary from less than 1% to in some cases over 100%, due mainly to problems in the fitting procedure encountered in trying to fit closely space resonances with measured values close to the underlying background.

Table 1 gives a comparison between fitted values from REFIT and from Leal et al [2] using SAMMY of the neutron and fission widths summed in 10 eV intervals up to 100 eV. The sum of the neutron widths obtained in this evaluation are 1.42% greater than those found by Leal et al [2] in the neutron energy range up to 100 eV. The spread in the difference for the sum of the neutron widths over 10 eV intervals varies from -2.70% to +7.88%. The difference between the sums of the total fission width found in this avaluation are larger by 2.54% than that given by Leal et al, but there are larger difference between the individual channels and spins, even when they have been summed in energy ranges of 10 eV.

Energy (eV)	* Neutron width (meV)	#Neutron width (meV)	*Fission width(eV) Channel 1	#Fission width(eV) Channel 1	*Fission width(eV) Channel 2	#Fission width(eV) Channel 2
0 to 10	1.8320	1.8139	0.9085	1.327	1.5344	1.0547
10 to 20	6.9775	6.7233	1.5663	1.6657	1.5357	1.8174
20 to 30	6.7090	6.8151	2.6018	2.5061	2.0001	1.2783
30 to 40	14.8983	14.8909	2.0650	1.9476	1.6547	1.6584
40 to 50	10.7045	10.6353	1.5559	1.4513	1.1692	1.3137
50 to 60	23.1063	23.0108	2.1721	2.2290	1.1176	1.0150
60 to 70	6.9853	6.4751	1.8000	1.7270	3.1293	2.2689
70 to 80	15.2329	15.6565	2.3417	2.1509	1.0861	1.8610
80 to 90	16.1023	15.7860	1.5186	1.4909	2.3896	2.4362
90 to 100	20.0071	19.0316	1.8543	1.8780	1.7104	1.7255
0 to 100	122.5552	120.8385	18.3842	18.3735	17.3271	16.4291

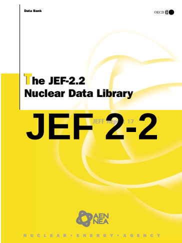
Table 1 The sum of the neutron and fission channel widths summed over 10 eV intervals from the fits using REFIT * and SAMMY # (ref. 1).

The average nuclear parameters obtained in the neutron energy range up to 100 eV when used in the unresolved region from ~2 to 100 keV reproduce the fission and total cross-sections when integrating a point wise cross-sections calculated using a full R-matrix program. The calculated capture cross-section generally agreed with the ENDF evaluation in the region below a few keV. However in the region from 10 to 100 kev it was never lower than the ENDF values but in most calculation was some 5 to 15 % higher than the ENDF evaluation.

A lack of time has made it only possible to look at only a few of the discrepancies shown up by the simultaneous analysis of a lot of measurements of ^{235}U using the fitting code REFIT. In the future it well be of interest to examine more closely the preliminary processing of the raw time of flight data, i.e. the determination of the background and count loss correction. The spitting of the fission width into its various channels is possible affected by the shape and energy dependence of the neutron resolution function, especially any long tails that may be hidden in the background or consider to be part of the background.

To help resolve the some of the problems of the analysis of the cross-sections future measurements of the fast neutron yield from a liquid nitrogen cooled sample should be considered. This measurement could be carried out on a long flight path ~80 m and would help in the separation of the resonances in the energy range from about 30 to 200 eV. As it can be carried out with a thickish sample the between resonance cross-section should be well determined and this will help in the determination of the widths of the individual fission channels from the observed interference effects.

If more measurements of the capture cross-section are planned it might be better if the γ-ray yield is not separated into the fission and capture cross-section in the initial processing of the data but is carried out in the analysis codes such as REFIT or SAMMY, where the relative efficiency for capture to fission events can be one of the experimental variables.



Appendix

Table A shows the integrated results from the simultanious fit to all the data sets used in the evaluation in the neutron energy range below 15 eV.

Chi-squared is defined as the sum of measured values minus the calculated values divided by the error in the measured data points.

The measured and calculated areas for the transmission measurements are defined as $\sum (1 - T(t))\ DE(t)$, where T(t) is the observed/calculated transmission at time t and DE(t) the energy increment at time t.

The measured and calculated areas for the yield measurements are defined as $\sum Y(t)\ DE(t)$, where Y(t) is the observed/calculated yield at time t and DE(t) the energy increment at time t.

Table A

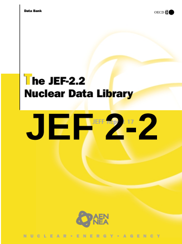
Recommended thermal fission cross-section at 0.0253 eV

Energy min	Energy max	Chi-squared	No. points	Recommended	Error	Calculated
0.0253	0.0253	5.3	1	584.24	1.1	581.7

Recommended thermal capture cross-section at 0.0253 eV

Energy min	Energy max	Chi-squared	No. points	Recommended	Error	Calculated
0.0253	0.0253	0.9	1	98.96	0.74	98.27

Energy min	Energy max	Chi-squared	No. points	Area measured	Error	Area calculated
Coherent scattering ref. [13] and [14]						
0.0303	0.0914	18.3	7	0.7314E+01	0.8775E-02	0.7337E+01
Transmission ref. [5] n = 0.1148E-02 a/b						
1.56	1.75	20.0	24	0.4058E-02	0.2105E-02	0.6515E-02
0.31	1.53	134.2	102	0.1064E 00	0.3395E-02	0.1129E 00
0.0713	0.3040	39.2	51	0.5835E-01	0.3391E-03	0.5828E-01
0.0043	0.0670	107.6	50	0.2297E-01	0.2726E-04	0.2307E-01
Transmission ref. [5] n = 0.1148E-02 a/b						
0.759	1.78	63.9	80	0.7062E-01	0.1659E-02	0.6944E-01
0.170	0.736	58.6	51	0.8427E-01	0.5565E-03	0.8432E-01
Transmission 80.0 m ref. [3] n = 0.3296E-01 a/b						
13.75	15.00	438.4	262	0.1039E 01	0.5488E-03	0.1040E 01
4.502	13.74	1650.4	1145	0.6960E 01	0.1619E-02	0.6957E 01
Transmission 80.0 m ref. [3] n = 0.2345E-02 a/b						
13.75	15.00	283.6	262	0.1868E 00	0.1594E-02	0.1895E 00
4.502	13.74	1399.4	1145	0.1565E 01	0.3946E-02	0.1567E 01
Transmission 18.0 m ref. [3] n = 0.3296E-01 a/b						
5.043	15.00	1589.3	3028	0.7638E 01	0.1547E-02	0.7633E 01
4.414	5.041	232.4	183	0.3639E 00	0.2808E-03	0.3653E 00
2.396	4.407	233.1	440	0.1353E 01	0.4336E-03	0.1353E 01
1.447	2.391	86.9	200	0.6297E 00	0.2045E-03	0.6295E 00
0.676	1.439	88.6	100	0.6886E 00	0.7425E-04	0.6884E 00
0.390	0.670	13.4	50	0.2747E 00	0.2340E-04	0.2748E 00
Transmission 18.0 m ref. [3] n = 0.2345E-02 a/b						
5.043	15.00	922.7	3028	0.1684E 01	0.4306E-02	0.1686E 01
4.414	5.041	61.0	183	0.6670E-01	0.6404E-03	0.6666E-01
2.396	4.407	116.6	440	0.1756E 00	0.1022E-02	0.1745E 00
1.447	2.391	60.2	200	0.7698E-01	0.4846E-03	0.7634E-01
0.676	1.439	27.2	100	0.1315E 00	0.2923E-03	0.1315E 00
0.390	0.670	28.2	50	0.6144E-01	0.1752E-03	0.6210E-01



Energy min	Energy max	Chi-squared	No. points	Area measured	Error	Area calculated
Transmission 18.0 m ref. [3] n = 0.5775E-03 a/b						
5.043	15.00	795.8	3028	0.5403E 00	0.4685E-02	0.5423E 00
4.141	5.041	52.3	183	0.1896E-01	0.6837E-03	0.1879E-01
2.396	4.134	96.4	400	0.4363E-01	0.9681E-03	0.4341E-01
1.447	2.391	44.3	200	0.1938E-01	0.5078E-03	0.1959E-01
0.676	1.439	22.2	100	0.3496E-01	0.3204E-03	0.3511E-01
0.390	0.670	13.0	50	0.1673E-01	0.1994E-03	0.1680E-01
Fission fragment 8.37 m ref. [7] n = 0.3500E-05 a/b						
10.02	15.00	604.8	547	0.7651E-03	0.4794E-05	0.7544E-03
4.041	10.01	814.7	766	0.1013E-02	0.5393E-05	0.9931E-03
1.011	4.007	173.1	147	0.2537E-03	0.1059E-05	0.2528E-03
0.497	0.978	20.4	16	0.1098E-03	0.4258E-06	0.1093E-03
0.206	0.479	49.8	29	0.1440E-03	0.3647E-06	0.1454E-03
0.0168	0.196	70.5	28	0.7017E-04	0.1617E-06	0.7059E-04
Fission neutron yield 9.6 m ref. [5] n = 0.1004E-01 a/b						
4.501	15.01	897.5	926	0.2343E 01	0.1370E-01	0.2308E 01
0.285	1.129	240.7	256	0.4260E 00	0.1435E-02	0.4318E 00
0.715	0.282	148.2	128	0.1593E 00	0.3366E-03	0.1611E 00
0.0179	0.0707	179.6	128	0.4537E-01	0.5536E-04	0.4511E-01
0.0045	0.0175	100.6	64	0.1148E-01	0.3264E-04	0.1132E-01
Fission neutron yield 9.6 m ref. [5] n = 0.1004E-01 a/b						
4.501	15.03	872.2	926	0.2340E 01	0.8453E-02	0.2310E 01
1.127	4.505	517.8	512	0.5121E 00	0.1671E-02	0.5133E 00
0.282	1.122	226.0	256	0.4287E 00	0.8913E-03	0.4299E 00
0.0705	0.279	149.4	128	0.1604E 00	0.2405E-03	0.1596E 00
0.0176	0.0697	147.6	128	0.4458E-01	0.3721E-04	0.4454E-01
0.0044	0.0173	92.7	64	0.1113E-01	0.1919E-04	0.1116E-01
Transmission 17.0 m ref. [6] n = 0.1468E-02 a/b						
7.682	10.00	71.2	91	0.3477E 00	0.5557E-02	0.3516E 00
4.499	7.651	80.7	112	0.3724E 00	0.4935E-02	0.3772E 00
1.365	4.518	344.6	390	0.1627E 00	0.3065E-02	0.1607E 00
0.548	1.360	185.6	250	0.9151E-01	0.7429E-03	0.9140E-01
0.183	0.545	147.1	200	0.7764E-01	0.2686E-03	0.7873E-01
0.0066	0.180	180.1	191	0.2517E-01	0.6321E-04	0.2526E-01
Fission fragment ref [8] n = 0.2660E-03 a/b						
12.21	15.03	125.5	163	0.4253E-01	0.9963E-04	0.4258E-01
6.563	12.19	336.4	300	0.7345E-01	0.1092E-03	0.7308E-01
4.497	6.545	69.8	117	0.1237E-01	0.3667E-04	0.1228E-01
3.142	4.497	34.6	134	0.6582E-02	0.2094E-04	0.6607E-02
1.412	3.123	54.3	100	0.7012E-02	0.1778E-04	0.6988E-02
0.479	1.398	46.2	65	0.9154E-02	0.1344E-04	0.9153E-02

Absorbtion 25 m ref. [8] n = 0.2660E-03 a/b

Energy min	Energy max	Chi-squared	No. points	Area measured	Error	Area calculated
12.21	15.03	230.5	163	0.6200E-01	0.9314E-04	0.6262E-01
6.563	12.19	700.1	300	0.1052E 00	0.1009E-03	0.1050E 00
4.497	6.545	379.8	117	0.3277E-01	0.4822E-04	0.3247E-01
3.142	4.497	87.4	134	0.8503E-02	0.2280E-04	0.8487E-02
1.412	3.123	113.3	100	0.8010E-02	0.2034E-04	0.8075E-02
0.479	1.398	60.5	65	0.8610E-02	0.1181E-04	0.8612E-02

Fission fragment 25 m ref [10]

Energy min	Energy max	Chi-squared	No. points	Area measured	Error	Area calculated
7.318	15.04	201.5	173	0.1373E-03	0.1472E-05	0.1349E-03
4.476	7.255	123.1	40	0.2080E-04	0.3600E-06	0.2016E-04
0.499	4.505	347.5	362	0.3341E-04	0.2642E-06	0.3228E-04
0.0616	0.493	220.4	200	0.2272E-04	0.8182E-07	0.2305E-04
0.0477	0.0606	243.9	200	0.1012E-04	0.2155E-07	0.1006E-04

Fission + capture γ-ray yield ref. [11] n = 0.9740E-03 a/b

Energy min	Energy max	Chi-squared	No. points	Area measured	Error	Area calculated
7.341	15.04	300.8	286	0.6743E 00	0.1972E-02	0.6665E 00
4.500	6.316	230.5	181	0.1032E 00	0.3547E-03	0.1085E 00
3.182	4.451	82.1	107	0.3809E-01	0.1161E-03	0.3721E-01
1.273	3.159	68.2	100	0.4639E-01	0.8538E-04	0.4623E-01
0.856	1.259	67.0	30	0.3575E-01	0.5268E-04	0.3490E-01
0.209	0.841	188.8	85	0.7189E-01	0.4436E-04	0.7050E-01
0.0583	0.2056	86.2	80	0.2302E-01	0.9436E-05	0.2297E-01
0.0103	0.0561	272.2	44	0.2172E-01	0.4716E-05	0.2181E-01

Fission γ-ray yield ref. [11] n = 0.9740E-03 a/b

Energy min	Energy max	Chi-squared	No. points	Area measured	Error	Area calculated
7.341	15.04	282.8	286	0.3868E 00	0.1314E-03	0.3742E 00
4.500	6.316	231.7	181	0.2848E-01	0.2317E-04	0.2979E-01
3.182	4.451	121.9	107	0.2354E-01	0.1137E-04	0.2242E-01
1.273	3.159	112.6	100	0.3235E-01	0.9823E-05	0.3139E-01
0.856	1.259	111.6	30	0.2911E-01	0.6912E-05	0.2743E-01
0.209	0.841	299.3	85	0.6173E-01	0.6270E-05	0.5915E-01
0.0583	0.2056	115.6	80	0.1934E-01	0.1389E-05	0.1936E-01
0.0103	0.0561	108.3	44	0.1855E-01	0.6647E-06	0.1851E-01

Acknowledgements

The author would like to thank the following organisation for the funds and facilites to enable this work to be carried out:-
Magnox Electric via the Indusrtial Management Committe,
Commisiariate a l'Energie Atomique,
Locheed Martin Energy Research at Oak Ridge National Laboratory
Knolles Atomic Power Laboratory,
A.E.A. Harwell

The author would like to thank all those who supplied the data to enable this analysis to be carried out, the people at the Paris Data Bank, especially C. Nordborg and M. Konieczny for their patience and understanding of all the request for data, J. Harvey for finding and supplying the uncorrected cooled transmission data.

I would also like to thank R. Rousan for his help and organisation at Oak Ridge and the many other people at the laboratory who help me during my visit, in particular L. Leal, H. Derrian, R. Q. Wright and N. Larson for the help and discussion during my visit, C. Lubitz from Knolls Atomic Power Laboratory for his discussions about the problems, C. Dean from AEA Winfrith for all his organisation in the U. K. that made the visit to Oak Ridge possibel and his help and discussions over the telephone about the problems during the work. D. Webb from AEA Harwell for his help in running the computer and transfer of data files. And finally to thank D. Findlay for allowing the use of the computer and other facilities at building 418 at Harwell.

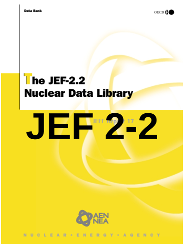


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Figure 1 Comparison of the measured transmission for the thick ^{235}U [3] sample using an 80 m flight path and that calculated from the fitted parameters in the neutron energy range 4.5 to 22.0 eV.

Figure 2 Comparison of the measured transmission data [3] sample using a 80.0 m flight path and that calculated from the fitted parameters in the neutron energy range 22 to 47 eV.

Figure 3 Comparison of the measured fission neutron yield for ^{235}U [5] using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 4.5 to 22.0 eV.

Figure 4 The fit in the region of the 2.03 eV resonance. The oscillation in the residual indicates a neglect of the solid state effects in the calculation of the Doppler broadening.

Figure 5 The fit in the region of the 4.28 eV resonance. The oscillation in the residual indicates a neglect of the solid state effects in the calculation of the Doppler broadening.

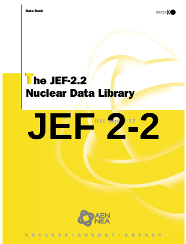
Figure 6 Comparison of the measured transmission for the medium thick ^{235}U [3] sample using an 17.9 m flight path and that calculated from the fitted parameters in the neutron energy range 0.4 to 10.0 eV.

Figure 7 Comparison of the measured fission data [7] sample using a 8.36 m flight path and that calculated from the fitted parameters in the neutron energy range 0.015 to 10.0 eV.

Figure 8 Comparison of the measured fission neutron yield for ^{235}U [5] using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 0.001 to 10.0 eV.

Figure 9 Comparison of the measured fission data [7] sample using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 0.015 to 0.1 eV.

Figure 10 Comparison of the measured fission neutron yield for ^{235}U [5] using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 0.001 to 0.1 eV.



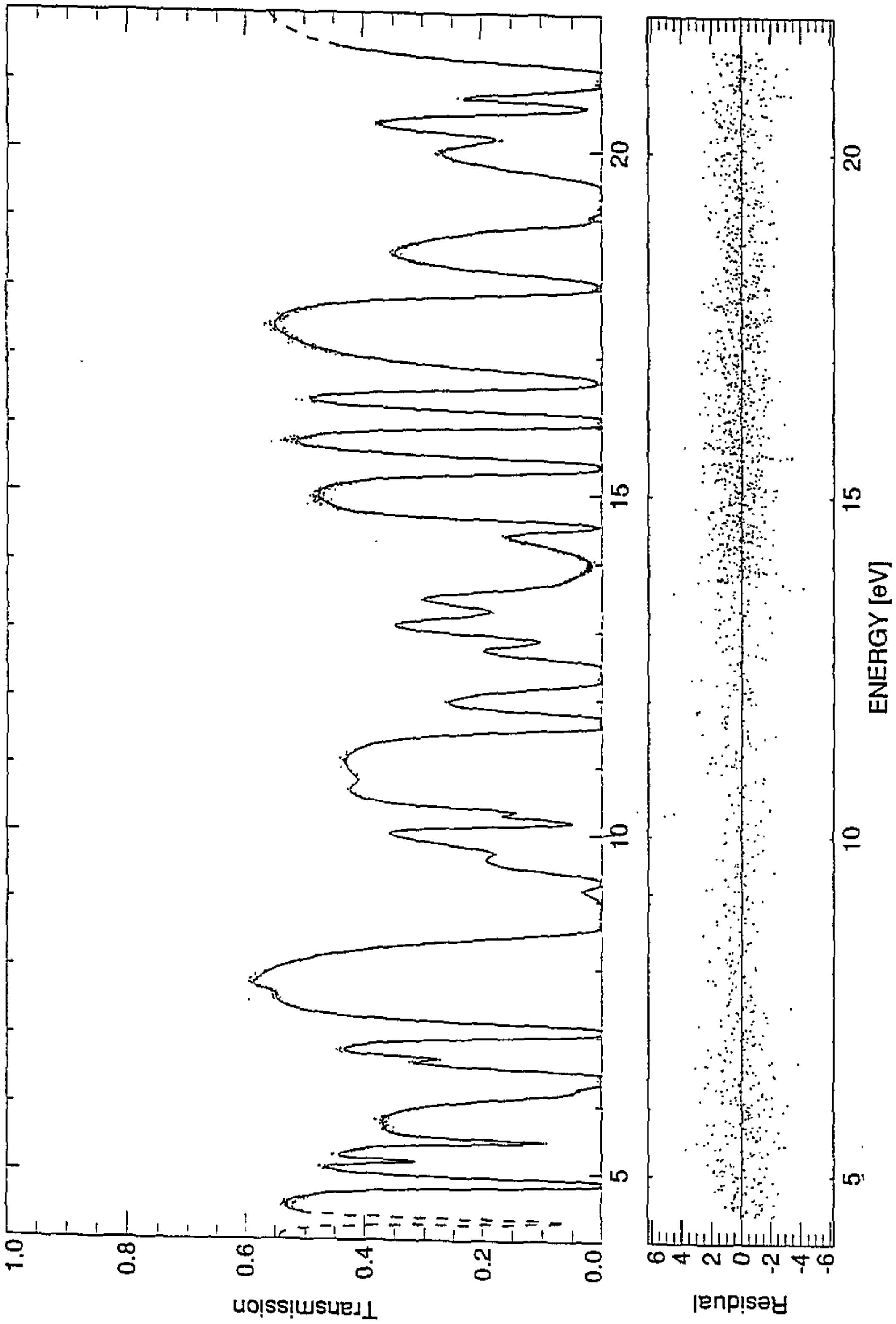
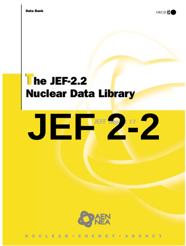


Figure 1 Comparison of the measured transmission for the thick ^{235}U [3] sample using an 80 m flight path and that calculated from the fitted parameters in the neutron energy range 4.5 to 22.0 eV.



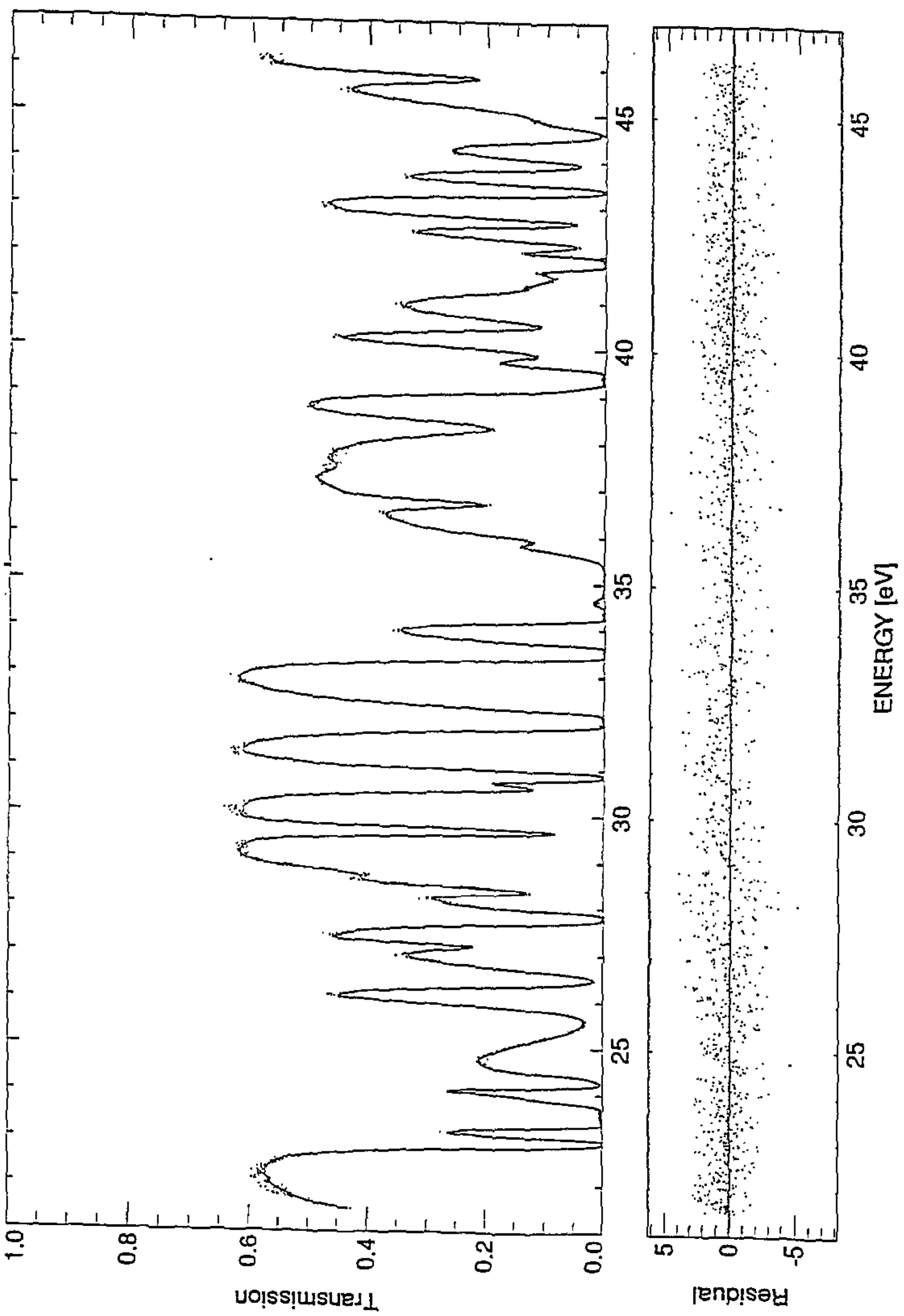
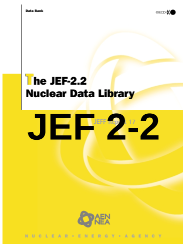


Figure 2 Comparison of the measured transmission data [3] sample using a 80.0 m flight path and that calculated from the fitted parameters in the neutron energy range 22 to 47 eV.



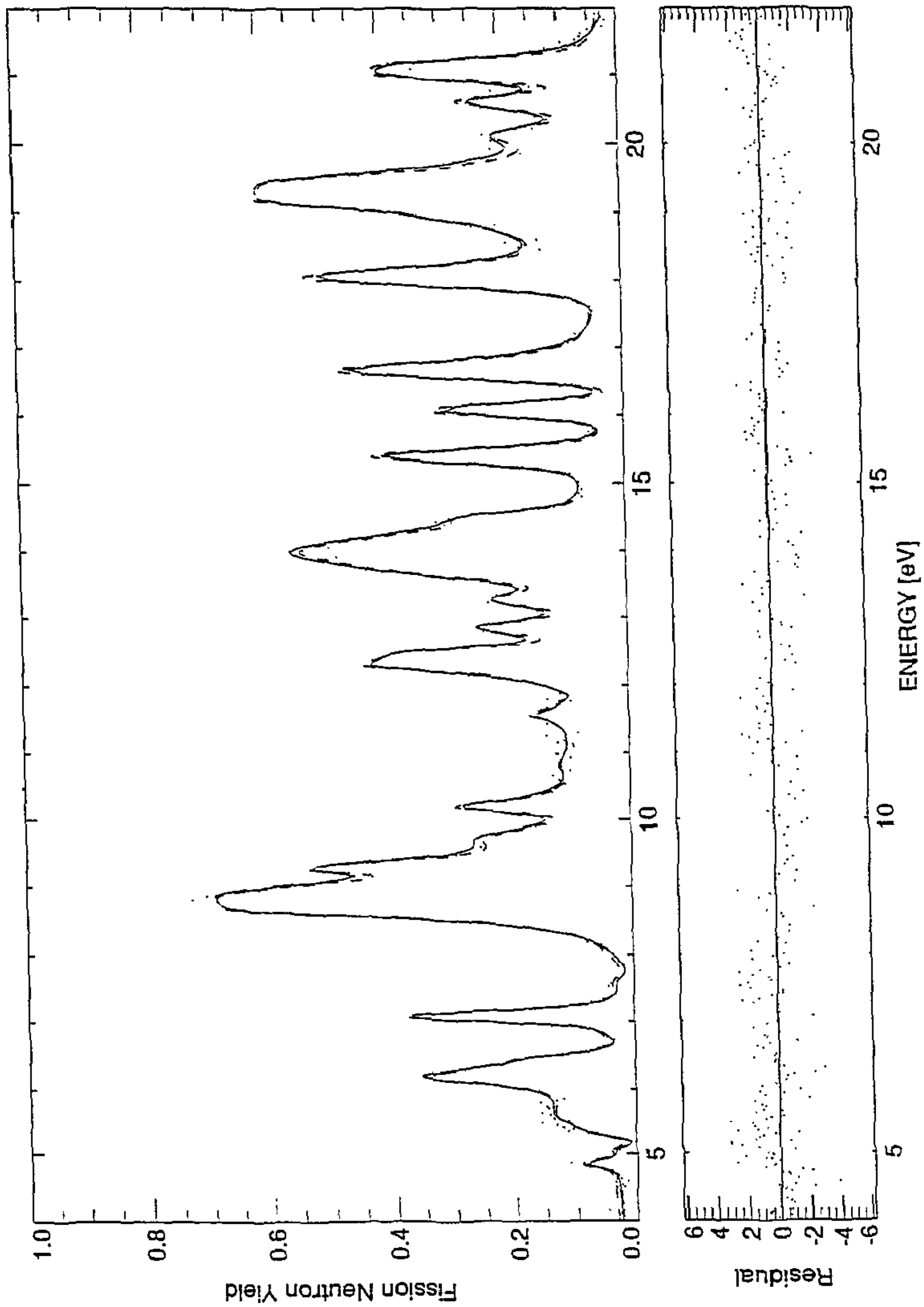
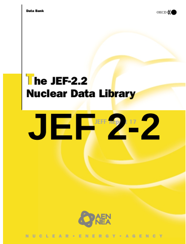


Figure 3 Comparison of the measured fission neutron yield for ^{235}U [5] using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 4.5 to 22.0 eV.



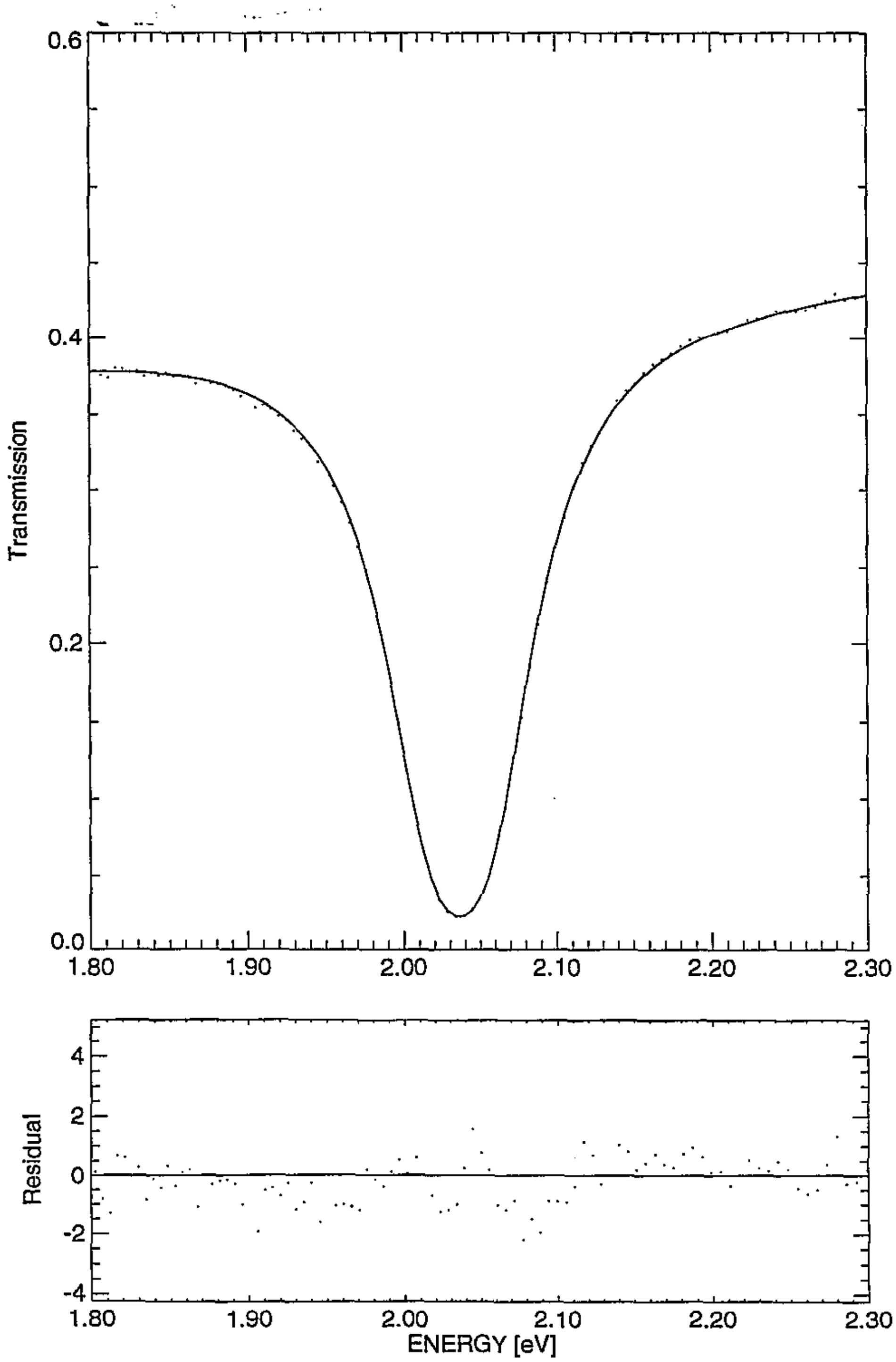
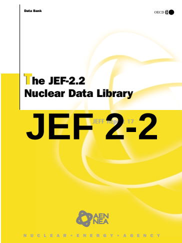


Figure 4 The fit in the region of the 2.03 eV resonance. The oscillation in the residual indicates a neglect of the solid state effects in the calculation of the Doppler broadening.



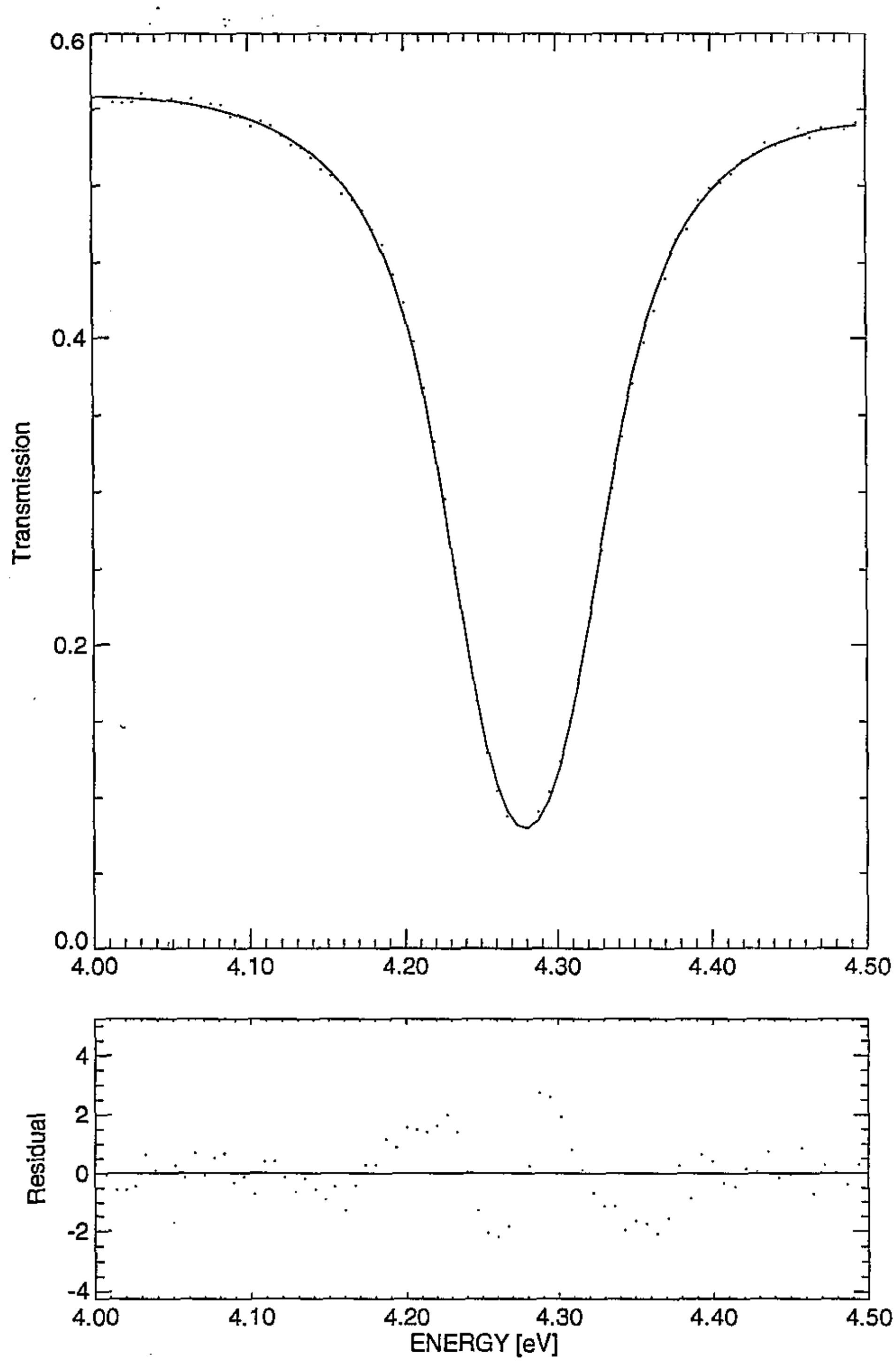
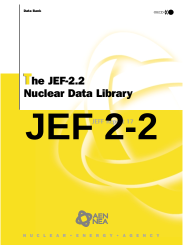


Figure 5 The fit in the region of the 4.28 eV resonance. The oscillation in the residual indicates a neglect of the solid state effects in the calculation of the Doppler broadening.



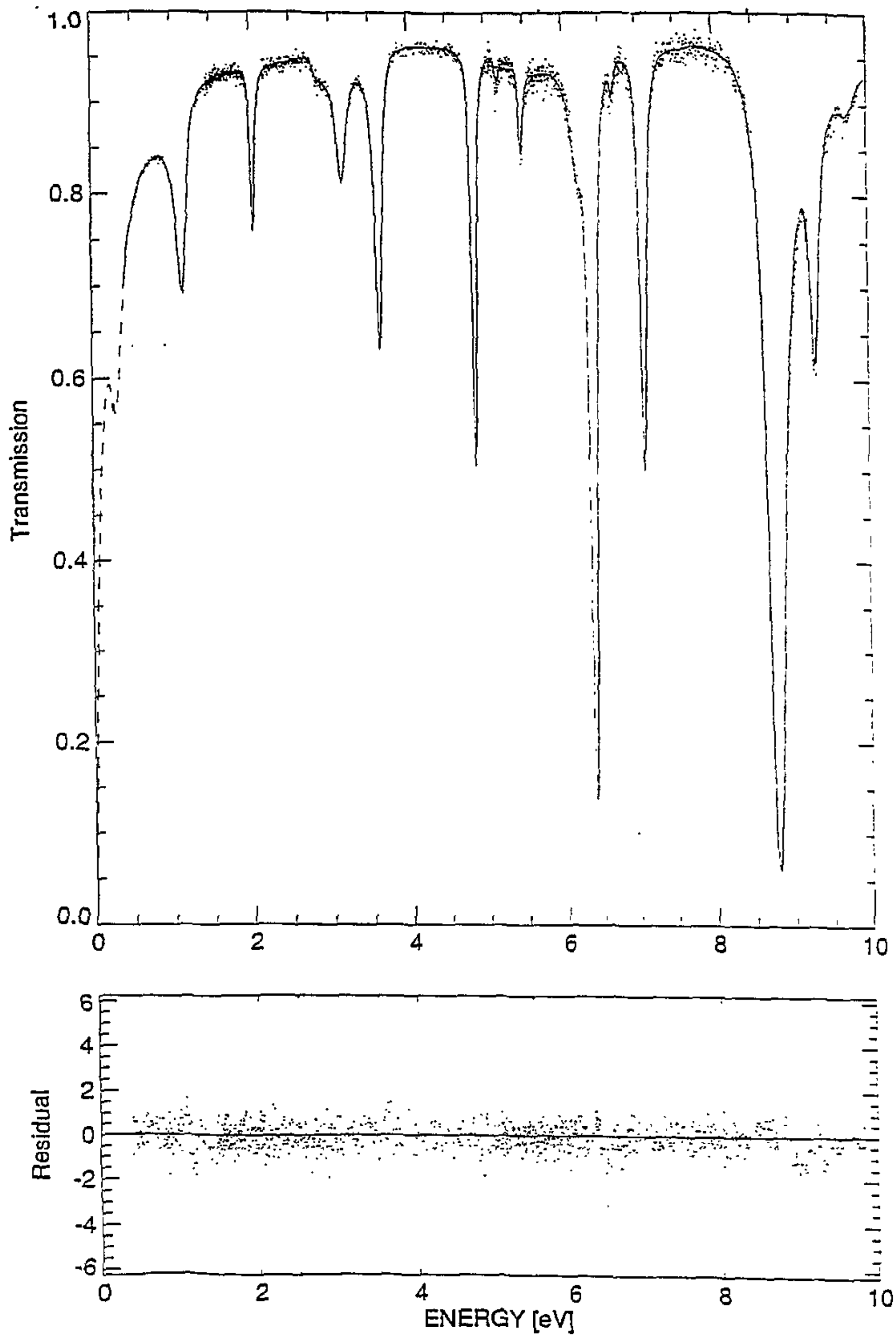


Figure 6 Comparison of the measured transmission for the medium thick ^{235}U [3] sample using an 17.9 m flight path and that calculated from the fitted parameters in the neutron energy range 0.4 to 10.0 eV.

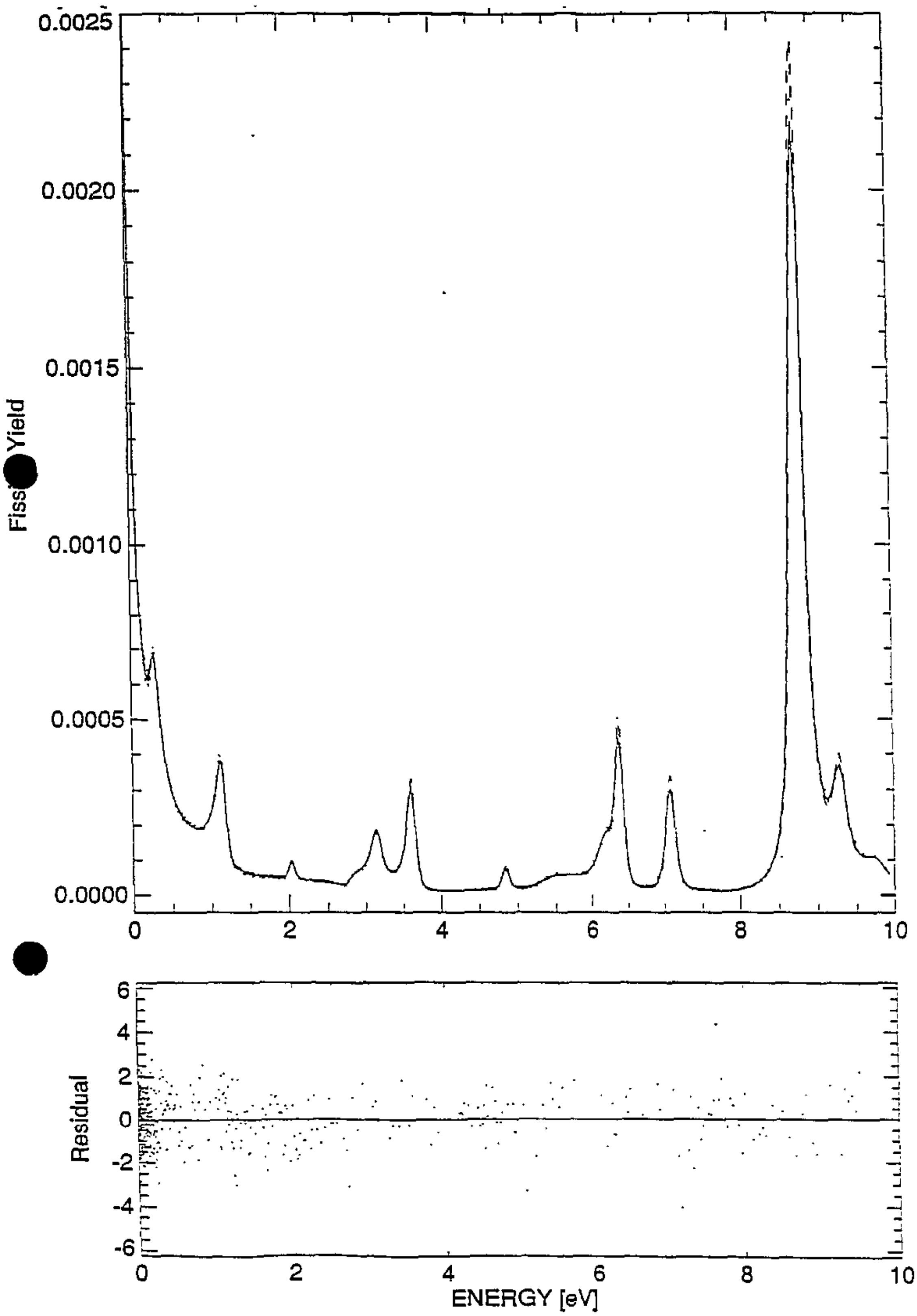
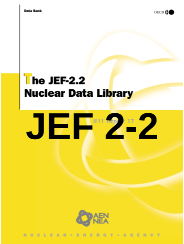


Figure 7 Comparison of the measured fission data [7] sample using a 8.36 m flight path and that calculated from the fitted parameters in the neutron energy range 0.015 to 10.0 eV.



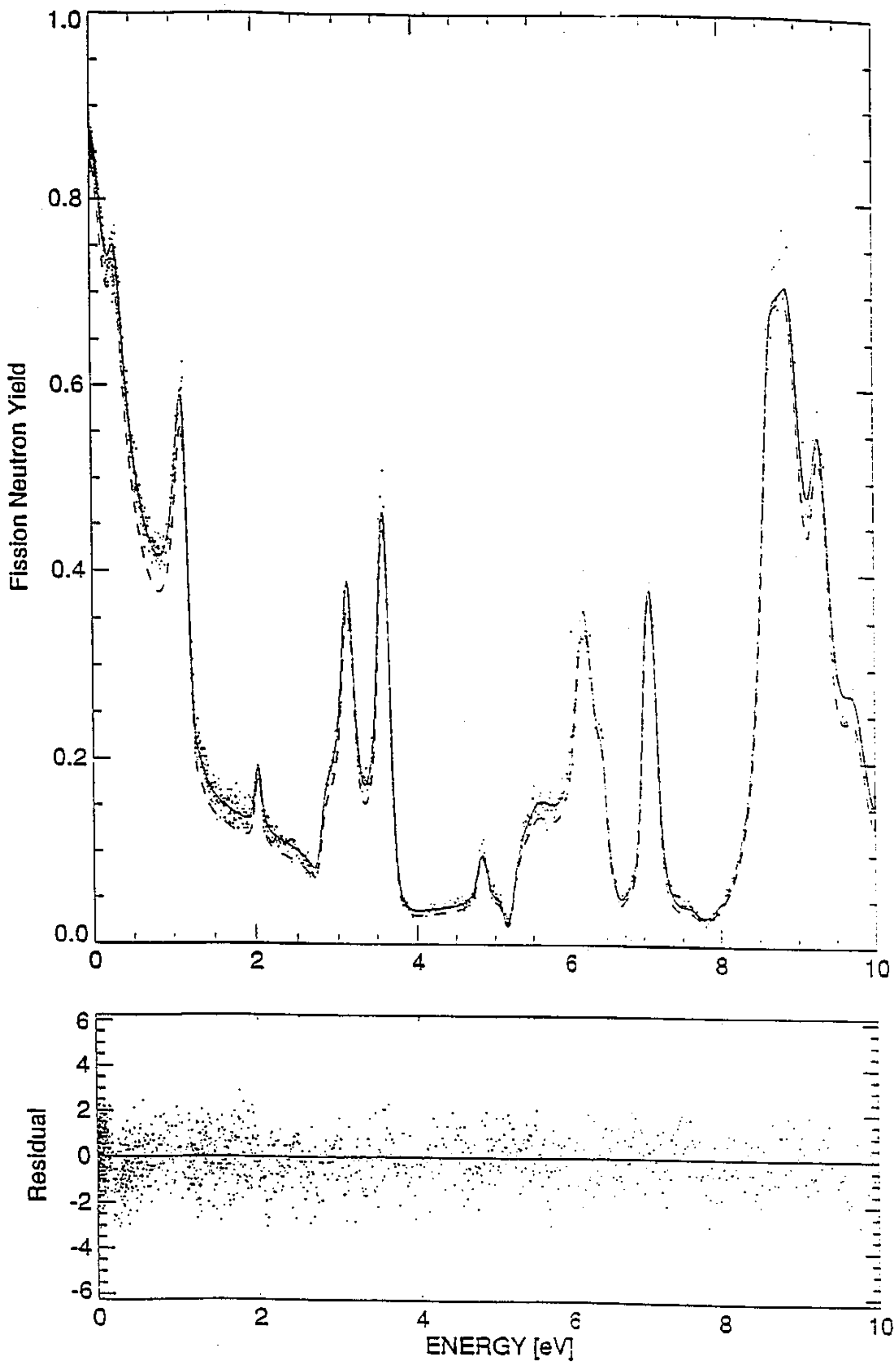
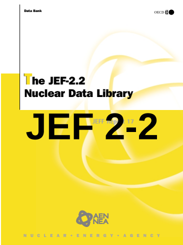


Figure 8 Comparison of the measured fission neutron yield for ^{235}U [5] using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 0.001 to 10.0 eV.

1615'023



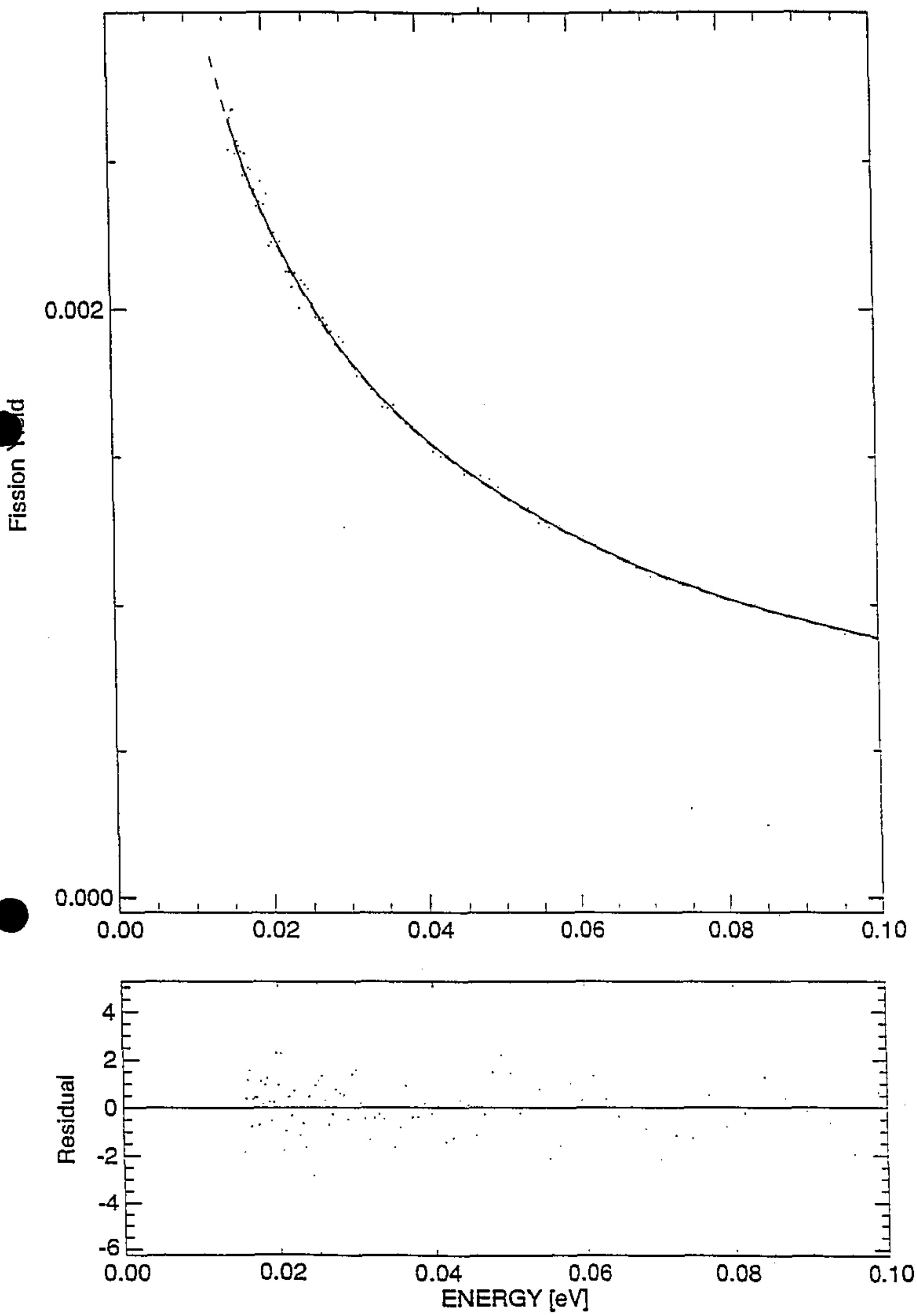
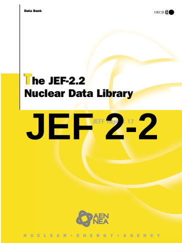


Figure 9 Comparison of the measured fission data [7] sample using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 0.015 to 0.1 eV.



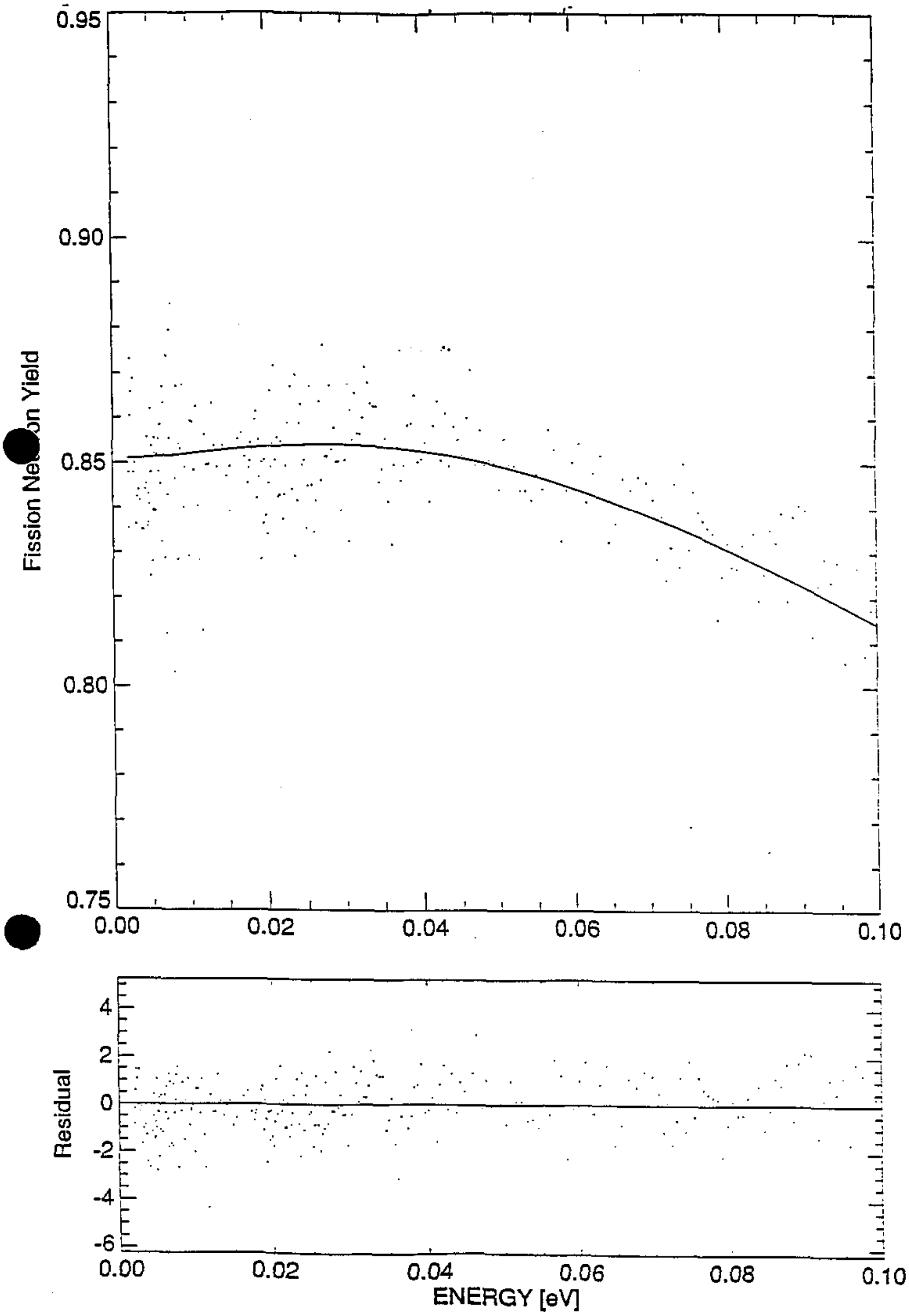


Figure 10 Comparison of the measured fission neutron yield for ^{235}U [5] using a 9.6 m flight path and that calculated from the fitted parameters in the neutron energy range 0.001 to 0.1 eV.