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P R E F A C E

This document is prepared at the request of the U.K. Nuclear Data Committee. It brings together progress reports on nuclear reactor data from A.E.R.E., A.W.R.E. and N.P.L.

A CINDA type index is included at the front of the document.

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LI	6	N, ALPHA	EVAL-PROG	2.5-2	1.5 7	UKNDC	P37	23	6/72	HAR	UTTLEY+ EVAL FOR UKNDL DFN 914 GRPH
LI	6	EVALUATION	EVAL-PROG	2.5-2	1.5 7	UKNDC	P37	23	6/72	HAR	UTTLEY+ EVAL FOR UKNDL DFN 914
LI	7	EVALUATION	EVAL-PROG	2.5-2	1.5 7	UKNDC	P37	26	6/72	HAR	CONLON OKS AWRE O 61/64
N	14	N2N XSECTION	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
F	19	N2N XSECTION	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
MG	24	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
AL	27	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
AL	27	N, ALPHA	EXPT-PROG	1.5 7		UKNDC	P37	55	6/72	NPL	ROBERTSON+ ABS ACT REL P RECOIL DET
SI	28	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
SI	29	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
SI	30	N, ALPHA	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
P	31	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
S	32	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
S	34	N, ALPHA	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
CL	35	N, PROTON	EXPT-PROG	FAST		UKNDC	P37	45	6/72	HAR	CUNINGHAME+ REL U-235 SIGF DFR SPECT
SC	45	N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
V	51	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
V	51	N, ALPHA	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
CR		INELST GAMMA	EXPT-PROG	5.5 5	3.8 6	UKNDC	P37	48	6/72	ALD	COLES REL 100DEG SIGMA 12 GS GE-LT
CR		N, ALPHA	EVAL-PROG		1.5 7	UKNDC	P37	51	6/72	ALD	DOUGLAS+ BASED ON DATA FREEMAN ET AL
FE		TOTAL XSECT	EXPT-PROG			UKNDC	P37	6	6/72	HAR	BELCHER+ TOF CYCLOTRON GRPH TBC
FE		N, ALPHA	EVAL-PROG		1.5 7	UKNDC	P37	51	6/72	ALD	DOUGLAS+ BASED ON DATA FREEMAN ET AL
FE	56	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	55	6/72	NPL	ROBERTSON+ ABS ACT REL P RECOIL DET
CO	59	N, ALPHA	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
NI		N, ALPHA	EVAL-PROG		1.5 7	UKNDC	P37	51	6/72	ALD	DOUGLAS+ BASED ON DATA FREEMAN ET AL
CU	65	N2N XSECTION	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
CU	65	N, PROTON	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
Y	89	N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
NB	93	DIFF ELASTIC	EXPT-PROG	1.0 6	5.0 6	UKNDC	P37	48	6/72	ALD	COLES SEE AWRE O 66/71
NB	93	DIFF INELAST	EXPT-PROG	1.0 6	5.0 6	UKNDC	P37	48	6/72	ALD	COLES SEE AWRE O 66/71
NB	93	N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
MO		N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
MO		N, ALPHA	EVAL-PROG		1.5 7	UKNDC	P37	51	6/72	ALD	DOUGLAS+ BASED ON DATA FREEMAN ET AL
MO		DIFF ELASTIC	EVAL-PROG			UKNDC	P37	51	6/72	ALD	DOUGLAS+ EVALUATION TBD
MO		DIFF INELAST	EVAL-PROG			UKNDC	P37	51	6/72	ALD	DOUGLAS+ EVALUATION TBD
RH	103	N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC

ENERGY		QUANTITY	TYPE	ENERGY		DOCUMENTATION				LAB	COMMENTS
S	A			MIN.	MAX.	REF.	VOL.	PAGE	DATE		
IN	115	N, GAMMA	EXPT-PROG	1.6 5	6.2 5	UKNDC	P37	55	6/72	NPL	RYVES+ SIG TO ISOM REL LONG COUNTER
BA		TOTAL XSECT	EXPT-PROG	4.0 0	2.0 3	UKNDC	P37	39	6/72	HAR	VAN DE VYVER+ SEE NP A177 393 1971
PM	147	N, GAMMA	EXPT-PROG	PILE		UKNDC	P37	42	6/72	HAR	GIBBONS+ SIG TO ISOM TBD
GD	160	N2N XSECTION	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
ER	167	SPECT NGAMMA	EXPT-PROG	2.0 1	1.5 2	UKNDC	P37	26	6/72	HAR	THOMAS+ TO BE ANAL NON STAT EFFECTS
TM	169	N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
PT	198	N2N XSECTION	EXPT-PROG	1.5 7		UKNDC	P37	56	6/72	NPL	ROBERTSON+ REL FE-56(N,P) ACTIVATION
AU	198	N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
PB		N2N XSECTION	EXPT-PROG	1.2 7		UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
U	233	FRAG SPECTRA	EXPT-PROG	4.0-1	2.0 3	UKNDC	P37	40	6/72	HAR	KUIKEN+ ANG DIST ALIGNED NUC TBP
U	234	FISSION	EXPT-PROG	1.8 5	6.0 6	UKNDC	P37	34	6/72	HAR	JAMES+ TOF CYCLOTRON MEDT ANALYSED
U	235	N2N XSECTION	EXPT-PROG	6.1 6	1.2 7	UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
U	235	FISSION	EXPT-PROG	1.0 3	1.0 6	UKNDC	P37	5	6/72	HAR	GAYTHER+ TOF LINAC OKS LINKED EVAL
U	235	FISSION	EVAL-PROG	1.0 2	2.0 7	UKNDC	P37	17	6/72	HAR	SOWERBY+ LINKED EVAL PU239 U238 GRPH
										SEE ALSO	UKNDC P37 PAGE 50
U	235	SPECT FISS N	EXPT-PROG	1.3 5		UKNDC	P37	13	6/72	HAR	ROSE TOF FIT TO DOUBLE WATT SPEC
U	235	FRAG SPECTRA	EXPT-PROG	1.0 3	1.0 6	UKNDC	P37	5	6/72	HAR	GAYTHER+ ANG DIST FISSION NEUTRONS
U	235	FRAG SPECTRA	EXPT-PROG	2.0-1	2.0 3	UKNDC	P37	40	6/72	HAR	PATTENDEN+ SEE NP A167 225 1971
U	235	FISS YIELD	EXPT-PROG	FAST		UKNDC	P37	43	6/72	HAR	CUNINGHAME+ LOW YLD FOR MO99 FOUND
U	235	FISS YIELD	EXPT-PROG	1.0 5	2.0 6	UKNDC	P37	44	6/72	HAR	CUNINGHAME+ YLD MO99 VDG TBC
U	235	FISS YIELD	EXPT-PROG	FAST		UKNDC	P37	44	6/72	HAR	CROUCH+ YLD BY MASS SPEC TBC
U	238	DIFF INELAST	EXPT-PROG	1.1 6	2.4 6	UKNDC	P37	1	6/72	HAR	ARMITAGE+ ANAL TBC ANG DIST TBD
U	238	N2N XSECTION	EXPT-PROG	6.1 6	1.2 7	UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
U	238	FISSION	EVAL-PROG		2.0 6	UKNDC	P37	17	6/72	HAR	SOWERBY+ LINKED EVAL PU239 U235 GRPH
U	238	FISS YIELD	EXPT-PROG	FAST		UKNDC	P37	43	6/72	HAR	CUNINGHAME+ YLDS IN DFR TYPE SPEC
U	238	N, GAMMA	EXPT-PROG	1.6 5	6.2 5	UKNDC	P37	55	6/72	NPL	RYVES+ SIG REL TO IN-115M
U	238	N, GAMMA	EVAL-PROG	1.0 3	2.0 7	UKNDC	P37	17	6/72	HAR	SOWERBY+ LINKED EVAL PU239 U235 GRPH
NP	237	FISSION	EXPT-PROG	4.0-1	2.0 3	UKNDC	P37	40	6/72	HAR	KUIKEN+ ANG DIST ALIGNED NUC TBP
PU	238	FISSION	EXPT-PROG	1.7 1	2.0 6	UKNDC	P37	50	6/72	ALD	MOAT BOMB SHOT EXPT SEE AWRE O 13/72
PU	239	N2N XSECTION	EXPT-PROG	6.1 6	1.3 7	UKNDC	P37	49	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
PU	239	FISSION	EXPT-PROG	1.0 3	1.0 6	UKNDC	P37	5	6/72	HAR	GAYTHER+ SIG REL U-235 SIGF
PU	239	FISSION	EVAL-PROG	1.0 2	2.0 7	UKNDC	P37	17	6/72	HAR	SOWERBY+ LINKED EVAL U235 U238
PU	239	SPECT FISS N	EXPT-PROG	1.3 5		UKNDC	P37	13	6/72	HAR	ROSE TOF FIT TO DOUBLE WATT SPEC
PU	240	TOTAL XSECT	EXPT-PROG		1.0 3	UKNDC	P37	9	6/72	HAR	MOXON+ TOF LINAC TO GET RESON PARAMS
PU	240	RESON PARAMS	EXPT-PROG		1.0 2	UKNDC	P37	9	6/72	HAR	MOXON+ MEAN WG APPROX 30 MILLIVOLTS
PU	240	FISSION	EXPT-PROG	2	1.0 6	UKNDC	P37	27	6/72	HAR	BELCHER+ TOF CYCLOTRON GRPH
PU	240	N, GAMMA	EXPT-PROG	6.0-1	2.0 2	UKNDC	P37	9	6/72	HAR	MOXON+ TOF LINAC TO GET RESON PARAMS
PU	240	SPECT NGAMMA	EXPT-PROG		3.0 2	UKNDC	P37	26	6/72	HAR	THOMAS+ TOF LINAC TBC
PU	241	FISSION	EXPT-PROG			UKNDC	P37	50	6/72	ALD	MOAT ANAL DATA BOMB SHOT STARTED
CF	252	NU	EXPT-PROG	SPON		UKNDC	P37	56	6/72	NPL	AXTON+ PROV VALUE 3.72 NEW SAMPLE
MANY		FISS YIELD	EVAL-PROG			UKNDC	P37	44	6/72	HAR	CROUCH OBJECTIVE EVAL TBD

NUCLEAR PHYSICS DIVISION, A. E. R. E.

(Division Head: Dr. B. Rose)

EDITORIAL NOTE

Since the results obtained from the various machines are not easily classified according to the energy of the charged beams, individual research items are labelled with a single letter indicating on which machine the experiments were performed. These labels are as follows:

Cockcroft Walton Generator (G. Dearnaley)	A
3 MV pulsed Van de Graaff Generator IBIS (A.T.G. Ferguson)	B
6 MV Van de Graaff Generator (A.T.G. Ferguson)	C
13 MV Tandem Generator (J.M. Freeman)	D
45 MeV Electron Linac (E.R. Rae and J.E. Lynn)	E
50 MeV Proton Linac: S.R.C.	F
Variable Energy Cyclotron: Chemistry Division	G
Synchrocyclotron (A.E. Taylor)	H

B. Inelastic neutron scattering from ^{238}U (B.H. Armitage, J.L. Rose and W. Spencer)

Measurements of inelastic neutron scattering from natural uranium using time-of-flight techniques at seven neutron energies between 1129 and 2371 keV have been described in a previous report(1). The scattering measurements at 90^{o} are now complete but further work on data reduction is required.

The objective is to obtain values for the inelastic scattering cross sections of ^{238}U to an accuracy of 5%. There are in fact many problems to be overcome before such an accuracy can be obtained. Following the acquisition of a secondary neutron spectrum from time-of-flight measurements it is necessary to strip contributions due to fission, elastic scattering, natural activity and fission induced activity before the inelastic scattering spectrum can be obtained. Errors arise from uncertainties in the shape of the fission neutron spectrum and from difficulties of normalization. In addition problems arise in obtaining the precise shape of the low energy side of the elastic peak.

One of the principal sources of error is concerned with inelastic scattering to the more highly excited states where the secondary neutron energy is low. In this situation errors stem from the rapid variation of detector efficiency with energy together with the poor statistical accuracy obtainable from the low energy region of the secondary neutron spectra.

The accuracy of the present inelastic scattering data will also be dependent on the error introduced by assuming isotropy in the angular distributions of the inelastically scattered neutron groups. Measurements of angular distributions from $^{238}U(nn')$ made by Knitter et al.(2) at neutron energies of 1.5 and 2.3 MeV indicate significant departures from isotropy and imply that the error introduced by assuming that the ratio $\sigma / \left(\frac{d\sigma}{d\Omega}\right)_{90^{o}} 4\pi$ is unity may be considerable. As a consequence it is planned to make additional inelastic scattering measurements at angles other than 90^{o}.

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(1) UKNDC(72)P36 EANDC(UK)139AL INDC(UK)-14G.

(2) Knitter H.H., Coppola M., Ahmed N. and Jay B. Z. Physik 244, 358 (1971).

B. Experimental test of the calculated neutron detection efficiency of the black detector at high energies (M.S. Coates, D.A. Boyce, D.B. Gayther and G.J. Hunt (Imperial College))

The efficiency of the Harwell black detector has been calculated in the energy region 10 eV → 700 keV with an estimated accuracy of 1-2%[(1)]. As an experimental test calibration measurements using the Harwell long counter have been made on the pulsed Van de Graaff IBIS over the energy range 68 keV → 2 MeV. The efficiency of the long counter has been recently re-measured[(2)] to an accuracy of 1-2% using the technique of associated activity. For technical reasons the black detector could not be installed easily on IBIS so a secondary detector was used for the comparison. This secondary detector, which is a boron vaseline cylinder 7 cm dia × 10 cm long surrounded by four Na-I scintillation counters to detect the 478 keV γ-rays from the $^{10}B(n,\alpha,\gamma)^{7}Li$ reaction, had been calibrated previously against the black detector on the 300 m flight path of the neutron booster. In the IBIS measurements the Li(p,n) and the T(p,n) reactions were used to cover the required neutron energy range with the secondary detector and the long counter set at 20^{o} to the incident proton beam to allow counts to be accumulated simultaneously at a given neutron energy. Time of flight analysis was used with the secondary detector in order to obtain accurate background determinations. The data are shown in Fig. 1 where the continuous curve gives the secondary detector efficiency deduced from the black detector calibration and the points give that obtained with the long counter. The two data sets are normalised to give the best eyeball fit of the continuous curve through the points between 68 keV and 700 keV. There is evidence for a systematic difference in shape between the two determinations although the overall agreement is ~±3%. The discrepancy is presently under investigation. It should be noted that above 700 keV the IBIS measurements can be regarded as giving a calibration of the efficiency of the black detector since in this region its efficiency cannot be calculated with precision.

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(1) Coates M.S., Hunt G.J. and Rae E.R., Nuclear Data for Reactors 1 211, IAEA Vienna (1970).

(2) Adams J.M., Ferguson A.T.G., McKenzie C.D. AERE - R 6429 (1970).

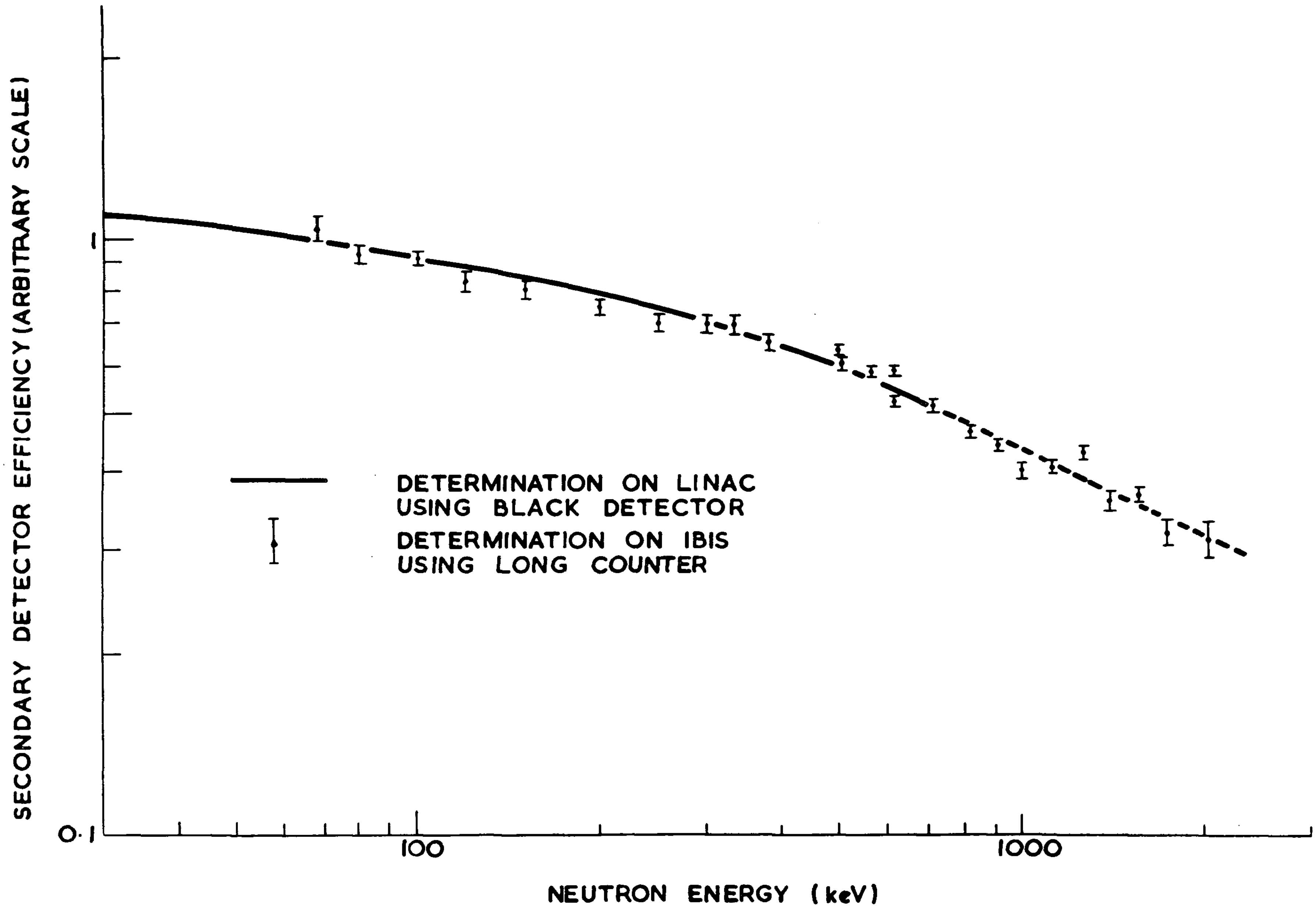

Fig. 1 The relative variation in efficiency of the secondary detector with incident neutron energy

E. Measurements of standard cross-sections using the Harwell black detector (M.S. Coates, G.J. Hunt and C.A. Uttley)

The discrepancy between the determinations of the $^{6}Li(n,\alpha)$ cross-section using thin (1 mm) and thick (9.5 mm) ^{6}Li glass scintillators reported previously[(1)] remains unresolved. The possibility remains that the total cross-section used in the Monte Carlo correction for multiple scattering in the glass is incorrect since the nominal element abundance as given by the manufacturer could be in error and the total cross-sections of the constituents are not all known accurately. An experimental measurement of the total cross-section of the 9.5 mm glass was attempted using a 2.5 cm thick ^{6}Li glass scintillator as a detector. Inconsistencies in the observed data were noted which were shown to be due to unexpected losses in the counting equipment in the regions with high instantaneous count rates. This technical difficulty has been overcome and the work will be repeated. It is possible that this rate dependent loss affects the cross-section data obtained with the 9.5 mm glass and this measurement is presently being repeated. A measurement with a ½ mm thick ^{6}Li glass has just been completed but the data are not yet fully analysed.

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(1) UKNDC(72)P36, EANDC(UK)139AL, INDC(UK)-14G.

E. Neutron spectrum measurements (H.M. Antunez (Comision Nacionale de Energia Atomica, Argentina), M.C. Moxon and D.A.J. Endacott)

The discrepancies of 10 to 25 per cent between capture cross sections measured at Harwell, using the Moxon-Rae neutron capture detector, and other laboratories, using various γ-ray detectors, has long been a source of anxiety. These discrepancies could in part be due to measurements of the neutron flux incident on the samples.

The calibration by M.S. Coates et al[(1)] of some ^{6}Li glass neutron detectors, has enabled us to carry out an accurate comparison of the neutron spectrum measured with the Li glass and the ^{10}B samples used in conjunction with the capture detector to measure the neutron spectrum at the sample position. A preliminary examination of the data indicates good agreement in the shape of the spectrum below 10 keV, but some discrepancies of the order of several per cent occur in the region between 10 and 200 keV. These are being investigated at the present time.

In conjunction with these measurements, transmission measurements on the boron and Li glass detector are being carried out in order to measure and check their composition. Fits to the results of the measurements on the $^{10}B_2O_3$ sample to the form $n\sigma = A + B/\sqrt{E}$ (where n is sample thickness in atoms of ^{10}B per 10^{-24} cm^2) give a value of B = 8.191±0.079, which is in good agreement with the value of 8.206±0.048 obtained from the composition and dimensions of the sample and the energy-dependent cross-section of ^{10}B (taken to be 610±3b at 1 eV). However, the value of A = 0.1371±0.009 is some 20% higher than the value 0.1116±0.0015 calculated from the total and scattering cross sections of the constituents. Additional measurements are now planned to investigate the problem.

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(1) Coates M.S. et al. This report, p. 4.

E. Fission cross-section measurements in the energy range from 1 keV to 1 MeV (D.B. Gayther, D.A. Boyce and J.B. Brisland)

The programme of time-of-flight fission cross-section measurements on the electron linac has continued. Fission events are recorded by observing the prompt fission neutrons in one or more of four NE 213 proton recoil detectors which surround the sample but are placed out of the incident neutron beam. Gamma-rays from neutron capture or inelastic scattering are rejected with a pulse shape discrimination system. The detection of scattered neutrons with incident energies below 1 MeV is prevented by setting the neutron discriminator bias of each detector above this energy. Pu-240 sub-threshold fission measurements made on the synchrocyclotron with this detector arrangement are described elsewhere in this report.

The $^{235}U(n,f)$ cross-section

Absolute cross-sections are not measured with this system and the earlier data[1] were normalised in the region 10 to 100 keV to the evaluation of Sowerby, Patrick and Mather[2]. Reasonable agreement was found below 250 keV but at higher energies the measured cross-section was smaller than the evaluation, the difference being as much as 15% above 800 keV. These preliminary data were based on the assumption that the neutron beam spectrum at the 100 m station used for the measurements was the same as that measured on a closely similar flight path. The possible error introduced by this assumption could not be estimated. The 100 m spectrum has now been measured with a neutron detector which has been calibrated against the Harwell long counter and the flat response detector of Coates et al[3]. A preliminary analysis of our recent fission data using the measured spectrum and normalised as before now agrees with the evaluation to within about ±6% over the complete energy range (1 keV to 1 MeV). The accuracy of the measured cross-section is estimated to be ±5% over most of the range but this error will be reduced with improved measurements of the 100 m spectrum.

These results are based on the detection of the prompt fission neutrons which are emitted at right angles to the incident neutron beam. At incident energies greater than 100 keV the fragment angular distribution is known to be forward peaked, the anisotropy increasing with increasing energy up to at least 1 MeV. It is to be expected that the fission neutrons will be emitted with a similar but less pronounced anisotropy. In order to allow for a possible distortion of the data due to this effect, measurements have been made with detectors at 45^{o} and 135^{o} as well as at 90^{o} to the incident neutron beam. A preliminary analysis shows that the cross-sections obtained with the three detectors differ by less than 3% over the complete energy range.

The $^{239}Pu(n,f)/^{235}U(n,f)$ cross-section ratio

Some measurements have now been made with a ^{239}Pu sample and these can be combined with the ^{235}U measurements to determine the cross-section ratio which, unlike the individual cross-sections, is not subject to uncertainties in the incident neutron spectrum. Comparison with the evaluation of Sowerby et al[(2)] shows general agreement within the experimental errors (about ±5%).

(1) UKNDC(72)P36, EANDC(UK)139AL, INDC(UK)-14G.

(2) Sowerby M.G., Patrick B.H. and Mather D.S. AERE - M 2497 (1972).

(3) Coates M.S., Hunt G.J. and Rae E.R., Nuclear Data for Reactors 1 211, IAEA Vienna (1970).

H. High resolution neutron total cross-section measurements on the synchrocyclotron (I.T. Belcher, I.M. Blair, P.H. Bowen, G.C. Cox, P.E. Dolley, A. Langsford, W.R. McMurray, N.J. Pattenden, and G.S. Valail (Queen Mary College, London))

The purpose of the measurements is to contribute to meeting the nuclear data requirements for neutron capture cross sections of structural materials in the energy range 100 eV to 1 MeV. Initial experimental investigation showed that the existing time-of-flight spectrometer equipment was inadequate for this purpose. Therefore our effort over the year has been concentrated on a progressive improvement of the system, specimen data being taken from time to time to provide a quantitative assessment of effectiveness of the of the steps taken. We list below the details of these improvements, and conclude with our latest data illustrating the present status of the project.

1. Deflection and target system

Measurements of distribution of the deflected beam have shown that less than half the beam is striking the target, some of the remainder going to heat (and distort) the deflector plates. The existing deflection system has been progressively modified to minimize the latter effect.

2. Collimation and shielding

The existing steel collimators and shielding walls allowed excessive neutron penetration in energy regions in which the iron cross section is low. We are progressively replacing the collimations with others of brass-tantalum and supplementing the shielding with boron-loaded resin blocks.

3. Electronics

Work is proceeding to convert the single-shot to a multi-shot system (up to four events per burst) which is essential if we are to utilise the full beam intensity.

4. Neutron detector

The timing uncertainty of the ^{6}Li glass neutron detector has been reduced from 17 nsec to 3 nsec, principally by replacing the photomultiplier (EMI 9618) by a faster one (RCA 4522).

5. Data handling

An on-line data collection program has been written for the DDP-516 computer with 10,000 time channels of variable width. Time spectra can be written on magnetic tape for each experimental condition. Another program is now being written to utilise the facilities of the disc store.

A suite of programs is now available on the IBM 370/165 computer for data reduction to transmission and total cross section as a function of neutron energy.

To illustrate the stage we have reached we present in Fig. 2 some data on the total cross-section in iron.

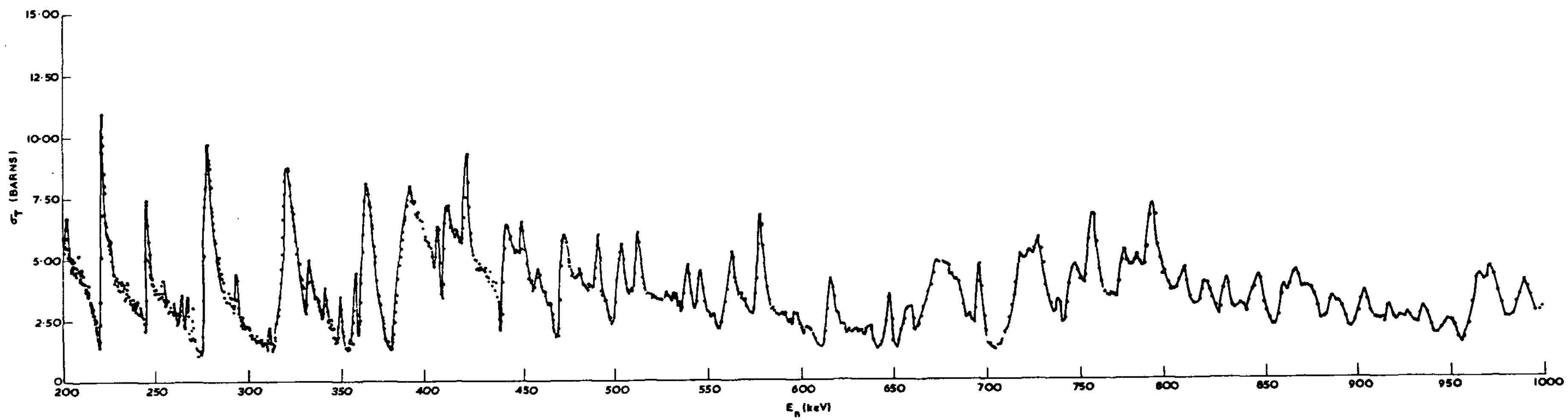

Fig. 2 Observed total cross section of natural iron sample (n = 0.259 atom/barn) against incident neutron energy. The nominal spectrometer resolution (limited by detector time jitter) was about 0.17 ns/m.

E. ^{240}Pu resonance parameters (M.C. Moxon, J.E. Jolly and D.A.J. Endacott)

Two metallic samples of ^{240}Pu were leased from the U.S.A.E.C. to investigate the normalisation of the neutron capture data taken in 1966 at Harwell(1).

Capture yield measurements as a function of neutron energy were made on a 4.6 m flight path from a plain uranium target of the Harwell 45 MeV electron linac. These measurements covered the energy range from 0.6 eV to ~200 eV. The data for the thinner of the two samples are shown in Fig. 3. Most of the small resonances observed can be attributed to ^{239}Pu. The one at 2.70 eV may be the resonance in ^{242}Pu reported at 2.65 eV by Coté et al(2). These data are normalised to the peak yield in the 1 eV resonance; this is virtually the maximum possible yield and is almost independent of the resonance parameters used to calculate it. For the resonances up to ~100 eV the capture areas are ~30% above the values calculated from the parameters obtained from the previous data. The 1966 capture data were normalised using the peak yield of the 20.43 eV resonance. As this resonance did not black out, i.e. the peak yield was not close to unity, the normalisation was dependent on the resonance parameters used (Γ_n = 2.1 meV and Γ_γ = 20.0 meV), and this probably accounts for the difference in yield.

To help confirm these higher values, transmission measurements were made with both samples, on the 14 m flight path from the booster target of the linac. The transmission data for the thicker sample are shown in Fig. 4 in the energy range ~15 to ~1000 eV. Figure 5 shows the results of area analysis on the present capture and transmission data (curves 1-6) together with the earlier transmission and scattering data for the 20.43 eV resonance. A least squares fit to the data gives a best value of 2.65±0.07 meV for Γ_n and 32.2±3.4 meV for Γ_γ. From these new parameters a higher peak yield is calculated than from the previous values and the old data have now been renormalised using these values. Preliminary results indicate an average radiation width of ~30 meV which is in agreement with the value of 29.5 meV obtained by Hockenbury et al(3) at RPI.

(1) Asghar M., Moxon M.C. and Pattenden N.J. Proc. Conf. on Nuclear Data for Reactors, II, 145 (1967) (CN-23/81).

(2) Coté R.E., Bollinger L.M., Barns R.F. and Diamond H. Phys. Rev. 114, 505 (1959).

(3) Hockenbury R.W., Boice J.D., Moyer W.M. and Block R.C. RPI-328-218, 2 (1971).

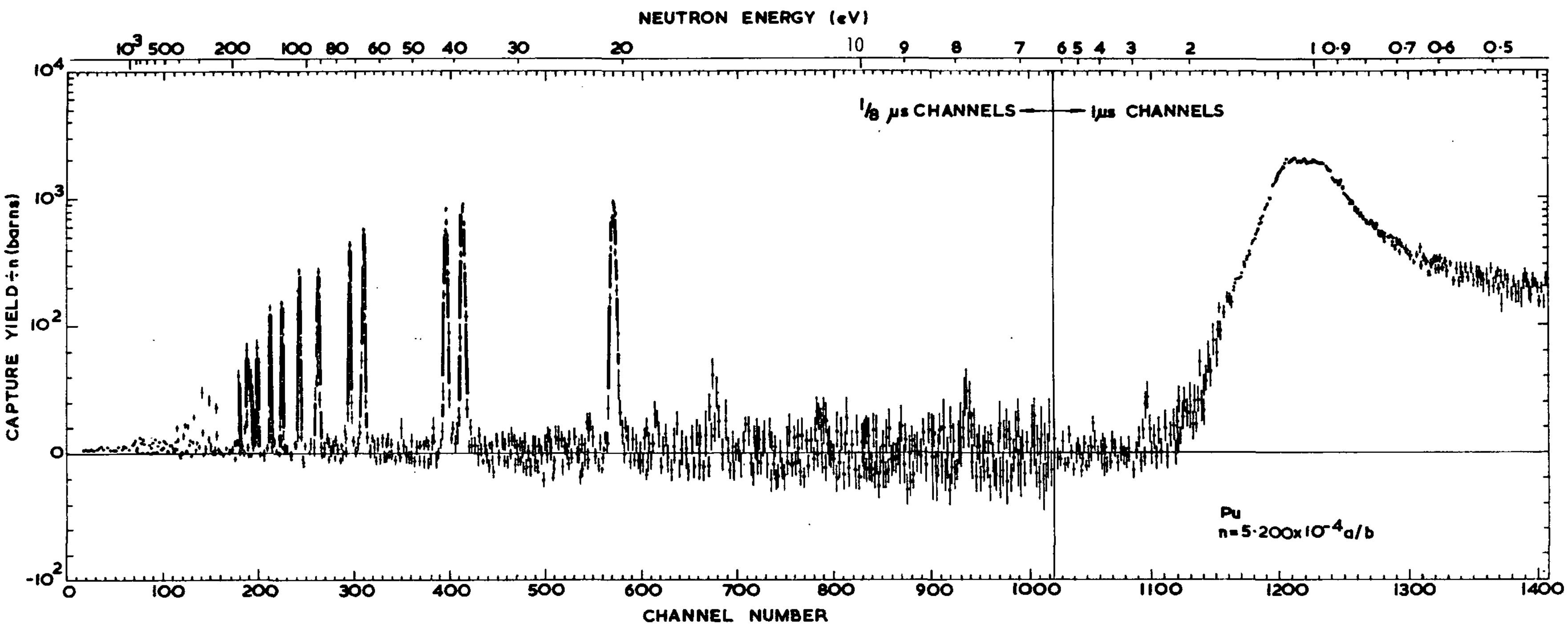

Fig. 3 The capture yield divided by the sample thickness as a function of neutron energy for a sample of ^{240}Pu

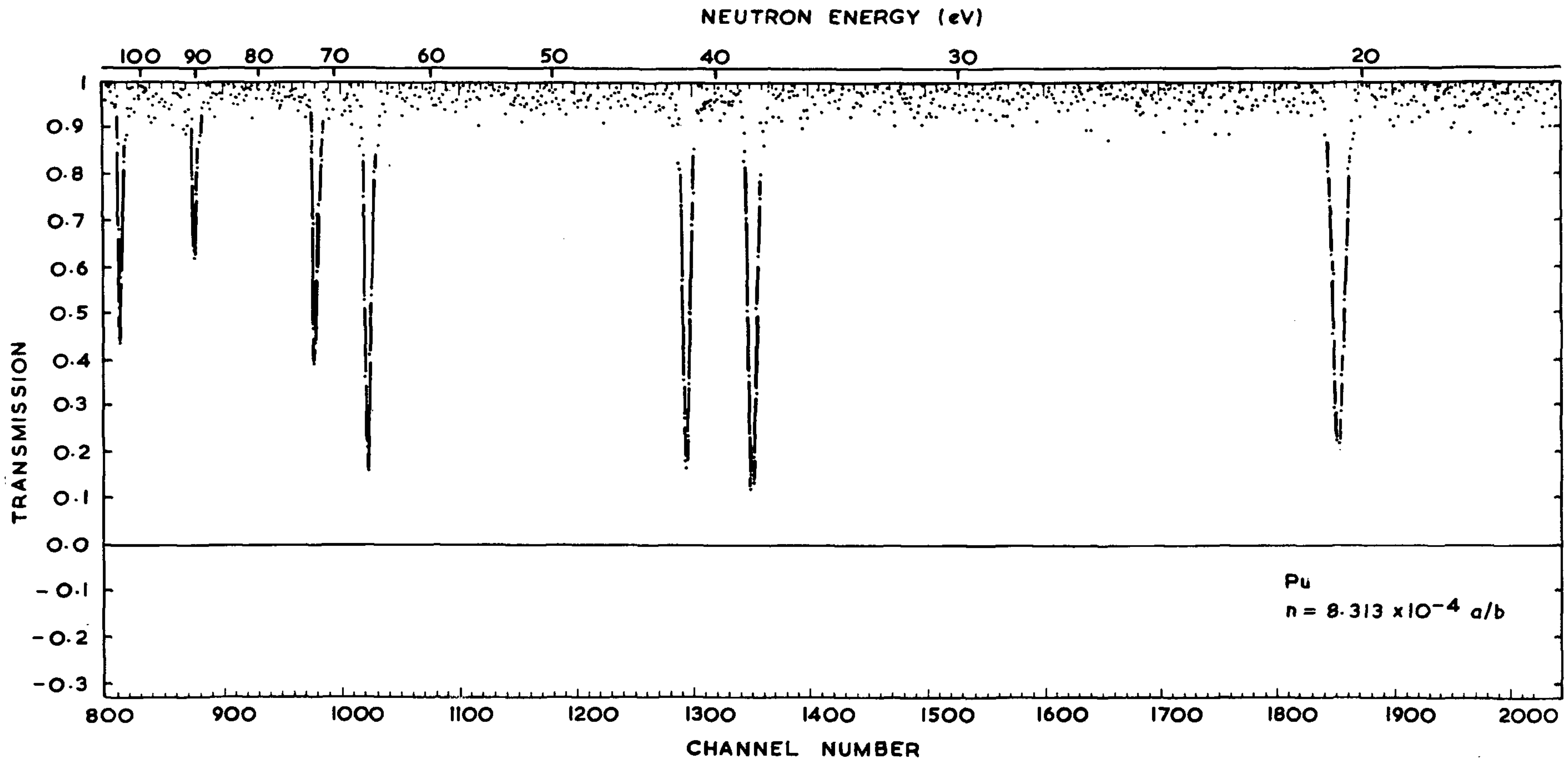

Fig. 4 The transmission of a sample of ^{240}Pu as a function of neutron energy

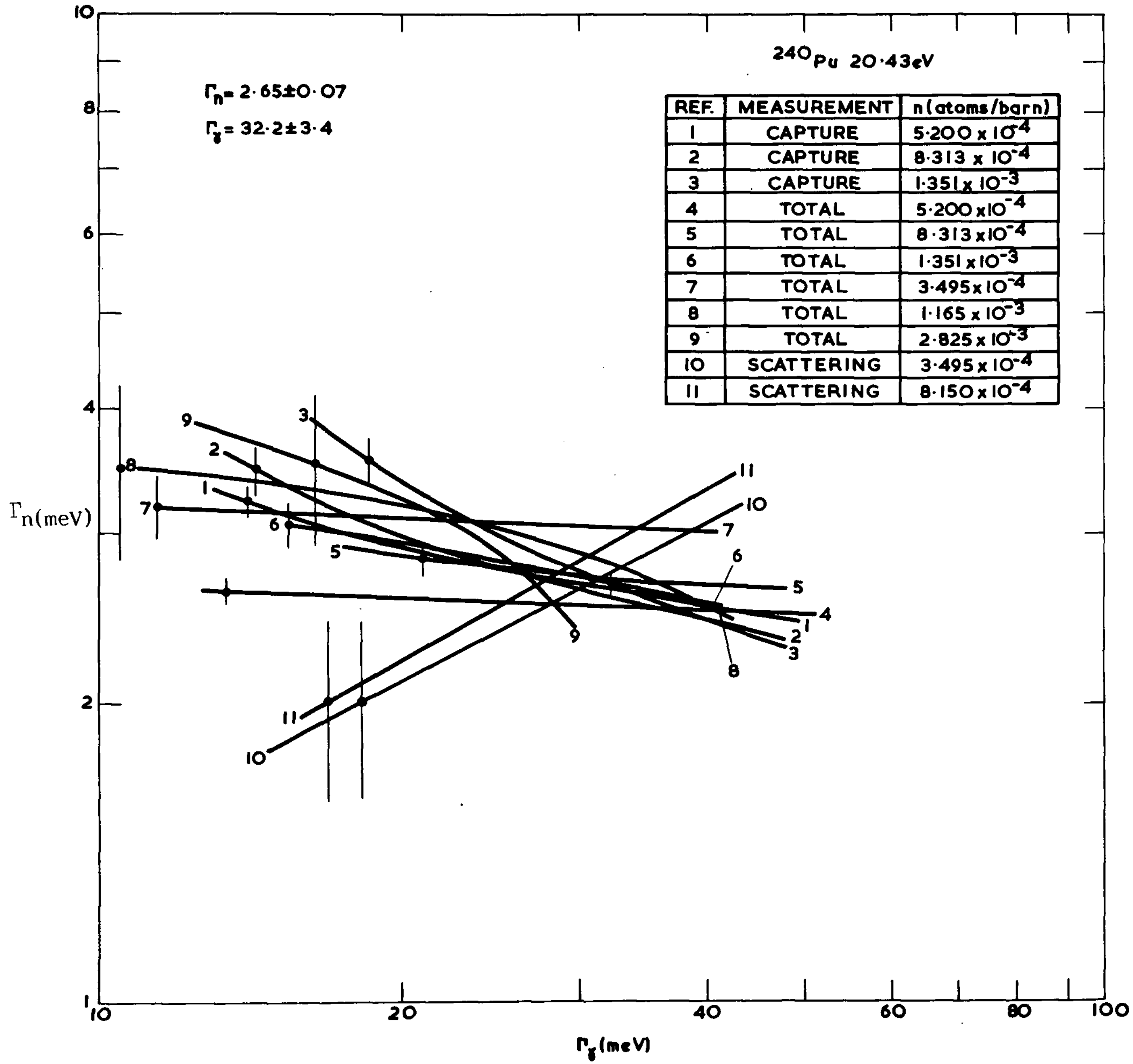

Fig. 5 Curves of Γ_n versus Γ_γ for different measurements on the 20.43 eV resonance of ^{240}Pu

B. Spectra of neutrons from prompt fission of ^{235}U and ^{239}Pu (J.L. Rose)

Measurements have been made of the spectra of neutrons following prompt fission of ^{235}U and ^{239}Pu by a time of flight method, using the pulsed 3 MeV Van de Graaff (IBIS) as a primary neutron source. Initial measurements have been made at an incident neutron energy of 130 keV using cylindrical samples of ^{235}U and ^{239}Pu. Flight paths were typically 2 metres, thus allowing good time resolution for the high energy end of the spectrum.

The neutron detector was a liquid phosphor type NE213A, in the shape of a cylinder 5 cm dia. by 4 cm thick. The scintillator was coupled to an ultra low noise photomultiplier biased to cut off neutrons of energy less than 0.040 MeV. Pulse shape discrimination was used to cut down background and to reduce the effect of the fission gamma rays, enabling neutrons of high energy to be measured with little interference. The detector was calibrated by the measurement of angular distribution of neutrons scattered from hydrogen, in the form of polythene, over the energy range 0.5 - 13.5 MeV. Multiple scatter effects, never more than 7½%, were corrected for using a Monte Carlo programme. Over the energy range 0.04 - 2 MeV further calibration using the Harwell long counter was carried out. These calibrations were accurate to $\pm 2.3\%$ overall. For the range 13.5 - 20 MeV extrapolation was carried out from the known data utilising the theoretical efficiency curves.

Care was taken over the time/energy calibration, the energy scale being set by observation of the spacing between the fission gamma peak and the elastic group as the primary neutron energy was varied. This ensured an energy calibration to better than 1%.

The resulting fission neutron spectra were corrected for multiple scattering in the solid samples but in fact very little correction was needed as little effect was observed on the spectral shape.

Following on the work of Barnard et al.[(1)] the data was analysed in their same limited energy regions for comparison purposes, as well as over the range 0.150 - 20.0 MeV.

If either a Maxwellian or Watt form was fitted to the limited regions good fits were obtained and matched the Barnard results quite significantly. However over the wider range a significant excess of neutrons was seen at higher energies and in Fig. 6 one can see this diversion from about 6 MeV and up. Attempts to fit both Maxwell and Watt gave deceptively low results for the average fission neutron energy $\bar{E}$. It was for this reason that after reference to some of Watt's original work[(2)] it was decided to use a different form of fit. In his paper Watt felt that while his original form took some account of recoil of the fission fragments, as having an effect on the neutron energy distribution, the assumption of only one averaged fragment might not be sufficient. Following on an earlier suggestion of Feather[(3)] the splitting up of the Watt form into two discrete parts, one representing the averaged light fragments and the other the heavy fragments, might lead to a better fit. Utilising this, the data were analysed on the assumption of two fragments, each having an independent neutron "temperature" and the neutrons emitted in association with each fragment also being independent. This double-Watt formula thus takes the following form:-

$$N(E) \propto C_1 \ \mathrm{Sinh}\ ((4\ EF_1)^{\frac{1}{2}}/T_1)e^{-E/T_1} + C_2 \ \mathrm{Sinh}\ ((4\ EF_2)^{\frac{1}{2}}/T_2)e^{-E/T_2}$$

$$\text{where } F = \frac{\text{Average fragment kinetic energy}}{\text{Average fragment mass number}}$$

the suffix 1 denoting light mass and 2 heavy mass.

Utilising this formula an excellent fit was obtained for both ^{235}U and ^{239}Pu over the complete energy range 0.15 - 20 MeV. In the limited Barnard regions this form gives results close to the earlier ones. When taken over the whole range however the discrepancy in the high energy neutron tail clearly shows up the increased values for $\bar{E}$. See Tables (1) and (2) for a summary of these results.

Work is now in progress to extend the measurements to higher primary energies using a gas scintillator fission chamber. It is hoped that these results will go a long way to reconciling the difference in results between the microscopic and macroscopic measurements thus far carried out.

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(1) Barnard E., Ferguson A.T.G., McMurray W.R. and Van Heerden I.J., Nuc. Phys. 71 (1965) 228-240.

(2) Watt B.E., Phys. Rev. 87 (1952) 1037.

(3) Feather N., USAEC Document BR335A (1942).

Table 1

Average Energy of ^{235}U Fission Neutrons

Range of fit	Maxwell	Watt	Double-Watt	Comment
0.3 - 4 MeV	1.937±0.050	1.948±0.054	1.960±0.065	Present Work.
0.3 - 4 MeV	1.945±0.045			Barnard et al.(1)
0.15-20 MeV	2.025±0.054	2.002±0.054	2.201±0.065	Present Work.

Table 2

Average Energy of ^{239}Pu Fission Neutrons

Range of fit	Maxwell	Watt	Double-Watt	Comment
0.15- 6 MeV	2.039±0.060	2.007±0.055	2.111±0.075	Present Work.
0.15- 6 MeV	2.110±0.030			Barnard et al.(1)
0.15-20 MeV	2.082±0.060	2.029±0.055	2.136±0.075	Present Work.

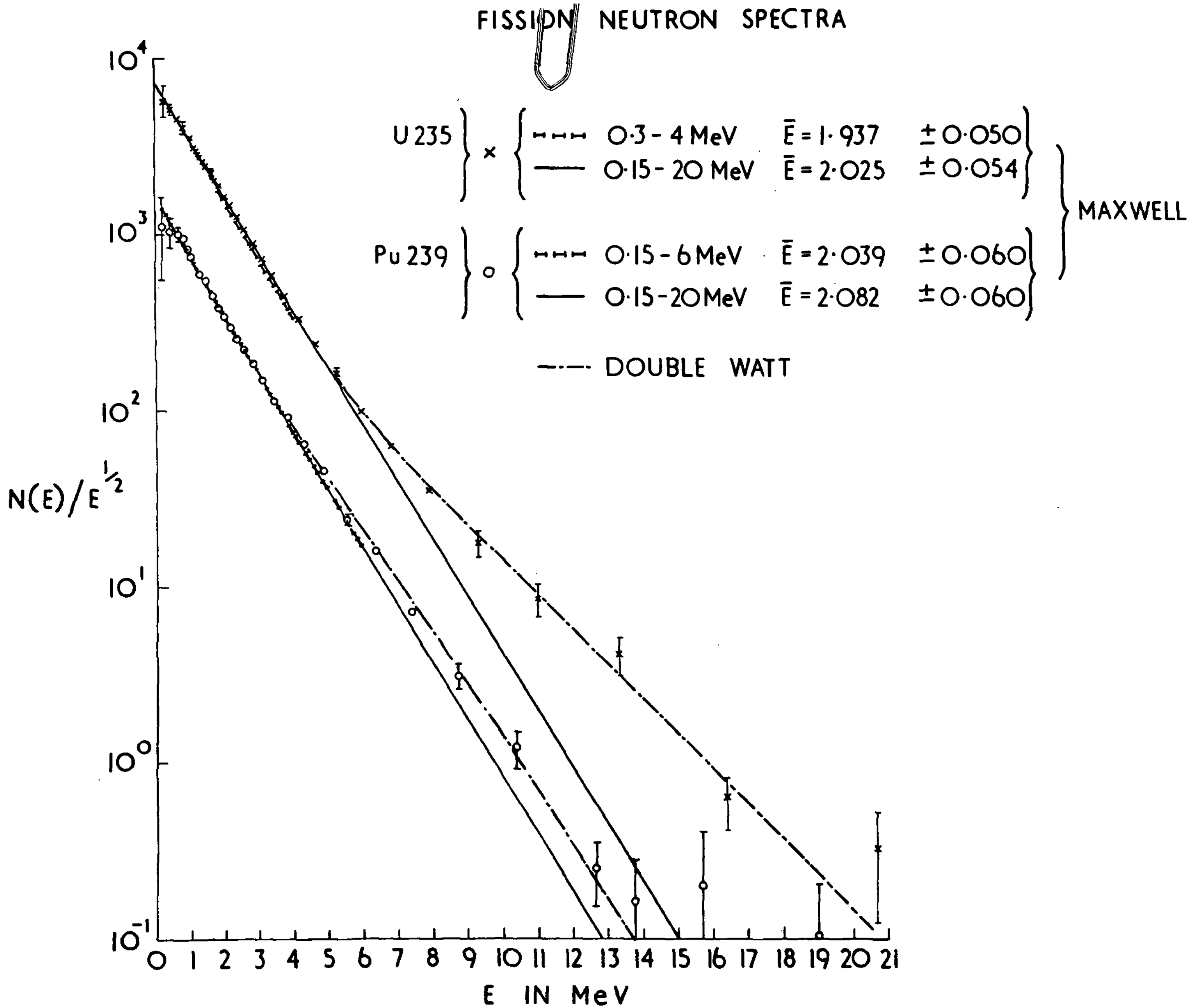

Fig. 6 The obscured fission neutron spectra of ^{235}U and ^{239}Pu compared with various fits

NEUTRON CROSS-SECTION EVALUATION

Simultaneous evaluation of the fission cross-sections of ^{235}U, ^{239}Pu and ^{238}U and the capture cross-section of ^{238}U (M.G. Sowerby, B.H. Patrick, Mrs. R. North with D.S. Mather (AWRE))

As reported in the previous progress report[1] a simultaneous evaluation of the ^{235}U, ^{239}Pu and ^{238}U fission cross-sections and the ^{238}U capture cross-section has been performed and the results incorporated by AWRE into new files in the U.K. Nuclear Data Library. The ^{235}U (DFN 271), ^{239}Pu (DFN 269A) and ^{238}U (DFN 272) files use these evaluated cross-sections above 25.5, 27.5 and 25 keV respectively. It was not possible to document the evaluation before the files were created, but over the past year a detailed document has been prepared. In doing this slight errors and omissions have been found and these together with revised experimental data have meant that the numbers finally recommended will be slightly different from those used to create the files. Two documents will therefore be issued; a memorandum[2] describing the evaluated data used for the U.K. Nuclear Data Library files and the detailed paper giving the final recommendations.

Figs. 7, 8 and 9 show some of the evaluated data compared with experimental measurements. (The starting values shown on Figs. 7 and 8 are the input values for the simultaneous evaluation technique which has been discussed by Sowerby and Patrick[3]). Three comments can be made on these figures:

(1) It can be seen from Fig. 7 that the recent measurements of the ^{235}U fission cross-section of Szabo et al, Kappeler and Poenitz agree well with our evaluated curve below 1 MeV. Above 1 MeV there are few reliable data.

(2) There are also few acceptable data on the ^{238}U fission cross-section below 6 MeV (see Fig. 8) but those that have been accepted form a very consistent set with the ^{235}U fission cross-section measurements and ratio data since the results of the simultaneous evaluation are very little different from the starting values.

(3) The ^{238}U capture cross-section measurements between 1 and 100 keV shown in Fig. 9 do not agree within the estimated errors of typically $\sim\pm5\%$.

An important conclusion reached from this work is that the evaluated data have not got the accuracy required by the reactor physicists; the accuracy of the cross-sections being estimated to be typically ±5–6% while the requested accuracy is ~±3%. It does not appear that further evaluation work will solve the discrepancies as there is a good consensus between evaluators on the reliability of experimental data and most differences between evaluations are philosophical in origin (e.g. should integral data be allowed to influence the evaluation?). Therefore, it appears that the resolution of the discrepancies must come from additional measurements of high quality. In many cases one additional measurement will not be sufficient because it is an extreme assumption that only the most recent experiments are correct. Hence we must look to an international programme of work to do this.

Rowlands[(4)] has reported how well the present evaluated data calculate fast reactor properties. Assuming that most of the errors are in the cross-section measurements (which is not proven) the major discrepancies appear to be related to the ^{238}U fission and capture cross-sections. In order to bring the calculated and measured integral reactor properties into agreement it is necessary to increase the ^{238}U fission cross-section relative to the ^{235}U fission cross-section above the fission threshold and decrease the capture cross-section below 500 keV. The adjustments to the fission cross-section are not independent of the adjustments to the ^{238}U inelastic scattering cross-section and the fission neutron energy spectrum. Depending on the errors assigned to the various parameters the fission cross-section adjustments vary between +6 and +14%. It is difficult to accept that the cross-section is in error by 14% but a 6% adjustment, which also implies large adjustments to the fission spectrum, is reasonable.

The proposed adjustments for the ^{238}U capture cross-section vary between −6% at 500 keV to −12% below 25 keV. The 6% adjustments are quite reasonable but those of 12% are difficult to accept. Part of the problem may be that the integral measurements comment upon the shielded cross-sections while the differential data give the infinitely dilute values. The cross-sections calculated from the resonance parameter measurements of Rahn et al[(5)], however, tend to support the integral evidence but the accuracy of the average cross-sections deduced by this method must be poor.

(1) UKNDC(72)P36, EANDC(UK)139AL, INDC(UK)-14G.

(2) Sowerby M.G., Patrick B.H. and Mather D.S. UKAEA Memorandum AERE - M 2497 (1972).

(3) Sowerby M.G. and Patrick B.H. Proc. IAEA Conf. Nuclear Data for Reactors (Helsinki 1970) Vol. II, p. 703.

(4) Rowlands J.L. Private communication (1972).

(5) Rahn F.J., Camarda H., Hacken G., Havens W.W., Jr., Liou H.I., Rainwater J., Slagowitz M., Wynchank S., Arbo J. and Ho C. Proc. Third Conf. Neutron Cross-Sections and Technology (Knoxville, 1971) Vol. 2, p.658.

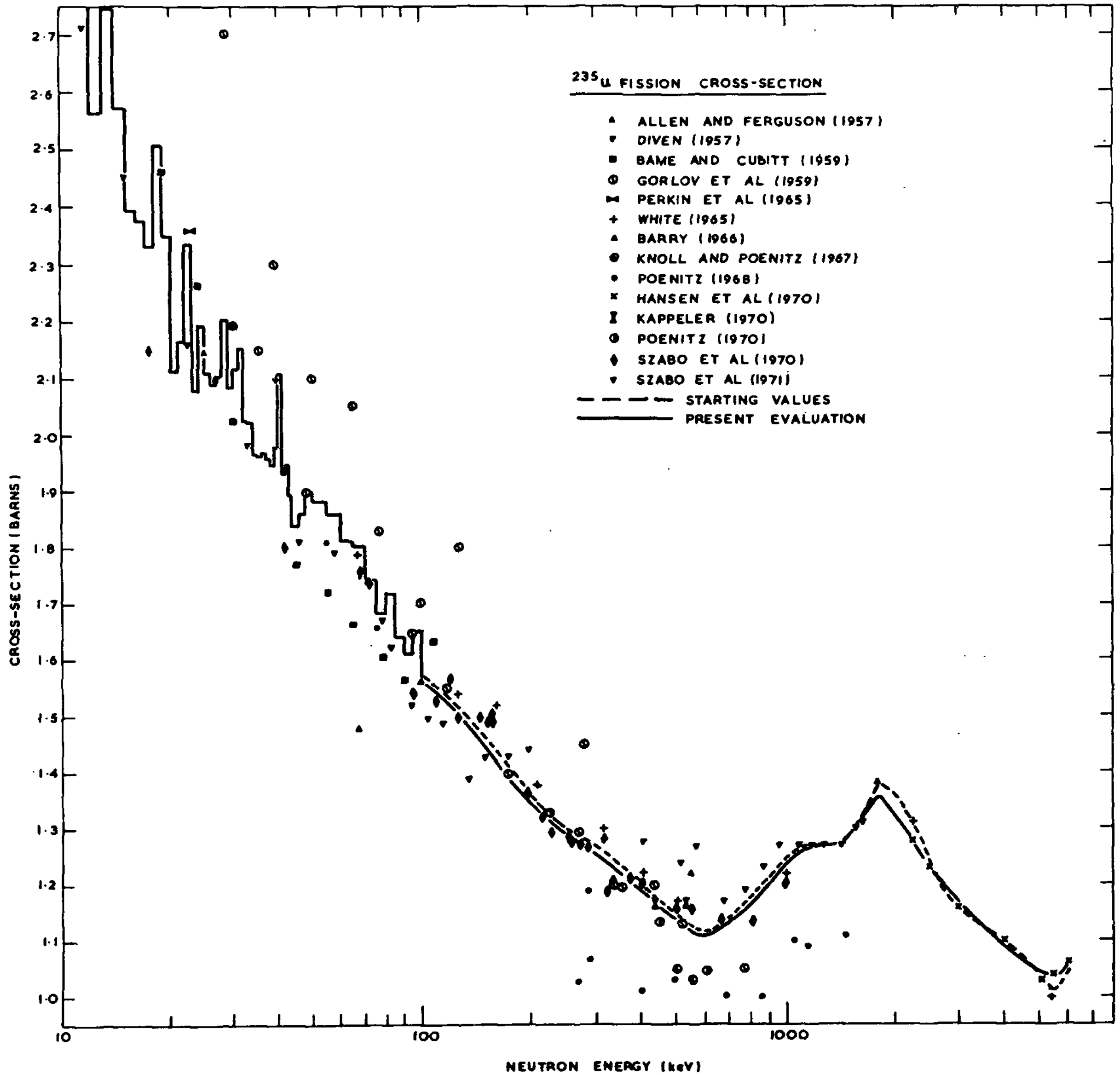

Fig. 7 The fission cross-section of ^{235}U from 10 keV to 6 MeV

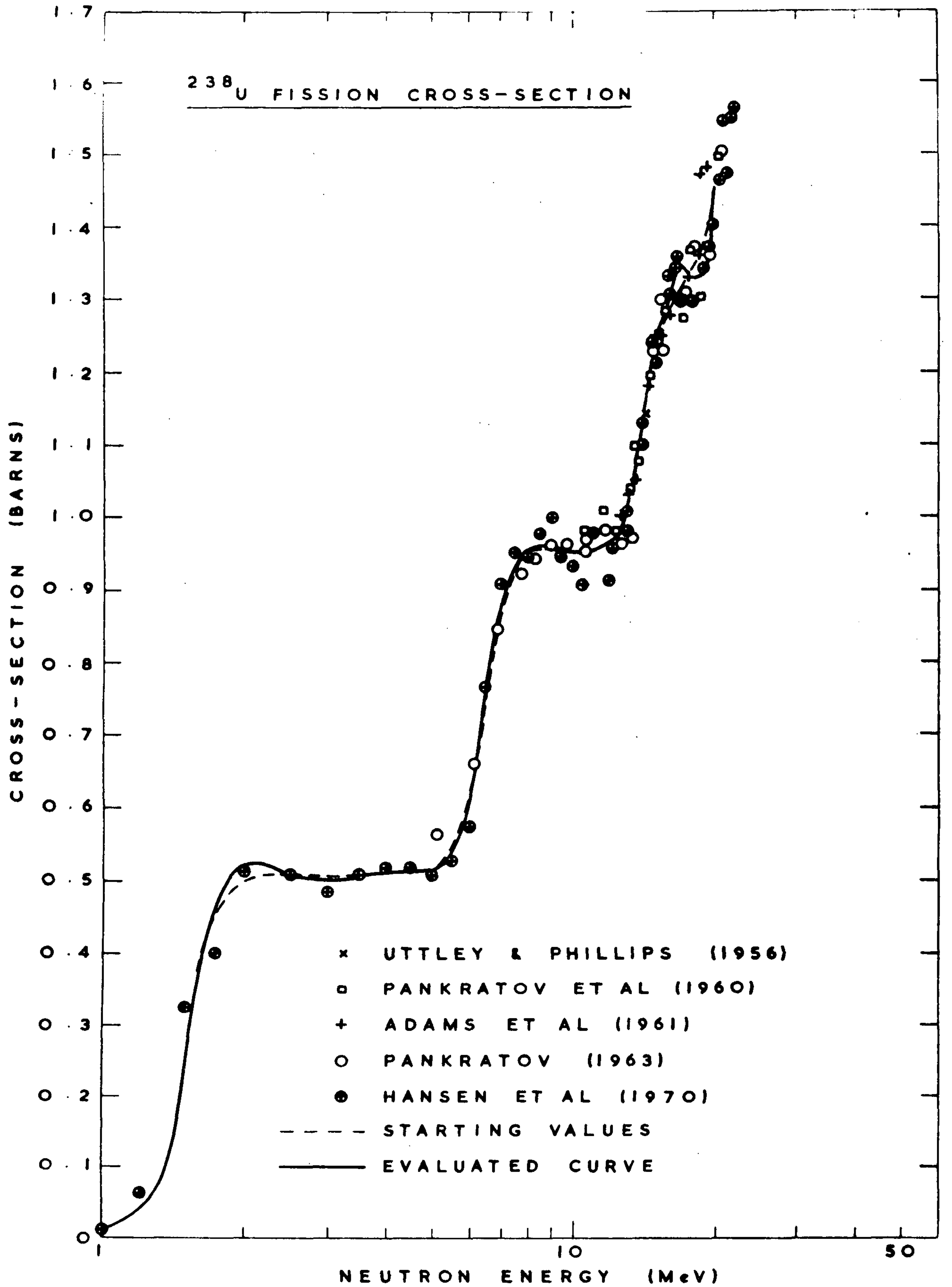

Fig. 8 The fission cross-section of ^{238}U from 1 to 20 MeV

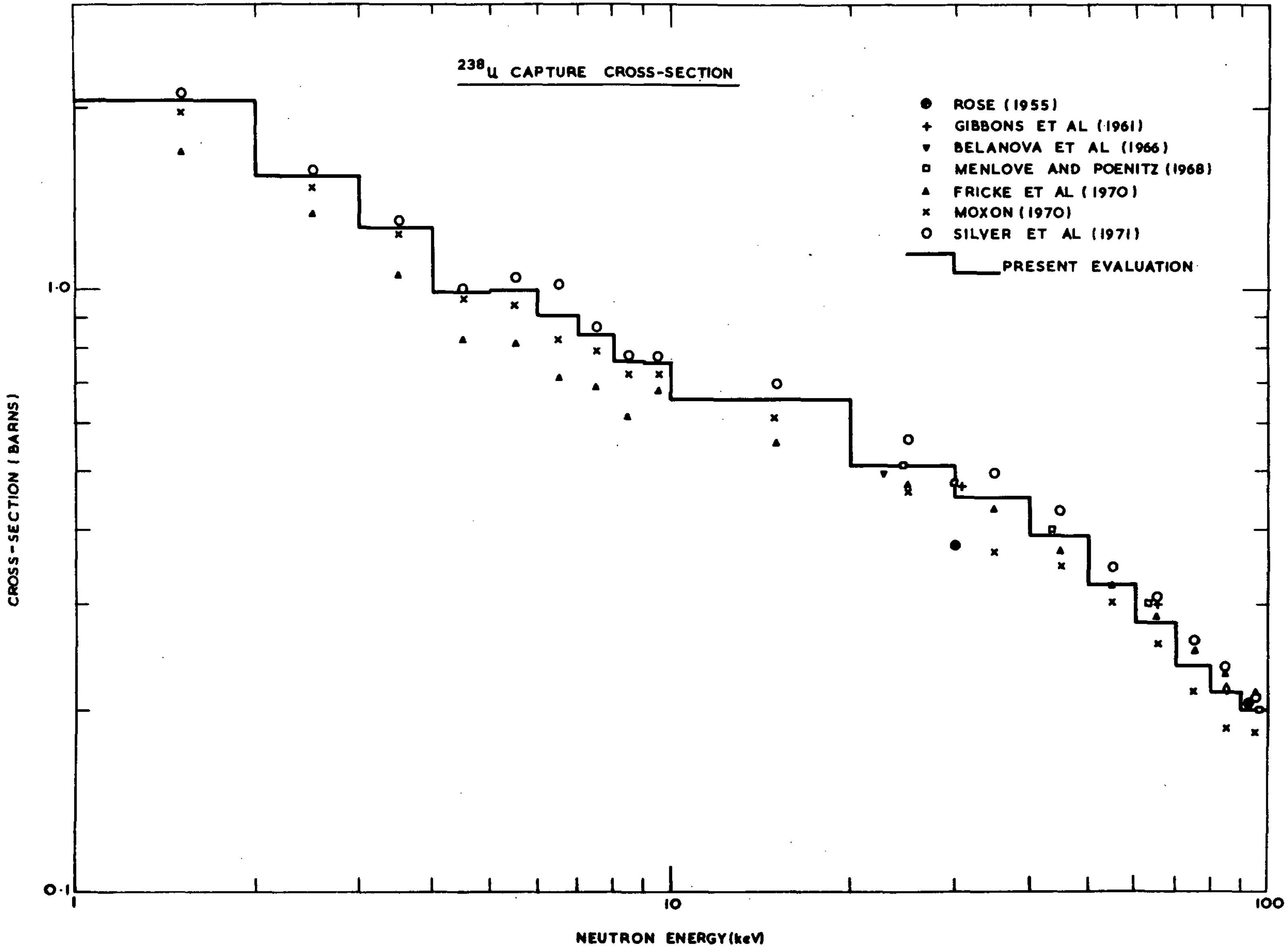

Fig. 9 The capture cross-section of ^{238}U from 1 to 100 keV

The evaluation of the cross-sections of ^{6}Li (C.A. Uttley, M.G. Sowerby and Mrs. R. North)

The ^{6}Li(n,α) cross-section is an important standard for cross-section and reactor spectrum measurements. A review of the cross-sections of ^{6}Li below 1.718 MeV was prepared for the EANDC Symposium on Neutron Standards and Flux Normalisation[(1)] and this was subsequently updated to include angular distribution data[(2)]. This work has now been extended to 15 MeV and the results compiled into a new file (DFN 914) in the U.K. Nuclear Data Library.

The evaluated cross-sections and angular distributions below 0.5 MeV are based on the calculated cross-sections of Uttley and Diment as recommended in References 1 and 2. No adustments have been made to make the results coincide with the absorption cross-section (σ_{nA}) measurements at 2,200 m/sec since the best value of σ_{nA} (924.4 b) is only 0.26±0.26% higher than the value recommended by Uttley and Diment. Above 0.5 MeV the cross-sections have been re-evaluated though time has prevented a thorough examination of all the experimental data. In the new file all the secondary energy distributions and the angular distributions of the (n,nα)d and (n,2n) reactions have been taken from the existing file.

In selecting the cross-section values for the present evaluation we have given particular emphasis to the (n,α) cross-section ($\sigma_{n\alpha}$) especially in the energy range 0.5 to 4 MeV. It has been shown previously[(1)] that the most recent measurements of $\sigma_{n\alpha}$ agree with the Uttley and Diment calculation between 300 and 500 keV and we have therefore normalised the relative measurements of both Gabbard et al[(3)] and the recent data of Clements and Rickard[(4)] to Uttley and Diment at 500 keV. As can be seen in Fig. 10, however, these disagree by up to a factor of 2 with the other available data in the energy range 0.5 to 4 MeV which are themselves reasonably consistent with the inaccurate values obtained from the difference between the nearly identical total and scattering cross-sections below 1.7 MeV (only the ^{6}Li(n,α)t reaction channel is significant below 1.7 MeV and at this energy the scattering cross-section is 88% of the total cross-section of 1.18b). Nevertheless we have chosen to follow the low (n,α) cross-section for the following reasons:-

(a) The measurements giving high values were performed at least 12 years ago and do not have the accuracy of Clements and Rickard.

(b) The measurements of the total cross-section in the minimum between 1 and 1.6 MeV are not particularly reliable since the samples used were too thin.

The (n,α) cross-section adopted below 4 MeV introduces a problem at higher energies since the available data from 4 to 8 MeV come from experiments which have been assumed to be in error below 4 MeV. However one experiment gives data both below 8 MeV and at 14 MeV, the latter being in agreement with other measurements at this energy. Thus the evaluation curve is an interpolation between ~4 MeV and 14 MeV and it assumes that the errors in the data of Ribe[5] and Murray and Schmitt[6] decrease as the energy increases. It is clear from this discussion that the data on the $^{6}Li(n,\alpha)$ cross-section are not adequate in accuracy above 500 keV and further measurements are urgently needed to confirm the data of Clements and Rickard.

One of the problems encountered in producing this ^{6}Li file in UKNDL format has been that at certain energies all the partial cross-sections and the total cross-section are known. In the UKNDL it is necessary at each energy where data are given that the sum of the evaluated partial cross-sections must be equal to the evaluated total cross-section. We have seen that between 0.7 and ~2 MeV this condition is not obeyed if we use our evaluated (n,α) cross-section. Therefore to achieve consistency we have adjusted both the total and scattering cross-sections. At higher energies where adjustments are necessary, they have been made mainly in the elastic scattering and (n,nα)d cross-sections.

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(1) Uttley C.A., Sowerby M.G., Patrick B.H. and Rae E.R. Neutron Standards and Flux Normalisation 80, USAEC Oak Ridge (1971).

(2) Uttley C.A., Sowerby M.G., Patrick B.H. and Rae E.R. Proc. Conf. on Neutron Cross-sections and Technology, Knoxville (CONF 710301) 2, 551 (1971).

(3) Gabbard F., Davis R.H. and Bonner T.W. Phys. Rev. 114, 201 (1959).

(4) Clements P.H. and Rickard I.C. AERE - R 7075, to be published.

(5) Ribe F.L. Phys. Rev. 103, 741 (1956).

(6) Murray R.B. and Schmitt H.W. Phys. Rev. 115, 1707 (1959).

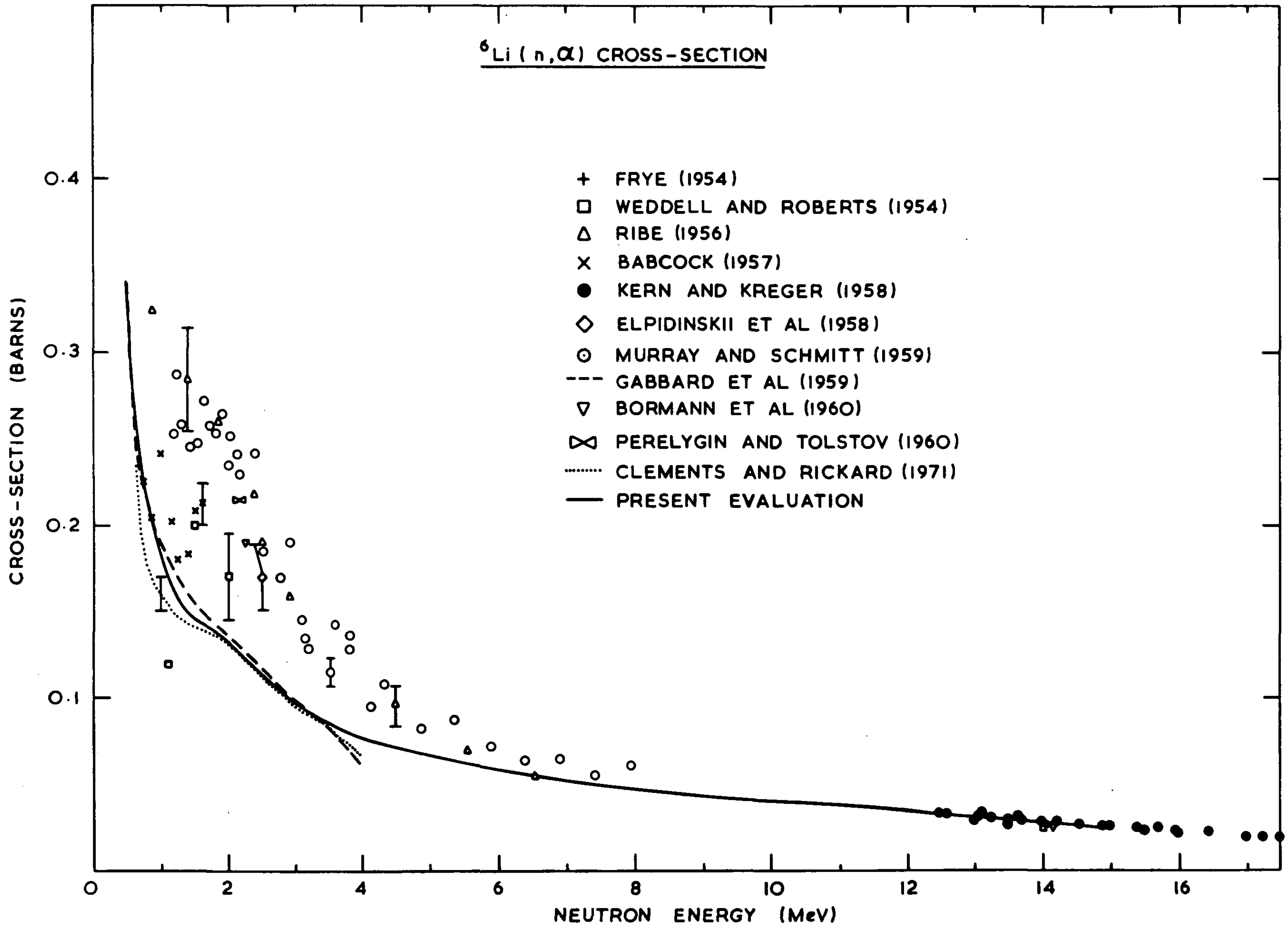

Fig. 10 The evaluated ^{6}Li(n,α) cross-section above 0.5 MeV

Evaluation of Neutron Data for ^{7}Li (T.W. Conlon)

The UKNDC file for ^{7}Li contains essentially the evaluated data presented by Pendlebury in 1964.(1) Due to the possible extensive use of ^{7}Li in a thermonuclear fusion reactor, an appraisal of more recent data was considered necessary but a study of these indicates that few alterations need to be made to the existing file. A report describing this work is being written.

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(1) Pendlebury E.D., AWRE 0-61/64.

GENERAL NUCLEAR DATA FOR REACTORS

E. Neutron resonance capture gamma-ray studies (B.W. Thomas and H.P. Axmann (Vienna))

Recent work has concentrated on the high energy primary transitions (partial radiation widths) following resonance neutron capture by ^{240}Pu and ^{167}Er. Experimental data were obtained using a 40 cm^3 Ge(Li) detector on a 10 metre flight path from the booster target of the electron linac. Data collection was carried out using the on-line PDP-4 computer system for collecting dual parameter data.

$^{240}Pu(n,\gamma)^{241}Pu$ reaction

This reaction was investigated to obtain a better basic understanding of the neutron capture process in transuranic nuclei that are of importance to the fast reactor programme. A 24 g sample of metallic ^{240}Pu (97%) was used in this experiment and gamma-ray spectra were obtained for 17 individual resonances below 300 eV. Similar spectra for several unresolved regions up to 2 keV were measured in the same experiment to investigate resonances observed in sub-threshold fission. No previous experiments of this type have been carried out but information concerning the low lying levels of ^{241}Pu is available from (d,p) data(1). The capture states (for s-wave neutron capture) have spin and partiy $1/2^+$ so that primary transitions to the low lying positive parity states are weak. The highest energy transition observed in the present experiment (5079 keV) is thought to populate the $1/2^+$ state at 163 keV giving a total binding energy of 5242±5 keV. This figure confirms well the value of 5239±5 keV given by (d,p) data(1) rather than the figure of 5.4 MeV from mass defects. Many primary gamma rays in the range 2.8 → 5 MeV have been observed and a complete analysis is currently in progress.

An unusual feature of the present data is the existence of a series of lower energy transitions (1 → 2.2 MeV) which introduce a time dependent component in the background with a decay half-life in the range 0.5 → 1 milliseconds. The gamma ray energies are not consistent with those expected from target activity or fission products, and could suggest the existence of a delayed component in the decay of an excited state of ^{241}Pu.

$^{167}Er(n,\gamma)^{168}Er$ reaction

High energy capture gamma ray spectra for individual resonances in the range 20 eV to 150 eV have been obtained using a 20 g separated isotope target (87.2%) of ^{167}Er. Primary transitions in the energy range 5 to 8 MeV are being analysed to investigate possible non-statistical effects associated with an anomolous distribution of partial radiation widths or with radiation width - neutron width correlations.

(1) Braid T.H., Chasman R.R., Erskine J.R. and Friedman A.M., Phys. Lett. 18, 149 (1965)

H. ^{240}Pu neutron-induced fission measurement on the synchrocyclotron (I.T. Belcher, I.M. Blair, P.H. Bowen, D.A. Boyce, J. Brisland, G.C. Cox, P.E. Dolley, D.B. Gayther, N.J. Pattenden)

The neutron time-of-flight spectrometer facility of the Harwell synchrocyclotron has been used in a measurement of the energy dependence of the fission cross section of ^{240}Pu, relative to ^{235}U. The energy range covered was from a few hundred eV to about 1 MeV. The measurement used a 50 m flight path, giving a best time resolution of about 0.35 ns/m. The fission rate was determined by counting fission neutrons with four liquid scintillator detectors using pulse shape discrimination to remove the γ-ray background, and a discrimination level set at about 1 MeV neutron energy.

Previous resonance measurements(1) have shown groups of resonances with significant fission widths up to 2.7 keV, which have been explained by the Strutinsky double-humped barrier theory. Measurements at higher energies(2) have shown a tail on the threshold extending down to about 15 keV. The object of our measurement was to study both of these effects simultaneously, with a substantial improvement in resolution.

A detailed analysis of our results is proceeding. A preliminary survey indicates that the previous measurements have been confirmed qualitatively, with most of the reported sharp fission resonances having been observed. There appears to be structure both on the side of the threshold and on the low energy tail, which extends down to 4 keV. Some of the observed time-of-flight spectra are shown in Fig. 11.

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(1) Migneco E. and Theobold J.P., Nuc. Phys. A112 603 (1968).

(2) Gilboy W.B. and Knoll, G.F., KFK-450 (1966).

FUNDAMENTAL AND BASIC RESEARCH

NUCLEAR STRUCTURE AND DYNAMICS

G. Nuclear structure information from the study of isomeric states (T.W. Conlon)

New examples of isomeric states have been produced and the occurrence of isomerism in several distinct regions of nuclei have been studied using pulsed beams of both light and heavy ions from the Harwell Variable Energy Cyclotron. The analysis of the data continues and several reports concerning aspects of this work have been prepared[1,2,3] and either published[4] or are in course of publication[1,2]. Reference is made to a previous Progress Report[5] which, in conjunction with the sections below, provides a more complete summary of this work.

I. Isomeric States in the Region Z=63-83

New isomeric states produced by reactions of the form (p,Xn) and (^{4}He,Xn) have been produced in ^{189}Pt, ^{172}Ta and ^{201}Bi although there is some doubt as to the identity of the final nucleus in the latter two examples. The analysis of these data is continuing.

II. Shape Isomerism

(1) The ^{127}Cs isomer

A report on this case entitled 'Evidence for states of prolate and oblate deformation and for shape isomerism in ^{127}Cs' has been published.[4]

(2) The region Z~50, N~82

Neutron deficient nuclei of odd Z elements in the neighbourhood of ^{127}Cs (Z=55) have been studied to see if further examples of the effects described in reference 4 for the nucleus ^{127}Cs could be found. Isomeric states have been observed in all three elements studied, viz. I (Z=53),

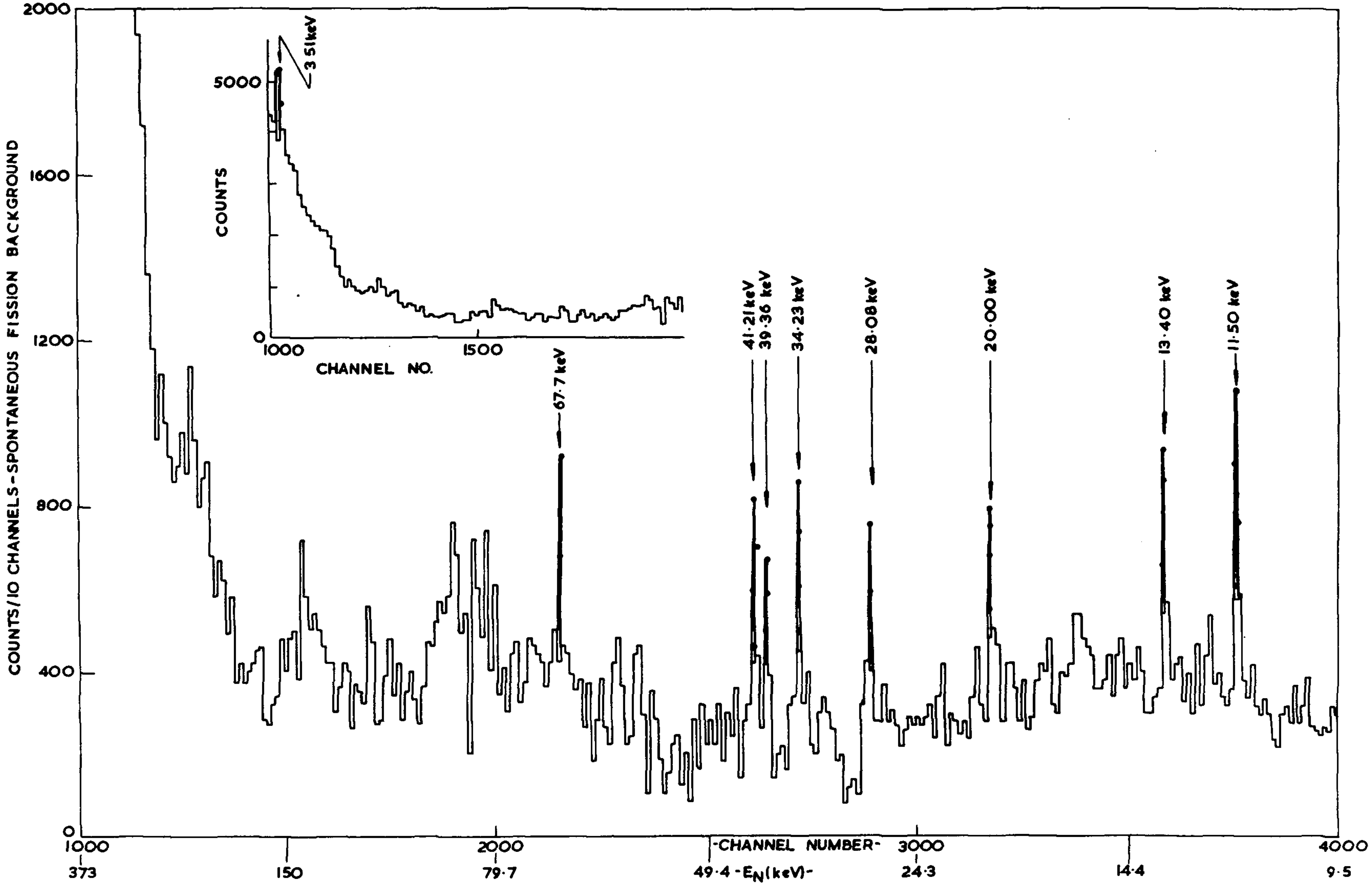

Fig. 11 Observed ^{240}Pu neutron-induced fission neutron yield against incident neutron time-of-flight. The histogram represents the counts in channels grouped in 10's. The points represent counts ×10 in some individual channels, to indicate some of the structure observed.

La (Z=57) - two examples, Pr (Z=59). A preliminary analysis of these data indicates that in all four cases isomeric decay of states may be involved as was observed in ^{127}Cs.

(1) Conlon T.W. AERE - R 6479 (1970).

(2) Conlon T.W. and Knudsen D.B. AERE - 7062 (1972).

(3) Conlon T.W. AERE - R 7070 (1972).

(4) Conlon T.W. Nucl. Phys. A161, 289 (1971).

(5) UKNDC(71)P28, EANDC(UK)134AL, INDC(UK)12/G.

H. Nuclear isomers (O.N. Jarvis, C. Whitehead, D. West, A.C. Sherwood)

The study of the proton induced spallation reactions, mentioned in the previous progress report[(1)], has been diverted to an investigation of the dearth of known nuclear isomers with lifetimes in the millisecond to second time range[(2)]. The shell-model predicts a certain amount of structure in the isomer-abundance versus lifetime plot thus leading to a belief that the observed minima are genuine, but on the other hand many new isomers have been discovered in recent years.

A suite of programs has been written which permits the DDP 516 computer to be used as a two-parameter analyzer with 20 time channels and 1000 channels for pulse height. This suite can store data, on to the Burroughs fixed-head disc, at event rates of up to a maximum of 6 KHz. This has proven to be quite adequate for use with the 60 cc Ge(Li) detector used to detect decay γ-rays from the selected target.

Preliminary work using 160 MeV proton bombardment of a selection of targets showed two main problems:

(i) for a time-scale of several milliseconds the copious positron production yielded a 511 keV γ-ray background which was most serious; a partial solution to this difficulty is to avoid the use of scattering chambers and simply to support the targets in the open air.

(ii) for short lifetimes ($\lesssim$ 1 msec) there is a serious γ-flash problem, which is being attacked by modification of the preamplifier.

At present attention is being devoted to the observation of short-lived isomers produced by thermal neutron absorption: for this experiment both γ-flash and positron production problems are unimportant. The thermal neutrons are obtained by bombarding a uranium target with about 30 na of 160 MeV protons, the uranium being placed within a large polythene cylinder which acts as a moderator. A position is provided within the cylinder at which the samples experience a neutron flux of up to 10^9 n/cm^2 sec and are viewed by the well-shielded Ge(Li) detector placed at a distance of 1.5m. The shielding is, as yet, unsatisfactory but nevertheless known isomers may be observed if a few grammes of material are available.

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(1) AERE - PR/NP 18 (1972).

(2) Kantele J. and Tannila O., Nuclear Data A4 359 (1968).

Interpretation of data on excitation of spontaneously fissioning isomers by neutron capture (J.E. Lynn)

Most work on the excitation of the spontaneously fissioning isomers (which are believed to be the 'ground' or low-lying states associated with the secondary well of the double-humped Strutinsky fission barrier) has involved charged particle excitation followed by multiple neutron evaporation, the final neutron evaporation having some small chance of leaving the residual nucleus in the secondary well shape (see Fig. 12). There is also a sizable body of work on excitation of such isomers by neutron capture at slow to moderate energies, and we have been engaged in analysing such data to determine the Strutinsky barrier parameters.

The neutron capture process for excitation of shape isomers is in some respects more complicated than the multiple neutron evaporation process. It is indicated schematically in Fig. 13; the essential point is that 'shape transitions' from either the normally deformed class-I region to the highly deformed class-II region or vice versa can occur at points a long way down the gamma-ray cascade chains and at the same time branching towards prompt fission decay across the outer barrier B can occur in the class-II gamma-ray cascade. The energy region around the top of the intermediate barrier A is particularly important for such transitions in determining the ultimate yield of delayed fission from the shape isomer. In this energy region the calculation of 'shape transition' rates is complicated by the occurrence of nearly discrete states on both sides of barrier A.

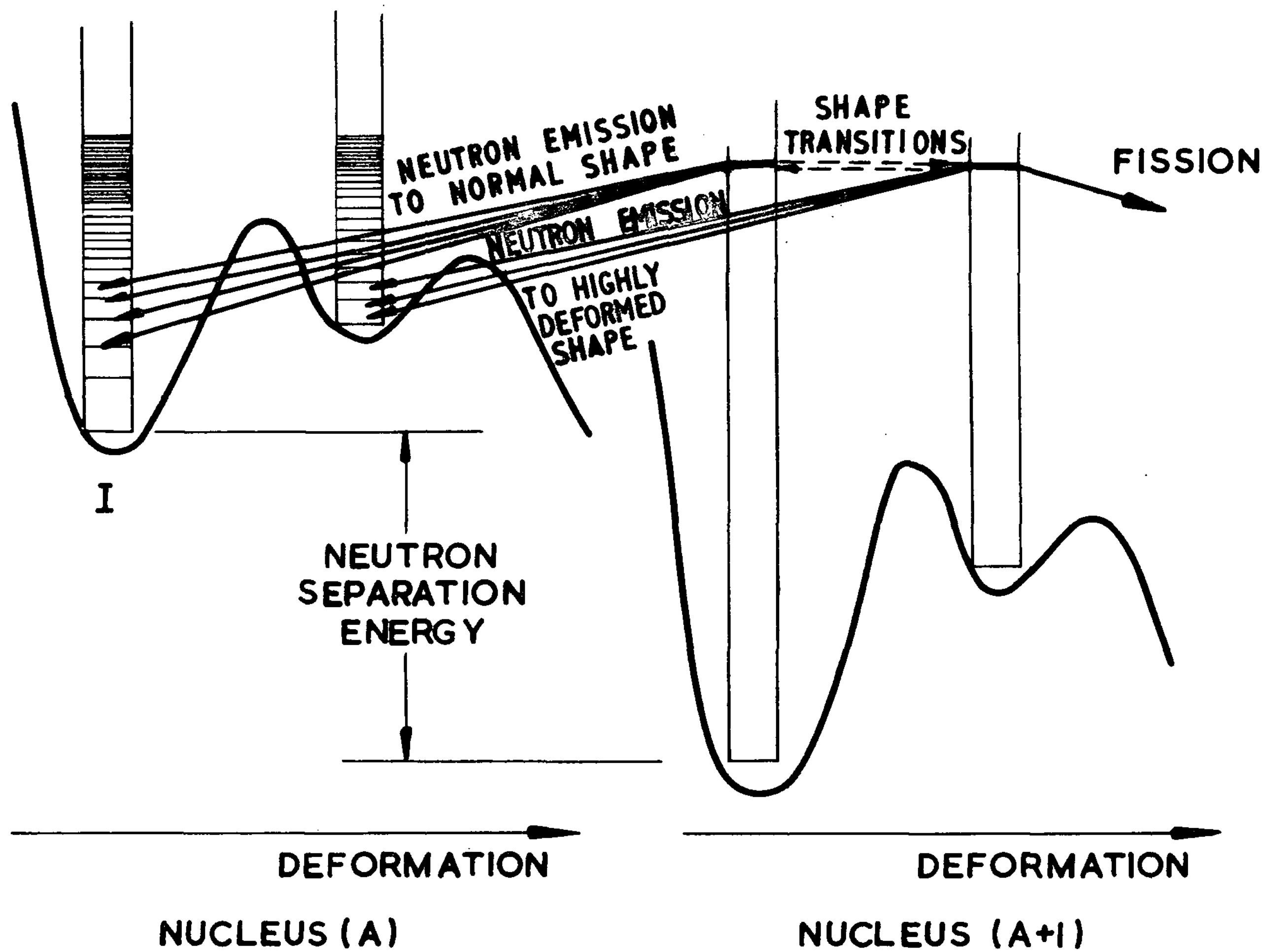

Fig. 12 Statistical decay of nucleus excited far above the double-humped fission barrier

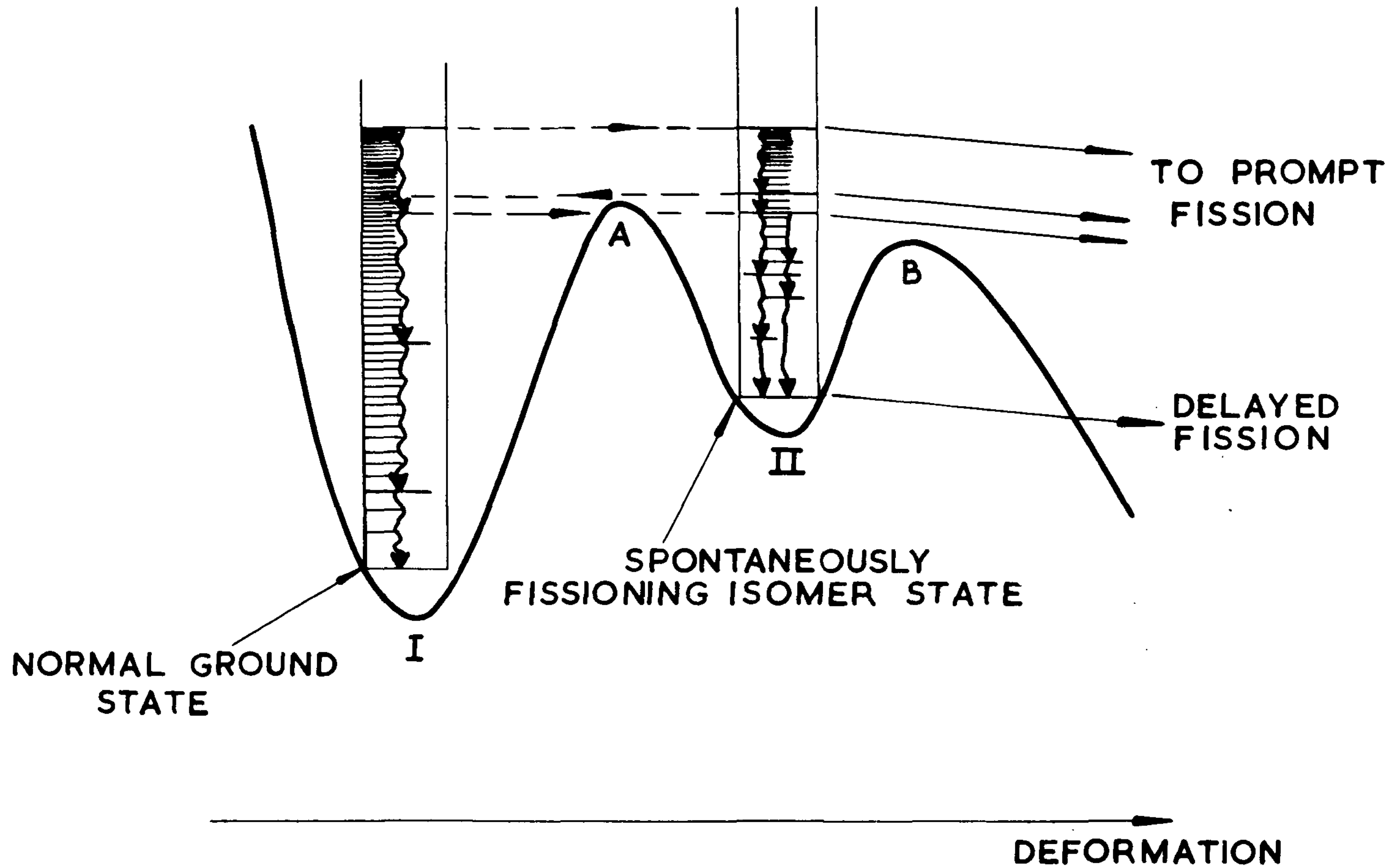

Fig. 13 Decay of nucleus of moderate excitation through γ-ray and fission processes

A computer programme has been written to calculate the delayed fission production rate in such a process. It has been used so far to analyse data on the reactions $^{241}Am(n,\gamma)^{242m}Am$ (spon. fiss.) and $^{243}Am(n,\gamma)^{244m}Am$ (spon. fiss.). The results indicate that for ^{242}Am the intermediate barrier A, known to be 6.4 MeV above the ground state from the cross-section of the (n,f) reaction, is 1.2 MeV higher than the outer barrier B, while for ^{244}Am, with barrier A at 6.5 MeV, the barrier difference is just over 1 MeV. These results are in qualitative agreement with deductions from neutron evaporation measurements, but we are not satisfied with the level density behaviours we have assumed at low excitation energies for the calculations, and we have embarked on a programme to improve these by a study of the behaviour of neutron-induced fission cross-sections.

This work has a strong bearing on the evaluation of the cross-sections of higher transuranic nuclei for the fast reactor programme.

H. Structure in the fast fission cross-section of ^{234}U (G.D. James, A. Langsford and Miss A. Khatoon)

The fission cross-section of ^{234}U over the energy range 180 keV to 6 MeV has been measured by neutron time-of-flight at the synchrocyclotron. In the existing data on this cross-section[(1)] a "break" is apparent at about 320 keV, and in recent years it has been assumed that this is due to a vibrational resonance in the secondary well of a double-humped fission barrier. The present measurements have been made with much higher energy resolution, and it is apparent that not only does the peak (at 318 keV) associated with the vibrational level exist, but there is also intermediate structure on a much narrower scale within this peak. It is believed that the narrow intermediate structure in this region is due to class-II levels, (the compound nucleus states associated with the nucleus in its strongly distorted shape at the secondary well) clear evidence for which has previously been found at much lower energies.[(2,3)] The experimental energy resolution is comparable with the expected class-II level spacing and this precludes a direct analysis of the data. However, the results have been analysed by computer simulation and yield barrier parameters which are comparable with those derived from analysis of the low energy data.

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(1) Lamphere R.W. Nuc. Phys. 38, 561 (1962); Physics and Chemistry of Fission I (IAEA, Vienna, 1965) 63.

(2) James G.D. and Rae E.R. Nuc. Phys. A118, 313 (1968).

(3) James G.D. and Slaughter G.G. Nuc. Phys. A139, 471 (1969).

The time-of-flight measurements were carried out using three Si-Au surface barrier detectors to detect the fission fragments from three foils of 98.82% ^{234}U. A fourth detector was used to monitor the neutron spectrum by detecting fragments from 92.9% ^{235}U. The flight path length was 16.83 m and the synchrocyclotron produces pulses of neutrons of 6 ns duration at a repetition frequency of 800 pps from a circulating proton beam of 140 MeV energy and 4.5 μA current. Neutrons were detected in a direction at 180^o to the direction of the proton beam. The timing channel width was 3.64 ns and the data were analysed into a number of counts per timing channel and recorded on magnetic tape separately for each detector by a DDP-516 computer. The results obtained over the energy range 180 keV to 6 MeV averaged over five and over fifty timing channels are shown in Fig. 14. The data have been normalised over the energy range 1.003 MeV to 1.3 MeV to the results of Lamphere[(1)] ($\Sigma\sigma_f dE$ = 374.7 b eV) which are shown for comparison by the solid line in Fig. 14. Data for each timing channel over the energy range 262 keV to 400 keV are presented in Fig. 15, together with Lamphere's data.

In Fig. 15 the triangular points, defining line A, represent average values over twenty timing channels. This line provides a poor representation of the single channel data as shown by the value of χ^2 = 203.0, for the 123 data points lying between 250 keV and 375 keV, which gives a probability of less than 0.00003% that the data are from a population by line A. Line B, sketched through the data, gives χ^2 = 105.8 for the same 123 points indicating that the data can be derived from a population represented by this line with a probability of 24%. It is clear therefore that the data near 318 keV show structure, the properties of which we represent by the following properties of curve B: Average height of the structure resonances, $\langle H \rangle = 0.072 \pm 0.005$ b, average width $\langle W \rangle = 6.8 \pm 0.8$ keV and average spacing $\langle D \rangle = 12.5 \pm 2.1$ keV.

In order to decide whether these parameters are consistent with the low energy data, the fission cross-section over the energy range 250 keV to 400 keV has been simulated by Monte Carlo techniques using the following equations which describe a vibrational level damped into compound class II levels which in turn are coupled to class I levels.

$$\Gamma_{vib(f)} = D_{vib}/\{2\pi[1 + \exp(2\pi(V_B - E_{II})/\hbar\omega_B)]\} \qquad (1)$$

$$\Gamma_{II(f)} = D_{II}\, W\, \Gamma_{vib(f)} / \{2\pi[(E_{II}-E_{vib})^2 + \tfrac{1}{4}(W + \Gamma_{vib(f)})^2]\} \qquad (2)$$

$$\Gamma_{II(c)} = D_{II} / \{2\pi[1 + \exp(2\pi(V_A - E_{II})/\hbar w_A)]\} \qquad (3)$$

$$\Gamma_{I(f)} = D_I\, \Gamma_{II(c)}\, \Gamma_{II(f)} / \{2\pi[(E_{II}-E_I)^2 + \tfrac{1}{4}\Gamma_{II}{}^2{}_{(c)}]\} \qquad (4)$$

$$\langle\sigma_f\rangle = \sum_J 2\pi^2 \lambda\!\!\!^{-2} g_J \langle \Gamma_{nJ}\, \Gamma_{I(f)} / D_I{}^J (\Gamma_{nJ} + \Gamma_\gamma + \Gamma_{I(f)} + \Sigma\, \Gamma_{n'J}) \rangle_{Average} \qquad (5)$$

In these equations V_A, V_B, $\hbar w_A$ and $\hbar w_B$ are the heights (above the neutron binding energy) and frequencies of inverted parabolic potentials representing the intermediate and outer barriers, E_{vib}, $\Gamma_{vib(f)}$ and D_{vib} are the resonance energy, fission width and level spacing of the vibrational level, E_{II}, $\Gamma_{II(f)}$ and D_{II} represent the energy fission width and level spacing of class II levels, W is the damping width of class II levels into the vibrational levels, E_I, $\Gamma_{I(f)}$ and $D_I{}^J$ represent the energy, fission width and level spacing of class I levels, $\Gamma_{II(c)}$ is a coupling width between class I and class II levels, $\lambda\!\!\!^{-}$ is the neutron wave number, g_J is the spin weighting factor for total spin J, Γ_{nJ} and Γ_γ are the neutron width and capture width of class I resonances, $\Sigma\, \Gamma_{n'J}$ represents the sum of neutron inelastic scattering widths over channels that are open at 318 keV for a given spin state.

At 318 keV, the contribution of the vibration level to the fission cross-section is estimated - by subtracting the background - to be 0.068 b. The intermediate barrier height V_A has a weaker effect on the fission cross-section than V_B and has been fixed at 460 keV as deduced from the value $\Gamma_{II(c)} = 57.5$ eV measured at low energy. Assumed values of 1000 keV and 800 keV are taken for $\hbar w_A$ and $\hbar w_B$ in this analysis. For a value of W = 46.6 keV deduced from the width of observed vibration level, $D_{vib} = 800$ keV, $D_{II} = 3$ keV derived from the value of 7 keV observed at low energy[(3)] and $D_I = 6.3$ eV derived from the low energy level spacing, it is found that $V_B = 892$ keV gives the correct average fission cross-section at 318 keV. This gives an average class II fission width at 638 eV of 0.062 eV ($\Gamma_{II(f)}{}^{1/2} = 0.25 \pm 0.176$). The value measured by James and Slaughter, $\Gamma_{II(f)} = 0.3$ eV lies at 1.7 standard deviations from and is therefore consistent with the average value deduced here. The parameters of the structure in the fission cross-section over the energy range 250 keV to 400 keV obtained by simulation with $V_B = 892$ and $V_A = 460$ keV are given in Table 1 which shows that they agree with the experimental values.

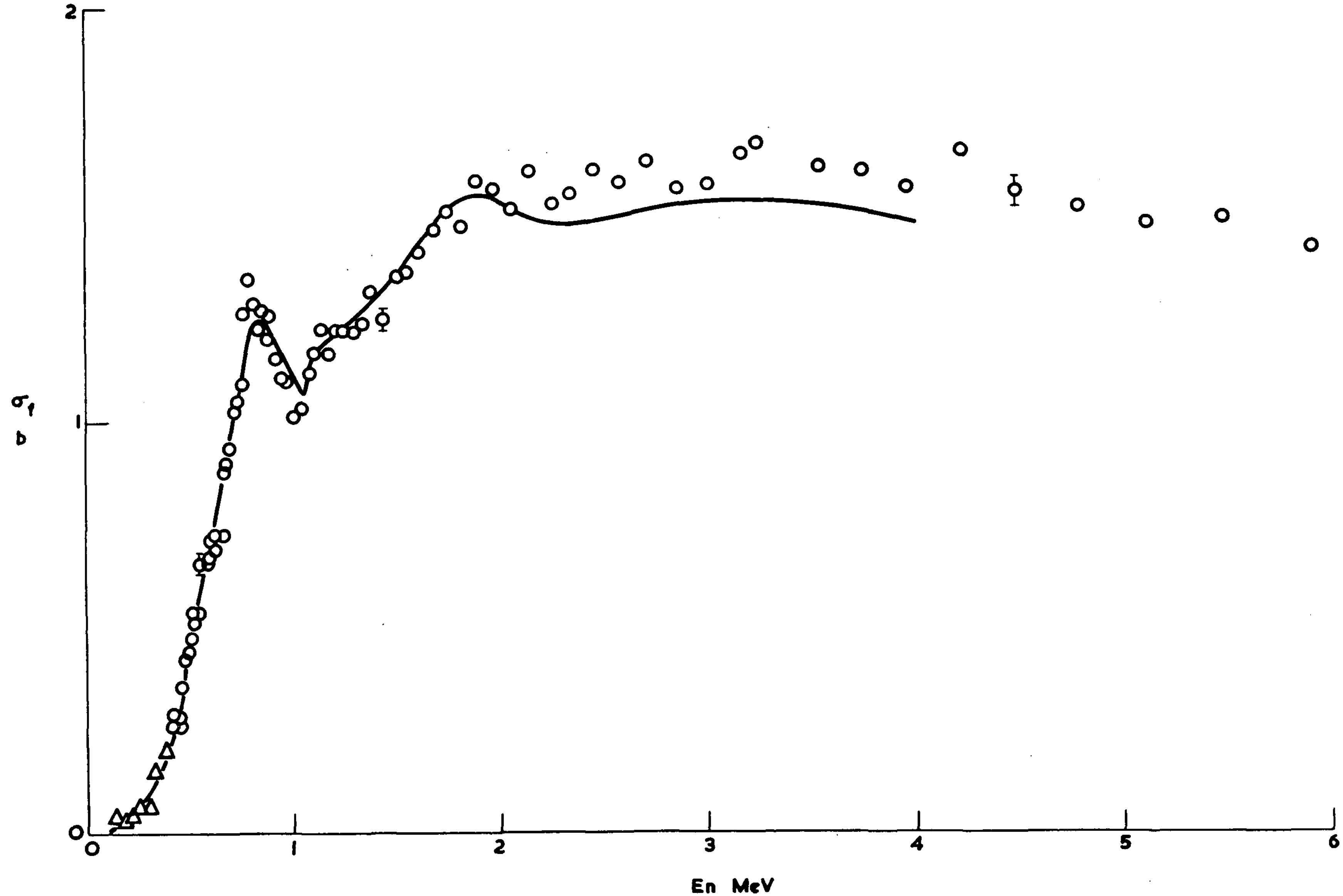

Fig. 14 The fission cross-section of ^{234}U over the energy range 180 keV to 6 MeV. The circles indicate average values over groups of five timing channels and the triangles indicate average values over groups of fifty timing channels.

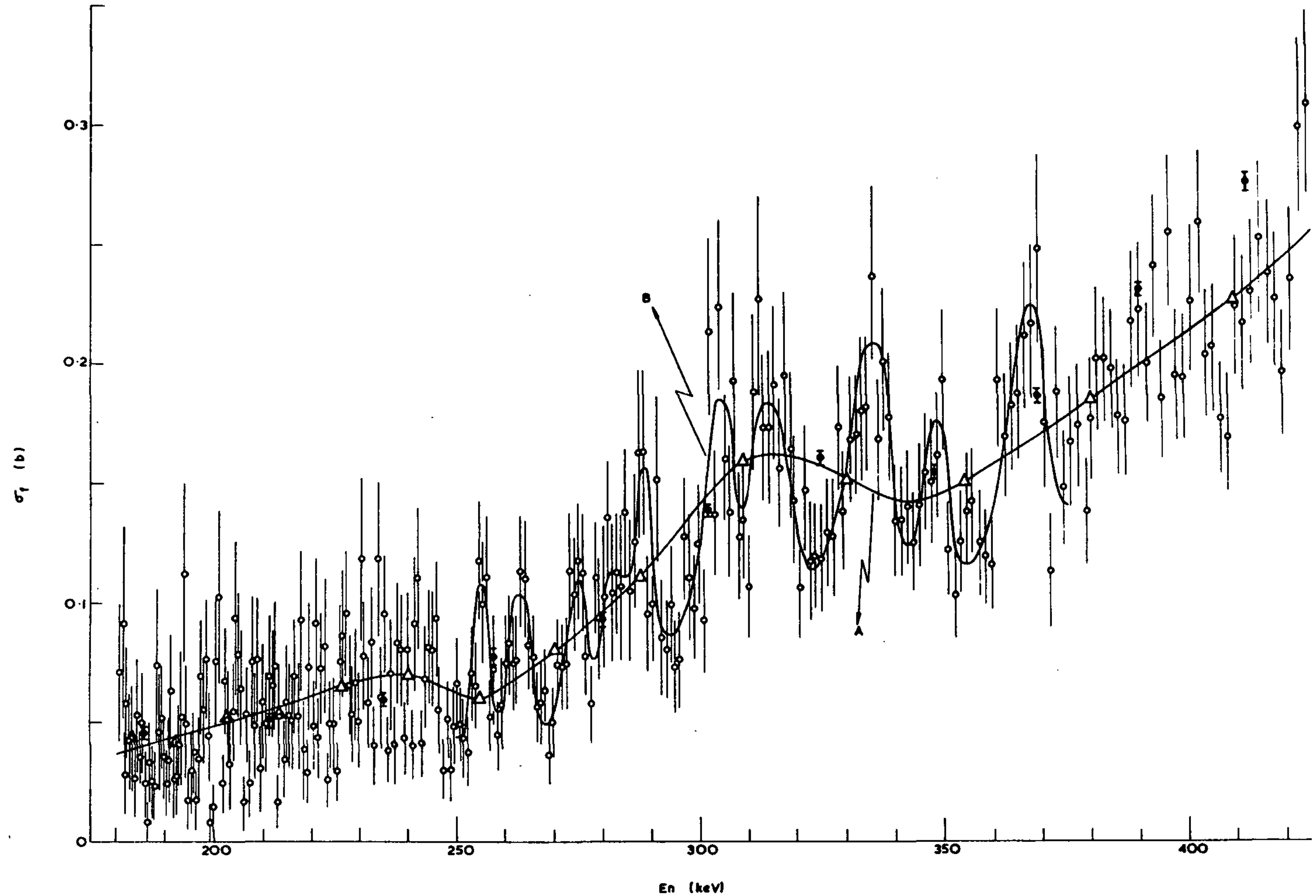

Fig. 15 The fission cross-section of ^{234}U over the energy range 262 keV to 400 keV shown by circles. The triangles represent average values over twenty timing channels. Line A, drawn through the triangular points is a poor fit to the data whereas line B, indicating intermediate structure, represents the data at a 24% significance level. Solid circles show Lamphere's data, which have an energy spread of ~25 keV.

Table 1

Experimental and simulated structure parameters for ^{234}U near 318 keV

	Experimental Values	Simulated Values
Average structure height <H>	0.072±0.005b	0.060±0.008b
Average structure width <W>	6.8 ±0.8 keV	5.6 ±0.5 keV
Average structure spacing <D>	12.5 ±2.1 keV	11.1 ±0.9 keV

This work can be summarised thus: The data of Fig. 2 show conclusive evidence for structure in the fission cross-section near a vibrational resonance at 318 keV. The fission potential barrier parameters of V_A = 460 keV (deduced from a low energy measurement) and V_B = 892 keV (deduced from the average fission cross-section due to the vibrational resonance at 318 keV, as well as low energy parameters) give an average value of the low energy class II fission width and average properties of the structure at 318 keV which are in agreement with experimental observations.

E. Neutron transmission measurements on Ba separated isotopes using the electron linac small sample facility

The following paper has been published:

Nuclear Physics A177 (1971) 393-400;

Neutron Resonances in Barium Isotopes

R.E. Van De Vyver and N.J. Pattenden

Abstract

The neutron transmissions of enriched samples of ^{134}Ba, ^{135}Ba, ^{136}Ba and ^{137}Ba have been measured for energies from 4 to about 2000 eV. Observed resonances have been assigned to particular isotopes and neutron widths have been determined by area analysis. A comparison with recently published data is made.

E. Angular distributions of fragments from aligned fissioning nuclei

1. The following paper has been published:

Nuclear Physics A167 (1971) 225-246

Fission of Aligned ^{235}U Nuclei Induced by Neutrons of 0.2 to 2000 eV

N.J. Pattenden and H. Postma (Kamerlingh Onnes Laboratorium, Leiden, Netherlands)

Abstract

The anisotropy of fragments from the neutron-induced fission of aligned ^{235}U has been measured as a function of neutron energy from 0.2 to 2000 eV. The nuclei were aligned in single crystals of rubidium uranyl nitrate, cooled to about 0.1 K. The anisotropy was found to show a rather small variation over the observed resonances and in the unresolved region, indicating that for the open transition states at the barrier K = 0 and 1 and that some states with K = 2 are partially open.

2. The following papers have been submitted to Nuclear Physics for publication:

Fission of Aligned ^{233}U Nuclei by Neutrons from 0.4 to 2000 eV

R. Kuiken
(Kamerlingh Onnes Laboratorium, Leiden, the Netherlands)

N.J. Pattenden
H. Postma
(Natuurkundig Laboratorium, Rijks-Universiteit Groningen, the Netherlands)

Abstract

The anisotropy in the angular distribution of fission fragments from neutron-induced fission of aligned ^{233}U has been measured as a function of neutron energy from 0.4 to 2000 eV. The ^{233}U nuclei were aligned in thin layers of monocrystalline rubidium uranyl nitrate, effectively cooled to about 0.3 K. The variation in the anisotropy over the resonances in the energy region from 0.4 to 60 eV and also over the unresolved region from 60 to 2000 eV was found to be rather small. Comparing the experimental distribution of anisotropy values with theoretical distributions showed, that for the J=3 resonances channels with K=3 are not open; K being the projection of the compound spin J on the deformation axis. Channels with $(J^{\pi};K) = (2^{+};2)$ are at most partially open. Several channels must be assumed to be open in order to explain the experimental distribution.

A slight systematic variation observed in the anisotropy values averaged over 100 eV intervals may indicate the presence of intermediate structure.

Subthreshold Neutron-Induced Fission of Aligned ^{237}Np Nuclei

R. Kuiken
(Kamerlingh Onnes Laboratorium, Leiden, the Netherlands)

N.J. Pattenden
H. Postma
(Natuurkundig Laboratorium, Rijks-Universtiteit Groningen, the Netherlands)

Abstract

The anisotropy in the angular distribution of fission fragments from neutron-induced fission of aligned ^{237}Np has been measured as a function of neutron energy from 0.4 to about 2000 eV. The ^{237}Np nuclei were aligned in thin layers of monocrystalline rubidium neptunyl nitrate, cooled to about 0.1 K. The interpretation of the group structure in the subthreshold fission cross section of ^{237}Np by Strutinsky's double-humped deformation barrier implies that the spins of all resonances in one group are equal. The anisotropy values for the individual resonances in the first group around 40 eV agree with the fission channel $(J^{\pi};K)=(2^{+};2)$, where K is the projection of spin J on the symmetry axis of the compound nucleus. Some resonance groups at higher energies, which could not be resolved into individual resonances, have also been studied, but the information is still rather inconclusive.

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JAMES G.D. Fission yield from freshly prepared ^{241}Pu. J. Nuc. Energy 26, 99 (1972).

GAYTHER D.B. The Electron. Physics Education 6, 6, 406 (1971).

BRITT H.C., BURNETT S.C., ERKKILA B.H., LYNN J.E. and STEIN W.E. Systematics of spontaneously fissioning isomers. Phys. Rev. C, 4, 1444 (1971).

JAMES G.D. Application of distribution-free statistics to the structural analysis of slow neutron cross-section and resonance parameter data. Nuc. Phys. A170, 309 (1971).

Van De Vyver R.E. and Pattenden N.J. Neutron Resonances in Barium Isotopes. Nuc. Phys. A177, 393 (1971).

REPORTS

AERE - R 6901 Nuclear spectroscopy of highly deformed Th-231.
J.E. Lynn, G.D. James and L.G. Earwaker.

AERE - M 2497 The simultaneous evaluation of the fission cross-sections of U-235, Pu-239 and U-238 and the capture cross-section of U-238 in the energy range 100 eV to 20 MeV.
M.G. Sowerby, B.H. Patrick and D.S. Mather.

AERE - M 2505 Nuclear structure associated with the fission barrier.
J.E. Lynn.

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CONTRIBUTED

THOMAS B.W. Investigation of the capture gamma-ray spectra for individual resonances in the Tm-169(n,γ) reaction. Presented at the International Conference on Statistical Properties of Nuclei, Albany, New York, August 1971.

WINHOLD E.J., BOWEY E.M., PATRICK B.H. and REID J.M. Photodisintegration of ^{13}C leading to excited states of ^{12}C and ^{12}B. Meeting of the American Physical Society, Cambridge, Massachusetts, December 1971.

INVITED

LYNN J.E. Nuclear Structure associated with the fission barrier. Third International Symposium on Trans-plutonium elements, Argonne, October 1971.

IN COURSE OF PUBLICATION

LYNN, J.E., JAMES G.D. and EARWAKER L.G. Nuclear spectroscopy of highly deformed Th-231. Nuc. Phys.

ANALYTICAL SCIENCES DIVISION, A. E. R. E.

(Division Head: Dr. A.A. Smales)

Measurement of the cross-section of the reaction ^{147}Pm(n,γ)^{148m}Pm for reactor neutrons (D. Gibbons, J.W. McMillan and M. Wilkins)

Measurements of the cross-section for the reaction ^{147}Pm(n,γ)^{148m}Pm for reactor neutrons are in hand and as a necessary first step an accurate value of the half-life of ^{148m}Pm is being obtained.

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CABELL M.J. and WILKINS M. The absolute determination of ^{148g}Pm by γ-ray spectrometry and a measurement of the emission probability of its 1.465 MeV γ-ray. J. Inorg. Nucl. Chem. 33, 1957 (1971).

CABELL M.J. and WILKINS M. The thermal neutron capture cross-section of ^{233}U. J. Inorg. Nucl. Chem. 33, 3972 (1971).

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CABELL M.J. and WILKINS M. The capture and absorption cross-sections of ^{232}U for thermal neutrons. Int. Conf. on Chemical Nuclear Data, Canterbury, P.161 (1971).

CABELL M.J. Some half-life measurements by mass and gamma-ray spectrometry. Int. Conf. on Chemical Nuclear Data, Canterbury, P.189 (1971).

CHEMISTRY DIVISION, A. E. R. E.

(Division Head: Dr. W. Wild)

For administrative reasons this section of the report covers the period Mid-1970 - March 1972.

Fission yields measured in a low power run of the Dounreay Fast Reactor (DFR) (J.G. Cuninghame, Mrs. J.A.B. Goodall and H.H. Willis)

An absolute measurement of about 40 fast fission yields in DFR has been performed[(1)]. The very low yield for ^{99}Mo in ^{235}U fission found by Bowles and Willis[(2)] is confirmed by these measurements. The value, which is about 10% lower than the previously accepted one, is of vital importance since ^{99}Mo is the most frequently used reference nuclide to which other relative fission yields are referred.

(1) Cuninghame J.G., Goodall Mrs. J.A.B. and Willis H.H. Unpublished.

(2) Unpublished work at AERE (1968).

The fast fission yield of ^{99}Mo (J.G. Cuninghame, Mrs. J.A.B. Goodall and H.H. Willis)

In view of the low value of the ^{99}Mo yield measured in DFR for ^{235}U (see above) and its vital importance as a reference standard, an experiment has been started to measure it using monoenergetic neutrons. The neutrons are being obtained from IBIS using various reactions such as $^{7}Li(p,n)$. The yields are being measured for both ^{235}U and ^{239}Pu over the energy range 100 keV to 2 MeV and fission track detectors are being used to measure the neutron flux.

Fast reactor fission yields by mass spectrometry (E.A.C. Crouch, I.C. McKean and M. Brownsword)

Fast reactor fission yields are being measured by mass spectrometry using samples irradiated in DFR. The UO_2 samples irradiated in DFR core (pitch 10) have now been chemically separated and mass-analysis is proceeding. Irradiated UO_2 samples from the vicinity of the DFR blanket (pitch 38) have also been chemically separated and the components await mass-analysis. Samples from a position inside the blanket (pitch 42) await separation and analysis. The difficulties experienced in extracting the capsules of the core irradiation have not been encountered with samples from irradiations near and in the blanket.

Mass-analysis of UO_2 used in these experiments using the two isotope spike method shows an overall accuracy of 3 parts in 800 ($1\ \sigma$) for one analysis, in estimation of the ^{235}U content. It seems therefore that the absolute error in the fission-product yields will in fact be less than 5%.

Fission yield assessments by objective methods (E.A.C. Crouch)

A library of all known neutron induced fission product yields, which can be updated as new information comes to hand, has been established on magnetic tape.

A program, which searches the library for specific information, has also been written and is running. It will print out a complete copy of the library, all the references to fission products of a given reaction, all the references to a list of individual fission products of a given reaction, all absolutely determined yields of a given reaction, or combinations of these options.

A further program has been written but not debugged, which takes the output of the library search program and fits to it the best two-humped mass-yield curve, taking account of the neutron emission from fission fragments, but assuming a distribution of neutron emission from fragments of a given mass as no theoretical or experimental values are available. This is the first approach to the problem of objective assessment of fission-product yields.

Estimation of the $^{35}Cl(n,p)^{35}S$ fast neutron cross-section (J.G. Cuninghame, Mrs. J.A.B. Goodall and H.H. Willis)

The value of the $^{35}Cl(n,p)^{35}S$ cross-section in a DFR type spectrum has been measured using a tailored neutron spectrum obtained from the Harwell neutron booster and linac. The cross-section, which was measured relative to the ^{235}U fission cross-section by activation techniques, was found to be 46 ± 9 mb.

Design of a low energy neutron source for the V.E.C. (S.J. Boot, J.G. Cuninghame, J.A. Dennis and H.H. Willis)

A neutron source has been constructed for the Harwell Variable Energy Cyclotron which provides a neutron spectrum very similar to that of the DFR core centre. The fast neutron flux produced by a proton current of 20 μa at 53 MeV is $\sim 2 \times 10^9$ n/cm^2/sec which is sufficient for the performance of on-line fission fragment experiments.

DIODE - A computer programme for the evaluation of gamma spectra (R.J. Bullock and N.R. Large)

A computer programme (DIODE), which analyses the pulse height spectrum produced by γ-rays incident on Ge(Li) detectors, has been written and documented[(1)]. This programme is widely used in the U.K. and has been improved by the addition of a sub-routine which enables data to be read from a magnetic tape written by the Intertechnique DIDAC analyser. The changes to the programme are documented and issued as supplements to the original report.

(1) Bullock R.J. and Large N.R. AERE - R 6748 (1971), Supplement 1 (1971).

Measurement of Coulomb distortion by heavy ion scattering in the V.E.C. (J.G. Cuninghame and A.M. Friedman of Argonne National Laboratory)

The experiment to study the distortion of heavy target nuclei bombarded by heavy ions has been completed. The distortion is caused by the interaction of the target and projectile Coulomb fields and some calculations made before the experiments commenced suggested that the Coulomb barrier might be raised as much as 30% by the distortion. By studying the elastic scattering of the projectiles the radius for strong absorption in the reactions of ^{12}C, ^{16}O and ^{20}Ne ions with ^{144}Nd, ^{146}Nd, ^{148}Nd, ^{152}Sm, ^{154}Sm, ^{206}Pb and ^{209}Bi targets have been measured. The results, which are being prepared for publication in "Nuclear Physics", show that the Coulomb effects are quite small and that all radii can be described by a radius parameter, R_o, of between 1.35 and 1.46f. These results are in accord with the latest theoretical calculations.

Fission measurements (J.G. Cuninghame and Mrs. J.A.B. Goodall)

Earlier work in this project[1] studied the effect of change in angular momentum and excitation energy of the fissioning nucleus $^{210}Po^*$ on fission transition state parameters such as fragment kinetic energy and mass distributions. The current work is seeking to extend this from the practically non fissile $^{210}Po^*$ to $^{238}Pu^*$ and $^{239}Pu^*$ and thereby to learn more about the fundamental fission characteristics of a nucleus of importance to the reactor programme. The compound nuclei are being produced using the following reactions on the Harwell Variable Energy Cyclotron.

$$^{237}Np + {}^{1}H \rightarrow {}^{238}Pu^*$$
$$^{235}U + {}^{3}He \rightarrow {}^{238}Pu^*$$
$$^{234}U + {}^{4}He \rightarrow {}^{238}Pu^*$$

$$^{236}U + {}^{3}He \rightarrow {}^{239}Pu^*$$
$$^{235}U + {}^{4}He \rightarrow {}^{239}Pu^*$$

The experiments carried out so far have shown that the experiments are feasible though more difficult than the Po* experiment.

(1) Unik J.P., Cuninghame J.G. and Croall I.F. Physics and Chemistry of Fission, IAEA Vienna (1969) 717.

Rapid separation of tellurium from fission products (M.H. Hurdus and L. Tomlinson)

It is theoretically expected that tellurium fission products of short half-life will be delayed neutron precursors.

Investigations of a rapid technique of tellurium separation based on isotopic exchange with H_2Te gas have continued. A method of storing and metering the highly unstable H_2Te has been developed and has led to reproducible experiments with improved yields. Decontamination tests have shown no contamination from I, Br, Sb, Ge or Sn. However, contamination from selenium and arsenic has been found. Some success has been achieved in reducing the serious arsenic contamination and attempts are being made to reduce the levels even further. The best results obtained to date are: a yield of 20% Te in 10 seconds with 0.11% Se and 1.7% As contamination. The method will be tested out on a mixture of fission products in the near future.

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AERE - R 6596 Theory of delayed neutron physics.
L. Tomlinson.

AERE - R 6626 Preliminary experiments with an evaporation neutron source on the Variable Energy Cyclotron designed to simulate fast reactor spectra.
S.J. Boot, J.G. Cuninghame, J.A. Dennis and H.H. Willis.

AERE - R 6642 A library of neutron induced fission product yields maintained and interrogated by computer methods.
E.A.C. Crouch.

AERE - R 6748 DIODE. A computer programme for the comprehensive evaluation of gamma spectra.
R.J. Bullock and N.R. Large.

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Tomlinson L. Theory of delayed neutron physics. Trans. Am. Nucl. Soc. 13, 707 (1970).

Tomlinson L. and Hurdus M.H. Delayed neutron emission from selenium isotopes: identification of ^{89}Se. Proc. Conf. on Properties of Nuclei far from the Region of Beta-stability (Leysin). Report No. CERN 70-30, Vol. 1, 519 (1970).

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International Conference on Chemical Nuclear Data, Canterbury, 20-22 September 1971

Crouch, E.A.C. The assessment of fission yields (Proc. Page 1).

Cuninghame J.G. Fission yields in accelerator neutron spectra (Proc. Page 39).

Crouch, E.A.C. The determination of the capture to fission ratio and the fission product yields of materials irradiated in the Dounreay Fast Reactor (Proc. Page 147).

Tomlinson L. Fission delayed neutrons: a review (Proc. Page 239).

NUCLEAR RESEARCH DIVISION, A. W. R. E.

(Chief of Nuclear Research: Dr. H.R. Hulme)

During the period of this report, work has continued, in the Nuclear Research Division, along three main lines of work in the field of neutron data. These are:

(i) Measurement and analysis of experimental data on neutron induced reactions.

(ii) Evaluation of neutron data.

(iii) Production and maintenance of computer codes connected with the evaluation project.

I. MEASUREMENT AND ANALYSIS OF EXPERIMENTAL DATA

1. Neutron Scattering (R.E. Coles)

The analysis of neutron scattering data obtained using the 6 MV Van de Graaff generator has been continued. For natural chromium and niobium, the analysis has been completed and reports have been published giving detailed results. The abstracts of these reports are as follows:

(i) Natural Chromium AWRE Report O 41/71

"The AWRE 6 MV Van de Graaff accelerator has been used to study $(n,n'\gamma)$ reactions in natural chromium for incident neutrons in the energy range 0.55 to 3.85 MeV. Lithium-drifted germanium spectrometers were used to detect de-excitation γ-rays following inelastic scattering from samples in ring geometry. In all, twelve transitions were observed and relative differential cross sections, at a mean angle of 100^{o}, are presented as a function of incident neutron energy, together with improved values of γ-ray and level energies."

(ii) Niobium AWRE Report O 66/71 (EANDC(UK)137AL)

"The time-of-flight method has been used to study fast neutron elastic and inelastic scattering by niobium in the energy range 1.0 to 5.0 MeV. Differential cross sections were measured at ten angles from 30^{o} to 135^{o}, at 0.5 MeV intervals between 1.5 and 5.0 MeV incident neutron energy, for elastic scattering, inelastic scattering to levels up to 2590 keV excitation in the target nucleus and inelastic scattering to a continuum above 2950 keV excitation.

Excitation functions were derived from 125^{o} yields measured at 0.2 MeV intervals between 1.0 and 3.0 MeV incident neutron energy for inelastic scattering. The continuum spectra for incident neutron energies between 3.5 and 5.0 MeV have been analysed in terms of statistical evaporation theory and parameters describing the secondary energy distributions of the continuum scattered neutrons extracted.

No attempt has been made to compare the data in this report with theoretical predictions. However, comparisons are made with other published data where appropriate.

This work was originated as a result of a request for improved data, in the energy range we cover, for use in fast reactor design."

These publications complete the work on neutron scattering.

2. (n,2n) Measurements (D.S. Mather, G. James, P.J. Nind and R.E. Coles)

Measurements of the (n,2n) cross section using the large liquid scintillator have been continued. Data have been obtained at 12.4 MeV for ^{45}Sc, ^{89}Y, ^{93}Nb, Mo (natural), ^{103}Rh, ^{169}Tm, ^{197}Au, Pb, ^{235}U and ^{238}U.

In addition, further measurements have been made on the fissile isotopes ^{235}U, ^{238}U and ^{239}Pu and data have been obtained at 6.1, 6.5, 7.0 and 8.0 MeV. For ^{239}Pu only, a further measurement was made at 13 MeV.

The analysis of the data is in progress.

3. Neutron Cross Section Measurements using Neutrons from Nuclear Explosions (A. Moat)

The analysis of the data on the neutron induced fission cross section for ^{238}Pu, obtained using neutrons from the underground nuclear explosion Persimmon has been completed. A report[1] with the following abstract has been published giving details of the results.

> "The neutron induced fission cross section of ^{238}Pu has been measured from 17 eV to 2 MeV using neutrons in a collimated beam from the underground nuclear explosion Persimmon. A thin deposit of ^{238}Pu was located in the beam, together with flux and background monitors. Their reaction rates were recorded as functions of time and used to determine the ^{238}Pu fission cross section as a function of energy. Data presented here were determined from fission fragments emitted at 90^{o} to the neutron beam."

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(1) Moat A. AWRE O 13/72.

A more complete presentation of the data on ^{238}Pu fission from Persimmon, written in collaboration with M.G. Silbert of LASL is in preparation.

A start has been made on the analysis of the data on the fission cross section of ^{241}Pu obtained on the 1968 USA Physics Shot.

The modifications to the film disc assessor have been completed and the system is working satisfactorily. In addition to the original polar co-ordinate facility, an optional cartesian stage is now available. Trace digitising is accomplished simply by 'driving' the datum point along the trace using a steering wheel and a speed control pedal.

II. EVALUATION OF NEUTRON DATA

1. Fission Cross Section Evaluation (D.S. Mather)

Recent experimental data have been incorporated in the simultaneous evaluation resulting in recommended values slightly different from these entered in the data files. A draft version of a report describing all this evaluation work has been completed. A brief note, (AERE - M 2497), gives a much shorter description of the work to provide the recommended numbers entered in the data files.

2. Revision of Files in the UK Nuclear Data Library (A.C. Douglas)

A number of corrections and amendments were made to the data files recently produced for ^{235}U and ^{238}U.

The fast neutron capture cross section in the new ^{235}U data file has been revised in the range 25 keV to 1 MeV so that the capture-to-fission ratio α is the same as in the earlier files. The revised file is labelled DFN-271D.

In the new ^{238}U file, the secondary neutron energy distribution for inelastic scattering to the continuum has been revised. The revised file is labelled DFN-272A.

The new files for ^{235}U, ^{238}U and ^{239}Pu are briefly described in the Nuclear Research Note NRN 4/72.

3. Evaluation of the (n,α) Cross Section for Natural Cr, Fe, Ni and Mo (A.C. Douglas and K. Wyld)

An evaluation has been made of the (n,α) cross sections for natural Cr, Fe, Ni and Mo. Experimental data are very scarce usually being restricted to values at 14 MeV for particular isotopes. The recommended cross sections are chosen basically from systematics and nuclear theory but are adjusted to be consistent with recent measurements of Freeman et al at AWRE[(1)] of the fission-spectrum-averaged cross section.

For Cr and Fe, the cross sections appearing in earlier files do not differ significantly from the present evaluation, but for Ni, the earlier evaluations give cross sections that are much too small and the effective threshold should be much lower at about 2 MeV.

For Mo, where the cross section is small, there appears to be no earlier evaluation.

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(1) Freeman N.J., Barry J.F. and Campbell N.L., J. Nucl. En. 23 713 (1969).

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4. Evaluation of the Elastic and Inelastic Scattering Cross Sections by Natural Molybdenum (A.C. Douglas and K. Wyld)

A start has been made on a survey of the available experimental data on elastic and inelastic scattering cross sections for natural molybdenum.

5. Conversion of ENDF/B II Files using MISSIONARY (J. Cameron and A.C. Douglas)

An early version of the MISSIONARY programme was used to convert the ENDF/B files for Fe and Ni (MAT-1124 and 1123) into the UK Nuclear Data Library Format. Special modifications were needed for Ni, to add the (n,n'p) data which had been omitted from MAT-1123 and to add the (n,α) cross section recommended by the evaluation mentioned above.

Because of difficulties encountered in the conversion of the Fe and Ni files, a series of conversions on shorter data files was undertaken to gain experience in using the programme and to help find errors and omissions in the programme. The materials converted were chosen to fill gaps in the UK Nuclear Data Library or else to replace very old files.

After making a number of corrections and amendments to MISSIONARY, the main difficulties remaining were:-

(i) Errors in the original ENDF/B files. These were generally dealt with by altering the ENDF/B file before conversion.

(ii) Errors caused by the need for interpolation between energy points in the ENDF/B file. This often led to partial cross sections which, when summed, differed from the total cross section by an unacceptable amount. This was dealt with after conversion by a judicious change of one or more of the cross sections.

(iii) Because of the completely different approaches taken by the two libraries in representing secondary energy distributions, an exact translation is not possible. It has been found best, in many instances, to return to the original evaluation and produce the secondary energy distributions in the UK format directly

It is found that each conversion presents its own particular problems, so that each file produced by MISSIONARY requires some assessment and modification before being used in applications.

The files that have been converted in this exercise are listed in the Table below:

MATERIAL	ENDF/B II MAT	UKNDL DFN	MATERIAL	ENDF/B II MAT	UKNDL DFN
V	1017	952	Am^{241}	1056	956
U^{234}	1043	953	Am^{243}	1057	957
U^{236}	1046	954	Cm^{244}	1058	958
Pu^{242}	1055	955	Pu^{238}	1050	964

III. PRODUCTION AND MAINTENANCE OF COMPUTER CODES

1. The SCORE Programme (J. Cameron)

An improved version of SCORE, with semi-automatic resonance parameter fitting has been received from Atomics International and implemented at AWRE. Some modifications for AWRE use were added.

2. The MISSIONARY Programme (J. Cameron)

MISSIONARY is a programme to convert data files in the ENDF/B Format to the UK Nuclear Data Library Format. It has been tested by being used to convert several materials. A number of errors, omissions and inadequacies were made good. A description of the programme and how it is used, is in preparation.

3. The CHECK 1 Programme (A.C. Douglas)

CHECK is a programme for checking the self-consistency of neutron cross section data in the UK Nuclear Data Library Format. It has been converted to FORTRAN IV for running on the IBM 360/370. At the same time a number of corrections were made and the opportunity was taken to bring it up to date with the present Library Format.

4. The GROD Programme (A.C. Douglas)

The programme GROD produces a graphical representation of data in the UK Nuclear Data Library. It has been converted to FORTRAN IV for running on the IBM 360/370. The programme has been split up into a number of sub-routines and some sections essentially re-written. In particular secondary energy distributions are now treated much more completely. At the same time a number of errors have been corrected.

PUBLICATIONS

COLES R.E. $(n,n'\gamma)$ Reactions in Natural Chromium. AWRE O 41/71.

COLES R.E. Elastic and Inelastic Scattering of Neutrons in the Energy Range 1.0 and 5.0 MeV in Natural Niobium. AWRE O 66/71 (EANDC(UK)137AL).

MARINOV A., BATTY C.J., KILVINGTON A.I., WEIL J.L., FRIEDMAN A.M., NEWTON G.W.A., ROBINSON V.J., HERRINGWAY J.D., MATHER D.S. Spontaneous Fission Previously Observed in a Mercury Source. Nature 234, No. 5326, 212 November 1971.

MOAT A. Fission Cross Section of Pu-238 from Persimmon. AWRE O 13/72.

SOWERBY M.G., PATRICK B.H., MATHER D.S. The Simultaneous Evaluation of the Fission Cross Sections of U-235, Pu-239 and U-238 and the Capture Cross Section of U-238 in the Energy Range 100 eV to 20 MeV. AERE - M 2497 (1972) (EANDC(UK)138AL).

DOUGLAS A.C. New Data Files for ^{235}U, ^{238}U and ^{239}Pu Prepared at AWRE during 1971. AWRE Nuclear Research Note NRN 4/72.

NATIONAL PHYSICAL LABORATORY

DIVISION OF RADIATION SCIENCE

(Superintendent: Dr. P.J. Campion)

A collimated vanadium bath system for the relative measurement of keV neutron flux (J.C. Robertson, T.B. Ryves and J.B. Hunt)

A collimated vanadium sulphate bath system has been used to measure the relative neutron flux in the keV energy region. The variation in the detection efficiency of the system with neutron energy has been studied by Monte Carlo methods and in particular the effective "neck" size of the collimator and its position relative to the neutron source have been calculated as a function of neutron energy and compared with experimental measurements. The system has been used to measure the relative 0^{o} yield from the ^{7}Li(p,n)^{7}Be reaction and a comparison of the results with measurements made with a long counter demonstrate that the long counter response is independent of neutron energy in the range 150-600 keV. The development of these detectors is important for the accurate measurement of neutron flux. A paper on this work is being prepared for publication.

The long counter as a secondary standard for neutron flux density (J.B. Hunt and J.C. Robertson)

A De Pangher type long counter has been adopted as the secondary standard for neutron dosimetry in the United Kingdom. This counter and an NPL type long counter have been calibrated and the vanadium bath system used to test their flatness of response in the keV energy range. Measurements have also been made of the variation of the counting centres of the counters with neutron energy. The results of this work are being prepared for publication.

The $^{238}U(n,\gamma)^{239}U$ and $^{115}In(n,\gamma)^{116}In(54m)$ cross sections in the keV energy range (T.B. Ryves, J.B. Hunt and J.C. Robertson)

The $^{238}U(n,\gamma)^{239}U$ cross-section has been measured relative to In (54^{m} activity) and the indium cross-section has been measured absolutely using a calibrated long counter to determine the neutron flux, at several energies between 160 and 620 keV. The final results are not yet available, because several small corrections are still required. Provisional results for ^{238}U are in close agreement with the starting values used in the minimisation procedure in the evaluation reported by Sowerby and Patrick[(1)].

The $^{56}Fe(n,p)^{56}Mn$ and $^{27}Al(n,\alpha)^{24}Na$ cross-sections at 14.78 MeV (J.C. Robertson, B. Audric and P. Kolkowski)

The $^{56}Fe(n,p)^{56}Mn$ and $^{27}Al(n,\alpha)^{24}Na$ cross-sections have been measured at the average energy of 14.78 MeV with an energy width of 200 keV. Aluminium and iron samples in the form of foils were irradiated in an accurately known neutron flux and the resulting ^{56}Mn and ^{24}Na activities determined using absolute $4\pi\beta$-γ counting techniques. The flux was determined using a recoil proton monitor to an accuracy of ±2.1%. The cross-section values given by Hopkins and Breit[(2)] for the n-p reaction in hydrogen were used in the flux calculation. The values obtained were 109.8±2.9mb and 115.5±3mb where the errors have been obtained by adding the systematic error in determining the neutron flux linearly to the random error calculated at the 99% confidence level in determining the ^{56}Mn and ^{24}Na activities.

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(1) Sowerby M.G. and Patrick B.H. Nuclear Data for Reactors II, 703, IAEA Vienna (1970).

(2) Hopkins J.C. and Breit G. Nuclear Data Tables A9, 137 (1971).

Some neutron activation cross-sections at 14.78 MeV (J.C. Robertson, B. Audric and P. Kolkowski)

Several neutron activation cross-sections have been measured at 14.78 MeV relative to the $^{56}Fe(n,p)^{56}Mn$ cross-section. The samples were in the form of thin foils and the activities produced after irradiation were determined using absolute $4\pi\beta$-γ coincidence counting techniques. The value of the $^{56}Fe(n,p)^{56}Mn$ cross-section used as standard was 109.8±2.9mb. The results have been compared with those of other authors and it has been found that by considering the ratio of individual cross-sections it is possible to determine whether a single measurement of a cross-section is likely to be in error or not. The following values are obtained where the error given is the error at the 99% confidence level in the ratio of the cross-section to the iron standard cross-section but does not include the systematic errors in determining the $^{56}Fe(n,p)^{56}Mn$ value. The results expressed in mb are:-

$^{14}N(n,2n)^{13}N$	7.45±0.4	$^{27}Al(n,\alpha)^{24}Na$	115.5±0.6	$^{24}Mg(n,p)^{24}Na$	179.7±0.8
$^{32}S(n,p)^{32}P$	219±1	$^{19}F(n,2n)^{18}F$	47.9±0.5	$^{30}Si(n,\alpha)^{27}Mg$	90±10
$^{27}Al(n,p)^{27}Mg$	68±1.5	$^{51}V(n,p)^{51}Ti$	31±0.9	$^{65}Cn(n,2n)^{64}Cu$	1043±10
$^{34}S(n,\alpha)^{31}Si$	194±1.4	$^{28}Si(n,p)^{28}Al$	265±3.2	$^{65}Cu(n,p)^{65}Ni$	26±0.5
$^{160}Gd(n,2n)^{159}Gd$	1456±10	$^{51}V(n,\alpha)^{48}Sc$	19.5±0.9	$^{29}Si(n,p)^{29}Al$	131±13
$^{198}Pt(n,2n)^{197}Pt$(total)	2091±60	$^{59}Co(n,\alpha)^{56}Mn$	32.3±1	$^{31}P(n,p)^{31}Si$	85.6±1.6

The use of associated particle counting to measure 14 MeV neutron flux (J.C. Robertson and G. Jackson)

Preliminary results obtained using an associated particle system with charged particle detectors at 3 angles indicate that there are problems involved in the scattering of the alpha particles in the tritium target which could distort a flux measurement relying on the alpha particle counting.

Measurement of $\bar{\nu}$ for ^{252}Cf (E.J. Axton, A.G. Bardell and B.N. Audric)

Measurements on a newer sample of ^{252}Cf give a provisional value of 3.72 n/f, about 0.8% higher than the value obtained in 1969 with an old sample. The difference is in part due to small changes in manganese bath correction factors but it may also be partly due to refinements in fission counting technique since the early measurements. It is necessary to repeat the measurements on the old sample before it can be established with certainty whether or not there is a difference between old and new samples. The old sample was sent to Geel as part of a fission counting comparison between the two laboratories. No progress has been made to date in the fission counting comparison. It is now planned that the comparison should take place at the conclusion of the NPL measurements on this project.

PUBLICATIONS AND CONFERENCE PAPERS

PUBLICATIONS

ROBERTSON J.C. and ZIEBA K.J. The (n,α) and (n,p) reactions in silicon and the (n,p) reaction in aluminium at energies up to 5.6 MeV. J. Nucl. En. 26, 1 (1972).

RYVES T.B. and ROBERTSON J.C. The $^{197}Au(n,\gamma)^{198}Au$ cross-section at 22.8 keV. J. Nucl. En. 25, 557 (1971).

CONFERENCE PAPER

RYVES T.B. Thermal neutron capture cross-section measurements at the NPL. Proc. of Int. Conf. on Chemical Nuclear Data, Canterbury P.139 (1971).