Nuclear Data for Science and Technology (1988 MITO), 75– 78, Copyright © 1988 JAERI.

THE MEASUREMENT OF ETA FOR ^{235}U IN THE ENERGY REGION BELOW 1 eV

Michael C. Moxon, John B. Brisland and David S. Bond

Harwell Laboratory, Oxon., UK

Abstract: Measurements of the neutron energy dependence of eta for ^{235}U in the region below 1 eV have been carried out on the Condensed Matter Target of the Harwell 136 MeV electron linear accelerator HELIOS, using a 10 m flight path.

The measurements were carried out with a NE213 liquid scintillator in conjunction with a pulse shape discriminator to separate events due to fast neutrons and gamma-rays incident on the detector. The detector was used to detect both the fast neutrons from the thick ^{235}U samples and gamma-rays emitted from 'thick' ^{10}B, Cd and Gd samples used to measure the shape of the incident neutron spectrum. The ratio of the fast neutron counts from the ^{235}U to the gamma-ray counts from the spectrum measurements gives the neutron energy dependence of eta after some small corrections for finite sample thickness effects. The accuracy of the measurement is ~½% in the energy region between 15 and 100 meV. Below 15 meV uncertainties in the background cause an increase in the errors which are ~5% at ~3 meV and above 200 meV uncertainties in the cross-sections used in the corrections for the ^{235}U sample size introduce errors of the order of 2 to 3% in the eta values.

(^{235}U, eta, measurement, time-of-flight, 3-400 meV)

Introduction

There continues to be a need for improvement of basic data for the precise understanding of core neutronics in thermal reactor systems with somewhat hard spectra such as PWR. Particularly there is a need for improvement to data affecting temperature coefficients. Existing differential data do not agree in their calculated effect with measured integral data on thermal reactor temperature coefficients[1]. For the UK reactors, physicists have adjusted the ^{235}U eta curve; the French adjust both the ^{235}U eta curve and the shape of the ^{238}U capture cross-section. This results in two significantly different representations of the eta ^{235}U variation with neutron energy. Furthermore both of these representations differ from the curve used in the USA.

Measurements have been made of the neutron energy variation of eta for ^{235}U using a 10 m flight path on the 136 MeV electron linear accelerator (HELIOS). The pulsed neutron source was provided by the moderated natural uranium neutron producing target of the Condensed Matter Cell[2]. This paper describes the experimental method and equipment and gives the results of our measurements.

Principles of the eta measurement

Eta(η) is defined as the average number of fission neutrons emitted for each neutron absorbed, viz.

$$\eta = \bar{\nu}\sigma_f/(\sigma_f + \sigma_\gamma) \qquad (1)$$

where $\bar{\nu}$ is the average number of neutrons emitted per fission and σ_f and σ_γ are the fission and capture cross-sections. The experimental approach used in these measurements is to count as a function of time-of-flight of the incident neutrons the relative number of fission neutrons emitted by a fissile sample which absorbs essentially all of the incident neutron beam and to determine the energy spectrum of the incident neutrons in a separate measurement using suitable totally absorbing samples. The method has the advantages of allowing high count rates to be achieved, and thus high statistical accuracy, and minimising the dependence of the measurement on a knowledge of the individual partial cross-sections. In practice a NE213 scintillation counter and a pulse shape discrimination system has been used to measure the fast neutron yield from thick ^{235}U samples. In separate measurements, the same detector has been used to measure the neutron spectrum of the incident neutron beam by measuring the gamma-ray yields from thick samples of ^{10}B, Cd and Gd. Corrections to these basic measurements are applied for:-

1) count losses
2) cross talk and pile up effects
3) background
4) finite sample size effects

[The gamma-rays detected in the NE213 scintillation counter emitted following fission and capture events are also recorded.] It must be stressed that this experimental method yields only the relative variation of η with neutron energy. The absolute variation relies on normalisation of the data to the accurately known value of $\eta = \eta_0$ at 2200 m/sec.

Equipment

The neutron source

The 10 m flight path used in these measurements and shown in figure 1 views the Condensed Matter Target of the Harwell 136 MeV pulsed electron linear accelerator (HELIOS).

An electron pulse of width 5 μsec and at a repetition frequency of 75 Hz was used in most of these measurements. The electron pulse is incident on a water-cooled natural uranium target. The fast neutrons are slowed down in a

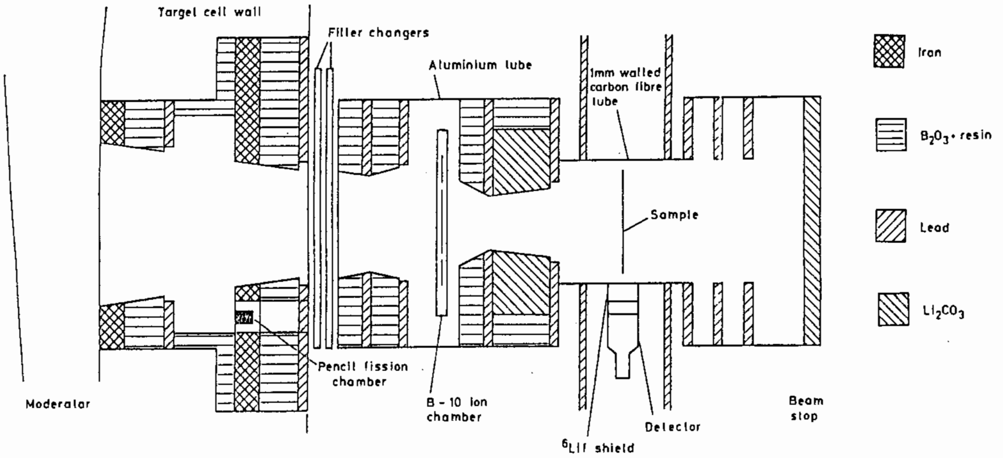

Fig. 1 The 10 m flight path.

25 mm thick water moderator canned in an aluminium vessel.

The flight path

The 10 m long flight path was designed for the measurement of partial cross-sections. The collimation gives a neutron beam diameter of 80 mm at the 10 m station. A 300 mm air gap is provided for the filter changer used in background determinations.

The NE213 scintillation counter system

The scintillation liquid is contained in a thin walled aluminium vessel 100 mm diameter and 10 mm thick coupled to a photomultiplier which is coupled directly to a Link System pulse shape discriminator unit. Three separate signal outputs from the system were taken. Two indicated whether an event was due to a neutron or a gamma-ray interaction in the scintillator. The third was used for accurate timing purposes and to provide information used in the corrections for count loss and pulse pile up.

Neutron flux monitors

Four ^{235}U pencil fission chambers used to monitor the integrated output of the source were mounted in the second collimator. A thin walled double ^{10}B parallel plate ion chamber, at 7 m distance from the neutron source, was used to check the constancy in the shape of the neutron flux spectrum during the course of the experiment.

Data acquisition

Data collection was based on a PDP 11/34 minicomputer. The time-of-flight scaler was capable of recording the data input from 8 detectors.

A hard wired program unit was built to cover the required time range of 13 milliseconds with the 4096 time channels available for each detector.

Measurements

The NE213 scintillation counter system

The 'eta' detector was set up with a variety of gamma-ray sources and a Cf fission neutron source to give the best separation of signals due to neutron and gamma-rays interacting in the scintillator. The lower and upper bias limits were set to correspond to neutrons with energies of 250 keV and 10 MeV respectively using the relationship given by Batchelor[2] for the light output of a NE213 scintillator for gamma-rays and neutrons.

The combined dead time of the detector and PSD unit of 1470±10 nsec was measured with a fast time-of-flight scaler by determining the minimum time between adjacent pulses.

The coefficients for the pile up and cross talk correction (390±8 nsec and 51.9±0.9 nsec respectively) of the PSD unit were determined from the count rate in the neutron and gamma output channels of the PSD unit from a 300 µCi ^{60}Co source as a function of distance above the detector.

Time-of-flight measurements

Time-of-flight measurements were carried out on two metallic samples of enriched ^{235}U (~93%), and thick samples of ^{10}B, Cd and Gd which were used to measure the shape of the incident neutron spectrum.

Background

It was assumed that there were five background components. The first three components are independent of the time after the neutron burst.

(i) cosmic rays and local activity
(ii) induced activity with half lives much larger than the time between neutron bursts
(iii) delayed neutrons mainly from the ^{238}U(γ,f) reaction in the neutron source. This is the main component and is proportional to the total count rate from the sample.

(iv) three exponential decaying components, possibly due to short lived activities in the neutron source. These are a minor component in the range below 1 eV.

(v) an exponential decaying tail on the resolution function that is thought to be due to the thermalised neutrons causing delayed fission events in the ^{235}U present in the natural uranium of the source. This was the contribution that proved very difficult to measure.

The shape and amplitude of the background was measured using the 'black resonance' technique. In this technique filters made from Ag, Cd, Ta, In and Er, thick enough to remove all the neutrons in the energy regions around the lowest resonances, are placed in the neutron beam. The parameters for the above background components, together with the attenuation coefficient for the filters are determined from a least squares fit to the data in the minima of the 'black resonances'. The time dependence of the background for the ^{10}B measurement is shown in figure 2. In the region below 10 meV the delayed neutrons account for 75% and 90% of the background for the ^{235}U and ^{10}B spectrum measurement respectively. In the case of the ^{235}U sample the remaining 25% was nearly all due to delayed neutrons from the fission events in the sample itself.

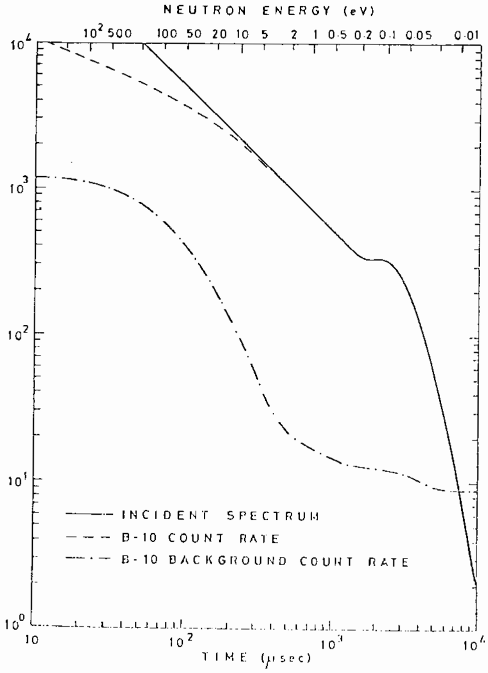

Fig. 2 The incident neutron spectrum calculated from the ^{10}B slab, Cd, Gd and ^{10}B ion chamber measurements. Also shown are the observed counts from the ^{10}B slab and its background.

Results

Figure 2 shows the incident neutron spectrum determined from the ^{10}B measurements after correction fo count loss, pile up, background and gamma-ray absorption together with the observed ^{10}B measured count rate. [The incident neutron energy dependence of the gamma-ray absorption in the ^{10}B sample is shown in figure 3, curve (a).] In the region below ~15 meV the uncertainty in the background was too large for the ^{10}B data to be used to measure accurately the shape of the spectrum. The measurements on samples of Cd, Gd and the ^{10}B ion chambers were also used to determine the shape of the incident neutron spectrum in the neutron energy region of ~50 meV to ~3 meV.

The ratio of the time-of-flight spectra from the ^{235}U to the incident spectrum is carried out after correction for count loss, pile up and background subtraction giving the fast neutron yield from the ^{235}U sample.

The neutron energy dependence of eta is determined from this fast neutron yield by correcting for:

(i) incident neutrons not absorbed

(ii) multiplication of fission neutrons in the sample and fission neutrons that interact initially in the shield, etc. surrounding the detector.

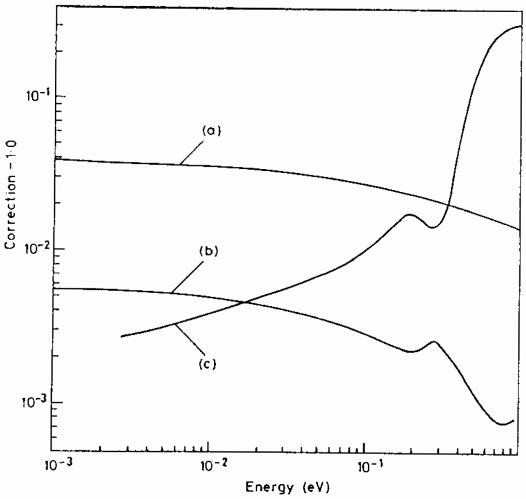

Fig. 3 The finite sample corrections
(a) the absorption of the 480 keV gamma-ray in the ^{10}B sample
(b) the absorption and multiplication of the fission neutrons in the 5 mm ^{235}U sample
(c) the correction to the 5 mm ^{235}U sample data for non-absorption of the incident neutrons.

The first correction was calculated with a modified version of the resonance shape fitting code REFIT using the JEF-1 data library and is shown as curve (c) in figure 3. The second correction was calculated by Swinhoe[3] using the Monte Carlo code MCNP.

To meet the required accuracy this calculation took several hundred hours on a VAX computer. The resulting energy dependence is shown as curve (b) in figure 3.

The neutron energy dependence of eta shown in figure 4 was obtained as follows from the ratio of the corrected counts:

$$\eta(E) = C_{235}(E).c(E).K/(\text{Ø}(E).b(E)) \qquad (2)$$

where $C_{235}(E)$ is the true fission neutron count rate from the ^{235}U sample, Ø(E) is the incident neutron spectrum at an incident neutron energy E,

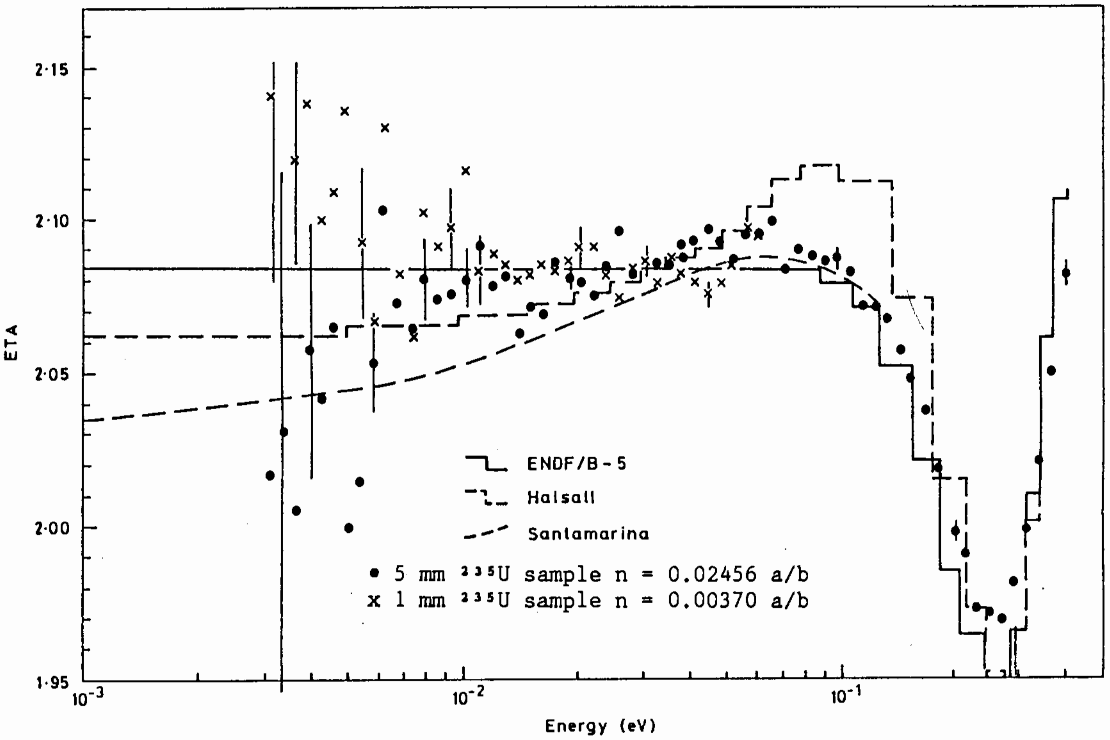

Fig. 4 The neutron energy dependence of η for ^{235}U

b(E) and c(E) are the correction factors given in figure 3, and K is the normalisation factor to give η an average value of 2.0845 between the neutron energies of 20 and 30 meV.

In general the statistical error for the data for the thickest ^{235}U sample is less than ½%. Uncertainties due to errors in the background both for the ^{235}U and spectrum measurement are ½% at 1 eV decreasing to a constant value of 0.17% between 0.5 and 0.02 eV. Below this energy the error due to the background increases with decreasing energy to a value of 0.65% at 10 meV and several per cent at ~3.8 meV. Also shown in figure 4 is the energy dependence of η determined from the ratio of the counts from the 1 mm sample of ^{235}U and the Gd spectrum measurement. The statistical accuracy on these data is less than on the thicker sample but the corrections for gamma-ray absorption and fast neutron multiplication are much smaller than for the thick sample. However, these data show the same shape as the thicker sample. The measured energy dependence of eta for ^{235}U shown in figure 4 is compared with the presently accepted evaluations. The larger than expected observed spread of the data points especially in the region of 14 meV may be accounted for by anisotropic scattering angular distribution of the incident neutrons due to solid state effects. (In the correction for non-absorbed neutrons it was assumed that the scattering was isotropic.)

Conclusions

This measurement of the neutron energy dependence of eta for ^{235}U in the region below 1 eV does not completely meet the reactor physicists' needs of an accuracy of ±½% over the energy range 1 eV to 3 meV. However it does reach the required accuracy over most of the energy range and as can be seen from figure 3, the neutron energy dependence of the corrections to the observed data requires very accurate calculations. These corrections require experimental validation which is under investigation at present.

The measurement does not confirm the increase in eta in the neutron energy range 60 to 120 meV in the Halsall evaluation and the data are lower than the evaluation by Santamarina in the energy region 50 to 130 meV when the data are renormalised to the value of evaluation at 25 meV. In the region below 10 meV the data do not favour any of the evaluations due to the large uncertainties.

References

1. WRENDA 76/77, INDC(SEC)-55/URSF, Editor: R. M. Lessler (1976).
2. R. Batchelor: Nuc. Instr. and Meth. 13, 70 (1961).
3. M. Swinhoe: private communication.
4. M.J. Halsall: Recent adjustments to the WIMS nuclear data library, UKAEA Winfrith Report AEEW-R-1492 (1982).
5. A. Santamarina, G. Golinelli and L. Erradi: Topical Meeting on Reactor Physics and Shielding, September 1984.