UNCLASSIFIED

UKNDC(72)P.36
EANDC(UK)139AL
INDC(UK)-14G

514

U.K. NUCLEAR DATA PROGRESS REPORT

MID 1970 – MID 1971

Editor M. G. Sowerby

Nuclear Physics Division,
UKAEA Research Group,
AERE,
Harwell.

June, 1972

HL 72/2352

PREFACE

This document is prepared at the request of the U.K. Nuclear Data Committee. It brings together progress reports on nuclear reactor data from AERE, AWRE and NPL. A CINDA type index is included at the front of the document.

CONTENTS

ELE-MENT S	ELE-MENT A	QUANTITY	TYPE	ENERGY MIN.	ENERGY MAX.	DOCUMENTATION REF	DOCUMENTATION VOL	DOCUMENTATION PAGE	DOCUMENTATION DATE	LAB	COMMENTS
LI	6	N, ALPHA	EXPT–PROG	1.5 3	5.0 5	UKNDC	P36	14	6/72	HAR	COATES+ LINAC TOF REL BLACK DET GRPH
LI	6	N, ALPHA	EXTH–PROG	2.5-2	5.0 5	UKNDC	P36	16	6/72	HAR	UTTLEY ANG DIST CALC CFD EXPT GRPH
LI	6	DIFF ELASTIC	EXTH–PROG	2.5-2	5.0 5	UKNDC	P36	16	6/72	HAR	UTTLEY ANG DIST CALC CFD EXPT GRPH
LI	6	N, ALPHA	REVW–PROG	2.5-2	1.7 6	UKNDC	P36	16	6/72	HAR	UTTLEY+ SEE 71 KNOX 551
LI	6	ELASTIC	REVW–PROG	2.5-2	1.7 6	UKNDC	P36	16	6/72	HAR	UTTLEY+ SEE 71 KNOX 551
B	10	N, ALPHA	EXPT–PROG	1.0 3	2.2 5	UKNDC	P36	14	6/72	HAR	COATES+ LINAC TOF REL BLACK DET GRPH
C		TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF NDG
C		EVALUATION	EVAL–PROG	1.0 0	1.5 7	UKNDC	P36	37	6/72	ALD	DOUGLAS+ EVALUATION FOR UKNDL
NA	23	DIFF ELASTIC	EXPT–PROG	5.0 6		UKNDC	P36	36	6/72	ALD	COLES+ SEE AWRE REPORT O 3/71
NA	23	DIFF INELAST	EXPT–PROG	5.0 6		UKNDC	P36	36	6/72	ALD	COLES+ SEE AWRE REPORT O 3/71
AL	27	N, PROTON	EXPT–PROG		5.6 6	UKNDC	P36	40	6/72	NPL	ROBERTSON+ SEE J NUCL EN 26 1 1972
SI		N, PROTON	EXPT–PROG		5.6 6	UKNDC	P36	40	6/72	NPL	ROBERTSON+ SEE J NUCL EN 26 1 1972
SI		N, ALPHA	EXPT–PROG		5.6 6	UKNDC	P36	40	6/72	NPL	ROBERTSON+ SEE J NUCL EN 26 1 1972
FE		N, GAMMA	EVAL–PROG	1.0 3	1.0 6	UKNDC	P36	12	6/72	HAR	MOXON EVALUATION FOR UKNDL
FE		TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF NDG
FE		TOTAL XSECT	EXPT–PROG		1.0 6	UKNDC	P36	2	6/72	HAR	BLAIR+ CYCLOTRON TOF HIGH RESOL TBD
NI		TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF GRPH
NI		TOTAL XSECT	EXPT–PROG		1.0 6	UKNDC	P36	2	6/72	HAR	BLAIR+ CYCLOTRON TOF HIGH RESOL TBD
NI		N, GAMMA	EVAL–PROG	2.5-2	2.0 5	UKNDC	P36	12	6/72	HAR	MOXON EVALUATION FOR UKNDL GRPH TBP
NI		RESON PARAMS	EVAL–PROG		2.0 5	UKNDC	P36	12	6/72	HAR	MOXON EVALUATION FOR UKNDL
NI		TOTAL XSECT	EVAL–PROG	2.5-2	2.0 5	UKNDC	P36	12	6/72	HAR	MOXON EVALUATION FOR UKNDL
NI		N, GAMMA	EXPT–PROG		1.0 5	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF M-R NDG
NI	58	TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF NDG
NI	58	N, GAMMA	EXPT–PROG		1.0 5	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF M-R NDG
NI	58	RESON PARAMS	EXPT–PROG	1.5 4		UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF WG<1.7EV
NI	62	RESON PARAMS	EXPT–PROG	4.6 3		UKNDC	P36	4	6/72	HAR	AXMANN+ WG=2.5EV WN=2.075EV
Nb	93	N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
Mo		N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
Mo		DIFF ELASTIC	EXPT–PROG	1.0 6	5.0 6	UKNDC	P36	36	6/72	ALD	COLES+ SEE AWRE REPORT O 89/70
Mo		DIFF INELAST	EXPT–PROG	1.0 6	5.0 6	UKNDC	P36	36	6/72	ALD	COLES+ SEE AWRE REPORT O 89/70
RH	103	N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
CS	133	RESON PARAMS	EXPT–PROG	5.9 0	3.6 2	UKNDC	P36	23	6/72	HAR	THOMAS+ J ASSIGNED FROM CAPT GS TBL
CS	133	SPECT NGAMMA	EXPT–PROG		3.6 2	UKNDC	P36	23	6/72	HAR	THOMAS+ LINAC TOF LOW EN GS TO GET J

ELEMENT S	ELEMENT A	QUANTITY	TYPE	ENERGY MIN.	ENERGY MAX.	DOCUMENTATION REF	DOCUMENTATION VOL	DOCUMENTATION PAGE	DOCUMENTATION DATE	LAB	COMMENTS
PM	147	N, GAMMA	EXPT–PROG	PILE		UKNDC	P36	35	6/72	HAR	CABELL SEE JIN 32 3433 (1970)
PM	147	RES INT ABS	EXPT–PROG	PILE		UKNDC	P36	35	6/72	HAR	CABELL SEE JIN 32 3433 (1970)
ER	166	TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF NDG
ER	167	N, GAMMA	EXPT–PROG		1.0 5	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF M-R GRPH
ER	167	TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF GRPH
ER	167	SPECT NGAMMA	EXPT–PROG		1.4 2	UKNDC	P36	23	6/72	HAR	THOMAS+ LINAC TOF LOW EN GS TO GET J
ER	167	RESON PARAMS	EXPT–PROG	2.0 1	1.4 2	UKNDC	P36	23	6/72	HAR	THOMAS+ J ASSIGNED FROM CAPT GS TBL
ER	170	TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF NDG
TM	169	N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
TM	169	TOTAL XSECT	EXPT–PROG	4.0 0	1.0 4	UKNDC	P36	4	6/72	HAR	AXMANN+ LINAC TOF NDG
TM	169	SPECT NGAMMA	EXPT–PROG		1.5 2	UKNDC	P36	23	6/72	HAR	THOMAS+ LINAC TOF LOW EN GS TO GET J
TM	169	RESON PARAMS	EXPT–PROG	1.4 1	1.5 2	UKNDC	P36	23	6/72	HAR	THOMAS+ J ASSIGNED FROM CAPT GS TBL
TM	169	RESON PARAMS	EXPT–PROG	3.9 0	1.5 2	UKNDC	P36	23	6/72	HAR	THOMAS+ NO CORR WN AND PARTIAL WG
TA	181	SPECT NGAMMA	EXPT–PROG		1.0 2	UKNDC	P36	23	6/72	HAR	THOMAS+ LINAC TOF LOW EN GS TO GET J
TA	181	RESON PARAMS	EXPT–PROG	4.3 0	9.9 1	UKNDC	P36	23	6/72	HAR	THOMAS+ J ASSIGNED FROM CAPT GS TBL
AU	197	N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
AU	197	N, GAMMA	EXPT–PROG	2.3 4		UKNDC	P36	40	6/72	NPL	RYVES+ SEE J NUCL EN 25 577 (1971)
TH	230	FISSION	EXTH–PROG	6.8 5	1.4 6	UKNDC	P36	29	6/72	HAR	JAMES+ SEE AERE–R 6901
TH	230	FRAG SPECTRA	EXTH–PROG	7.0 5	9.5 5	UKNDC	P36	29	6/72	HAR	JAMES+ SEE AERE–R 6901
U	232	ABSORPTION	EXPT–PROG	PILE		UKNDC	P36	34	6/72	HAR	CABELL+ THR SIG 148.3+ –4.4B
U	232	N, GAMMA	EXPT–PROG	PILE		UKNDC	P36	34	6/72	HAR	CABELL+ THR SIG 73.1+ –1.5B
U	233	FRAG SPECTRA	EXPT–PROG		2.0 3	UKNDC	P36	28	6/72	HAR	PATTENDEN+ FRAG ANG DIST ALIGNED NUC
U	233	N, GAMMA	EXPT–PROG	PILE		UKNDC	P36	34	6/72	HAR	CABELL+ THR SIG 48.35+ –1.62B
U	234	N, GAMMA	EXPT–PROG	PILE		UKNDC	P36	34	6/72	HAR	CABELL+ SEE AERE–R 6529
U	235	FISSION	EVAL–PROG	1.0 2	2.0 7	UKNDC	P36	7	6/72	HAR	SOWERBY+ LINKED EVAL PU239 U238 GRPH
											SEE ALSO UKNDC P36 PAGE 38
U	235	FISSION	EXPT–PROG	1.0 3	1.0 6	UKNDC	P36	6	6/72	HAR	GAYTHER+ LINAC TOF NU*SIGF GRPH TBC
U	235	N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC
U	235	NU	EVAL–PROG	2.5-2	1.5 7	UKNDC	P36	38	6/72	ALD	MATHER+ SEE AWRE O 55/71
U	235	FRAG SPECTRA	EXPT–PROG	2.0-1	2.0 3	UKNDC	P36	28	6/72	HAR	PATTENDEN+ FRAG ANG DIST ALIGNED NUC
U	236	N, GAMMA	EXPT–PROG	PILE		UKNDC	P36	34	6/72	HAR	CABELL+ SEE AERE–R 6529
U	238	DIFF INELAST	EXPT–PROG	1.1 6	2.4 6	UKNDC	P36	3	6/72	HAR	ARMITAGE+ VDG TOF ACCURATE MEAS TBC
U	238	DIFF INELAST	EVAL–PROG	4.4 4	2.0 6	UKNDC	P36	37	6/72	ALD	DOUGLAS+ EVAL FOR UKNDL DFN 272
U	238	N2N XSECTION	EXPT–PROG	1.4 7		UKNDC	P36	36	6/72	ALD	MATHER+ ANALYSIS OF DATA TBC

ELE-MENT		QUANTITY	TYPE	ENERGY		DOCUMENTATION				LAB	COMMENTS
S	A			MIN.	MAX.	REF	VOL	PAGE	DATE		
U	238	FISSION	EVAL–PROG	6.0 5	2.0 7	UKNDC	P36	7	6/72	HAR	SOWERBY+ LINKED EVAL PU239 U235 SEE ALSO UKNDC P36 PAGE 38
U	238	N, GAMMA	EVAL–PROG	1.0 2	2.0 7	UKNDC	P36	7	6/72	HAR	SOWERBY+ LINKED EVAL PU239 U235
U	238	NU	EVAL–PROG	4.5 5	1.5 7	UKNDC	P36	38	6/72	ALD	MATHER+ SEE AWRE O 44/71
NP	237	FRAG SPECTRA	EXPT–PROG		2.0 3	UKNDC	P36	28	6/72	HAR	PATTENDEN+ FRAG ANG DIST ALIGNED NUC
PU	238	FISSION	EXPT–PROG			UKNDC	P36	37	6/72	ALD	MOAT ANALYSIS OF DATA CONTINUING
PU	239	DIFF INELAST	EVAL–PROG		1.5 6	UKNDC	P36	37	6/72	ALD	DOUGLAS+ EVAL FOR UKNDL DFN 269
PU	239	RESON PARAMS	EVAL–PROG	1.0 2	3.0 4	UKNDC	P36	10	6/72	HAR	SOWERBY+ AVG VALUES TO FIT SIGF+SIGG
PU	239	ALPHA	EVAL–PROG	1.0 2	1.5 7	UKNDC	P36	10	6/72	HAR	SOWERBY+ EVAL GRPH ERROR 12PV <30KEV
PU	239	FISSION	EVAL–PROG	1.0 2	2.0 7	UKNDC	P36	7	6/72	HAR	SOWERBY+ LINKED EVAL U235 U238
PU	239	NU	EVAL–PROG	2.5-2	1.5 7	UKNDC	P36	38	6/72	ALD	MATHER+ SEE AWRE O 86/70
PU	241	FISSION	EXPT–PROG	5.0-3	2.0 1	UKNDC	P36	20	6/72	HAR	JAMES+ SIGF SAME FOR OLD AND NEW 241

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)	E
50 MeV Proton Linac: S.R.C.	F
Variable Energy Cyclotron: Chemistry Division	G
Synchrocyclotron (A. E. Taylor)	H

E. Fast neutron spectra from spherical shells of reactor materials (J. G. Williams and A. J. H. Goddard (Imperial College) and H. Lichtblau (University of Birmingham)

Work on fast neutron spectra in spherical assemblies is continuing on the 45 MeV Linac. The experimental arrangement has been described earlier[1]. The results of vector flux measurements at the surface of natural uranium shells are shown in Figs. 1 and 2 in which θ refers to the angle between the radius vector at the surface of the spheres and the direction of the neutron flight path. The measurements were made with an angular resolution δ, $\Delta\theta$ of $\pm 7^{0}$, and a timing resolution of 2 ns per metre. The neutron spectra of the lead and uranium targets used as sources in these experiments were reported previously[2]. The data have been corrected for the small (less than 6%) effect of room return in the energy range 10 keV - 40 keV by means of S_n calculations.

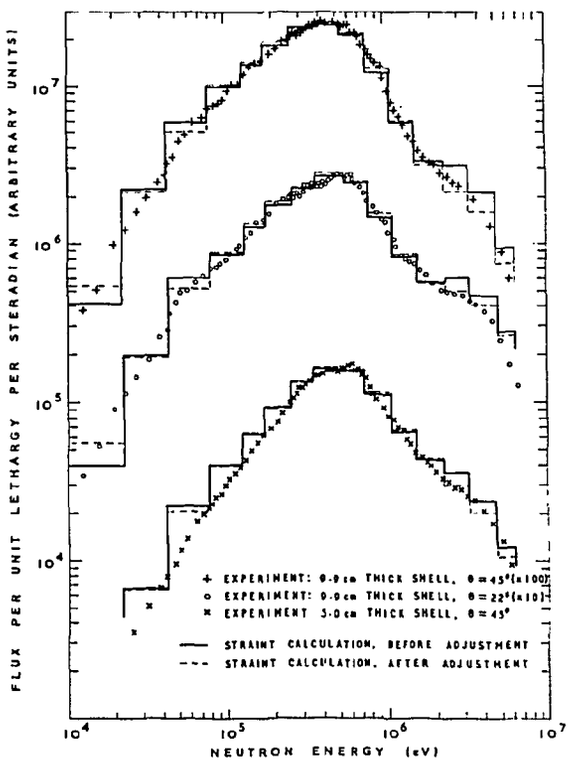

Fig. 1 Neutron spectra from natural uranium shells with a uranium target.

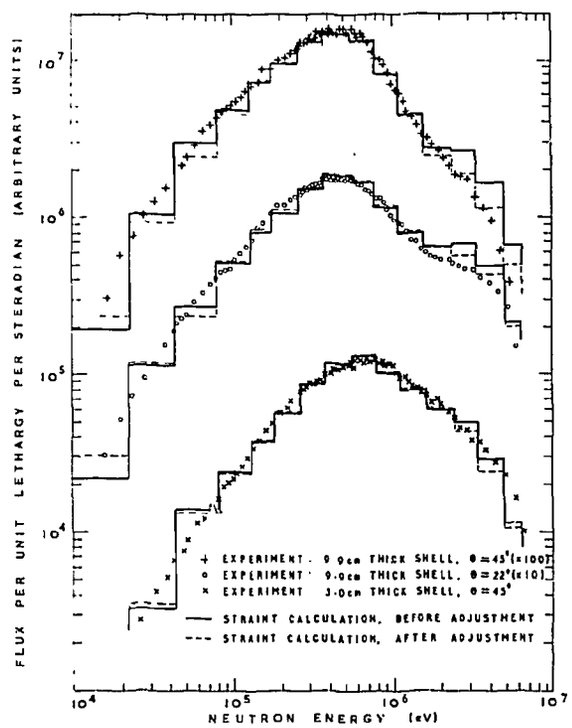

Fig. 2 Neutron spectra from natural uranium shells with a lead target.

Also shown in Figs. 1 and 2 are some results of a preliminary theoretical study by Pendlebury and West[3] of A.W.R.E. The 'before adjustment' spectrum was an S_8,P_5 STRAINT calculation using 32 group set 11 data with DFN 1041 for ^{235}U and DFN 1005 for ^{238}U. These data included adjustments to fit critical sizes. The 'after adjustment' calculation is the result of adjusting the nuclear data to minimise the discrepancies between the present experiments and the calculated spectra from the above data sets using the optimisation routine PEN1CUIK[5]. The assumed standard deviations of the experimental results were from 15-20% at the extremes of the energy range down to less than 6% over the range 100 keV - 1 MeV. Before adjustment, 52% of the calculated spectrum values were outside

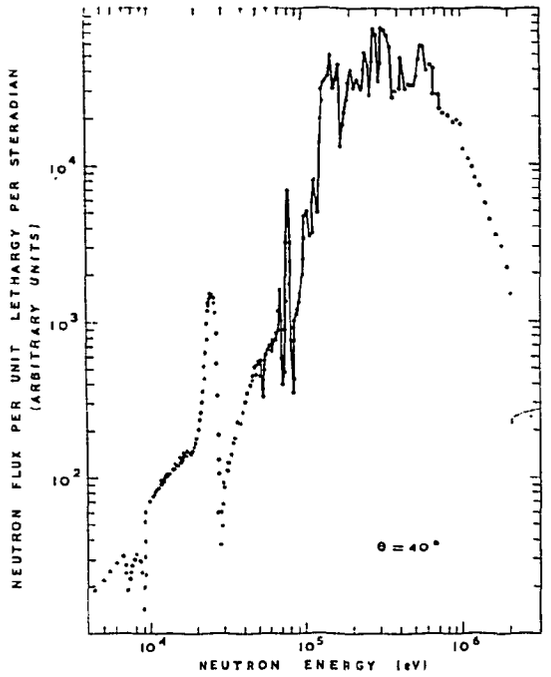

Fig. 3 Neutron spectrum from a 5.08 cm thick iron shell.

1 standard deviation and 21% outside 2 standard deviations, and this compares with 41% and 7% after adjustment. For an ideal fit, with no error attributable to nuclear data or calculational method, and if the variables were independent and normally distributed, the corresponding percentages would be 32% and 4.6%. The improved fit is obtained as a result of data adjustments of which the most significant appear to be an increase relative to DFN 1005 of the inelastic scattering to the continuum by 15% - 30% in the range 2.4 - 6.5 MeV, and a decrease in the capture cross section for ^{238}U of the order of 20% in the energy range 10 - 43 keV. These conclusions are subject to revision after further analysis.

Currently measurements are being made using spheres of mild steel with radii in the range 11.4 cm - 20.3 cm. Fig. 3 shows the spectrum of neutrons emerging at 40° to the radius vector from an 11.42 cm radius, 5.08 cm thick shell using a uranium target as neutron source.

(1) Goddard A. J. H., Williams J. G. and Lichtblau H. AERE - PR/NP 17, 1 (1970).

(2) Goddard A. J. H., Williams J. G. and Lichtblau H. AERE - PR/NP 16, 1 (1969).

(3) Pendlebury E. D. and West P. H. Private communication.

(4) Hemment Pamela C. E. and Pendlebury E. D. Proc. Int. Conf. on Fast Critical Experiments and their Analysis, Argonne, ANL-7320, P. 88 (1966).

(5) Pendlebury E. D. Proc. Conf. on Neutron Cross Sections and Technology, Washington, p. 1177 (1968).

H. Total cross section measurements using the transmission technique (I. M. Blair, P. H. Bowen, G. C. Cox and N. J. Pattenden)

The main outstanding priority 1 items in the United Kingdom Nuclear Data Request list which are included in RENDA[1] are for measurements of $\sigma_{n\gamma}$ in the energy range 100 eV to 1 MeV for various structural materials including Fe and Ni. In order to calculate $\sigma_{n\gamma}$ from direct capture yield measurements, it is necessary to have transmission measurements for these materials also. The initial program of nuclear data measurements on the Synchrocyclotron has been defined as transmission measurements on structural materials, starting with Fe and Ni, to help meet these requests. Preliminary data on Fe have been obtained.

(1) EANDC 85 "U".

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

Measurements of inelastic neutron scattering from natural uranium have been made using time-of-flight techniques at the following energies: 1129, 1250, 1368, 1620, 1870, 2120 and 2371 keV. The first four measurements were made with neutrons produced from Li targets varying in thickness between 20 and 35 keV, while the last four measurements were made with a ^{3}H gas cell maintained at a pressure of 0.5 atm. Data at 1620 keV was taken both with Li and ^{3}H targets.

Particular attention has been given to energy calibration since inconsistancies between energy level positions obtained by Coulomb excitation, inelastic neutron scattering and (n,n'γ) have been observed. The energy calibration has been made with a composite sample of Al and Li dimensionally similar to the U sample, which provides five reference points up to about 1.1 MeV excitation energy in ^{238}U when scattering measurements are made at 90°. When Li neutron producing targets are used additional calibration points may be obtained from neutrons associated with the second group of neutrons produced by the $^{7}Li(p,n)^{7}Be^{*}$ reaction.

The measurements are mainly being undertaken to provide accurate neutron inelastic scattering cross section data above 1.6 MeV. Above this energy the evaluated cross sections of Schmidt(1) rely almost entirely on the indirect method of subtracting the fission and radiative capture data from the non-elastic scattering data.

The scattering measurements are not yet complete but considerable progress has been made in data reduction.

---

(1) Schmidt J. J. Neutron cross sections for fast reactor materials. KFK120 (1966).

H. A search for a long lifetime isomeric state in ^{241}Pu and a new measurement of the half-life of ground state ^{241}Pu (C. Whitehead, A. C. Sherwood and B. Rose)

The gamma-ray activity of a number of freshly prepared ^{241}Pu sources has been followed for six months after a 21 day irradiation of ^{240}Pu in PLUTO at a flux of 2.10^{14} n/cm^{2}/sec. A thin-windowed Ge(Li) detector (made by ion implantation techniques) was used to follow the activity of the samples which had been subjected to differing clean-up processes.

In particular the build up of activity of ^{241}Am was followed using the well known 59.5 keV gamma-ray. Deviations from a linear increase with time of this activity would be expected if the decay component of 0.34 ± 0.11 years proposed by Nisle and Stepan(1) existed as well as the principal mode of decay of ^{241}Pu with ~ 15 year half-life.

In addition, the time dependence of two other (relatively weak) γ-rays was observed. A γ-ray of 147 keV, believed to be a transition in ^{237}U, and one of 209 keV, believed to be a transition between high levels in ^{237}Np, (both of which are fed by the weak α-branch of Pu^{241}) allowed independent assessments to be made of the admixture of an isomeric state in ^{241}Pu.

Within the uncertainties of the methods no deviations attributable to a ⅓ year half-life were observed. The following upper limits were deduced:

Energy of γ-ray	Isomeric state admixture
147 keV	< 6%
208 keV	< 3%
59.5 keV	< 1.5%

As a side product of this measurement the half-life of ^{241}Pu is obtainable relative to that of ^{241}Am. Taking the half-life of ^{241}Am as 434 years[2] the ^{241}Pu half-life is determined to be 14.91 ± 0.15 years which agrees well with that of Cabell[3] (15.16 ± 0.19 years).

More data are now available for analysis and may improve the quoted values.

---

(1) Nisle R. G. and Stepan I. E. Nuclear Science and Engineering 39, 257 (1970).

(2) Oetling and Gunn Journal of Inorganic and Nuclear Chemistry, 29, 2659 (1967).

(3) Cabell M. J. Journal of Inorganic and Nuclear Chemistry, 33, 903 (1971).

E. Neutron capture and total cross section measurements (H. P. Axmann (University of Vienna), D. A. J. Endacott, J. E. Jolly and M. C. Moxon)

(a) Capture

The capture detector at the 32 m station on the neutron booster target of the 45 MeV electron linac was used during the past year to carry out measurements on natural nickel, ^{58}Ni and additional runs on some of the erbium isotopes. Figure 1 shows the data for the 20 g sample of ^{167}Er as a function of time of flight. The peaks at 90, 35 and 6 keV are due to the aluminium can. There appears to be a modulation on the capture cross section with a period between 200 and 300 eV which is yet unexplained.

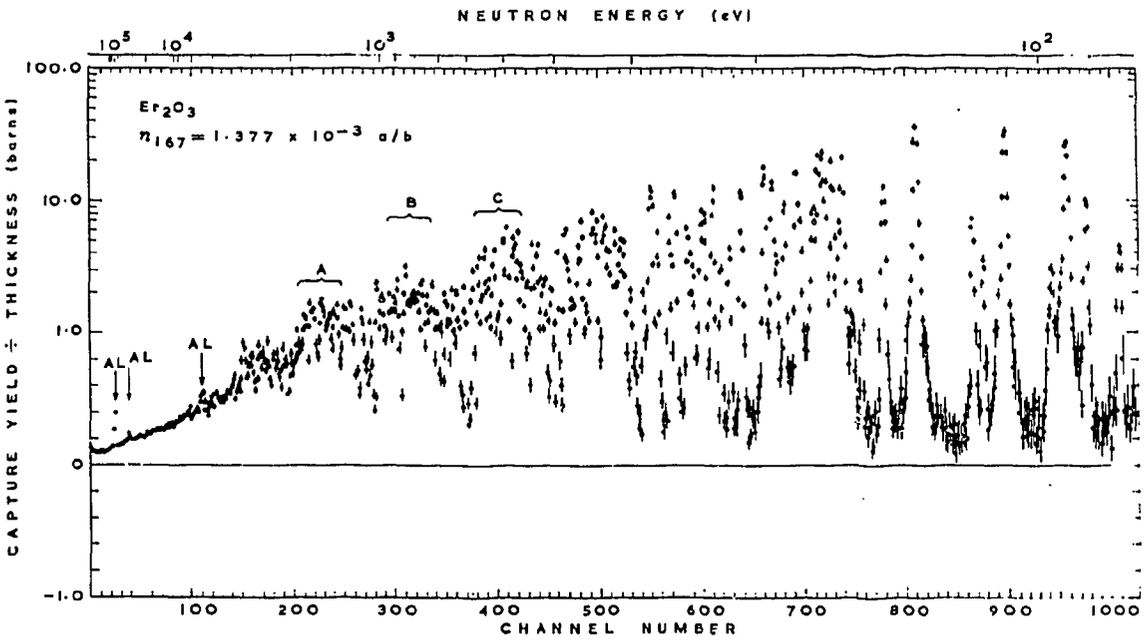

Fig. 1 Capture cross section of ^{167}Er as a function of time of flight.

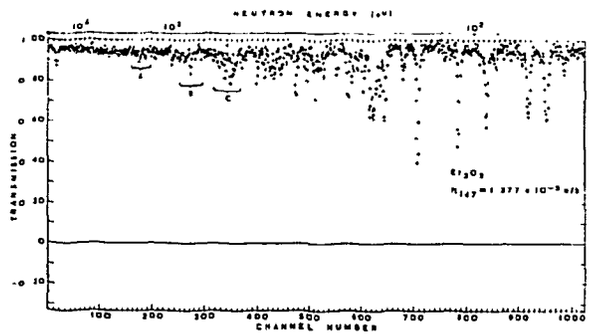

Fig. 2 The neutron transmission of a ^{167}Er sample with $n = 1.377 \times 10^{-3}$ a/b as a function of time of flight for $E_n > 65$ eV

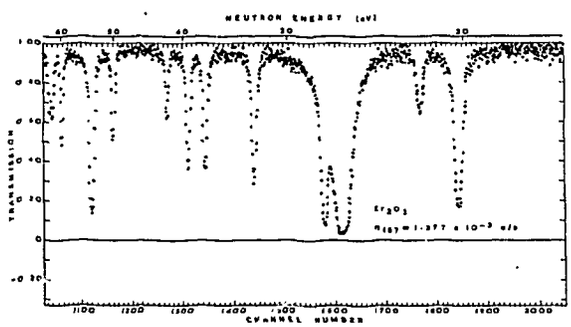

Fig. 3 As for Fig. 2 with $E_n < 65$ eV.

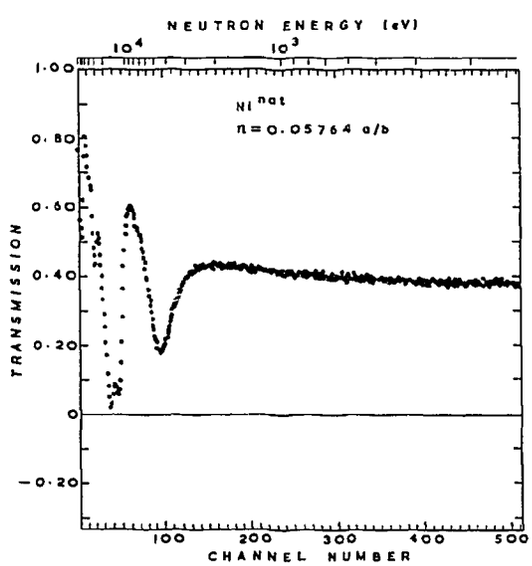

Fig. 4 The neutron transmission of a sample of natural nickel with $n = 5.76 \times 10^{-2}$ a/b as a function of time of flight.

The capture yields for ^{58}Ni and natural nickel were used in the evaluation work. An upper limit of 1.7 eV was obtained for the radiation width of the 15 keV s-wave resonance in ^{58}Ni and a value of 2.5 eV was obtained for the radiation width of the s-wave resonance at 4.6 keV in ^{62}Ni. This latter value is in agreement with the value of 2.3 eV obtained from the thermal data, but disagrees with a value of 0.76 eV quoted by Hockenbury et al at RPI(1). The increase in Γ_n, reported later in this section, may increase the RPI value for this radiation width.

(b) Total

The small sample facility at the 14 m station on the 'booster' target has been rebuilt during the past three months. A 4½ cm diameter, 1 cm thick Li glass scintillator is now used as a neutron detector. This gives an open beam count rate for a 0.8 cm diameter neutron beam of ~6 counts per machine cycle in 4096 timing channels of 1/8 μs with a 0.15 μs electron pulse, and ~60 counts per machine cycle in 4096 1 μs timing channels with a 0.5 μs electron pulse. The high count rate necessitates the use of the "on-line" data acquisition equipment developed by D. V. Morris and reported elsewhere in this progress report.

Total cross section measurements have been carried out on samples of natural nickel, ^{58}Ni, Fe, C, $^{166,167,170}Er$ and Tm. Transmission measurements have also been carried out on the 9 mm thick Li glass and ^{10}B oxide sample used in spectrum and absorption cross section measurements carried out by M. S. Coates et al.

Preliminary transmission data on the ^{167}Er sample are shown in Figs. 2 and 3. Possible modulations of the transmission curve are observed at the same energies as were seen in the capture data and corresponding groups are marked A, B and C.

Figure 4 shows the data on natural nickel; the resonance at 4.6 keV is in ^{62}Ni and a preliminary shape analysis gives $E_R = 4.569$ keV and $\Gamma_n = 2.075$ keV which is larger than the previously reported value of 1.3 keV(2).

(1) Hockenbury R. W., Bartolome Z. M., Tatarczuk J. R., Moyer W. R. and Block R. C. Phys. Rev. 178, 1746 (1969).

(2) Pawlicki G. W., Smith E. C. and Thurlow P. E. F. ORNL 1620, 42 (1953).

E. Measurement of the ^{235}U fission cross section in the energy range from 1 keV to 1 MeV (D. B. Gayther and D. A. Boyce)

Recent evaluations of the cross sections of fundamental significance for fast reactor design reveal serious discrepancies between the existing measurements[1,2,3]. Particularly important are the discrepancies in the $^{235}U(n,f)$ data above the resonance region, since this cross section is often used as a standard relative to which the cross sections of other reactions are measured. Further data on this reaction are required in the energy range from about 100 eV to at least 1 MeV with an accuracy preferably better than ±3%. Ideally, absolute cross sections should be measured, although relative measurements could be normalised at the lower energies where the existing data are in reasonable agreement.

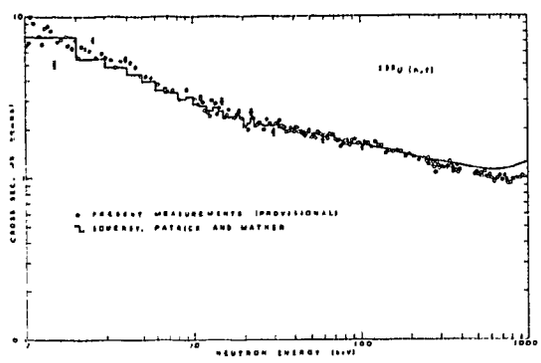

Fig. 1 The measured fission cross section of ^{235}U compared with the evaluation of Sowerby, Patrick and Mather. The measurements have been normalised to the evaluated cross section in the energy interval 10-100 keV.

The techniques used in previous measurements broadly separate into two groups according to the energy of the incident neutron. Above about 30 keV Van de Graaffs have generally been employed while at lower energies electron linacs and the time-of-flight method have predominated. No data have been published which cover the wide energy range of present interest using a single technique.

The preliminary time-of-flight measurements reported here were obtained on the 45 MeV linac using essentially the same detector as that described by Patrick et al[4]. The upper energy of the measurements, however, has been increased from 30 keV to 1 MeV by eliminating aluminium flight tube windows which create troublesome structure in the spectrum of the incident neutron beam. Fission events were recorded by observing the prompt neutrons in one or more of four NE 213 proton recoil detectors placed around the ^{235}U sample. The sample was mounted in a boron sleeve which served to reduce background from back scattered neutrons. The γ-rays from neutron capture were rejected by using pulse shape discrimination and neutrons scattered from the sample were rejected by setting the bias of the neutron detector above 1 MeV. With this arrangement and a thin sample for which the transmission is close to unity, the observed yield per incident neutron is proportional to $\bar{\nu}(E)\sigma_f(E)$ where $\bar{\nu}(E)$ is the number of prompt neutrons per fission and $\sigma_f(E)$ is the fission cross section.

Fig. 1 shows the result of our preliminary measurements. The sample was a 7.9 cm diameter disc of 93% ^{235}U with a thickness of 3.8×10^{-3} ^{235}U atoms/barn. Corrections for multiple scattering in the sample are known to be less than about 2% and have not been applied, nor has any allowance for the energy dependence of $\bar{\nu}(E)$ been made in these preliminary results. The fission yield data were obtained in 12 hr running time on a 100 m flight path using the neutron booster target of the linac, but a much longer period was spent investigating the neutron background. The nominal resolution of the measurements was 2 ns/m although this only applies to the present data above 250 keV, at lower energies timing channels have been grouped to improve statistical accuracy. The structure in the cross section agrees well with the recent measurements of Bowman et al[5] within the limitations of the present resolution. Statistical errors are shown on a few representative points in Fig. 1. The background of the time-of-flight measurement was determined with the "black" resonance filter technique using samples of Mn, Al and SiO_2. All the background points between the 2.38 keV Mn resonance and the 440 keV

oxygen resonance could be well fitted by a simple power law in time-of-flight and this was used to extrapolate the background beyond 440 keV to 1 MeV. The ratio of total background to true counts was 0.07 at 35 keV, 0.04 at 440 keV and 0.03 at 1 MeV. The gap in the data in the region of 440 keV is due to the unreliability of the measurements in the vicinity of the dip in the spectrum caused by the rather long flight path length in air.

The spectrum of the primary neutron beam, Ø(E), used to determine the cross section was taken from a measurement by Coates and Hunt who used a flat response detector[6] on a flight path looking at the opposite side of the booster to that viewed in the fission measurements. Both flight paths were normal to the booster moderator and there is no reason to suppose that the basic spectrum would be different in each case. However, in the spectrum measurement neutrons from a 12.5 cm diameter region of the moderator were detected while in the fission measurements the corresponding region was 20 cm in diameter. This difference could mean that the assumed spectrum contained a systematic error and for this reason the data shown in Fig. 1 must be considered provisional until the spectrum has been measured on the actual flight path used in the fission measurements.

The measurements have been normalised to the new evaluation of Sowerby, Patrick and Mather[3] in the decade 10-100 keV where the agreement in shape is very good. Future measurements will extend to below 100 eV and will be normalised at low energies. It can be seen that although there is moderate agreement with the evaluation below 10 keV, above about 250 keV the measurements fall below the evaluation reaching a maximum difference of about 15% at 800 keV. Any error in the assumed spectrum is most likely to be due to the difference in moderator areas "seen" on the two flight paths and since more moderator was viewed in the fission measurements it is possible that the true spectrum contained more low energy neutrons than has been assumed. Such a trend could account, at least in part, for the discrepancy. It is worth noting finally that the measurements are remarkably similar to the data of Poenitz[7] who also obtained low cross sections at energies above a few hundred keV.

(1) Poenitz W. P. Proc. of Second Int. Conf. on Nuclear Data for Reactors, (IAEA, Helsinki, 1970) Vol. II, p. 3.

(2) Davey W. G. Proc. of Second Int. Conf. on Nuclear Data for Reactors, (IAEA, Helsinki, 1970) Vol. II, p. 119.

(3) Sowerby M. G., Patrick B. H. and Mather D. S. Nuclear Physics Division Progress Report AERE - PR/NP 18, p. 7 (1971).

(4) Patrick B. H., Schomberg M. G., Sowerby M. G. and Jolly J. E. Proc. of Conf. on Nuclear Data for Reactors (IAEA, Paris, 1966) Vol. II, p. 117.

(5) Bowman C. D., Stelts M. L. and Baglan R. J. Proc. of Second Int. Conf. on Nuclear Data for Reactors, (IAEA, Helsinki, 1970) Vol. II, p. 65.

(6) Coates M. S. and Hunt G. J. Nuclear Physics Division Progress Report AERE - PR/NP 17, p. 4 (1970).

(7) Poenitz W. P. Proc. of Second Conf. on Neutron Cross sections and Technology (Washington, 1968) Vol. I, p. 503.

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 in the energy range 100 eV to 20 MeV (M. G. Sowerby, B. H. Patrick, Miss R. B. Brock and V. S. W. Sherriffs with D. S. Mather (AWRE))

Among the most important cross sections required for the calculation of fast reactor properties are the fission cross sections of ^{235}U, ^{239}Pu and ^{238}U and the capture cross section of ^{238}U. Recently there have been a number of new measurements of these cross sections and it has been found that there is structure in the ^{235}U fission cross section in the keV energy range[1] and the $^{10}B(n,\alpha)$ cross section,

which is the standard cross section for many measurements below 100 keV, has been shown to depart from a 1 v energy dependence[2]. In the light of these factors it is clear that new evaluations are necessary.

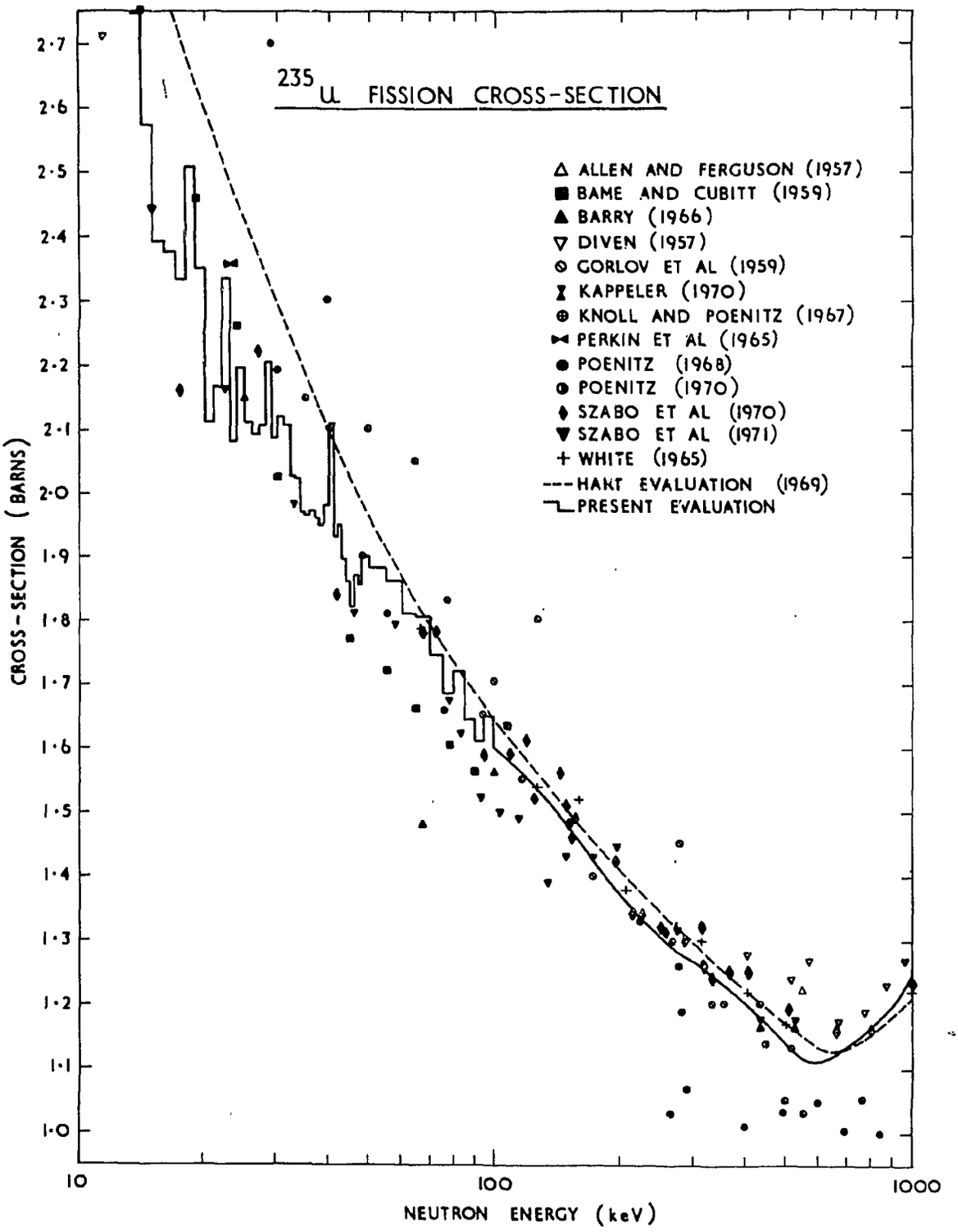

Fig. 1 The ^{235}U fission cross section from 10 to 1000 keV. The references to the experiments are given in reference (3) except for Szabo et al (1971) which is reference (6) of this report.

Evaluations of neutron cross sections have three main purposes; the first and primary purpose is to obtain recommended cross sections which can be incorporated in new data files for use in reactor calculations, the second is to see if the accuracy achieved in the experiments satisfies the requests of the reactor physicists and the third is to recommend where further measurements are desirable. There have been many evaluations of the cross sections of ^{235}U, ^{239}Pu and ^{238}U over the past few years and these have shown that the required accuracies have not been achieved. They have also suffered from two important defects. It is usual to evaluate the ^{235}U fission cross section data first and then use the values obtained together with cross section ratio measurements to get values of the other cross sections. This does not take full advantage of the available data because the measurements of the cross-sections and their ratios form a highly inter-related set and the best evaluation must consider all the available data simultaneously. The second major defect has been that the cross sections have been assumed to have a smooth energy dependence in the keV energy range. As a result of this, measurements with mono-energetic neutron sources have been given high weight above a few keV but because of structure this is a dangerous assumption particularly for the ^{235}U fission cross section. The present evaluation has been designed to overcome these defects.

The energy ranges above 100 keV and below 30 keV have been evaluated by different methods. Below 30 keV most of the data are continuous time-of-flight data while above 100 keV the values are mainly "spot points". In the energy interval below 30 keV true average cross sections over specified energy intervals can be obtained and there are few ratio measurements, so the cross sections need to be evaluated independently. Above 100 keV, where true average cross sections cannot be obtained there are measurements of cross sections and cross section ratios and a simultaneous evaluation has been performed as described in a report presented to the Helsinki Conference(3). In the energy range 30 - 100 keV the method has varied depending upon the cross section. For the ^{235}U fission cross section the evaluation was based on the measurements of Lemley et al(4) normalised to the evaluated curve between 10 and 30 keV. The ^{239}Pu fission cross section was obtained from the ^{235}U evaluation and measurements of the $^{239}Pu/^{235}U$ fission ratio as there are no continuous measurements in this energy range. The ^{238}U capture cross section was obtained from continuous cross section data renormalised between 20 and 30 keV.

The evaluation has been completed and is being compiled at A.W.R.E. into new data files in the U.K. Nuclear Data Library. However the documentation has only recently been started and it may be necessary to modify the recommended cross sections during the documentation stage.

Many interesting features have emerged from this work. As discussed in ref. (3) there is a serious discrepancy between the ^{235}U fission cross section measurements and ^{238}U capture cross section data in the energy range 100 to 600 keV. The ratio between the two cross sections is well measured and does not agree with the ratio of cross sections obtained from the direct measurements. In obtaining our final evaluated cross sections we have given high weight to the ^{235}U fission cross section data and hence have assumed that it is the ^{238}U data or ratio measurements which are in error.

The evaluated fission cross section curve for ^{235}U is shown in Fig. 1 in the energy range 10 keV to 1 MeV. It can be seen that below 70 keV the curve deviates significantly from the earlier evaluation of Hart(5). This difference arises because we have placed more emphasis on the continuous measurements. However, the recent spot point data of Szabo et al(6) strongly support our conclusions.

---

(1) Patrick B. H., Sowerby M. G. and Schomberg M. G. J. Nucl. Energy 24, 269 (1970).

(2) Sowerby M. G., Patrick B. H., Uttley C. A. and Diment K. M. J. Nucl. Energy 24, 323 (1970).

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

(4) Lemley J. R., Keyworth G. A. and Diven B. C. Nucl. Sci. and Eng. 43, 281 (1971).

(5) Hart W. UKAEA Report AHSB(S)R-169 (1969).

(6) Szabo I., Filippi G., Huet J. L., Leroy J. L. and Marquette J. P. Third Conf. on Neutron Cross sections and Technology, Knoxville, March 1971, Paper V.6.

Evaluation of ^{239}Pu alpha (M. G. Sowerby and Miss R. B. Brock)

There are now a number of measurements of the ratio of the average capture to average fission cross sections ($\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$) for ^{239}Pu in the energy range below 30 keV. These data are extremely important in the calculation of the breeding gain of fast reactors and hence an evaluation has been performed over the energy range 100 eV to 15 MeV. In Fig. 1 the evaluated curve is shown and compared with the available measurements below 30 keV. It is estimated that the accuracy of the curve is approximately 10-12% in this energy range.

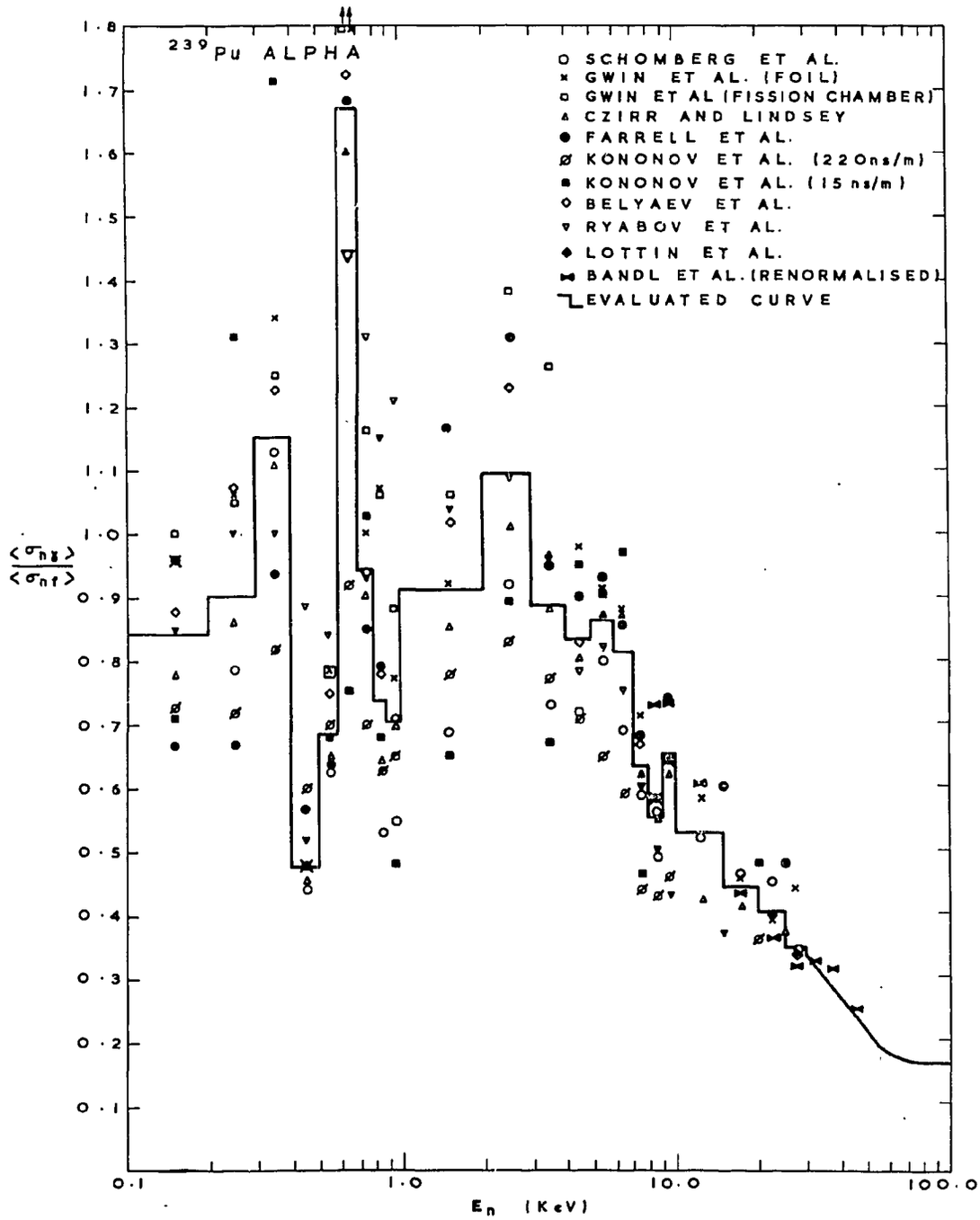

Fig. 1 Comparison of evaluated ^{239}Pu alpha with the available measurements below 30 keV.

It is now well known that the structure in $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ visible in the 0.1 to 1 keV energy range extends into the higher energy region. (It is masked in the evaluation by taking averages over broader energy intervals above 1 keV). The structure is most probably due to intermediate structure in sub-threshold fission for the s-wave neutron resonances of spin and parity (J^{π}) 1^+. For calculations of reactor properties such as the Doppler temperature coefficient it is important that this structure is represented in the evaluated data but because of strong fluctuations due to the fine compound nuclear resonances it is difficult to evolve objective criteria for determining the parameters of the intermediate structure modulations present in the experimental data. To overcome this difficulty we have assumed that the fission width of the s-wave resonances with spin and parity 1^+ can be represented by a Porter-Thomas distribution over energy intervals of 100 eV and we have used a computer programme of Lynn to calculate the average cross sections in the energy range 0.1 - 30 keV assuming the parameters as given in the Table I. The calculations were made in 100 eV intervals up to 7 keV; at higher energies the intermediate structure is of less importance due to the increase in the p-wave contributions. Allowance was made for inelastic scattering above 7.8 keV. The values of the s-wave strength function were adjusted (assuming a low energy potential scattering of 10.3 barns) so that the calculated total cross section agreed with values evaluated from the available data. The value of $\langle\Gamma_f\rangle$ (for $J^{\pi} = 1^+$) was then adjusted so that (a) the calculated values of $\langle\sigma_{nf}\rangle$ were close to an evaluated set of data (in 100 eV intervals below 7 keV) based on the evaluation of Sowerby et al[1] and (b) the calculated values of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ were close to the evaluation discussed above when averaged over the same energy intervals. It was found that good agreement was not possible for both $\langle\sigma_{nf}\rangle$ and $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ unless $\langle\Gamma_{\gamma}\rangle$ (for $J^{\pi} = 1^+$) was also slightly altered for some energy intervals.

TABLE I

Average resonance parameters

	s-wave		p-wave		
J^{π}	0^+	1^+	0^-	1^-	2^-
Neutron strength function (s)	Variable with $S(J=0^+)=S(J=1^+)$	Variable with $S(J=0^+)=S(J=1^+)$	2×10^{-4}	2×10^{-4}	2×10^{-4}
Average capture width (Γ_{γ}) (meV)	42	42	42	42	42
Mean level spacing (D) (eV)	9.6	3.2	9.6	3.2	1.92
No. of fission channels (Γ_f)	2	1	0	2	2
Mean fission widths in channels $(\langle\Gamma_f\rangle)$ (meV)	1464 218	Variable	-	510 510	306 306

The values of the average resonance parameters obtained are now being used by J. D. McDougall (A.E.E. Winfrith) to produce a set of unresolved resonances and cross sections with the RESP-GENEX system of computer codes[2]. The representation of the intermediate structure obtained is probably not too unreasonable but it may be dangerous to try to interpret seriously the values of $\langle\Gamma_f\rangle$ obtained in physical terms.

(1) Sowerby M. G., Patrick B. H. and Mather D. S. Nuclear Physics Division Progress Report AERE - PR. NP 18, p.7 (1971).

(2) Brissenden R. J. and Durston C. UKAEA Report AEEW-R 622.

Evaluation of total and capture cross sections of structural materials (M. C. Moxon)

An evaluation on the capture cross section of iron in the energy range from ~1 keV to ~1 MeV has been completed[1].

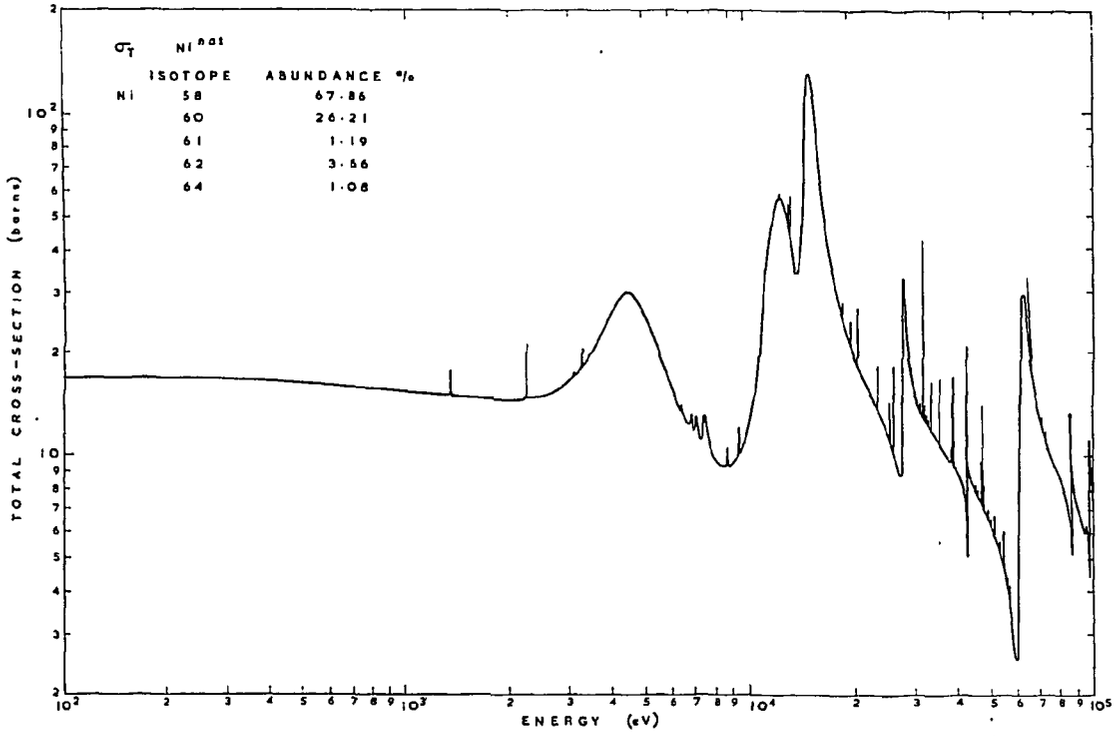

Fig. 1 The calculated neutron total cross section of natural nickel.

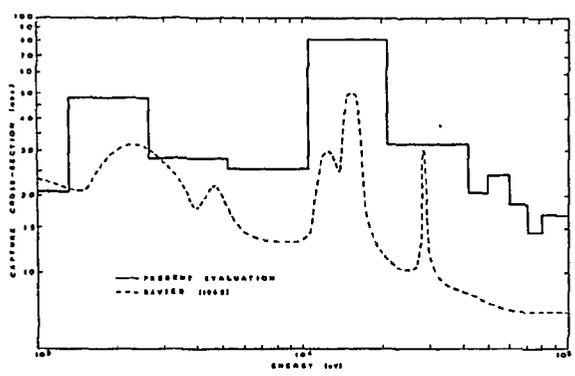

Fig. 2 The calculated average neutron capture cross section of natural nickel compared with the Ravier evaluation of 1965.

In the case of nickel, an evaluation has been carried out on the total and capture cross section in the neutron energy range from thermal to ~200 keV. Figs. 1 and 2 show the calculated total and capture cross sections respectively of natural nickel in the energy region 100 eV to 100 keV. Figure 2 shows the averaged capture cross section in the energy region 1 to 100 keV compared with the evaluation of Ravier[2]. The estimated uncertainties on the total cross section are small in the peaks of the s-wave resonances, and are mainly due to the uncertainty in the potential cross section which amounts to ~±0.5 barn and ±2 barns at ~1 eV and 100 keV respectively. The estimated uncertainty in the capture cross section in the resolved resonance region is ~±50% near s-wave resonances, ±10 to 30% in the region around the narrow p-wave resonances and ±5% in the 1/v region.

These evaluated cross sections were calculated using weighted mean values of the neutron and radiation widths, when several sets of data were available. As there are very few published values of the radiation widths for s-wave resonances in nickel, mean values were used for most of the resonances. There are no reported values of radiation widths for the p-wave resonances and to obtain agreement with the average cross section data in the energy region 50 to 200 keV requires either strength function values of 0.01×10^{-4} and 0.5×10^{-4} for p- and d-wave neutrons respectively, or a radiation width for both p- and d-wave resonances of between 1/3 and 1/2 the average value for s-wave resonances. The latter suggestion appears to be more plausible as the p-wave strength function calculated from the individual resonance capture data between 20 and 50 keV is $\sim 0.15 \times 10^{-4}$ and the d-wave strength function value is $\sim 3 \times 10^{-4}$ from transmission measurements. The reduction in the p-wave radiation width is also consistent with the fact that the first level of the opposite parity to the p-wave resonances is some 2-3 MeV above the ground state of the compound nucleus, hence giving a factor of 2-3 reduction in the E1 transition probability compared with that of the s-wave resonances, which can de-excite via E1 transitions to the ground state or nearby levels.

---

(1) Moxon M. C. and Rae E. R. Neutron cross section of iron, AERE Committee paper UKNDC(70)P.12.

(2) Ravier J. PNR/SEPR/CA/65.010 (1965).

A contribution to international co-operation in nuclear data evaluation (J. E. Lynn and P. G. Timms)

It is common practice among workers in the neutron resonance field to reduce cross section data to a set of resonance parameters. From the point of view of provision of nuclear data for reactor physics and design, there are two purposes in this practice. One is simply to provide a convenient parametrisation of a set of complex data; the other, more important, is to achieve an understanding of the basic nuclear physics controlling the cross section, and thus to be able, by theoretical extrapolation, to make statistical estimates of cross section properties in energy regions inaccessible to present experimental techniques. For fissile nuclei, however, there are great difficulties in extracting the resonance parameters(1). It is not clear, therefore, whether discrepant results by workers in different laboratories are due to differences in the basic data, to different methods of resonance analysis, or to lack of uniqueness in the resonance parameter sets.

To help resolve this situation it was proposed by Ribon at the 1970 Helsinki Conference on Nuclear Data that a theoretically simulated set of cross section data (with resonance parameters known to the simulator but not to the experimenters) be given to the various workers in this field, who should be asked to analyse it with their existing methods. The results can then be compared amongst each other and with the correct set of parameters from which the "data" were simulated. In this way it is hoped that any shortcomings in the analysis methods can be revealed.

It was agreed that Harwell should provide the simulated data, and to this end we have been writing computer programmes that will generate a set of resonance parameters from a specified theoretical situation, and calculate the neutron total, fission and capture cross sections with the modifications due to Doppler and resolution broadening. These programmes have been completed and tested, and it only remains to generate the actual test case.

---

(1) Lynn J. E. Phys. Rev. Lett. 13, 412 (1964).

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

The experimental programme with the flat response detector (the Harwell black detector) previously reported[1] has continued on the 300 m flight path of the neutron booster. Preliminary measurements have been obtained, in the energy range 1.5 keV to several hundred keV, of the $^6Li(n,\alpha)$ cross section using ^6Li glass scintillation counters and of the $^{10}B(n,\alpha,\gamma)$ cross section using a $^{10}B_2O_3$ disc viewed by Na-I scintillation counters. The flux measurement using the black detector was made at the 300 m position while the reaction rate measurements were carried out at the 120 m station[1]. In the analysis the theoretically predicted[1] neutron detector efficiency of the black detector was used. In the low energy region below ~10 keV, where the two cross sections are already known to high accuracy (1-2%), the measurements provide a check on this calculated efficiency. At higher energies however the cross sections are not well enough known to be useful in this respect and experimental verification of the efficiency awaits a cross calibration against the Harwell long counter[2]. These measurements are to be carried out in the immediate future.

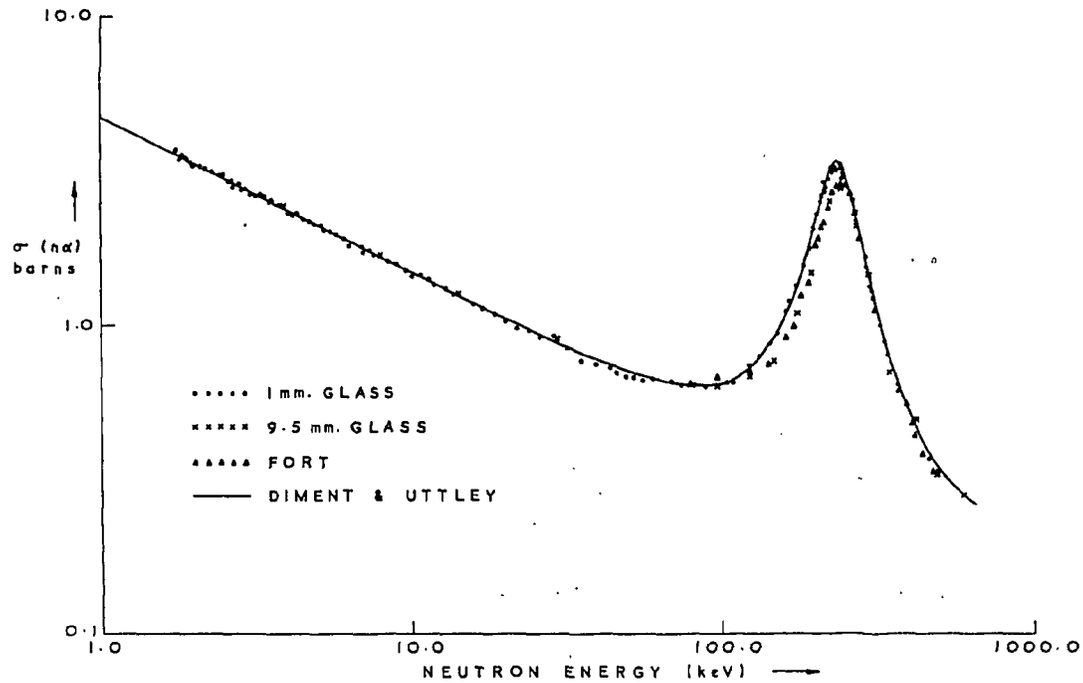

Fig. 1 Preliminary measurements of the $^6Li(n,\alpha)$ cross section.

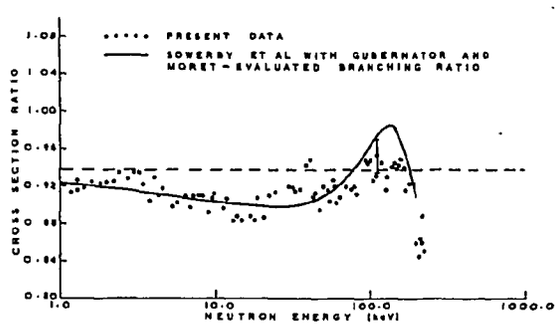

Fig. 2 $^{10}B(n,\alpha\gamma)$ cross section relative to $19.30/\sqrt{E}$ (keV).

Two determinations of the $^6Li(n,\alpha)$ cross section are given as measured with glasses 1 mm thick and 9.5 mm thick, each 6.35 cm dia. (type GS 20). The associated phototube mounting is that reported by Sowerby et al[3] of which the chief feature is the separation of the glass from the phototube by a distance of 5.25 cm to reduce the effects of neutron multiple scattering from the photocathode. Collimators of boron loaded wax (60 cm long) and lead (15 cm long) limited the neutron beam diameter to 5 cm at the detector position and ensured that the same neutron source area was viewed as for the neutron flux measurement.

Background was determined with filters of Al, SiO_2 and Mn using the black resonance technique. Discriminator bias conditions were such that a negligible fraction of the pulses produced in the $^6Li(n,\alpha)$ reaction were missed. The 1 mm glass was the thinnest available and corrections due to multiple scattering in the body of the glass are only 1-2% below ~300 keV. The 9.5 mm glass has nominally the same thickness and composition as that used by Fort[4] in his measurements using a Van de Graaff accelerator, and at present there is a significant and unexplained discrepancy between his cross section determination and that obtained by Uttley and Diment[5] from an analysis of their total cross section measurements made with ^6Li metal samples on the 300 m flight path referred to above. Fort[6] has carried out a detailed Monte Carlo calculation to obtain the correction factor to allow for the significant multiple scattering effects in his glass and we have used this factor in the treatment of our 9.5 mm glass data. Fort[7] has also calculated the correction factor applied to the 1 mm glass results.

Fig. 1 shows our results together with the data of Uttley and Diment, and Fort. Our data are normalised to those of Uttley and Diment in the energy region below 10 keV. Fort's determination is absolute, the neutron flux being measured using the associated particle technique on the $T(p,n)^3He$ reaction. Uttley and Diment claim to have measured the cross section to ±1% below 10 keV, ±2% at 100 keV and within ±5% at higher energies. Fort quotes an accuracy of ±4% on his data. It will be seen that the 1 mm glass data agree well overall with those of Uttley and Diment although the peak of the resonance in the cross section near 250 keV shows a discrepancy of ~5% and there is another local discrepancy in the energy region around 50 keV. On the other hand the cross section determined from the 9.5 mm glass measurement agrees closely with that of Fort. (For the sake of clarity only some of our data points are shown). This implies that both methods of flux measurement agree and leads to the preliminary conclusion that the source of the discrepancy between Fort and Uttley and Diment lies in the correction factor for the effects of multiple scattering. These effects are, of course, much more important in the thicker glass than in the 1 mm glass. It is difficult however to see how an error in the correction factor can account for the observations since in the region of maximum discrepancy, on the low energy side of the resonance up to the peak, the correction factor is calculated to be ~1.1 whereas the discrepancy is 25%, in the worst case. (On the high energy side of the resonance, where the data are in agreement the correction factor rises to 1.7 due to the effect of the 440 keV oxygen resonance). A possible explanation is that the actual composition of the glass differs significantly from that nominally given by the manufacturer and thus the effective total cross section assumed by Fort is significantly in error. We intend to measure the total cross section to investigate this possibility. In addition it is hoped in the near future to have our own Monte Carlo programme to calculate the correction factor.

The measurements of the $^{10}B(n,\alpha,\gamma)$ cross section were carried out in the same neutron beam geometry as the ^6Li measurements and the same technique for determining backgrounds was used. The $^{10}B_2O_3$ sample was a disc 4.4 mm thick and 7.65 cm dia containing 95% ^{10}B. Four NaI scintillation counters lying out of the neutron beam detected the 478 keV γ-rays from the $^{10}B(n,\alpha\gamma)^7Li$ reaction. Corrections for multiple scattering have been provided by Moxon[8], and the derived cross section data is shown in Fig. 2. The results are compared with a recent evaluation of the $^{10}B(n,\alpha)$ cross section by Sowerby et al[3] combined with the evaluated branching ratio of the $^{10}B(n,\alpha)$ reaction given by Gubernator and Moret[9]. The branching ratio is defined as the probability R for the reaction to go to the ground state, and thus the $^{10}B(n,\alpha\gamma)$ cross section is related to the $^{10}B(n,\alpha)$ cross section by $\sigma(n,\alpha\gamma) = \sigma(n,\alpha)(1-R)$. Our data are fitted by eye to the curve derived from the evaluations in the energy region below 10 keV. The data are divided by (constant)/$\sqrt{E}$ so that a 1/v dependence of the cross section is a horizontal straight line in the figure. Our results agree well with the evaluated curve below ~100 keV. The high points at 40 keV we observe were noted by Sowerby et al in the data sets used in their evaluation but were neglected in their analysis. Above 100 keV we do not see the resonance near 150 keV proposed by Sowerby et al, but it should be noted that the data points which contribute to this feature all depend on the scattering data of Mooring et al[10]. Sowerby et al quote the accuracy of their evaluated cross section at ±1% at 1 keV, ±2% at 10 keV, ±3% at 100 keV and ±5% at 200 keV. Even without allowance for the small error introduced by the uncertainty in the evaluated branching ratio our results do not conflict with this condition.

(1) Nuclear Physics Division Progress Report AERE PR/NP 17, p.4 (1970).
(2) Adams J. M., Feguson A. T. G. and McKenzie C. D. AERE - R 6429 (1970).
(3) Sowerby M. G., Patrick B. H., Uttley C. A. and Diment K. M. AERE - R 6316 (1970).
(4) Fort E. 2nd Int. Conf. on Nuclear Data for Reactors, Helsinki, Paper CN-26/72 (1970).
(5) Uttley C. A. and Diment K. M. AERE - PR/NP 14 (1968), 15 (1969) and 16 (1969).
(6) Fort E. Nuc. Inst. and Meth. 87, 115 (1970).
(7) Fort E. Private communication (1970).
(8) Moxon M. C. Private communication (1970).
(9) Gubernator K. and Moret H. EUR 3950e (1968).
(10) Mooring F. P., Monahan J. E. and Huddleston C. Nuc. Phys. 82, 16 (1966).

Review of ^{6}Li cross sections below 1.7 MeV (C. A. Uttley, M. G. Sowerby, B. H. Patrick and E. R. Rae)

The ^{6}Li(n,α) reaction is an important standard below a few hundred keV and at higher energies it is used for measurements of neutron spectra in fast reactors. The cross sections of ^{6}Li have been critically reviewed below 1.7 MeV and best values of the cross sections selected. Papers on this topic were presented to the EANDC Symposium on Neutron Standards and Flux Normalisation, Argonne, October 1970 and to the Knoxville Conference on Neutron Cross sections and Technology, March 1971. The abstract of the latter paper was as follows:-

"The data on the total, (n,α), (n,n) and (n,γ) cross sections of ^{6}Li have been reviewed below a neutron energy of 1.7 MeV. The data on the differential (n,α) and (n,n) reactions have been considered but particular emphasis has been placed on obtaining the variation of the (n,α) cross section with neutron energy. The best values of this cross section are indicated and it is estimated that the values are known (one standard deviation) to ±0.5% at thermal energies, ±1% from thermal to 10 keV, ±2% at 100 keV, ±5% from 150 to 300 keV, ±10% at 500 keV, and ±15% from 700 to 1700 keV".

Spin dependence of the s-wave neutron interaction with ^{6}Li (C. A. Uttley)

The neutron scattering length provides a measure of the s-wave neutron-nucleus interaction at zero energy and, in the case of ^{6}Li, the differential elastic scattering and reaction cross sections provide similar information at energies below the $P_{5/2}$ resonance at ~250 keV.

The scattering length $a_J (= x_J + iy_J)$ for each s-wave spin sequence in ^{6}Li is complex due to the reaction channel but the real part of the slow neutron coherent scattering length, a_{coh}, has been measured by Peterson and Smith[1] to be 1.8 fm. Since the spin of ^{6}Li is 1, compound states of spin J=1/2 and 3/2 are formed in the s-wave neutron interaction and $a_{coh} = (g_{1/2}a_{1/2} + g_{3/2}a_{3/2})$, where $g_{1/2} = 1/3$ and $g_{3/2} = 2/3$ are the statistical factors associated with the respective states. The measurement of Peterson therefore gives the linear relationship

$$2\,x_{3/2} + x_{1/2} = 4.62 \qquad (1)$$

between the real scattering lengths (in fm) after allowing for the effect of chemical binding. The low energy scattering cross section $\sigma_o = 4\pi(g_{1/2}\,a_{1/2}{}^2 + g_{3/2}\,a_{3/2}{}^2)$ provides another relationship between the scattering lengths and, using the value of 0.724±0.010 barns determined previously[2], we obtain

$$(x_{1/2}{}^2 + y_{1/2}{}^2) + 2(x_{3/2}{}^2 + y_{3/2}{}^2) = 17.285. \qquad (2)$$

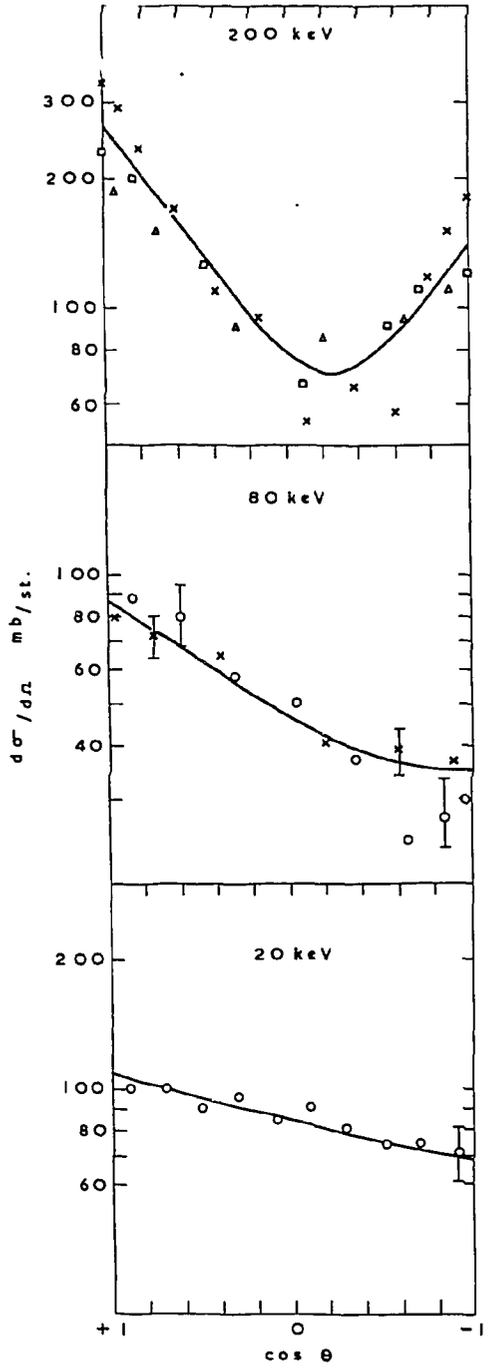

Fig. 1 Calculated differential (n,a) cross section at 20, 80 and 200 keV for 25% s-wave absorption in channel spin 3/2 compared with measured values normalised to same total cross section.

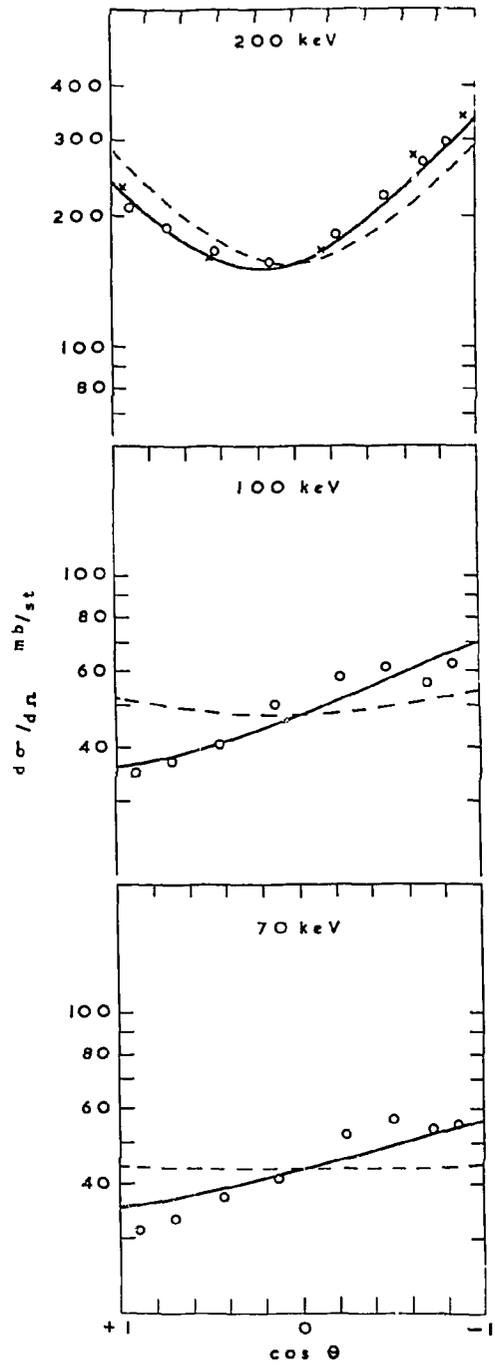

Fig. 2 Calculated differential elastic scattering cross section for two values of the s-wave scattering length in channel spin 3/2 normalised to the same total scattering cross section as the measured data at 70, 100 and 200 keV.

Finally it can be shown that the imaginary components, which, unlike the real scattering lengths, are always positive, are related to the thermal absorption cross section of 940 barns[2,3] to give

$$y_{1/2} + 2y_{3/2} = 2.244\ 10^4\ k_{th} \tag{3}$$

where k_{th} (in fm) is the neutron wave number at thermal energy.

Marshak[4] has shown that most of the s-wave absorption cross section at low energies (~1 eV) is formed in channel spin 1/2 by measuring the transmission of polarized neutrons through a polarized ^{6}Li target. A more quantitative estimate was obtained by Mahaux and Robaye[5] who fitted the differential reaction cross section data in the vicinity of the $P_{5/2}$ resonance (E < 600 keV), assuming a $1/\sqrt{E}$ s-wave background cross section in each channel spin, and found the differential cross section to be consistent with 75% s-wave absorption in channel spin 1/2. Thus both $y_{1/2}$ and $y_{3/2}$ are known approximately and the real lengths $(x_{1/2}, x_{3/2})$ can be obtained from equations (1) and (2). In fact two pairs of solutions exist because of the quadratic nature of the total cross section. These are (4.10, 0.26) and (-1.02, 2.82) in fm for $(x_{1/2}, x_{3/2})$ respectively and it is clear that the s-wave spin-parallel interaction is very weak in the first case but is the stronger in the second solution.

The weak asymmetry observed[6] in the scattering of polarized neutrons of about 250 keV by a ^{6}Li target suggests that the first solution above is correct and this has been confirmed by fitting the differential elastic scattering data of Lane et al[7], discussed below, and by the data of Asami and Moxon[8]. An analysis of the neutron total cross section of ^{6}Li has been discussed previously[2], in which the relatively large value of $x_{1/2} = 4.10$ fm was interpreted as due to a bound $1/2^+$ state at 6.56 MeV excitation in ^{7}Li compound nucleus, while the small value of $x_{3/2}$ relative to the interaction radius must be due to a $3/2^+$ state several MeV above the neutron separation energy. In the latter case, calculations based on the two components $(x_{3/2}, y_{3/2})$ of the scattering length show that the energy variation of the scattering and absorption cross sections below 1 MeV are insensitive to both the precise energy of the state and the value chosen for the interaction radius. The energy dependence of the scattering and absorption cross sections for a $1/2^+$ state at 6.56 MeV, on the other hand, are very sensitive to the chosen interaction radius and the fit to the total cross section in the minimum near 75 keV determines this radius and consequently the parameters for the bound state from the components ($x_{1/2} = 4.10$, $y_{1/2} = 0.50$) of the scattering length. In this work the parameters of the $P_{5/2}$ resonance have been measured separately[2] and therefore the p-wave contributions to the total and partial cross sections are readily calculated.

The differential scattering and reaction cross sections can be calculated since the resonance phase shifts β are defined for the s-wave $1/2^+$ and $3/2^+$ states and the $5/2^-$ p-wave resonance at 247 keV according to

$$\beta = \tan^{-1} \frac{\frac{1}{2}\Gamma}{E_\lambda + \Delta_\lambda - E}$$

where E_λ is the energy eigenvalue, Δ_λ is the level shift factor and Γ is the total width of each state. For energies below ~1 MeV only incident orbital angular momenta 0 and 1 need be considered resulting in a second order Legendre polynomial expansion to describe the differential cross sections. The differential scattering cross section, assuming the p-wave potential phase shift δ_1 is negligible below the $P_{5/2}$ resonance, is given by

$$\begin{aligned}\sigma_{n,n}(\theta) = \lambda^2 [&(\sigma^s_{0,\,1/2}/4\pi\lambda^2 + \sigma^s_{0,\,3/2}/4\pi\lambda^2 + \sigma^s_{1,\,5/2}/4\pi\lambda^2) \\ &+ (2\,(\Gamma_n/\Gamma)_{3/2}\,(\Gamma_n/\Gamma)_{5/2} \sin\beta_{3/2} \sin\beta_{5/2} \cos(\beta_{3/2} - \beta_{5/2} + 2\delta_0 \\ &+ 2(\Gamma_n/\Gamma)_{5/2} \sin\beta_{5/2} \sin\delta_0 \cos(\beta_{5/2} - \delta_0))P_1(\cos\theta) \\ &+ 14/25\,(\Gamma_n/\Gamma)^2_{5/2} \sin^2\beta_{5/2}\, P_2(\cos\theta)]\end{aligned}$$

where $\sigma^s_{l,J}$ is the integral scattering cross section for states J formed by partial wave ℓ, $(\Gamma_n/\Gamma)_J$ is the ratio of neutron to total width for compound state J and δ_0 is the s-wave potential scattering phase shift. The coefficient of $P_1(\cos\theta)$ can be shown to be proportional to $x_{3/2}$ as $E \to 0$; thus the asymmetry about $\pi/2$ in $\sigma_{n,n}(\theta)$, both above and below the resonance, is determined by the s-wave scattering amplitude in channel spin 3/2. The differential reaction cross section is given by

$$\sigma_{n,\alpha}(\theta) = \lambda^2 [(\sigma^r_{0,1/2}/_{4\pi\lambda^2} + \sigma^r_{0,3/2}/_{4\pi\lambda^2} + \sigma^r_{1,5/2}/_{4\pi\lambda^2}) + (2\sqrt{6/5}$$

$$\sin \beta_{3/2} \sin \beta_{5/2} \sqrt{(\Gamma_n/\Gamma \cdot \Gamma_\alpha/\Gamma)_{5/2}} \sqrt{(\Gamma_n/\Gamma \cdot \Gamma_\alpha/\Gamma)_{3/2}}$$

$$\cos (\beta_{5/2} - \beta_{3/2} + \rho)) P_1 (\cos \theta) + 4/5 (\Gamma_n/\Gamma \cdot \Gamma_\alpha/\Gamma)_{5/2}$$

$$\sin^2 \beta_{5/2} P_2 (\cos \theta)]$$

where $\sigma^r_{l,J}$ is the integral absorption cross section for states with specified spin J formed by partial wave l, $(\Gamma_\alpha)_J$ is the alpha width of the relevant states and ρ is the net phase angle for potential scattering in the entrance and exit channels. The deviation from isotropy at energies < 200 keV is again determined by the coefficient of P_1 (cos θ) which is proportional to the reaction amplitude in s-wave channel spin 3/2 and equal to $(y_{3/2})^{1/2}$ as $E \to 0$.

The differential reaction cross section has not been well measured but the available data are adequately fitted by a value of $y_{3/2}$ which corresponds to 25% absorption occurring in channel spin 3/2. This is illustrated in Fig. 1 at three energies below the $P_{5/2}$ resonance at 247 keV. In Fig. 2 the calculated differential elastic scattering cross section is compared with the scattering data of Lane et al[7]. The dashed curve is the scattering resulting from a scattering length $x_{3/2}$ = 0.26 fm obtained from the coherent scattering length of Peterson in the first solution mentioned above. Clearly this value of $x_{3/2}$ is too small and the full curve is the calculated differential scattering cross section for a value of $x_{3/2}$ = 0.85 fm. Here the low energy scattering cross section σ_0 is maintained constant to yield values $(x_{1/2}, x_{3/2})$ of (3.95,0.85)fm respectively and better agreement is obtained with the data of Lane et al.

The result of this analysis is in accord with the data of Asami and Moxon who obtain a value for the s-wave potential scattering radius of 0.70±0.15 fm in channel spin 3/2 from a fit to their differential scattering data on ^{6}Li relative to carbon at four angles below ~100 keV. Their value for the low energy scattering cross section σ = 0.753±0.043 barns is in agreement with the one used here and thus a coherent scattering length of 2.20±0.10 fm is indicated which is larger than the value of 1.8 fm measured, unfortunately with no quoted error, by Peterson and Smith. However, the data involving the low energy scattering lengths and the fits to the differential cross sections show that the parallel spin interaction of s-wave neutrons with ^{6}Li is the weaker and confirms the observations of Darden et al[6] that ^{6}Li is not useful as an analyser of neutron polarizations.

(1) Peterson S. W. and Smith H. G. J. Phys. Soc. Japan, 17, Supplement B-11, 335 (1962).

(2) Uttley C. A. and Diment K. M. Nuclear Physics Division Progress Report AERE - PR/NP 15 (1969).

(3) Meadows J. W. and Whalen J. F. Nucl. Sci. and Eng. 40, 12 (1970).

(4) Marshak H. Private communication (1969).

(5) Mahaux C. and Robaye G. Nucl. Phys. 74, 161 (1965).

(6) Darden S. E., Donoghue T. R. and Kelsey C. A. Nucl. Phys. 22, 439 (1961).

(7) Lane R. O., Langsdorf A., Monahan J. E. and Elwyn A. J. Ann. Phys. 12, 135 (1961).

(8) Asami A. and Moxon M. C. Proceedings of the Second IAEA Conference on Nuclear Data for Reactors, Vol. 1, p. 153 (1970).

Structure in the ^{235}U fission and total cross section (G. D. James)

The structure noted by Patrick et al[1] in the fission cross section of ^{235}U is reflected to some extent in the total cross section data of Bockhoff and Dufrasne[2]. This echoes the situation encountered during an investigation of structure in the fission and total cross section of ^{239}Pu[3]. A simulation experiment, designed to determine the confidence with which structure can be attributed to the variation of the mean fission width, is in progress. A preliminary investigation, entailing the application of the Wald and Wolfowitz analysis[4] directly to the cross section data, indicates that structure in the fission cross section is more pronounced than in the total cross section.

---

(1) Patrick B. H., Sowerby M. G. and Schomberg M. G. Report AERE - R 6350 and J. Nuc. Energy 24, 269 (1970).

(2) Bockhoff K. H. and Dufrasne A. Unpublished memorandum.

(3) James G. D. and Patrick B. H. Physics and Chemistry of Fission (IAEA, Vienna, 1969) 391.

(4) James G. D. Report AERE - R 6633 (1971).

Fission yield from freshly prepared ^{241}Pu (G. D. James and D. A. J. Endacott)

Evidence for a short lived (0.34±0.11 y) component[1] in the time dependence of the reactivity of a sample of ^{241}Pu can be explained in many ways including the existence of a spontaneously fissioning isomer with a high thermal fission cross section. Experiments[2] to compare the fission cross section of freshly prepared ^{241}Pu with that for ^{241}Pu which is several years old have continued in order to improve their statistical accuracy. By normalising the two sets of data to each other at the 0.24 eV resonance, it is found that the thermal fission cross section of the two samples are equal to within 0.63%±0.2% (internal error) ±0.85% (external error). The latter error is deduced from the spread of the results from ten chronologically sequential sets into which the data could be divided. This result can be translated into a concentration of isomer only by making some assumptions about the shape of the fission cross section of the isomer, between thermal neutron energy and 0.24 eV, and about its value at thermal energy. For a 1/v fission cross section of 2500 b at thermal neutron energy, the concentration of isomer given by the data is negative but becomes 1.48% (at the end of the production irradiation) at one standard deviation. This should be compared with calculations by Lynn[3] that the concentration required to explain the most likely reactivity contribution from the isomer (at the end of the production irradiation) suggested by the results of Nisle and Stepan[1] is 20% for an assumed isomer thermal fission cross section of 2500 b. Comparisons for other assumptions are made in a recent report[4].

---

(1) Nisle R. G. and Stepan I. E. Idaho Nucl. Corp. Progress Report IN-1317, 149 (1969).

(2) James G. D. Report AERE - NP/PR 17, p. 25.

(3) Lynn J. E. Private communication and AERE - NP/PR 17, p. 25.

(4) James G. D. Report AERE - R 6676 and J. Nuc. Energy (to be published).

(γ,n) cross section measurements near threshold (B. H. Patrick and E. M. Bowey)

In the last progress report[1] an account of (γ,n) cross section measurements on tin near threshold was given and it was found that the cross sections for $^{117,119}Sn(\gamma,n_0)$ showed a giant resonance-like peak at 7.8 MeV. For various reasons, it is thought that the peaks are examples of the M1 giant resonance which has been predicted by theoretical arguments to lie in this energy region. This work has now been published[2]. It should be possible to determine whether the peak is due to an M1 or E1 interaction by measuring the angular distribution of the emitted neutrons. A technique which, to our knowledge, has not previously been employed, has been developed for such a measurement.

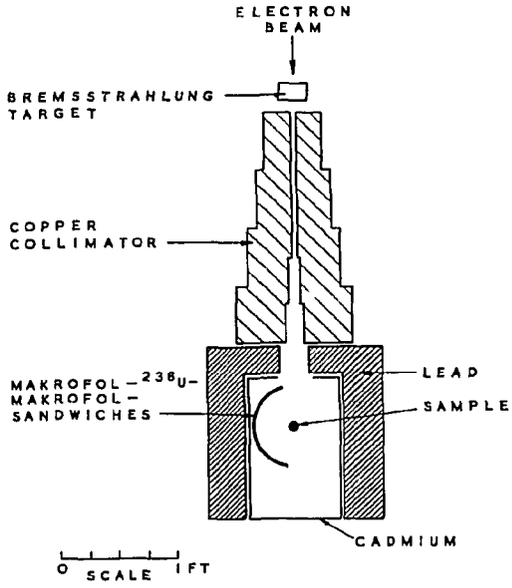

Fig. 1 Experimental arrangement.

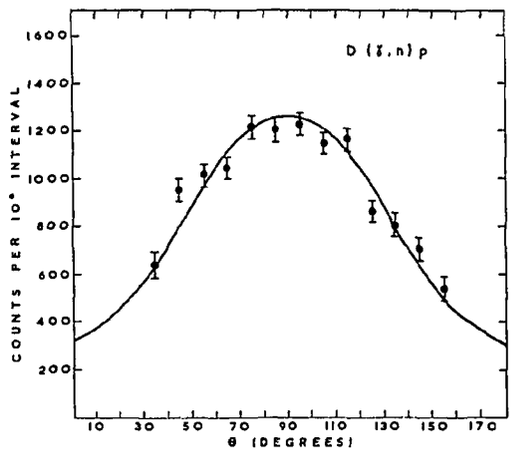

Fig. 2 Relative number of neutrons per 10° interval as a function of angle from the photodisintegration of deuterium. The curve is a theoretical calculation correctly weighted as explained in the list.

The use of track detectors, such as Makrofol, is now well established for measuring fission fragment angular distributions. The method devised for measuring neutron angular distributions makes use of this simple technique by using ^{238}U foils to convert the neutrons into fission fragments which are registered in the Makrofol. Fig. 1 shows the experimental arrangement. The energy analysed electron beam of the linac at the Wantage Research Laboratory strikes the bremsstrahlung target which is viewed by the sample through a copper collimator. The collimator is necessary to avoid direct photofission in the ^{238}U foils and copper was chosen because the neutron threshold lies above the 9 MeV end-point energy used. The sample was suspended at the centre of an 20 cm dia meter frame which held the ^{238}U and Makrofol. ^{238}U was chosen as the converter because of its high fission threshold and consequently its insensitivity to the low energy neutron background which usually exists in such photonuclear measurements. The ^{238}U foils were 30.5 cm long, 8.25 cm wide and 0.0013 cm thick. The thickness is very much greater than the range of the fission fragments but it makes handling very easy. It also means that there are no difficulties over non-uniformity of thickness and that Makrofol can be placed on both sides of the ^{238}U foil and each event counted only once. It was shown experimentally that fission fragments could not penetrate two thicknesses of Makrofol (10 microns thick) and this allowed sandwiches of Makrofol-^{238}U-Makrofol to be stacked together in the frame to get maximum statistics from a given run on the accelerator. Up to eight sandwiches were used at once. The assembly was shielded by lead and cadmium.

To prove that the technique works, we have measured the angular distribution of photoneutrons from deuterium since this is well known. A thin aluminium cylinder 3 in long and 0.75 in dia meter containing D_2O was hung at the centre of the frame, with H_2O being used for background runs. After exposure, the Makrofol was etched in 6N NaOH for 15 mins at 70°C. The resulting holes corresponding to the fission fragments were enlarged and made visible by the usual sparking process and counted by eye. Fig. 2 shows the measured angular distribution for deuterium with an end-point energy of 9 MeV. The curve was obtained from the theoretical calculations of Partovi(3) and is a weighted mean allowing for the effects of the bremsstrahlung spectrum, the total cross section and angular distribution of deuterium as a function of γ-ray energy and the fission cross section of ^{238}U. Also folded in are geometrical and scattering corrections. The curve was normalised to the same area as the experimental data and it can be seen that the agreement in shape is very good thus proving that the technique works.

In the deuterium runs, the background was about 20% and this was too high to allow a reasonable measurement on tin to be made. However, it is thought that the background was due to low energy neutrons which interacted in the 0.4% ^{235}U left in the depleted uranium. Unfortunately, the accelerator was closed down and dismantled at this point and it was not possible to make more measurements. However, we hope to make a further attempt using an accelerator very kindly put at our disposal by Mr. M. Kelliher of Vickers Ltd. at their factory. An improved neutron shield will be employed and hopefully this will reduce the background to an acceptable level.

The technique is extremely simple, requires no electronics and all angles are measured simultaneously. Although the result is an average over the bremsstrahlung spectrum, this is no great disadvantage in measurements of this kind.

---

(1) Nuclear Physics Division Progress Report AERE - PR/NP 17, p. 61 (1970).

(2) Winhold E. J., Bowey E. M., Gayther D. B. and Patrick B. H. Phys. Lett. 32B, 607 (1970).

(3) Partovi F. Ann. of Phys. 27, 79 (1964).

E. Isospin splitting in the giant resonance of ^{11}B (B. H. Patrick, H. A. Medicus*, G. K. Mehta+, E. M. Bowey and D. B. Gayther)

The degree to which the giant dipole resonance of some nuclides is divided into two fairly separate regions of different isospin has raised considerable interest but direct evidence of this has only recently been obtained(1). Since isospin selection rules permit only certain transitions, the splitting can be measured in suitable cases by observing which isospin states in the residual nuclide are reached when the giant resonance decays. This technique was applied by Murray(2) using a Ge(Li) detector to study the de-excitation γ-rays following particle emission from the giant resonance of ^{11}B but his results were inconclusive(3), possibly because of high background. We have also examined ^{11}B using the same technique and conclude that there is a splitting.

The isospin of the ground state of ^{11}B is T = 1/2 leading to T = 1/2 and T = 3/2 components in the giant resonance. Theoretical calculations by Fraser(4) place the bulk of the former between 16 and 21 MeV and that of the latter near 25 MeV. The selection rule of $\Delta T = 1/2$ means that the T = 0 states of ^{10}B cannot be reached directly by neutron emission from the T = 3/2 states of the ^{11}B giant resonance. If the dominant T = 1/2 and T = 3/2 states are indeed separated in energy, we should observe that transitions to the T = 1 states in ^{10}B and ^{10}Be originate predominantly from the higher energy region of the giant resonance and transitions to the T = 0 states in ^{10}B from the lower energy region.

The experimental arrangement and the method used in the data reduction have been described in detail elsewhere(5). The de-excitation γ-rays from a 49 gm sample of natural boron (purity >98%) were detected in a 30 cm^3 Ge(Li) detector.

---

* On leave from Rensselaer Polytechnic Institute, Troy, N.Y. 12181, U.S.A.

\+ On leave from Indian Institute of Technology, Kanpur-16 (U.P.), India.

γ-ray spectra were obtained using several bremsstrahlung end-point energies in the range 20 to 35 MeV and these data were used to give the energy dependence of the cross sections of the (γ,n) or (γ,p) reaction leading to a few particular states. The results are consistent with the interpretation that the lower energy region of the giant resonance of ^{11}B contains mainly T = 1/2 states whereas in the higher energy region T = 3/2 states are dominant. This is in reasonable agreement with the calculations of Fraser.

A more complete account of this work has now been published[6].

(1) Wu C. P., Firk F. W. K. and Berman B. L. Phys. Lett. 32B, 675 (1970).

(2) Murray K. M. Phys. Rev. Lett. 23, 1461 (1969).

(3) Hayward E., Schwartz R. B. and Murray K. M. Phys. Rev. C2, 761 (1970).

(4) Fraser R. J. Private communication. See also Kuan et al. Nuc. Phys. A151, 129 (1970).

(5) Medicus H. A., Bowey E. M., Gayther D. B., Patrick B. H. and Winhold E. J. Nuc. Phys. A156, 257 (1970).

(6) Patrick B. H., Medicus H. A., Mehta G. K., Bowey E. M. and Gayther D. B. Phys. Lett. 34B, 488 (1971).

E. Resonance capture gamma-ray studies (B. W. Thomas, H. P. Axmann (Vienna), P. Riehs (Seibersdorf) and E. R. Rae)

(a) Experimental improvements

Present work is concerned with the measurement of capture gamma-ray spectra for individual neutron resonances, and can be classified as follows:-

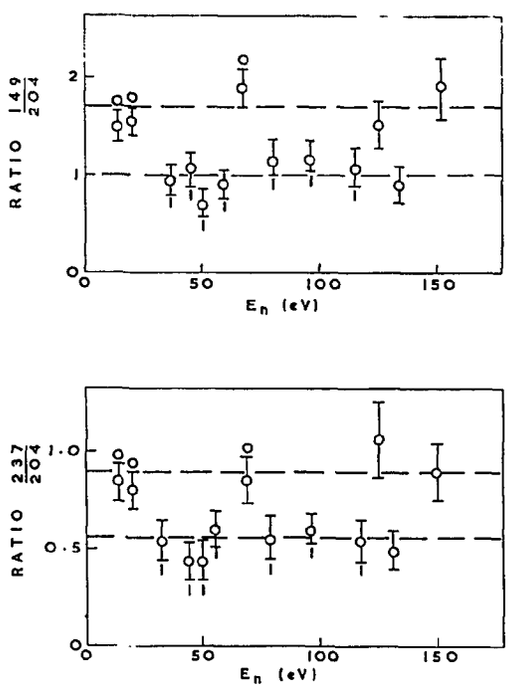

Fig. 1 Ratios of low energy transitions in ^{170}Tm: (Spin assignments are from ref. 1).

(1) Study of the variation of high energy primary gamma-rays (partial radiation widths) as a function of resonance energy

(2) Assignment of resonance spins using the intensity ratios of low energy gamma-rays.

It is apparent that the major difficulties associated with this type of work at present, particularly in the first group, are those due to the limited number of resonances available in any one measurement. This is largely due to the necessity for short flight paths because of the low efficiency of the detectors with the result that time-of-flight resolution is very poor. In past experiments at Harwell this work has been carried out at 10 and 20 metre stations, but recently a similar arrangement has been set up at 34 metres with a substantial gain in resolution. This has been made possibly by the purchase of a large volume Ge(Li) detector of 50 cm^3 with a higher efficiency and a general increase in flux from the Neutron Booster during "long pulse" running.

(b) Spin assignments for resonances in ^{181}Ta, ^{167}Er, ^{133}Cs and ^{169}Tm

The low energy neutron capture gamma-ray spectra for individual resonances of the above nuclei

have been measured with 4 cm^3 and 20 cm^3 Ge(Li) detectors at 10, 20 and 45 metre stations on the Neutron Booster. In the case of ^{181}Ta and ^{169}Tm metal samples were used while for the ^{137}Cs and ^{167}Er data the targets were caesium nitrate and enriched erbium oxide respectively. Data were collected by a two-parameter on-line system controlled by the PDP-4 computer. The results are shown in Tables 1 to 4, together with those of previous experiments.

Spin assignments for ^{169}Tm resonances have an important significance in connection with the discussion on correlations in the next section. The s-wave resonance spins are 0 or 1 and previous assignments have been made using identical techniques up to 115 eV by the Brookhaven group(1). The present experiment was necessary to check these results and extend them to 153 eV. The Brookhaven assignments were based on the ratio of two gamma-rays at 144.5 keV and 149.7 keV, the first of these being due to the decay of an isomeric state with a half-life of 3 microseconds. In the present experiment, however, the time-of-flight resolution is superior and prevents the use of this transition. Thus two additional gamma-rays at 204 keV and 237 keV have been adopted. The ratios of the 149 keV and 237 keV transitions to that at 204 keV are shown in fig. 1 and illustrate the degree of separation. The spin assignments listed in Table 4 are in perfect agreement with available data from the Brookhaven work. The assignments for the resonances at 125 eV, 136 eV and 153 eV differ from those derived from cross section measurements (BNL 325), but are considered more reliable.

(c) Investigation of possible correlations between reduced neutron widths and partial radiation widths in the $^{169}Tm(n,\gamma)$ reaction

The present investigation was carried out to clarify recent reports of significant correlations(2,3) between reduced neutron widths and partial radiation widths for resonance capture in ^{169}Tm. The previous work using both Ge(Li) and NaI detectors could be suspect due to either poor time of flight resolution(2) or incorrect spin assignments(2,3). The latter is particularly important since resonance spins for s-wave capture are 0 or 1, with the result that reduced neutron widths and partial radiation widths for J=0 resonances are generally enhanced. Previous attempts to show the presence of correlations have concentrated on the J=1 resonances and it is expected that incorrect spin assignments will lead to a false correlation. In the present analysis the spin assignments are taken from Table 4.

The experiment was carried out with a 4 cm^3 Ge(Li) detector at the 10 metre flight path of the Neutron Booster target. The thulium target consisted of 4 gms of metal in the form of two 1 inch discs. Data were collected by the two-parameter on-line system, which accepted all events for capture gamma-rays with energy greater than 1.5 MeV. Subsequent analysis of raw data yielded high energy capture gamma-ray spectra for all resonances below 160 eV. The spectra for 15 resonances [J=1(3,9,34,38,44, 50,59,83,94,115,136 eV),J=0(14,17,65,125,153 eV)] were analysed for individual partial widths in the energy range 5 MeV to 6.6 MeV. Resonances were normalised to the summed spectrum above 1.5 MeV and absolute widths obtained from a comparison of the 3.9 eV resonance spectrum with published data(2). The high energy spectra were in qualitative agreement with the spin assignments of Table 4 to the extent that transitions from J=0 resonances to 4 known final states of spin 0 or 2 were consistently weak. The data were tested for possible reduced neutron width-radiation width correlations for the ten J=1 resonances. The transitions included in the analysis were identical to those of previous authors (i.e. transitions to final states observed in d,p experiments). The average correlation coefficient for 15 final states was 0.1. This result contradicts previous evidence for correlations since Monte Carlo calculations indicate that the probability of obtaining by chance a value greater than this is at least 14%. Reasons for the discrepancies with previous data are difficult to establish, although in the case of the Argonne work(3) with NaI detectors the reassigned spin of the 153 eV resonance removes the correlation almost completely. The Brookhaven analysis(2) included the same resonance but is less sensitive to it. In this case if we neglect the 153 eV resonance the 3.9 eV resonance contributes most to the correlation. This fact, together with the knowledge that the sample of resonances is small, and that resolution is poor, may have introduced an artificial correlation in the data. In the immediate future an experiment is scheduled on the 34 metre flight path with a thulium oxide target to increase the range of data up to 300 eV.

(1) Bhat M. R. et al. Brookhaven National Laboratory Report BNL 14729 (1970).
(2) Beer M. et al. Phys. Rev. Letters 20, 340 (1968).
(3) Bollinger L. M. "Nuclear Structure, Dubna Symposium 1968" (IAEA Vienna, 1968) p. 317.

TABLE 1

Tantalum resonance spin assignments

E_R (eV)	J					
	Wood (1956)	Stolovy (1967)	Evans (1958)	Poortmans (1967)	Wasson (1969)	Present Work
4.3	4	4	(3,4)		4	4
10.3		3	4		3	3
13.9			(3,4)		4	3
20.3			(3,4)			4
22.7						3
23.9			(3,4)	3	3	4
30.0						3
35.1			4		(3,4)	3,4
35.9			4		(4,3)	4
39.1			4			4
49.1						3
63.1			(3,4)			4
76.8						4
77.6						4
78.9						3
82.9						4,3
85.1						3
89.6						3
91.4						3
99.3						4,3

Wood R. E. Phys. Rev. 104, 1425 (1956)
Evans J. E. et al. Nucl. Phys. 9, 205 (1958)
Poortmans F., Ceulemans H. Nucl. Phys. A97, 483 (1967)
Stolovy A. Phys. Rev. 155, 1330 (1967)
Wasson O. A. et al. Nucl. Phys. A132, 161 (1969)

TABLE 2

Erbium-167 resonance spin assignments

E_R (eV)	J		
	Sailor (1961)	Wetzel (1970)	Present Work
0.46	4	4	
0.58	3	3	
5.98	3	3	
7.92			
9.38	3	3	
20.26		4	4
22.03		3	3
26.05		3	3
27.44		4	4
32.90			4
37.70			4
39.48			3
42.30			3
50.30			4
53.65			4
60.00			3
69.53			4
74.54			) (4)
75.90			)
79.40			3
85.54			3
91.35			4
94.95			4
107.71			3
131.70			4
142.30			4

Sailor V. L. BNL 325 (Second Edition) (1961)
Wetzel K. J., Thomas G. E. Phys. Rev. 4C, 1501 (1970)

TABLE 3

Caesium-133 resonance spin assignments

E_R (eV)	J
5.90	3
22.6	3
47.8	3
83.1	4
94.8	3
126.1	4
145.9	4
200.9	4
220.4	4
234.4	4
295.6	4
359.0	4

TABLE 4

Thulium-169 resonance spin assignments

E_R (eV)	J	
	Present Work	Bhat (1970)
14.4	0	0
17.5	0	0
29.1		1
34.8	1	1
38.0		1
44.8	1	1
50.7	1	1
59.2	1	1
63.0		1
65.8	0	0
83.4	1	1
94.0	1	1
115.2	1	1
125.2	0	
136.1	1	
153.0	0	

Bhat M. R. et al. BNL 14 729 (1970)

E. Fission fragment angular distributions from resonance fission with oriented nuclei (N. J. Pattenden and J. E. Jolly; H. Postma, R. Kuiken and K. Ravensberg (F.O.M. Netherlands))

During the period covered by this report the ^{235}U and ^{233}U data, previously mentioned[1] have been re-analysed, with particular attention being given to possible systematic errors. For both nuclei the experimental distributions of resonance A_2 values[1] have been compared to distributions calculated on the assumption that the energetically available transition states (with known K-, and therefore A_2-values) correspond to fission channels, each of which may contribute a partial fission width to each neutron resonance. The variation of partial width for each channel from resonance to resonance should follow a Porter-Thomas distribution[2].

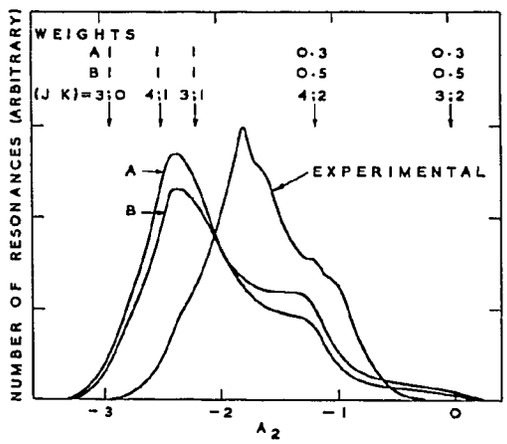

Fig. 1 Weighted frequency distribution of A_2(obs.) resonance values. Also two simulated distributions A and B of A_2(res.) are shown. The latter were obtained under the assumptions of equal contributions from the two spin states, a randum selection from a Porter-Thomas distribution for Γ_{fK} and assuming relative weights (W) for different channels as indicated in the figure. Positions of A_2(J,K) are also shown (except for K-3 and 4).

In the case of ^{235}U, the shape of the calculated distribution agrees well with the experimental one (see fig. 1), but the absolute magnitudes were discrepant by about 25%. An X-ray crystallographic study of the individual crystals of the samples, carried out by Dr. P. T. Moseley, Applied Chemistry Division, showed that one crystal of the thin and two crystals of the thick sample were incorrectly mounted. A correction for this gives an increase in magnitude of 10% to the experimental A_2 values. The difference between the experimental and calculated A_2 distributions is now about 15%, which is within the limits of possible systematic error (due to uncertainties in sample temperature, quadrupole coupling constant and solid angle effects) of about 20%.

In the case of ^{233}U, a similar situation exists, in that the shape of the calculated distribution corresponds with the experimental one, but the former is larger in magnitude by about 50%. It has not so far been possible to carry out an X-ray study of the crystal orientations. However, in this case, observations of anisotropy of α-particle emission indicate that the fraction of misoriented crystals is rather small and cannot explain such a discrepancy. Possible explanations could be (1) the value of quadrupole coupling constant is wrong, (2) the fission model used to obtain the calculated A_2 distribution is inadequate in the case of ^{233}U.

In the case of ^{237}Np[1], collection of data continued until January 1971. The analysis made so far strengthens the suggestion made previously[1] that the group of resonances at 40 eV has (J,K) values of (2,2). There are indications that most groups observed below 1000 eV have (J,K) values of either (2,2) or (3,2) with about equal occurrence of each.

(1) Nuclear Physics Division Progress Report AERE - PR/NP 17, p. 19 (1970).

(2) Porter C. E. and Thomas R. G. Phys. Rev. 104, 483 (1956).

Further analysis of the neutron-induced fission cross section of ^{230}Th (G. D. James and J. E. Lynn)

Since the last progress report on this topic, some new measurements, made by J. R. Huizenga's group at Rochester[1], have come to our notice. These are measurements of the angular distribution of the fission products over the 720 keV peak in the cross section, but made with much sharper neutron energy resolution than our own measurements. Mostly these new results agree with our measurements, but there is an exception in the data at 730 keV; the Rochester data show a much sharper degree of angular anisotropy at this energy, indicating that here there is a class-II state of high angular momentum with width much less than the main components of the 720 keV peak.

We have therefore re-analysed all the data, assuming that either the J = 5/2 or J = 7/2 component of the K = 1/2 class-II rotational band lies at 730 keV. A rather smaller degree of J = 7/2 than J = 5/2 component is required for reasonably acceptable angular distributions, so the former hypothesis fits the energy dependence of the cross section a little better; it also leads to a rotational band parameter, $\hbar^2/2\mathcal{J}$, equal to about 2.5 keV (suggesting an effective moment of inertia, $\mathcal{J}$, for the class-II state that is two to three times the value of the ground state rotational band) whereas the second hypothesis gives $\hbar^2/2\mathcal{J} \approx 0.5$ keV which seems unreasonably small ($\mathcal{J} \approx 10$ to 15 times $\mathcal{J}_{ground}$). The new data and analysis lower the value of the moment of inertia deduced in the previous work[2], but only by a relatively small amount.

All the data up to about 1200 keV have also been reanalysed, using numerical calculations of the fission strength function based on realistic models of the double-humped fission barrier. In this analysis the K = 1/2 band at about 1200 keV is best interpreted as the next vibrational state associated with the 720 keV band; this implies that the second well vibrational frequency, $\hbar\omega_{II}$, is about 0.6 MeV, the barrier tunnelling "frequencies", $\hbar\omega_{A,B} \approx 0.75$, 0.57 MeV and the barrier heights (with respect to zero neutron energy) are $V_{A,B} \approx 0.89$, 1.14 MeV.

---

(1) Huizenga J. R. Private communication.

(2) Nuclear Physics Division Progress Report AERE - PR/NP 17, p. 33 (1970).

Analysis of excitation functions for shape isomers formed by neutron evaporation processes (J. E. Lynn, in collaboration with H. C. Britt and W. E. Stein at Los Alamos Scientific Laboratory*)

Many spontaneously fissioning isomers of actinide nuclei have now been discovered, particularly among the isotopes of Pu, Am and Cm. In many cases cross sections for the formation of the isomer as a function of the energy of the particle initiating the reaction have been measured. It was the purpose of this study to use these data for the determination of properties of the Strutinsky fission barrier.

In these reactions the isomer is formed following the evaporation of one or more neutrons from the highly excited initial compound nucleus. At energies just above threshold a small fraction of the evaporated neutrons in the last stage will populate discrete class-II levels which then decay by γ-ray emission to the isomeric state. At higher energies the levels populated can no longer be classed as pure class-II or class-I and may no longer be discrete. Thus the details of the γ-ray cascade feeding eventually into the isomeric state have to be analysed. A statistical model to treat the various modes of decay (including the overall prompt fission decay mode, against which the delayed fission yield from the isomer is measured) has been postulated and analysed.

The general conclusions to emerge are as follows: (1) To be consistent with neutron-induced fission cross sections the intrinsic level densities at the barrier deformations have to be governed by a "Fermi-gas" parameter (proportional to the single-particle level density at the Fermi energy) that is

---

*This work was carried out while J. E. Lynn served as a Consultant at Los Alamos in the summer of 1970.

10 to 20% greater than the corresponding parameter for the primary and secondary well deformations; (2) In the cases where comparisons can be made the isomer threshold is rather higher than that deduced from intermediate structure in resonance neutron-induced fission reactions. This suggests that level density behaviour in the secondary deformed shape may be rather different from that in the primary shape, for it was on the assumption of similar level densities that the latter deduction was made; (3) In the Pu, Am and Cm nuclei it appears that the outer barrier of the double-humped potential is lower than the intermediate barrier. The energy difference of the barriers appears to be up to 0.8 MeV in the Pu nuclei, about 1 MeV in the Am nuclei and up to 1.5 MeV in the Cm nuclei. Further details can be found in Los Alamos Report LA-DC-12669.

Theoretical estimates of γ-ray decay of spontaneously fissioning isomers (J. E. Lynn)

In the shape isomers of the actinide nuclei, the spontaneous fission decay branch is the most dramatic and obvious mode of decay. Among other modes of decay gamma-ray emission is always possible in principle, but is expected to be extremely difficult to measure, and, in spite of sophisticated attempts, it has not yet in fact been unambiguously confirmed (but see, however, T. W. Conlon in the last progress report(1), in whose account it is made very plausible that the γ-ray decay of a shape isomer in ^{214}Ra, without an appreciable spontaneous fission branch, has been observed). The deduction from analysis of shape isomer excitation cross sections that the outer barrier is lower than the intermediate barrier in the Strutinsky potential of heavy actinide nuclei could therefore be upset by the existence of a γ-ray decay branch that is one to two orders of magnitude stronger than the spontaneous fission branch. Such a γ-ray decay branch would have to be reasonably systematic in its strength from nucleus to nucleus and therefore would have to be composed principally of a collective type of transition, the most probable such transition being an E2 transition across the states of a β-vibration-rotation band.

Earlier considerations(1) suggested that this type of transition in the isomer decay would be dominated (by a factor of the order of 10^2 to 10^3) by the normal transitions characteristic of compound states at the isomer excitation energy. In coming to this conclusion the estimate of the E2 collective transition was a simple one based on the amplitude within the primary well of the tail of the isomer state wave function; no account was taken of the behaviour of the wave functions of initial and final states between the primary and secondary wells. There are in fact very great numerical difficulties in calculating properly such a transition strength for realistic Strutinsky potentials composed of segmented harmonic oscillator curves.

A calculation has been made therefore for the case of two rectangular wells separated by a rectangular barrier. In this case the required matrix elements can be computed precisely. Three different arrangements of the lowest class-II (isomer) state relative to the class-I vibrational levels were considered. In one (isomer state about mid-way between two class-I vibrational levels) the increase in transition strength over that given by the simple prescription described above was a factor of 10. In a second (isomer state just below a class-I state) the enhancement factor was about 1.5, while in a third (isomer state just above a class-I state) the enhancement factor was about 10^2. While it appears from these calculations that the collective contribution to the transition can in some instances be much more important than estimated in ref. (2), it still does not seem likely that it can dominate the transition. We still expect, therefore, that the γ-ray mode of decay of a shape isomer should fluctuate strongly from nucleus to nucleus, that the apparent absence of a similarly strong fluctuation from spontaneous fission excitation cross sections indicates the predominance of the fission mode of decay, and that the conclusion of a low outer barrier is unaffected.

---

(1) Nuclear Physics Division Progress Report AERE - PR/NP 17, p. 38 (1970).

(2) Lynn J. E. "Physics and Chemistry of Fission" (IAEA, Vienna) p. 249 (1969).

C. The $^6Li\ (p,^3He)\ ^4He$ reaction (B. W. Hooton and M. Ivanovich)

The relevance of this reaction to the design of a fusion reactor based on a lithium plasma has been discussed by Crocker et al.[1] Measurements have been made on the differential cross section between 20° and 160° at proton energies between 1.0 and 2.4 MeV and on the differential cross section at 90° from 1.0 to 4.0 MeV. A strong emphasis was placed on obtaining reliable absolute cross sections since there is considerable disparity between previous results.[1]

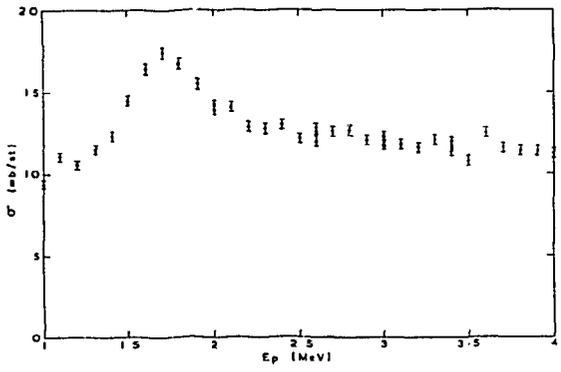

Fig. 1a Excitation function for the $^6Li(p,^3He)^4He$ reaction at $\theta_{Lab} = 90^o$ normalised to 12.88 mb/st at 2.2 MeV.

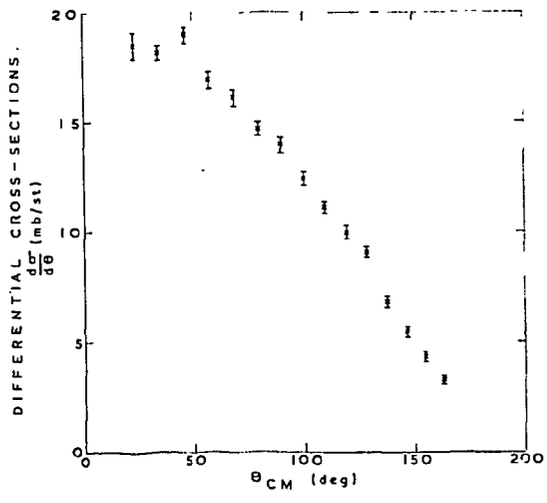

Fig. 1b Differential cross section at E_p=1.4 MeV

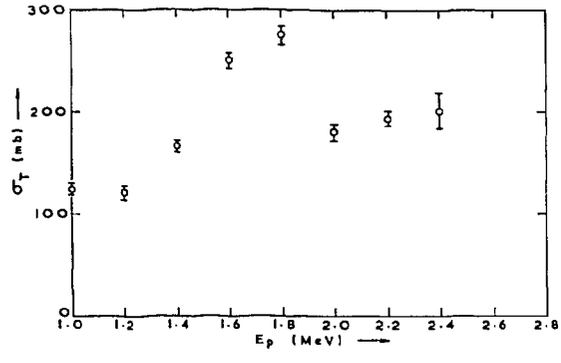

Fig. 2 Total cross section of the $^6Li(p,^3He)^4He$ reaction.

The most likely cause of systematic error in the previous work by other experimenters is the determination of ^6Li in the target; in the present measurements this is determined by Rutherford scattering of ^4He. Elastic scattering of ^4He at 30°, 35° and 40° was found to obey the $Cosec^4(\theta/2)$ Rutherford law and to have a E^{-2} energy dependence in the range 1.6 to 1.8 MeV. Targets of 15 $\mu gm/cm^2$ Li (95% ^6Li) on a 5 $\mu gm/cm^2$ carbon foil were used and elastically scattered ^4He particles were detected using a Si surface barrier detector. Checks for systematic errors in current intergration and counter geometry were made by determining the thickness of a thin Ni foil by both elastic scattering and weighing. The cross section for the $^6Li(p,^3He)^4He$ reaction at 90° (LAB) and E_p = 2.2 MeV was measured using three targets whose thicknesses were determined before and after the measurement. This cross section of 12.9 mb/st was used to normalise all subsequent runs which were repeatedly checked for target deterioration. An excitation function at 90° is shown in fig. 1a and an angular distribution in fig. 1b. The angular distributions were measured using a second Si counter as a monitor and fitted to a series of legendre polynomials to obtain the total cross section shown in fig. 2.

The total cross section is larger than all previous measurements[1], which show a considerable spread in values, and these earlier low cross sections can possibly be accounted for by the targets consisting of unsuspected amounts of lithium compounds such as the carbonate or hydroxide. The elastic scattering measurements on our targets, for example, showed considerable oxygen and a nominal 15 $\mu gm/cm^2$ Li target was found to contain less than 5 μgm of lithium.

---

(1) Crocker B. S., Blow S., and Watson C. J. H. Culham Report CLM-P240.

REPORTS, PUBLICATIONS AND CONFERENCE PAPERS

REPORTS

AERE - R 6429 An activation technique for the absolute calibration of a long counter. J. M. Adams, A. T. G. Ferguson and C. D. McKenzie.

AERE - R 6473 A study of the nuclei ^{12}N, ^{16}F, ^{22}Mg, ^{26}Si and ^{30}S by (^{3}He,n) reactions. J. M. Adams, A. Adams and J. M. Calvert.

AERE - R 6633 Application of distribution-free statistics to the structural analysis of slow neutron cross section and resonance parameter data. G. D. James.

AERE - R 6676 Fission yield from freshly prepared ^{241}Pu. G. D. James.

AERE - R 6812 Note on the energy spread versus radial oscillation amplitude for the synchrocyclotron regenerative beam extractor. D. West.

PUBLICATIONS

FERGUSON A. T. G. and ELWYN A. J. Short lived fission isomers from neutron studies. Nucl. Phys. A148, 337 (1970).

MEDICUS H. A., BOWEY E. M., GAYTHER D. B., PATRICK B. H. and WINHOLD E. J. The photo-disintegration of ^{12}C leading to excited states of ^{11}B and ^{11}C. Nuc. Phys. A156, 257 (1970).

PATRICK B. H., MEDICUS H. A., MEHTA G. K., BOWEY E. M. and GAYTHER D. B. Isospin splitting in the giant resonance of ^{11}B. Phys. Lett. 34B, 488 (1971).

PATRICK B. H., SOWERBY M. G. and SCHOMBERG M. G. Structure in the fission cross section of ^{235}U. J. Nuc. Energy 24, 269 (1970).

PATTENDEN N. J. and POSTMA H. Fission of aligned ^{235}U nuclei induced by neutrons of 0.2 to 2000 eV. Nuc. Phys. A167, 225 (1971).

RAE E. R. and BLOCK R. C. Neutron scattering and capture cross section measurements. Chapter 3 of "Experimental Neutron Resonance Spectroscopy", Ed. J. A. Harvey, Academic Press, New York (1970).

RAE E. R. and GOODE W. M. Pulsed accelerator time-of-flight spectrometers. Chapter 1 of "Experimental Neutron Resonance Spectroscopy", Ed. J. A. Harvey, Academic Press, New York (1970).

SOWERBY M. G., PATRICK B. H., UTTLEY C. A. and DIMENT K. M. The ratio of the $^{6}Li(n,\alpha)$ to $^{10}B(n,\alpha)$ cross sections from 10 eV to 80 keV and recommended values of the $^{10}B(n,\alpha)$ cross section. J. Nuc. Energy 24, 323 (1970).

WINHOLD E. J., BOWEY E. M., GAYTHER D. B. and PATRICK B. H. Structure in the gamma-ray strength function of ^{119}Sn and ^{117}Sn. Phys. Lett. 32B, 607 (1970).

IN COURSE OF PUBLICATION

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

JAMES G. D. Fission yield from freshly prepared ^{241}Pu. J. Nuc. Energy.

CONFERENCE PAPERS

Invited Papers

COATES M. S. Neutron flux measurements. American Physical Society Meeting, Division of Nuclear Physics, Houston, Texas, October 1970.

RAE E. R. Experimental neutron spectroscopy - present state and development prospects. Int. Meeting on Perspectives of Neutron Spectroscopy, Dubna, USSR, October 1970.

UTTLEY C. A., SOWERBY M. G., PATRICK B. H. and RAE E. R. A review of the ^{6}Li cross sections below 1.7 MeV. EANDC Symposium on Neutron Standards and Flux Normalisation, Argonne, October 1970.

Conference Papers

EANDC Symposium on Neutron Standards and Flux Normalisation, Argonne, October 1970

COATES M. S., HUNT G. J., UTTLEY C. A. and RAE E. R. Experimental tests using the time-of-flight method on a neutron detector with a flat energy response.

COATES M. S., HUNT G. J. and UTTLEY C. A. Preliminary measurements of the relative $^{6}Li(n,\alpha)$ cross section.

SOWERBY M. G., PATRICK B. H., UTTLEY C. A. and DIMENT K. M. Recommended values of the $^{10}B(n,\alpha)$ cross section below 200 keV.

UTTLEY C. A. An analysis of the total cross section of carbon up to 1.5 MeV.

Third Conference on Neutron Cross Sections and Technology, Knoxville, 15-17 March 1971

UTTLEY C. A., SOWERBY M. G., PATRICK B. H. and RAE E. R. A review of the data on the ^{6}Li cross sections below 1.7 MeV.

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

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

The half-life of ^{241}Pu (M. J. Cabell and M. Wilkins)

In an earlier publication[1] one of us gave details of a bias-free mass spectrometric measurement of the half-life of an 'old' (i.e. out of the reactor for at least three years) sample of ^{241}Pu. This experiment has been continued and, from an analysis of 17 data points taken over a period of exactly 8 years, it has now been concluded that the half-life of this nuclide is 15.10±0.14 years. The most recent measurements have yielded a constant half-life, with increasing precision as more data points have been acquired.

An isomeric state of ^{241}Pu? (M. J. Cabell and M. Wilkins)

A mass spectrometric measurement, similar to that described above, has been used to study the decay of a sample of freshly irradiated and purified ^{240}Pu. The first measurement was taken 39.4d after the end of the irradiation and the decay was studied for 120 days thereafter. The results did not result in the confirmation of a 0.34 yr isomer of ^{241}Pu which has been postulated[2]. It was concluded that, if the postulated isomer decays by direct β^- emission, less than 1% of the ^{241}Pu present in the sample could have been in this form. This result, combined with that of other investigations, makes the possibility of a short-lived isomer of ^{241}Pu most unlikely.

The thermal neutron capture cross sections of ^{234}U and ^{236}U (M. J. Cabell and M. Wilkins)

Aliquots of mixtures prepared from isotopically pure ^{234}U (98.84%) and isotopically enriched ^{236}U (99.76%) and ^{238}U (99.996%) were irradiated, with cobalt monitors, in the DIDO reactor for approximately two years. The irradiation positions chosen provided essentially thermal neutrons ($r = (7.5 \pm 1.0) \times 10^{-4}$) of known temperature (116±9°C). After irradiation the uranium was purified by reversed-phase partition chromatography, then mass analysed. Un-irradiated samples of the mixtures were mass analysed in a similar way.

The activities of the cobalt monitors were determined absolutely and the neutron doses they received could then be calculated.

The neutron capture cross sections of ^{234}U and ^{236}U for the reactor neutrons (i.e. $\hat{\sigma}$) were found to be 101.1±1.3b and 8.86±4.00b respectively, and from these figures the capture cross sections for Maxwellian neutrons (i.e. $\sigma_0 g$) were deduced as 100.5±1.3b and 8.47±4.00b.

The thermal neutron capture and absorption cross sections of ^{232}U and the thermal neutron capture cross section of ^{233}U (M. J. Cabell and M. Wilkins)

Aliquots of a mixture prepared from isotopically pure (98.9%) ^{232}U and isotopically enriched (99.76%) ^{236}U were irradiated, with cobalt monitors, in the DIDO reactor, for the same time, and under similar conditions as the samples described above. After irradiation the uranium was purified by reversed-phase partition chromatography, then mass analysed. Un-irradiated samples of the mixture were mass analysed in a similar way.

The thermal neutron absorption and capture cross sections of ^{232}U were found to be 148.3±4.4b and 73.1±1.5b respectively; $\hat{\alpha}$ was found to be 0.972±0.061. These results are more precise, but in substantial agreement with earlier measurements of the total, capture and fission cross sections of this nuclide[3].

---

(1) Cabell M. J. J. Inorg. Nucl. Chem. 30, 2583 (1968).

(2) Nisle R. G. and Stephen I. E. Nucl. Sci. and Eng. 39, 257 (1970).

(3) Cabell M. J. and Wilkins M. Proc. Int. Conf. on Chemical Nuclear Data, Canterbury, P. 161 (1971).

In a separate, and similar experiment, using mixtures of ^{233}U (99.76%) and ^{236}U (99.76%), the thermal capture cross section of ^{233}U for 2200 m/sec neutrons was found to be 48.35±1.62b.

Activation measurements of the cross section of the reaction $^{147}Pm(n,\gamma)^{148g}Pm$ for reactor neutrons (M. J. Cabell)

The effective cross section of the reaction $^{147}Pm(n,\gamma)^{148g}Pm$ has been measured for reactor neutrons. ^{197}Au and ^{59}Co monitors have been used to determine the 2200 m/sec neutron fluxes in the spectra employed, and cadmium ratio measurements for gold and the silver-cobalt activity ratio method have been used to determine the epithermal indices.

The amounts of ^{148g}Pm formed, and the amounts of ^{147}Pm from which they were formed, were both determined after purification of the irradiated material. Gamma spectrometry was used for the former purpose, and the $4\pi\beta$-γ tracer method, with ^{46}Sc as the tracer, was used for the latter.

The cross section of the reaction for Maxwellian neutrons ($\sigma_{o,g}$) and its reduced resonance integral (Σ') were found to be 96.0±1.8 barns (T = 60°C) and 1274±66 barns respectively.

The half-life of ^{144}Ce (M. J. Cabell and M. Wilkins)

An evaluation of published data has led to the conclusion that the half-life of ^{144}Ce is 284.4±0.4d.

Reports and Publications

Reports

AERE - R 6529 Concerning the half-life of ^{144}Ce. M. J. Cabell and M. Wilkins.

AERE - R 6761 The thermal neutron capture cross sections of ^{234}U and ^{236}U. M. J. Cabell and M. Wilkins.

Publications

Cabell, M. J. Activation measurements of the cross section of the reaction $^{147}Pm(n,\gamma)^{148g}Pm$ for reactor neutrons. J. Inorg. Nucl. Chem. 32, 3433 (1970).

Cabell M. J. and Wilkins M. An isomeric state of ^{241}Pu? J. Inorg. Nucl. Chem. 33, 903 (1971).

CHEMISTRY DIVISION, A. E. R. E.

(Division Head: Dr. W. Wild)

For administrative reasons it is inconvenient to report the work of the Chemistry Division in this document. The progress report for the period Mid 1971 to March 1972 (UKNDC(72)P.37, EANDC(UK)140AL, INDC(UK)15G) will include reports covering this period.

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

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

During the period of this report, the Nuclear Research Division has been engaged in 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 and D. Porter)

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

(i) Sodium AWRE Report O 3/71

"The time of flight method has been used to study 5.0 MeV neutron elastic and inelastic scattering by sodium. Differential cross sections at ten angles between 30° and 135° were measured for elastic scattering and for inelastic scattering to seven levels up to 3.88 MeV excitation in the target nucleus.

This work was originated to provide information on the shape of the elastic angular distribution and where appropriate, comparisons are made with existing data in the UKAEA Nuclear Data File No. 182 for sodium."

(ii) Natural Molybdenum AWRE Report O 89/70 (EANDC(UK)126AL)

"The time of flight method has been used to study fast neutron elastic and inelastic scattering in the energy range 1.0 to 5.0 MeV by natural molybdenum. Differential cross sections at ten angles from 30° to 135° were measured at 0.5 MeV intervals between 1.5 and 5.0 MeV for elastic scattering, inelastic scattering to groups of levels up to 1600 keV excitation in the target nucleus and inelastic scattering to a continuum above this 1600 keV level.

Excitation functions were derived from 125° yields measured at 0.2 MeV intervals between 1.0 and 3.0 MeV for inelastic scattering to groups of levels up to 1600 keV excitation in the target nucleus. The continuum spectra in the range 2.0 to 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.

Since the intention of this report is to provide detailed experimental data in the range 1.0 to 5.0 MeV prior to an evaluation of scattering cross sections for natural molybdenum, no attempt has been made to compare the data with theoretical predictions. Moreover, above 2.0 MeV incident neutron energy, few experimental data are available with which to make comparisons, although comparisons are made where appropriate to previously evaluated cross sections."

2 (n,2n) Measurements (D. S. Mather, G. James, P. J. Nind and P. F. Bampton)

Measurements of the (n,2n) cross section using the large liquid scintillator have been continued. Data have been obtained at 14 MeV for ^{93}Nb, Mo (natural), ^{103}Rh, ^{169}Tm, ^{197}Au, ^{235}U and ^{238}U. The

analysis of the data is in progress.

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

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 continued at a low priority.

II EVALUATION OF NEUTRON DATA

1 Evaluation of the Neutron Cross Sections for Carbon (A. C. Douglas, D. Porter and K. Wyld)

The evaluation of the available data for carbon had been completed and a report has been written describing this. The abstract is as follows:

> "A survey of all references and data available at June 1970 on the cross sections and angular distributions for total, elastic and inelastic scattering of neutrons from natural carbon in the energy range 1 eV to 15 MeV has been made. Evaluated data for use in neutronics calculations have been produced from semi-automatic fits to edited experimental cross sections while for the angular distributions of the elastically scattered neutrons eye-fits were made to the Legendre polynomial coefficients of these distributions as functions of incident energy guided where necessary, by theoretical estimates. Comparisons of the recommended data with the existing UKAEA data file contents for carbon are presented and show an overall reduction in the total cross section below 2 MeV and significant alterations in the inelastic cross section to the first excited state in ^{12}C below 9 MeV. The elastic scattering angular distributions are generally unchanged except in the range 2-9 MeV."

2 Evaluation of the Inelastic Scattering Cross Section for ^{238}U and ^{239}Pu (A. C. Douglas and K. Wyld)

(i) ^{238}U

An evaluation has been made of the experimental data available up until January 1971 on the cross section for inelastic scattering of neutrons from ^{238}U in the energy range up to 2 MeV. Recommended cross sections have been produced for the excitation of 10 discrete levels up to 1047 keV with the excitation of higher levels included in a continuum. These recommendations are based essentially on the recent data from Smith at Argonne and from Barnard in South Africa. Above 2 MeV no new experimental data are available and the recommended cross sections are similar to previous evaluations. These cross sections have been included in a new file DFN 272 in the UK Nuclear Data Library.

(ii) ^{239}Pu

An evaluation has been made of the available data on the cross section for inelastic scattering of neutrons from ^{239}Pu. Very few experimental data are available and so the recommended cross sections are based mainly on nuclear theory predictions. Recommended cross sections have been produced for the excitation of 9 discrete levels up to 392 keV with the excitation of higher levels included in a continuum. The recommendations are based on the calculations reported by Prince[1] at the 1970 Helsinki Conference but adjusted at energies below 1500 keV to give agreement with the experimental data of Cavanagh et al[2]. These cross sections have been included in a new file DFN 269 in the UK Nuclear Data Library.

---

(1) Prince A. Nuclear Data for Reactors II 825, IAEA Vienna (1970).

(2) Cavanagh P. E., Coleman C. F., Boyce D. A., Gard G. A., Hardacre A. G. and Turner J. F. AERE - R 5972 (1969).

3 Evaluation of the Number of Neutrons per Fission $\bar{\nu}$ for ^{235}U, ^{238}U and ^{239}Pu (D. S. Mather and P. F. Bampton)

Evaluations have been made of the available experimental data on $\bar{\nu}$ for neutron induced fission of the isotopes ^{235}U, ^{238}U and ^{239}Pu in the energy range up to 15 MeV. Reports have been published describing these three evaluations in detail. The abstracts of these reports are as follows:

(i) ^{239}Pu AWRE Report O 86/70 (EANDC(UK)125AL)

"Data available before July 1970 on direct measurements of $\bar{\nu}$ for the neutron induced fission of Pu-239 have been considered and an evaluation consisting of a set of four straight lines specifying the variation of $\bar{\nu}$ with neutron energy has been produced for entry in a new data file, DFN 269."

(ii) ^{238}U AWRE Report O 44/71 (EANDC(UK)136AL)

"An evaluation has been made of direct measurements of $\bar{\nu}$ for the neutron induced fission of U-238 using data available up to December 1970. A set of three straight lines is found to give the best representation of the variation of $\bar{\nu}$ with neutron energy and values specifying this evaluation have been produced for entry in a new Data File DFN 272."

(iii) ^{235}U AWRE Report O 55/71 (EANDC(UK)132AL)

"An evaluation has been made of direct measurements of $\bar{\nu}$ for the neutron induced fission of U-235 using data available before January 1971 and evaluated values entered into a new data file DFN 271. Below 1.75 MeV a non-linear variation is evident with a step-like structure between 0.2 and 1.4 MeV, a spline fitted curve has been used to describe this region. For the energy range 1.75 - 15.0 MeV the evaluation has been specified by a set of 4 straight lines."

The publication of these reports completes the $\bar{\nu}$ evaluations.

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

In collaboration with M. G. Sowerby and B. H. Patrick of AERE, Harwell, a simultaneous evaluation has been made of the fission cross sections of ^{235}U, ^{238}U and ^{239}Pu and the capture cross section of ^{238}U in the energy range 100 eV to 20 MeV. The recommended cross sections have been incorporated in new files in the UK Nuclear Data Library.

5 Production of Files for the UK Nuclear Data Library (A. C. Douglas, D. S. Mather, P. F. Bampton and K. Wyld)

The nuclear data recommended by the evaluations mentioned above have been incorporated in new data files for inclusion in the UK Nuclear Data Library. Data for other cross sections etc., were generally taken from earlier files in the Library i.e. from earlier evaluations but adjustments were made to ensure that, at each energy quoted, the sum of the partial cross sections was equal to the total cross section. The new files were checked for consistency with the Library Format and for arithmetic errors using the CHECK 1 programme. Graphical checks were made using the GROD 2 programme.

New files were produced for:

C - DFN 902	^{235}U - DFN 271
^{238}U - DFN 272	^{239}Pu - DFN 269

III PRODUCTION AND MAINTENANCE OF COMPUTER CODES

1 The SCORE Programme (J. Cameron)

SCORE is a semi-automatic neutron data evaluation programme written by a group at Atomics International. It is operational at AWRE. During the period of this report, only minor modifications have been made to SCORE to accommodate changes in computer operation.

2 The MISSIONARY Programme (J. Cameron)

A computer programme, named MISSIONARY, has been written. This converts data files in the ENDF/B Format to the UK Nuclear Data Library Format. The most usual quantities are converted: cross sections, angular distributions, secondary energy distributions and the number of neutrons per fission $\bar{\nu}$. Other quantities, such as photon production data are ignored.

Since the conversion involves changes in representation as well as in layout, an exact or "word-for-word" translation is not possible. The accuracy of the conversion is controlled by input parameters.

Briefly, tabulations are generated for ENDF/B parametric forms and extra points are added, where necessary, to ENDF/B tabulations. Surplus points and distributions are discarded and the data re-ordered to UK order before finally being output in the UKNDL format.

MISSIONARY is written in FORTRAN IV for IBM 360/370 under OS. Extensive use is made of auxiliary storage (disks) and the core requirement varies from about 180K depending on the amount of buffer space allocated. CPU time on the 360/75 for a long file with no resonance parameters is about 7 minutes. Files with resonance parameters, particularly if Doppler broadened, can take much longer; 30 minutes for 90 resonances.

PUBLICATIONS

Porter D., Coles, R. E. and Gilboy W. B. (n,n'γ) Reactions in ^{51}V and ^{89}Y. AWRE O 78/70.

Coles R. E. Elastic and Inelastic Scattering of 5.0 MeV Neutrons by Sodium. AWRE O 3/71.

Coles R. E. and Porter D. Elastic and Inelastic Scattering of Neutrons in the Energy Range 1.0 to 5.0 MeV by Natural Molybdenum. AWRE O 89/70 (EANDC(UK)126AL).

Mather D. S., Bampton P. F., James G and Nind P. J. Measurements of $\bar{\nu}_p$ for Pu-239 between 40 keV and 1.2 MeV. AWRE O 42/70 (EANDC(UK)121AL).

Mather D. S. and Bampton P. F. Evaluation of $\bar{\nu}$ for Pu-239. AWRE O 86/70 (EANDC(UK)125AL).

Mather D. S. and Bampton P. F. Evaluation of $\bar{\nu}$ for U-238. AWRE O 44/71 (EANDC(UK)136AL).

Mather D. S. and Bampton P. F. Evaluation of $\bar{\nu}$ for U-235. AWRE O 55/71 (EANDC(UK)132AL).

NATIONAL PHYSICAL LABORATORY

Division of Radiation Science

(Superintendent: Dr. P. J. Campion)

The (n,α) and (n,p) reactions in silicon and the (n,p) reaction in aluminium at energies up to 5.6 MeV (J. C. Robertson and K. J. Zieba)

A report on this work with the following abstract has been published[1].

"Cross sections are given for the n,p and n,α reactions in silicon and the n,p reaction in aluminium at energies up to 5.6 MeV. The silicon measurements were made using a silicon semiconductor detector as the target and detector and the aluminium measurements were made by β-counting the ^{27}Mg activity produced in aluminium foils. The results are compared with previous measurements. It is shown that in measuring excitation functions in this energy region, the use of a silicon semiconductor detector is a convenient method of measuring the incident neutron energy."

The ^{197}Au(n,γ)^{198}Au cross section at 22.8 keV (T. B. Ryves and J. C. Robertson)

A new measurement of the ^{124}Sb γ-ray energy gives a value of 1691.00±0.06 keV and this combined with other recent precise measurements gives a best γ-ray energy of 1691.03±0.04 keV and a value of 22.8±0.6 keV for the Sb-Be photoneutron energy. Ryves et al[2] measured the ^{197}Au(n,γ) cross section using a source of this type and performed Monte Carlo calculations to obtain their neutron source spectrum. An improved Monte Carlo calculation of this spectrum has now been performed and the ^{197}Au(n,γ) cross section determination re-evaluated to give a value of 684±20 mb. A report of this work has been published[3].

---

(1) Robertson J. C. and Zieba K. J. J. Nucl. En. 26, 1 (1972).

(2) Ryves T. B., Robertson J. C., Axton E. J., Goodier I. and Williams A. J. Nucl. En. 20, 249 (1966).

(3) Ryves T. B. and Robertson J. C. J. Nucl. En. 25, 577 (1971).