UNCLASSIFIED

UKNDC(73) P53

EANDC(UK) 151 L

INDC(UK) - 20 L

U.K. NUCLEAR DATA PROGRESS REPORT

APRIL 1972 - MARCH 1973

Editor M. G. Sowerby

This document contains information of a preliminary or private nature and should be used with discretion. Its contents may not be quoted, abstracted or transmitted to libraries without the express permission of the originator

Nuclear Physics Division,
U.K.A.E.A. Research Group,
Atomic Energy Research Establishment,
HARWELL

August, 1973

/TW

HL73/3159

Preface

This document is prepared at the request of the U.K. Nuclear Data committee. It brings together progress reports on nuclear data from A.E.R.E., A.W.R.E., A.E.E. Winfrith, N.P.L., the University of Birmingham and the University of Glasgow. Where the work is relevant to the requests listed in WRENDA 73 (INDC (SEC) - 32/U) the appropriate request numbers are listed in the margin alongside the report. A CINDA type index is included in the front of the document.

Element S	A	Quantity	Type	Energy Min	Energy Max	Documentation Ref	Vol	Page	Date	Lab	Comments
LI	6	N, ALPHA	EXPT-PROG	1.0 3	4.0 5	UKNDC	P53	10	8/73	HAR	COATES+ TOF LINAC GRPH. OKS. FORT
LI	6	RESON PARAMS	EXPT-PROG		2.5 5	UKNDC	P53	14	8/73	HAR	UTTLEY 2 LEVEL FIT TO SIGT, SIGALPHA
B	10	TOTAL XSECT	EXPT-PROG	2.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ LINAC TOF TBC
B	11	TOTAL XSECT	EXPT-PROG	2.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ LINAC TOF TBC
C		TOTAL XSECT	EXPT-PROG	1.0 0	1.0 4	UKNDC	P53	9	8/73	HAR	MOXON+ TOF LINAC PRECISE SIG 2-3 EV
C		THRMLSCATLAW	EVAL-PROG			UKNDC	P53	46	8/73	WIN	BUTLAND DATA BEING TESTED TBC
O		TOTAL XSECT	EXPT-PROG	1.0 0	1.0 4	UKNDC	P53	9	8/73	HAR	MOXON+ TOF LINAC PRECISE SIG 2-3 EV
F	19	N2N XSECTION	EXPT-PROG	1.1 7	1.5 7	UKNDC	P53	40	8/73	HAR	ADAMS+ TBD
F	19	TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC
AL	27	TOTAL XSECT	EXPT-PROG	1.0 0	1.0 4	UKNDC	P53	9	8/73	HAR	MOXON+ TOF LINAC PRECISE SIG 2-3 EV
AL	27	INELST GAMMA	EXPT-PROG		9.0 6	UKNDC	P53	58	8/73	GLS	CRAWFORD+ LINAC TOF CFD H-F THEORY
SI		TOTAL XSECT	EXPT-PROG	1.0 0	1.0 4	UKNDC	P53	9	8/73	HAR	MOXON+ TOF LINAC PRECISE SIG 2-3 EV
SI	28	INELST GAMMA	EXPT-PROG		9.0 6	UKNDC	P53	58	8/73	GLS	CRAWFORD+ LINAC TOF CFD H-F THEORY
SI	28	DIFF ELASTIC	EXPT-PROG	6.0 5	3.5 6	UKNDC	P53	58	8/73	GLS	HALL+ TOF LINAC DATA AT 12 ANGLES
P	31	INELST GAMMA	EXPT-PROG		9.0 6	UKNDC	P53	58	8/73	GLS	CRAWFORD+ LINAC TOF CFD H-F THEORY
S	32	INELST GAMMA	EXPT-PROG		9.0 6	UKNDC	P53	58	8/73	GLS	CRAWFORD+ LINAC TOF CFD H-F THEORY
S	32	DIFF ELASTIC	EXPT-PROG	6.0 5	3.5 6	UKNDC	P53	58	8/73	GLS	HALL+ TOF LINAC DATA AT 12 ANGLES
CA	40	TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC
CA	40	DIFF ELASTIC	EXPT-PROG	8.0 5	3.4 6	UKNDC	P53	58	8/73	GLS	HALL+ TOF LINAC DATA AT 8 ANGLES
V		TOTAL XSECT	EXPT-PROG	1.0 0	1.0 4	UKNDC	P53	9	8/73	HAR	MOXON+ TOF LINAC PRECISE SIG 2-3 EV
FE		TOTAL XSECT	EXPT-PROG	2.4 4	1.0 6	UKNDC	P53	23	8/73	HAR	PATTENDEN+ TOF CYCLOTRON AERE-R7425
FE	56	INELST GAMMA	EXPT-PROG		9.0 6	UKNDC	P53	58	8/73	GLS	CRAWFORD+ LINAC TOF CRD H-F THEORY
CU	63	RES INT ACT	EXPT-PROG			UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
CU	65	RES INT ACT	EXPT-PROG			UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
NB	93	RESON PARAMS	EXPT-PROG	1.0 2	1.5 3	UKNDC	P53	34	8/73	HAR	THOMAS+ J FOR 14 RES TBL
NB	93	SPECT NGAMMA	EXPT-PROG			UKNDC	P53	34	8/73	HAR	THOMAS+ TOF LINAC
MO		RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVAL BASED ON ENDF/B
AG	107	ACTIVATION	EXPT-PROG	2.5-2		UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
AG	107	RES INT ACT	EXPT-PROG			UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
IN	115	N, GAMMA	EXPT-PROG	1.5 5	6.3 5	UKNDC	P53	54	8/73	NPL	RYVES+ SIG TO IN-116M TBL TBP JNE
CS	133	RESON PARAMS	EXPT-PROG	1.5 2	9.0 2	UKNDC	P53	32	8/73	HAR	RIEHS LOW EN GS TO GET J TBC
LA		TOTAL XSECT	EXPT-PROG	2.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBC TBP 0.8-9 MEV
CE		TOTAL XSECT	EXPT-PROG	2.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBC TBP 0.8-9 MEV
PR	141	TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP
Nd		TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP
SM		TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP

Element S	A	Quantity	Type	Energy Min	Energy Max	Documentation Ref	Vol	Page	Date	Lab	Comments
Gd		TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP
Tb	159	N, GAMMA	EXPT-PROG	2.5-2		UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
Tb	159	RES INT ACT	EXPT-PROG			UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
Dy		TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP
Dy	164	RES INT ACT	EXPT-PROG			UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
HO	165	TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP
HO	165	ACTIVATION	EXPT-PROG	2.5-2		UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
HO	165	RES INT ACT	EXPT-PROG			UKNDC	P53	53	8/73	NPL	RYVES+ MEASURED REL AU MN TBP
ER		TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP
ER	167	RESON PARAMS	EXPT-PROG	5.0 0	1.3 2	UKNDC	P53	32	8/73	HAR	AXMANN TOF LINAC J WN AND WG 30 RES
ER	167	ELASTIC	EXPT-PROG		1.0 3	UKNDC	P53	32	8/73	HAR	AXMANN TOF LINAC TO GET BETTER WG
YB		TOTAL XSECT	EXPT-PROG	2.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBC
TA		RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVAL BASED ON ENDF/B
TH	232	RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVAL BASED ON ENDF/B
U	235	EVALUATION	EVAL-PROG		1.0 0	UKNDC	P53	29	8/73	HAR	SOWERBY+ TBC
U	235	RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVALUATION
U	235	FISSION	EXPT-PROG	1.0 3	1.0 6	UKNDC	P53	19	8/73	HAR	GAYTHER+ TOF LINAC GRPH OKS UK EVAL
U	235	FISSION	EXPT-PROG	8.0 4	1.6 6	UKNDC	P53	4	8/73	HAR	PEARLSTEIN+ VDG REL LONG COUNTER TBC
U	235	F NEUT DELAY	EXPT-PROG	FAST		UKNDC	P53	45	8/73	ALD	MCTAGGART 0.0174+-0.0008N/F TBC
U	235	SPECT FISS N	EXPT-PROG	1.0 5	5.0 5	UKNDC	P53	1	8/73	HAR	ADAMS+ ROSE DATA BEING FINALISED
U	235	FISS YIELD	EXPT-PROG	1.3 5	1.3 6	UKNDC	P53	43	8/73	HAR	CUNINGHAME+ YLD 5 PROD IND N EN TBP
U		TOTAL XSECT	EXPT-PROG	8.0 5	9.0 6	UKNDC	P53	59	8/73	GLS	SYME+ TOF LINAC TBP JNE
U	238	RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVALUATION
U	238	DIFF INELAST	EXPT-PROG	1.1 6	2.6 6	UKNDC	P53	2	8/73	HAR	ARMITAGE+ GRPH CFD H-F THEORY TBC
U	238	FISSION	EXPT-PROG	1.0 6	2.0 7	UKNDC	P53	27	8/73	HAR	COATES+ TOF CYCLTRN NORM 14 MEV GRPH
U	238	F NEUT DELAY	EXPT-PROG	FAST		UKNDC	P53	45	8/73	ALD	MCTAGGART 0.0472+-0.0025N/F TBC
U	238	N, GAMMA	EXPT-PROG	8.0 4	1.6 6	UKNDC	P53	4	8/73	HAR	PEARLSTEIN+ ACT REL 235, LONG COUNTER
U	238	N, GAMMA	EXPT-PROG	1.5 5	6.3 5	UKNDC	P53	54	8/73	NPL	RYVES+ ACT TBL TBP JNE
PU	239	EVALUATION	EVAL-PROG		1.0 0	UKNDC	P53	29	8/73	HAR	SOWERBY+ TBC
PU	239	RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVALUATION
PU	239	FISSION	EXPT-PROG	1.0 3	1.0 6	UKNDC	P53	19	8/73	HAR	GAYTHER+ TOF LINAC TBC
PU	239	F NEUT DELAY	EXPT-PROG	FAST		UKNDC	P53	45	8/73	ALD	MCTAGGART TBD
PU	239	SPECT FISS N	EXPT-PROG	1.0 5	5.0 5	UKNDC	P53	1	8/73	HAR	ADAMS+ ROSE DATA BEING FINALISED
PU	240	RESON PARAMS	EVAL-PROG	4.0-1	2.5 4	UKNDC	P53	48	8/73	WIN	JAMES+ GENEX EVAL WG=26.9 MILLIVOLT
PU	240	SPECT NGAMMA	EXPT-PROG		1.0 2	UKNDC	P53	33	8/73	HAR	THOMAS+ GS STRENGTH CORR GRPHS

Element S	A	Quantity	Type	Energy Min	Energy Max	Documentation Ref	Vol	Page	Date	Lab	Comments
AM	241	N, GAMMA	EXPT-PROG	FAST		UKNDC	P53	43	8/73	HAR	WILTSHIRE+ SIG TO CM-242
AM	241	FISSION	EVAL-PROG	2.5-2	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ FOR UKNDL DFN 1001
AM	241	N, GAMMA	EVAL-PROG	2.5-2	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
AM	242	FISSION	EVAL-PROG	2.5-2	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ FOR UKNDL DFN 1002
AM	242	N, GAMMA	EVAL-PROG	2.5-2	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
AM	243	FISSION	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ FOR UKNDL DRN 1003
AM	243	N, GAMMA	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
CM	242	FISSION	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ DFN 1004 BASED ON LYNN P
CM	242	N, GAMMA	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
CM	243	FISSION	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ DFN 1005 BASED ON LYNN P
CM	243	N, GAMMA	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
CM	244	FISSION	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ FOR UKNDL DFN 1007
CM	244	N, GAMMA	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
CM	245	FISSION	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ FOR UKNDL DFN 1006
CM	245	N, GAMMA	EVAL-PROG	1.0 3	1.0 7	UKNDC	P53	29	8/73	HAR	SOWERBY+ USES LYNNS CALC SIG P
CF	252	NU	EXPT-PROG	SPON		UKNDC	P53	49	8/73	NPL	AXTON VALUE 3.725N/F TBC
CF	252	NU	EVAL-PROG	SPON		UKNDC	P53	49	8/73	NPL	AXTON FOR IAEA 2200M/S EVAL TBL
CF	252	SPECT FISS N	EXPT-PROG	SPON		UKNDC	P53	1	8/73	HAR	ADAMS+ ROSE DATA BEING FINALISED
H2O		THRMLSCATLAW	EVAL-PROG			UKNDC	P53	46	8/73	WIN	BUTLAND SEE ALSO AEEW-R 814
MANY		FISSION	EVAL-PROG		6	UKNDC	P53	31	8/73	HAR	LYNN EVAL FISSION BARRIERS AND SIG
MANY		F NEUT DELAY	EVAL-PROG	2.5-2	1.5 7	UKNDC	P53	44	8/73	HAR	TOMLINSON NEW EVAL NO. AND EN TBC
MANY		FISS YIELD	EVAL-PROG	PILE		UKNDC	P53	44	8/73	HAR	CROUCH CHAIN YLD SEE AERE-R 7209
MANY		FISS YIELD	EVAL-PROG	FAST		UKNDC	P53	44	8/73	HAR	CROUCH CHAIN YLD SEE AERE-R 7394

CONTENTS

TABLES

ILLUSTRATIONS

Contents Cont'd | Page No.

Figure

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
14 MV Tandem Generator (J.M. Freeman)	D
45 MeV Electron Linac (J.E. Lynn)	E
Variable Energy Cyclotron: Chemistry Division	G
Synchrocyclotron (A.E. Taylor)	H

B Neutrons from Prompt Fission of ^{235}U, ^{239}Pu and ^{252}Cf (J.M. Adams and J.L. Rose)

The present series of experiments, conducted on IBIS, have been concluded and are in
the course of being finalised and written-up (by J.L.R.[+]). The measurements included
studies of the fast neutron fission spectrum of ^{235}U, and ^{239}Pu at primary incident neutron
944 energies of 100-200 keV and 500 keV using fast neutron time-of-flight techniques, and of
945 the spectrum of neutrons from the spontaneous fission of ^{252}Cf.

946 The neutron detector comprised a 5 cm diam. x 4 cm thick NE213 (bubble-free) liquid
1140 scintillator coupled to a low-noise RCA31000D photomultiplier. A stabilised version of the
1141 Harwell pulse shape discrimination system was employed to reduce both the time dependent
1342 and independent γ-ray background, and which, in conjunction with the neutron detector,
1343 enabled the detection of neutrons from ~40 keV to 20 MeV with negligible γ-ray contribution.
1344 Later experiments with higher neutron biases and reduced beam pulse repetition rate gave
much better signal-to-background in the time-of-flight spectra between the high neutron energy "cut-off" and the prompt fission γ time peak. For the majority of the measurements of the high neutron energy part of the fission neutron spectrum, it was found unnecessary to utilise the large dynamic energy capability of the neutron detection system. The relative neutron detection efficiency was measured by a combination of complementary methods, mainly polythene scattering, and normalised to the Harwell long counter at the low neutron energy end to make it absolute. The experimental calibration extended up to 12 MeV above which computed efficiencies were used.

The data have been analysed in terms of the conventional Maxwellian, Watt and Double-Watt formalisms for the fission spectral shape. The Double-Watt formalism assumed averaging over two fragments, representing the light and heavy fragments, each having an independent "temperature" and associated neutrons. The results indicate departure above ~ 10 MeV from the Double-Watt formalism, viz.

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

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

and suffix 1 and 2 refer to the light and heavy mass respectively.

+ As part of a Ph.D Thesis for submission to the Polytechnic of South Bank, London.

Detailed re-calibration of the neutron energy scale of the neutron spectra has been carried out, but does not remove this effect. There is, however, one aspect that has still to be considered in more detail, and this concerns the neutron detection efficiency of the counter itself. Above 12 MeV, theoretical efficiency curves were used to extrapolate to higher neutron energies. However, recently, work by Thornton and Smith[1], Drosg[2] and others, have shown that in this neutron energy region account must be taken of the $^{12}C(n,n')3\alpha$ contribution which has the effect of increasing the efficiency above 12 MeV by an amount which is very much bias dependent. The theoretical curves that have been used do not include this contribution, but a program that does should be available fairly soon at Harwell. Further experimental work on measuring the detector efficiency in the range 10-20 MeV is planned.

(1) Thornton S.T. and Smith J.R., Nuc. Instr. Meth. 96 551 (1971).

(2) Drosg M., Nuc. Instr. Meth. 105 573, (1972).

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

Measurements of inelastic neutron scattering from natural uranium using time-of-flight techniques at seven neutron energies between 1.13 and 2.37 MeV have been described in the previous progress report[1]. Time-of-flight spectra were obtained alternately with the uranium sample in position and with the sample removed. The secondary neutron spectrum was then obtained by subtracting the 'sample out' spectrum from the 'sample in' spectrum. Natural activity and induced activity following fission produced a uniform background in the secondary neutron spectrum which was estimated from the intensity of the low energy region of the spectrum where the detector bias has eliminated time dependent neutrons from the sample. The contribution due to fission was then subtracted on the supposition that the ^{238}U fission neutron spectrum was identical in shape to that obtained from ^{235}U with 130 keV neutrons: normalization was made to the region of the fission spectrum above the elastic peak. Separation of the ^{238}U elastic peak from the inelastic distribution was made with the aid of peak shapes obtained with Bi and C samples. With the help of the Bi peak shape data an attempt was made to estimate the cross sections of the inelastic groups associated with the unresolved 45 keV and 149 keV levels.

The present measurements have been made at an observation angle of 90^o and it is assumed that the integral cross section can be obtained by multiplying the differential cross sections by 4π. This assumption is questionable as significant departure from isotropy have been observed by Knitter et al[2], though other measurements made by Smith[3] and Barnard et al[4] at energies up to 1.5 MeV suggest that the error introduced by this procedure is unlikely to exceed 10%.

In Fig. 1 preliminary values for the measured cross sections are compared with calculations due to Prince.[5] The compound nuclear cross section, $\sigma_{nn'}$ (compound), was obtained from a combination of an optical model and Hauser-Feshbach theory using the width fluctuation correction. The compound nucleus cross section is also divided into a $\sigma_{nn'}$ (discrete) component, using existing level data and a $\sigma_{nn'}$ (continuum) component. The direct component $\sigma_{nn'}$ (rot) was obtained using a deformed optical potential and by coupling the first three excited states to the ground state.

(1) UKNDC (72) P37, EANDC (UK) 140AL, INDC (UK)-15G.

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

(3) Smith, A.B., reported by W.P. Poenitz, Nuclear Data for Reactors, 2, 3, IAEA, Vienna, (1970).

(4) Barnard, E., Villiers, J.A.M. and Reitmann, D., Nuclear Data for Reactors 2, 103, IAEA Vienna (1970).

(5) Prince, A., Nuclear Data for Reactors 2, 825, IAEA Vienna, (1970).

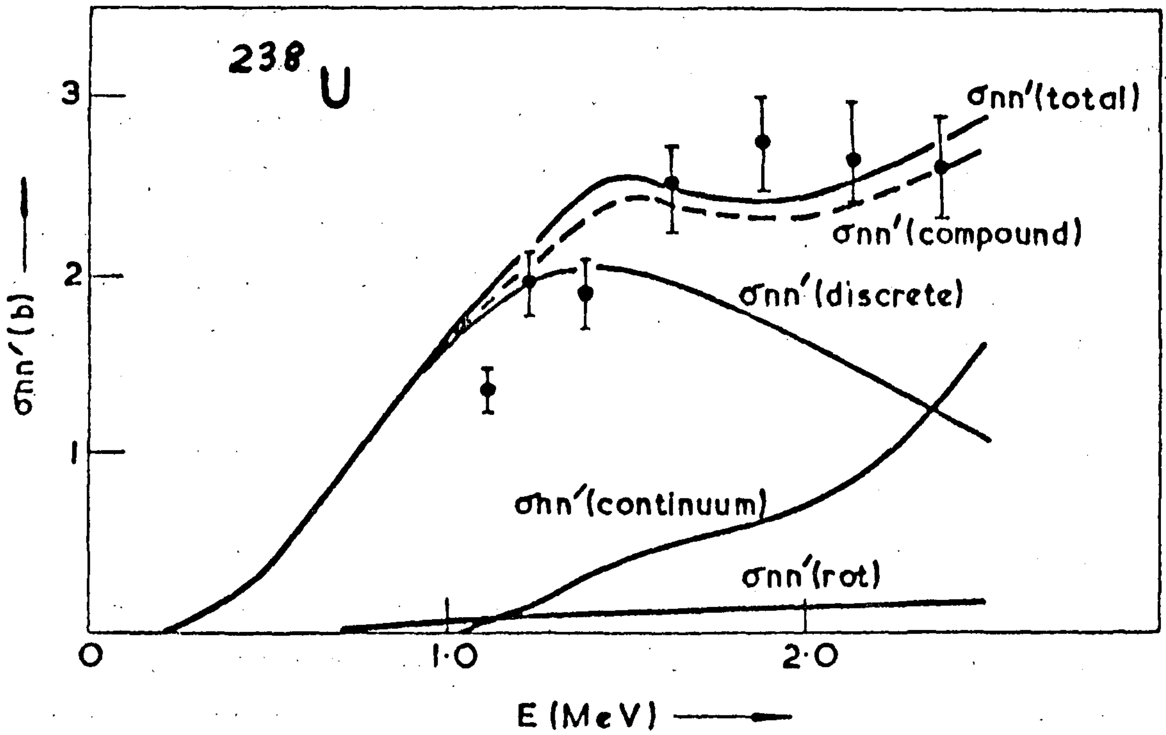

Fig. 1

Total ^{238}U (n,n') cross section for all levels above 0.045 MeV

B <u>Measurement of the $^{238}U(n,\gamma)$ and $^{235}U(n,f)$ cross-sections and ratio in the energy range 80 keV to 1.6 MeV</u> (S. Pearlstein (Brookhaven National Laboratory) and M.C. Moxon)

The $^{238}U(n,\gamma)$ cross section has been measured extensively using activation and direct capture methods. In the activation methods both the 23.54 minute ^{239}U and 2.355 day ^{239}Np nuclide decays have been used in various measurements by β, γ, or β-γ coincidence counting. Direct capture methods use the prompt gamma-rays emitted upon neutron capture. In each case the measurements are hindered by the presence of natural activity.

In this experiment $^{238}U(n,\gamma)$ and $^{235}U(n,f)$ reactions were measured simultaneously at several energies, using 'mono-energetic' neutrons from the Li(p,n) reaction, and it is hoped that from these measurements the cross-sections and their ratio can be obtained.

<u>Experimental Method</u>

Neutrons in the energy range 80 to 1600 keV are obtained from the $^{7}Li(p,n)^{7}Be$ reaction. A thin natural uranium foil backed by a thin enriched uranium foil is irradiated for 23.5 minutes in a simple cone shaped arrangement whereby the foil and the Harwell standard long counter subtend the same solid angle. In cases where the long counter was placed at large distances to reduce its count rate angular distribution measurements were made to correct for differences in solid angle. The amount of ^{239}U formed by ^{238}U capture in the natural uranium foil is measured with a high resolution Ge(Li) (0.7 keV) detector, by detection of the 74 keV gamma-ray emitted in its decay to ^{239}Np. Measurement in another Ge(Li) detector, having 5 keV resolution, of the gamma-ray spectra emitted by the fission products formed in the enriched uranium foil is used to determine the ^{235}U fission cross-section.

This experiment has the advantage that the 74 keV gamma-ray is easily resolved against a background of radiation arising from the natural decay of uranium and that arising from other neutron induced reactions in the sample (see fig. 2). Natural uranium can be used eliminating the need for separations prior to irradiation and counting. The ^{239}U half-life is convenient and the decay scheme well known. The natural activity present in the sample of uranium and its decay products provides a means to monitor and calibrate the Ge(Li) detector. The data used are given in Table 1.

Gamma ray spectra from the enriched uranium foil were integrated over five energy bands located between well defined peaks in the background spectra. Integration over energy intervals was chosen since the lines of individual fission products formed in a 23.5 minute irradiation would be relatively weak and their yield might have a significant dependence on incident neutron energy.

The uranium foils were also counted after irradiation in a well known thermal flux in the GLEEP[1] reactor. In order to maintain the same counting conditions as in the neutron beam measurements, a natural uranium foil had to be used in the thermal irradiation to measure fission product spectra. Efficiencies were determined according to the formula

$$E = \frac{R}{\phi\ \sigma_0 (g+rs)}$$

where R is the measured foil activity, ϕ is the neutron flux, σ_0 is the cross-section at 0.0253 eV, r is the epithermal index of the neutron flux and g and s are the usual Westcott parameters. The efficiency obtained from the thermal irradiation, after correction for foil self absorption, for detection of the 74 keV gamma ray is 0.0286±0.006 which lies above the 0.0255±0.0015 obtained earlier from source measurements and decay schemes. The latter value is preferred in this work due to the difficulties in applying the Westcott convention to a thick foil with an appreciable excess resonance integral.

<u>Neutron Source</u>

Neutrons were generated by the Harwell 3 MeV Van de Graaff accelerator, IBIS[2], using the $^7Li(p,n)\,^7Be$ reaction. Lithium was deposited on 0.01 inch tantalum backing. Different thickness targets were used to cover the energy range 50 to 1600 keV. Although the irradiations were performed with a steady beam, the characteristics of the source energy distribution were monitored before and after irradiations using time-of-flight measurements with plastic and lithium-glass scintillators. These measurements provided information to correct the cross-section data for the energy spread due to target thickness and the second group of neutrons present at primary neutron energies above 670 keV. Time-of-flight spectra were also taken, placing strong resonance filters between the target and detector. These measurements, together with irradiation of the uranium sample at different distances from the target, established that the neutrons originated from the target and that the neutron background was very small i.e. less than 2%.

The neutrons passing through the sample were measured with the standard Harwell long counter[3]. The counter absolute efficiency has been measured repeatedly and found to be stable over long periods. The variation with source energy of the efficiency and effective depth of the long counter were included in the analysis.

---

(1) Axton E.J. J. Nucl. Ener. <u>17</u>, 125 (1963).

(2) Ferguson A.T.G. Contemporary Physics <u>5</u>, 269 (1964).

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

Results

Preliminary analysis of the ^{238}U data is shown in figure 3. Below 500 keV the results are in reasonable agreement with the Sowerby et al[4] evaluation, and above 500 keV the data indicate that the capture cross-section may be lower than the evaluation.

The ^{235}U data is still being analysed. The ratio of the gamma-ray energy bands appear to be constant and have an average deviation between 4 and 6%. Within these limits no definite pattern of variation with incident neutron energy could be observed.

TABLE 1

List of nuclides, half-lives, gamma-ray energies, and intensities[5][6]

Nuclide	$T_{1/2}$	E (keV)	Intensity ((%)/decay)
Th-231	25.52 h	84.24	5.1
Th-234	24.10 d	92.8 92.3	6.72
		63.3 62.8	5.7
U-234	2.48×10^5 y	53.3 120.9	0.681 0.233
U-235	7.1×10^8 y	58.6 109.1 143.8 163.36 185.718 202.1 205.3	0.100 1.51 9.72 4.59 54.0 1.0 5.0
U-238	4.49×10^9 y		
U-239	23.54 m	43.53 74.67	5.63 59.3

(4) Sowerby M.G., Patrick B.H. and Mather D.S. AERE - R 7273 (1973).

(5) Cline J.E. Gamma rays emitted by the fissionable nuclides and associated isotopes, IN-1448 Rev. Jan. 1971.

(6) Nuclear Data Sheets, published by Nuclear Data Tables.

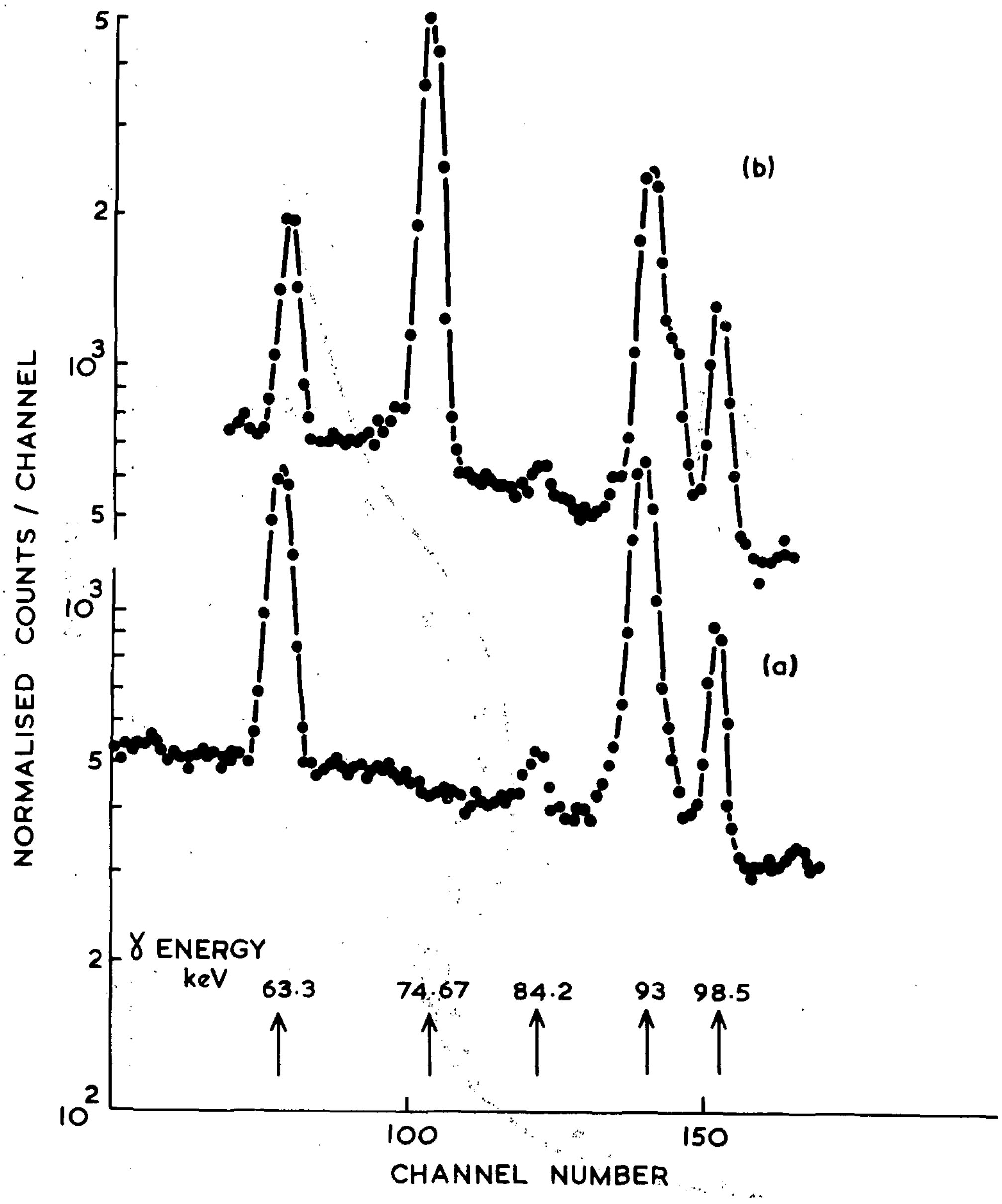

Fig. 2

(a) Gamma-ray spectra from a sample of natural uranium

(b) Gamma-ray spectra from the same sample (as in (a)) after a 23.5 minute irradiation with 700 kev neutrons for the period 2 to 11 minutes after the end of the irradiation.

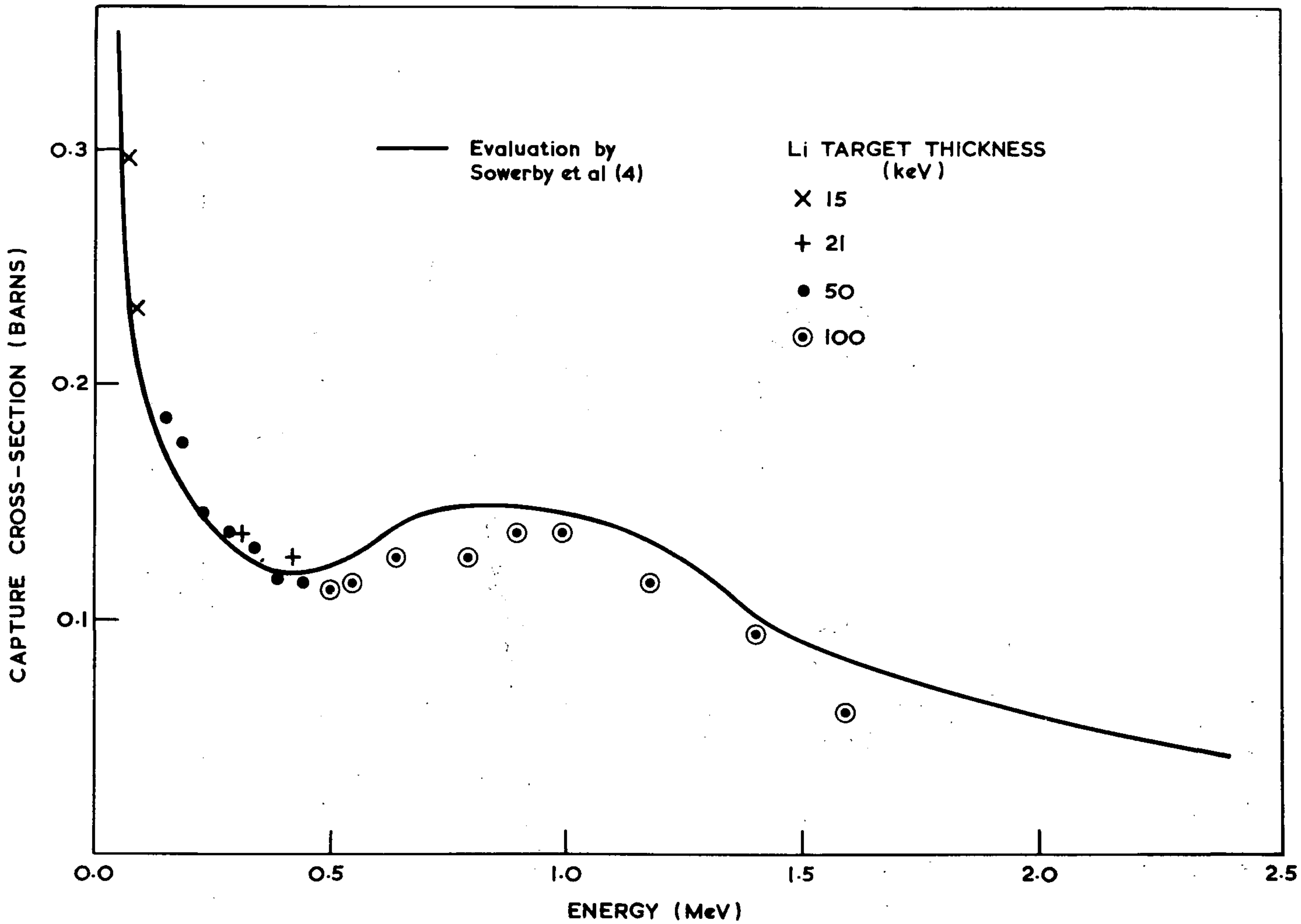

Fig. 3

Comparison of the preliminary data on the U-238 capture cross-section with the evaluated data of Sowerby et al[4].

E <u>Neutron total cross-section measurements</u> (M.C. Moxon, D.A.J. Endacott and J.E. Jolly)

Transmission measurements carried out on a ^{6}Li glass scintillator to determine the amount of ^{6}Li present indicated some discrepancies in the cross-sections of the constituent of the glass, i.e. Si, Al, O, ^{6}Li, ^{7}Li and Ce. At about the same time, some solid state physicists working on the linac also noticed discrepancies in their results on Si and SiO_2 which could in part be accounted for by changes in the cross-section and requested a measurement of the cross-section using samples supplied by them.

Transmission measurements were carried out at 14 m from the 'booster' target of the Linac using a neutron beam diameter varying from 2 mm to 1.5 mm depending on the sample size. Measurements were made on samples of Si, SiO_2, Al, Al_2O_3, V, C, $SrCO_3$ and CeO_2. The carbon has a well known cross-section and was used to check the equipment and method of analysis, while vanadium is a standard used by the solid state physicists. The CeO_2 was of poor quality and could only be used to give an indication of the cross-section and confirm that several resonances observed in the Li glass measurement belonged to Cerium. Strontium was another solid state physics request.

The measurements are carried out by cycling the samples in and out of the neutron beam. A set of resonance filters (Ta, In, Co, V) used to measure the background was cycled in and out of neutron beams both when the sample was in and out of the neutron beam. Measurements are also carried out with permanent samples of Rh, Co and Na in the beam to give background points at 1, 130 and 2400 eV. The measured background at 1 eV (In) and 4 eV (Ta) has very little time dependence and the region between varies smooth with neutron energy having a signal to background ratio of $\sim$10 between 2 and 3 eV. This region was used to give accurate transmission results with very little error due to uncertainties of interpolation of the background and the results in this region are given in Table 2.

TABLE 2

Total cross-section measurements in the neutron energy range 2 to 3 eV.

Element or Compound	Cross-section (barns)	Statistical Error (barns)	Total Error (barns)
C	4.749	0.044	0.055
Al	1.430	0.0052	0.011
Si	2.004	0.0146	0.020
V	5.395	0.0150	0.041
SiO_2	9.680	0.030	0.074
Al_2O_3	14.340	0.147	0.178
O	3.836	0.022	0.044

The datum on carbon is in good agreement with the value of 4.746 ± 0.007 barns given by Dilg and Vonach[1] and the value of 4.744 barns obtained by Uttley and Diment[2]. The cross-sections of Al and V are in reasonable agreement with the data in BNL 325 but the value for Si is about 12% lower than the value in BNL 325 and some 2% lower than the value of 2.0442 ± 0.0018 barns given by Dilg and Vonach[1]. The value for oxygen (3.836 ± 0.044) tends to be higher than the recent value of 3.761 ± 0.007 barns obtained by Dilg et al[3] and the recommended value in the U.K. Nuclear Data Library of 3.73 ± 0.04 barns[4].

These results cleared up the discrepancies in the Li glass measurement and helped to clear up some of the discrepancies in the solid state physics measurements.

(1) Dilg W and Vonach H., Z. Naturf. <u>26a</u> 442 (1971).

(2) Uttley C.A. and Diment K.M., Nuclear Data for Reactors <u>1</u>, 191, IAEA Vienna, (1970).

(3) Dilg W, Koester L and Nistler W., Phys. Lett., <u>36B</u>, 208 (1971).

(4) Story J.S. Private Communication.

E <u>Measurements of standard cross-sections using the Harwell black detector</u>
(M.S. Coates, G.J. Hunt (now at N.R.P.B., Sutton, Surrey) and C.A. Uttley)

Further measurements have been made to resolve the discrepancy between the $^6Li(n,\alpha)$ cross-section values determined using thin (~ 1 mm) and thick (9.5 mm) ^6Li glass scintillators. In the previous report[1] it was suspected that the data obtained with the thick glass could be in error due to a count rate dependent loss in the timing equipment. The thick glass measurements were repeated therefore with the equipment modified to

---

(1) UKNDC(72) P37, EANDC(UK) 140 AL, INDC(UK)-BG.

eliminate this effect. In addition new data were obtained with a ½ mm thick glass and the flux spectrum was remeasured to a greater statistical accuracy than achieved hitherto. The 9.5 mm glass data confirmed that the earlier results were affected by the count loss fault and now they agree with the thin (0.5 mm and 1 mm) glass data after corrections have been applied for multiple scattering of neutrons in the scintillators using Monte Carlo calculations of Fort[2,3] (9.5 mm and 1 mm glasses) and Macklin[4] (0.5 mm glass). The relative correction between ~ 1.5 keV and 300 keV is 30% for the 9.5 mm glass and ~ 3% for the 0.5 mm glass. Above this energy the correction factors increase because of the effect of the 440 keV oxygen resonance to a maximum of ~ 1.7 for the 9.5 mm glass and ~ 1.1 for the 0.5 mm glass. Our latest results agree well with those of Fort & Marquette[5] who measured the $^{6}Li(n,\alpha)$ cross-section absolutely over the region of the resonance at ~ 250 keV using glass scintillators of different thicknesses on a pulsed Van de Graaff at Cadarache. Flux measurements were made with a flat response detector of the super long counter type developed by Leroy et al[6]. The results of the two experiments in the resonance region are shown in Fig. 4. Included are some earlier absolute data[7] from Cadarache where the flux measurement was made using the associated particle technique on the $T(p,n)^{3}He$ reaction. The Harwell data are normalised to a cross-section value of $149.5/\sqrt{E}$ barns between 1.5 keV and 10 keV where E is the neutron energy in eV. There appears to be a systematic energy displacement of ~ 5 keV between the Harwell and Cadarache data (with the latter higher) which is slightly outside the measurement error (~ 3 keV). Work is being done in both laboratories to establish the correct energy scale. If an energy normalisation is made, however, the results from the two laboratories agree within the errors of measurement (~ ± 3-4% on the data points in both experiments) between 150 keV and 400 keV. In Fig. 4 is shown also the $^{6}Li(n,\alpha)$ cross-section deduced by Uttley and Diment[8] from total cross-section measurements assuming the (n,α) cross-section to be a

---

(2) Fort E., Nuc. Inst. and Meth. <u>87</u>, 115 (1970)

(3) Fort E., Private communication (1972).

(4) Macklin R.L., Private communication (1972).

(5) Fort E. and Marquette J.P., Cadarache Report DPRMA/SECPR/SEMNR/72/01 (1972).

(6) Leroy J.L., Huet J.L. and Gentil J, Nuc. Inst. and Meth. <u>88</u>, 9 (1970).

(7) Fort E., Nuclear Data for Reactors <u>1</u> 253, IAEA Vienna (1970).

(8) Uttley C.A., Sowerby M.G., Patrick B.H. and Rae E.R., Argonne Symp. on Neutron Standards and Flux Normalisation p.80 (1970).

single p-wave level superimposed on an s-wave background. It will be seen that the experimental data disagree significantly from this prediction particularly near the resonance peak. This discrepancy has led Uttley to consider a more sophisticated theoretical treatment which is described elsewhere in this report[9].

(9) This report page 14.

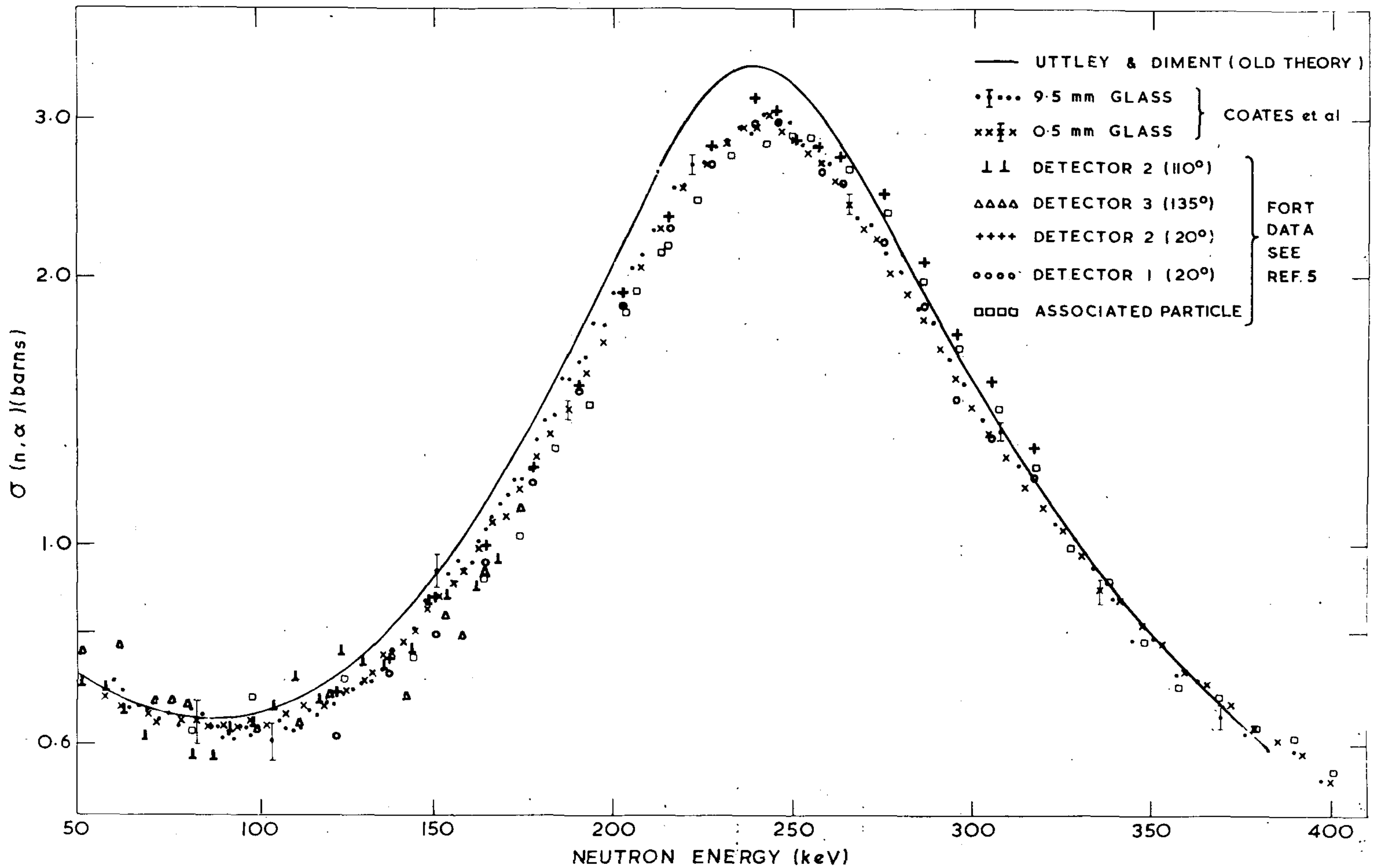

Fig. 4

Comparison of determinations of the ^{6}Li (n, α) cross-section.

The $5/2^-$ level at 0.25 MeV in the ^{6}Li + n reaction (C.A. Uttley)

The agreement between the $^6Li(n,\alpha)t$ cross-section over the $5/2^-$ level at 0.25 MeV obtained from thin ^{6}Li loaded glass scintillator measurements at Cadarache and Harwell, discussed elsewhere in this report (p. 10), and the agreement between several measurements of the total cross-section of this resonance in recent years demonstrates conclusively that a single level description is inadequate.

A single level p-wave expression gives a good fit separately to the measured total[1] and (n,α) cross-sections and yields the sets of parameters in Table 3.

TABLE 3

Parameters for the $5/2^-$ level at 0.25 MeV from single level fits to the total and (n,α) cross-sections

	Total cross-section data	(n,α) cross-section data
Reduced neutron width, MeV	1.540±0.005	1.934±0.028
Reduced alpha width, MeV	0.0356±0.0026	0.0301±0.0045
Channel radii: neutron = 3.5 fm, alpha-triton = 4.1 fm		

The discord between the two sets of parameters, particularly the reduced neutron width, is obvious and the parameters from the (n,α) data correspond to a peak total cross-section ~ 1 barn (10%) higher than observed.

The explanation of this apparent anomaly is the assumption that a single level analysis is valid. A recent survey of the literature by Prof. R.O. Lane[2] on the energy levels in ^{7}Li shows that the $5/2^-$ level at 6.64 MeV excitation has been confirmed by the later work of Tombrello[3] who, with Spiger[4], observes a broad level at this energy in (α,t) scattering with a reduced width of ~ 3 MeV and a small reduced neutron width from observations above the neutron threshold.

---

(1) Nuclear Physics Divisional Progress Report AERE PR/NP15, p.12 (1969).

(2) Lane R.O., Conf. on Nuclear Structure Study with Neutrons, Hungary, July 1972.

(3) Tombrello T.A. and Parker P.D., Phys. Rev. 130, 1112 (1963).

(4) Spiger R.J. and Tombrello T.A., Phys. Rev. 163, 964 (1967).

The analysis of the $5/2^-$ level at 0.25 MeV in conjunction with that at $\sim$ 0.7 MeV below the neutron separation energy, using the two level - two channel R-matrix formalism discussed by Lane and Thomas[5], shows that the total and (n,α) cross-sections are in accord within experimental errors for a reduced alpha width $\gamma_{1\alpha}^2$ = 3 MeV and a reduced neutron width $\gamma_{1n}^2 \approx$ 0.06 MeV for the bound $5/2^-$ state. The result of fitting both the total and (n,α) cross-sections separately is illustrated in Fig. 5. A constant $\gamma_{1\alpha}^2$ = 3.0 MeV is chosen for the bound state and the data are fitted for several values of the reduced neutron width γ_{1n}^2 of this state. The upper part of the figure shows the peak (n,α) cross-section (solid) and the peak scattering (n,n) cross-section (dashed) calculated from the parameters γ_{2n}^2, $\gamma_{2\alpha}^2$ (lower part of Fig. 5) obtained from the fits to the two sets of data which require that the product $\gamma_{1\alpha}\,\gamma_{2\alpha}$ is negative. It is seen that both the peak (n,α) and (n,n) cross-sections converge near γ_{1n}^2 = 0.06 MeV and that the parameters γ_{2n}^2, $\gamma_{2\alpha}^2$ are also in reasonable agreement near the same value of γ_{1n}^2. Thus the (n,α) cross-section obtained from analysing the total cross-section is consistent with the measured (n,α) cross-section across the $5/2^-$ resonance at $\sim$ 0.25 MeV. It is interesting to note that, of the intrinsic parameters for the upper $5/2^-$ level, the reduced alpha width $\gamma_{2\alpha}^2$ (R.H. ordinate, lower part of Fig. 5) is $\sim$ 10 times larger than the single level value (Table 3) obtained by fitting the data when $\gamma_{1n}^2 = \gamma_{1\alpha}^2 = 0$.

One inconsistency reflected in this analysis is a 2 keV difference between the peaks of the (n,α) cross-section directly measured (peak at 241 keV) and that obtained from the total cross-section (peak at 239 keV). As the total cross-section was measured at 300 m and the Li glass data were obtained at 120 m this is probably not outside the error associated with present timing uncertainties. However the $\sim$ 1% energy difference will affect any detailed conclusions from Fig. 5.

(5) Lane A.M. and Thomas R.G., Rev. Mod. Phys. 30, 257 (1958).

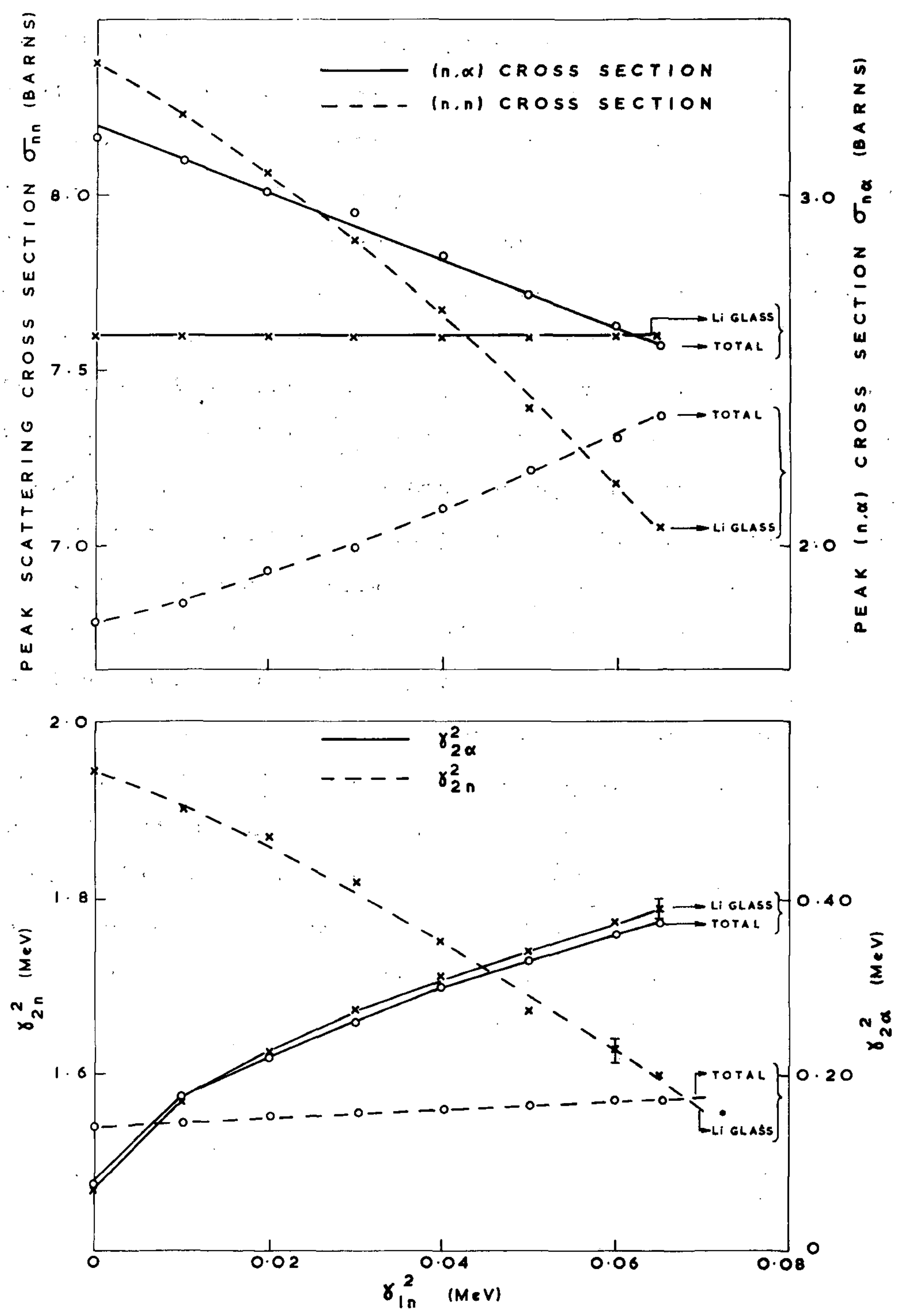

Fig. 5

Variation of parameters as a function of the reduced neutron width ($\gamma^2 1n$) of the bound $5/2^-$ level in ^{7}Li.

B <u>Experimental test of the calculated neutron detection efficiency of the Harwell black detector at high energies</u> (M.S. Coates, D.A. Boyce, D.B. Gayther and G.J. Hunt (now with N.R.P.B., Sutton, Surrey))

Results of an experimental test calibration of the Harwell black detector against the Harwell long counter using a secondary detector and the pulsed Van de Graaff IBIS were given in a previous report(1). Some evidence was noted of a small systematic discrepancy between the experimental results and the theoretical prediction. The measurements have been repeated on IBIS using essentially the same experimental method. The new results do not show the systematic discrepancy although individual data points are consistent within the errors of measurement with the earlier ones. It is concluded therefore that the apparent systematic effect in the earlier results is not real. The latest results are shown in Fig. 6 where the normalisation procedure described earlier(1) is used. It is considered that the experimental data confirm to ±2% that the theoretical efficiency of the black detector is correct over the energy region where this is considered valid (up to 700 keV). It was noted previously(1) that above 700 keV the IBIS measurements can be considered as a calibration of the black detector.

(1) UKNDC (72) P37 EANDC (UK) 140AL, INDC (UK) - 15G.

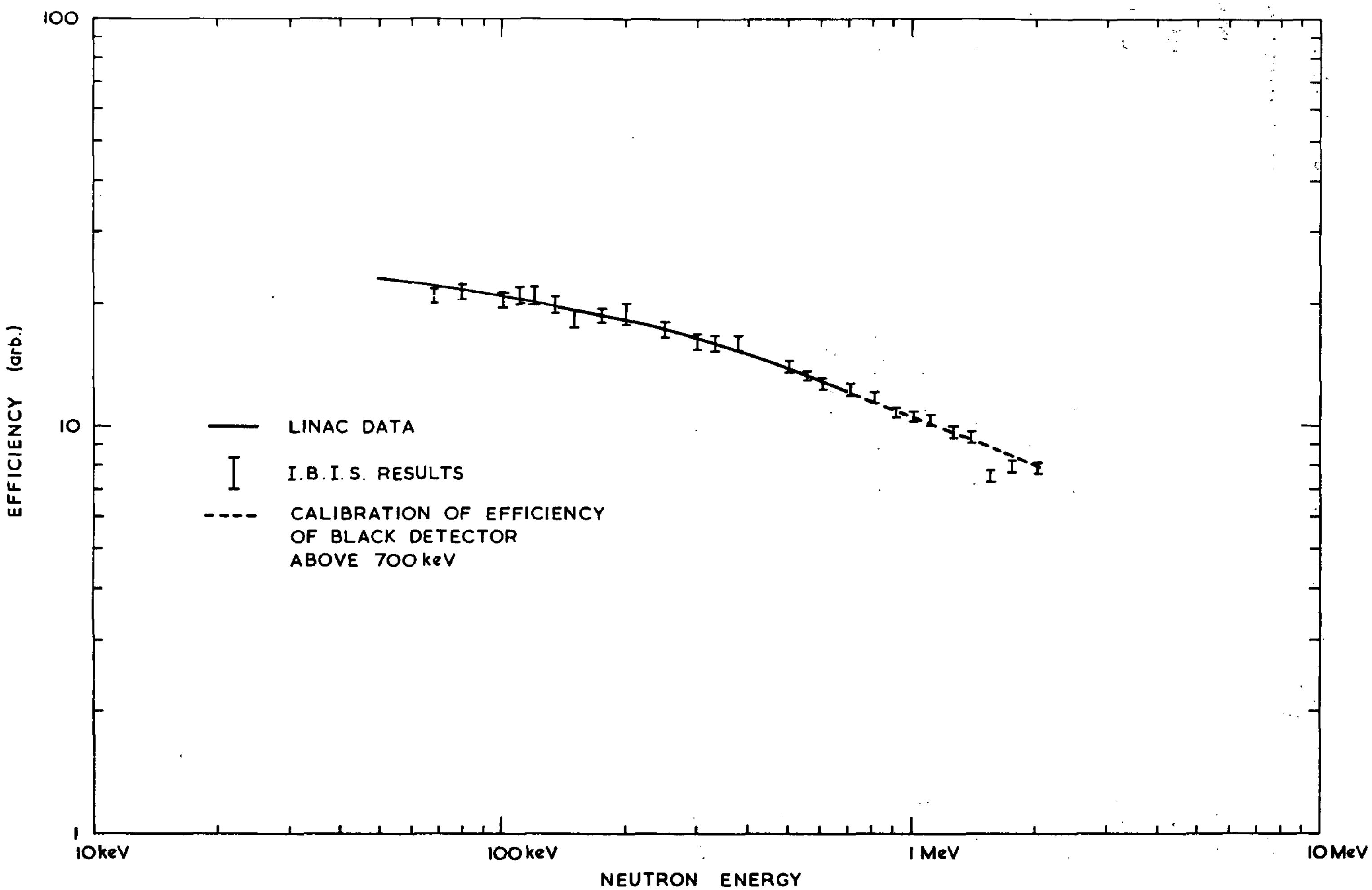

Fig. 6

Calibration of the secondary detector.

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

In the programme of time-of-flight fission cross-section measurements, data collection on the electron linac has been completed for the ^{235}U(n,f) and ^{239}Pu(n,f) reactions using prompt neutron detection to identify fission events[1]. The data for ^{235}U have been analysed and the results were presented at the Second IAEA Panel on Neutron Standard Reference Data (Vienna, 1972). Further analysis is required to obtain the cross-section for ^{239}Pu.

The measured relative shape of the ^{235}U(n,f) cross-section has been normalized to an average value in the 10 to 30 keV energy interval of 2.349 barns, to agree with the recently evaluated cross-section of Sowerby et al[2]. The measurements are shown in Fig. 7. The full experimental energy resolution is shown only above $\sim$ 300 keV, at lower energies the timing channels have been grouped to keep the statistical errors on all points less than $\pm$ 2% (one standard deviation). Systematic errors are estimated to lie between 3 and 4% depending on incident neutron energy.

It can be seen from the figure that even with grouped channels the well-known structure in the cross-section is very evident below 50 keV. At the full experimental resolution of about 1.7 nsec/m the structure is in broad agreement with the high resolution data of Bowman et al[3].

When the measured cross-section is averaged over wide energy intervals to remove structure, it is found not to deviate from the evaluated cross-section by more than $\pm$ 4% at all energies above 2 keV. In the 1 to 2 keV interval the difference between the measured and evaluated cross-sections is 5.7%. The agreement in the shape of the cross-section with other current evaluations is not as good. For example, to normalize the measurements to the ENDF/BIII evaluation in the 10 to 30 keV energy interval would lead to discrepancies of about 8 and 12% at the highest and lowest energies respectively of the present range. In the region from 30 to 100 keV the evaluation of Sowerby et al relies for its shape upon the bomb-shot data of Lemley et al[4]. The close agreement between

---

(1) Gayther D.B., Boyce D.A. and Brisland J.B., Nuclear Physics Division Progress Report AERE-PR/NP 19, p.1 (1972), also UKNDC(72) P37, EANDC(UK) 140AL INDC(UK) - 15G.

(2) Sowerby M.G., Patrick B.H. and Mather D.S., Harwell Report AERE - R 7273 (1973).

(3) Bowman C.D., Sidhu G.S., Stelts M.L. and Browne J.C., Proc. of Third Conf. on Neutron Cross-sections and Technology, Knoxville, p.584 (1971).

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

our cross-section and this evaluation can then be taken to confirm the shape measured by Lemley et al. It can be seen from Fig. 7 that the present data are in general agreement with the Van de Graaff measurements of Szabo et al[5,6] while generally lying below the measurements of White[7].

(5) Szabo I., Filippi G., Huet J.L., Leroy J.L. and Marquette J.P., Proc. of 1970 Argonne Symp. on Neutron Standards and Flux Normalization, p.257 (1971).

(6) Szabo I., Filippi G., Huet J.L., Leroy J.L. and Marquette J.P., Proc. of Third Conf. on Neutron Cross-sections and Technology, Knoxville, p.573 (1971).

(7) White P.H., J. Nucl. Energy, Vol. 19, p.325 (1965).

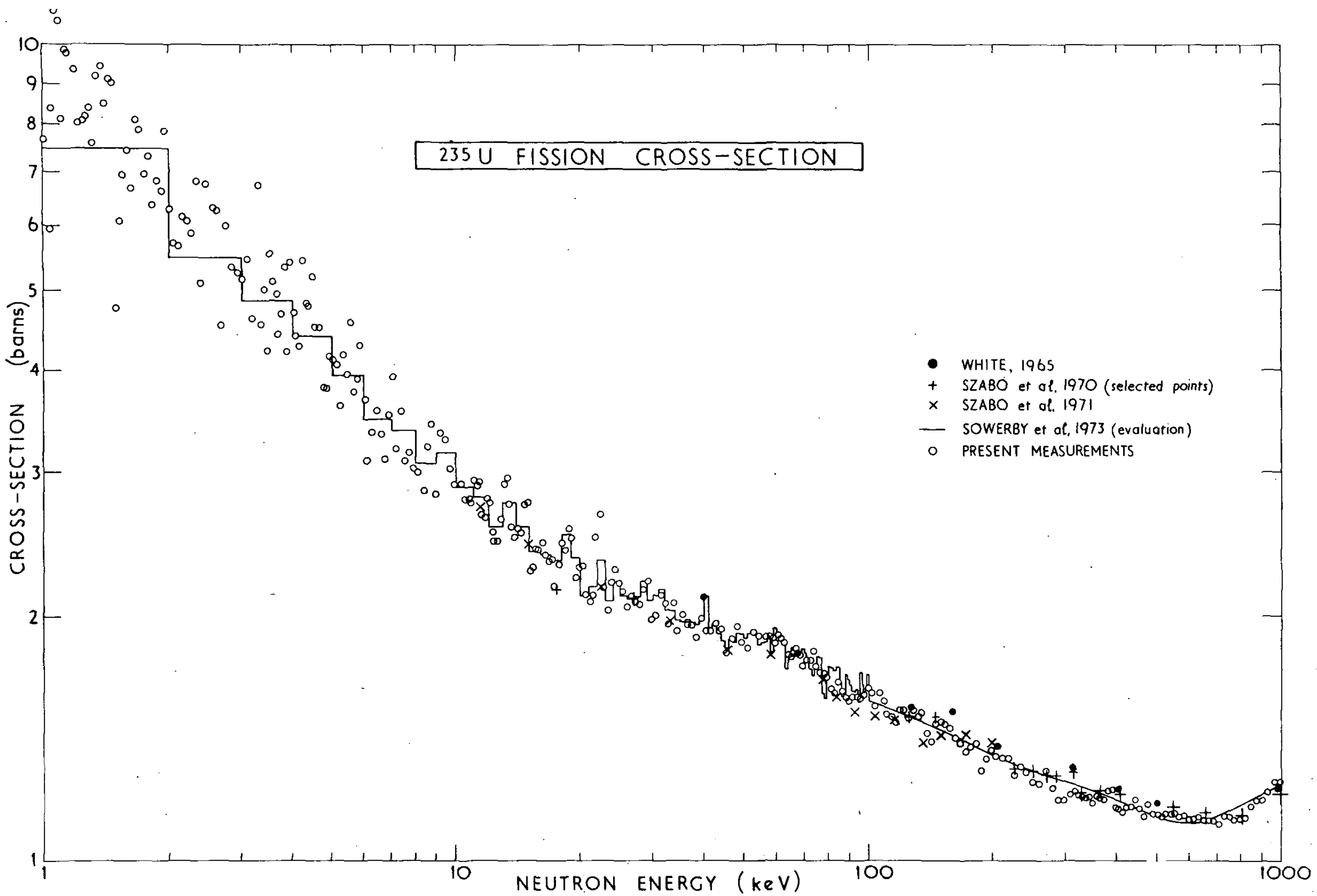

Fig. 7

The ^{235}U fission cross-section between 1 and 1000 kev.

H Development of the synchrocyclotron neutron time-of-flight spectrometer for nuclear data measurements (N.J. Pattenden, I.T. Belcher, I.M. Blair, P.H. Bowen, G.C. Cox, P.E. Dolley and W.R. McMurray (SUNI, South Africa))

The work mentioned in the previous report[1] has been continued. The main achievements in the system development have been as follows:

1. Neutron detector

The operating conditions for the ^{6}Li-loaded glass scintillator and RCA 4522 photomultiplier have been studied in detail and an electronic system using standard 2000 series units has been devised to provide fast timing and good discrimination against γ-rays, together with an easy setting-up arrangement. The timing resolution of the Li-glass detector was measured to be 3.4 nsec FWHM, and the γ-ray burst width as measured with the Li-glass detector was 5.1 nsec FWHM. This work has been described in a report[2].

2. Beam deflection and target system

Efforts have been directed to increasing the fraction of the deflected beam which strikes the target and minimising the risk of distortion of the deflector plates. The top plate and target base are now water-cooled, the centre plate is made of stainless steel and rigidly fixed at one end only, and there is a carbon beam clipper system to define the deflected beam position and protect the plates from excess current. The tungsten target is divided into quarters, insulated from each other and the earth, and the collected proton current can be measured on each quarter as well as on separate parts of the carbon clipper system. Thermocouples measure the target and top plate temperatures.

It was observed that, when the beam radial oscillation amplitude exceeded $\sim$ 7 cm, a multiple-pulsing effect was produced due to the deflected beam striking the target many revolutions after deflection. The effect was periodic, with the same frequency as the precession of the orbit centre ($\sim$ 1.4 MHz). It could be minimized by running at $<$ 1.8 μA mean beam current with the machine carefully adjusted for minimum radial oscillations, but these running conditions were not easy to predict or maintain. It was discovered that, if the large radial oscillations were removed by a carbon block located in the undeflected beam, then $\sim$ 4 μA of beam current could be given to the target with an acceptably-small multiple-pulsing effect. Moreover, the machine running conditions were not so critical. The carbon block was adjusted radially until an optimum position for target current and

(1) UKNDC (72) P37, EANDC (UK) 140AL, INDC (UK) - 15G.

(2) McMurray W.R., Pattenden N.J. and Valail G.S., AERE - R 7396 (1973).

multiple-pulsing was found.

Under these conditions, the machine worked with reasonable reliability for about a week continuously with ~ 4 μA target current, which corresponded to ~ 80% of the circulating beam. The target temperature was ~ 900°C and there appeared to be no danger of the deflector plates distorting by overheating.

3. Collimation and shielding

It was observed that a significant fraction of the background measured in the Li-glass detector was due to γ-rays from the general activity of the target. This effect was much reduced by placing a 7.5 cm thick tantalum shield in the neutron beam outside the synchrocyclotron tank. This attenuated radiation from the target itself, while allowing the detector to observe neutrons from over half of the moderator. The background was ~ 7% at 25 keV neutron energy.

In general the collimation and shielding for the neutron flight-path is now composed largely of boron-loaded resin, brass and tantalum. Additional evacuated sections have been added to the flight-path and all vacuum windows are made of thin plastic (Kapton).

4. The digital time analyser has been made to work reliably with a system which accepts up to 4 stop pulses per machine burst.

During the year, experiments on the time-of-flight spectrometer have included more iron total cross section measurements(3) and a measurement of the ratio of the ^{238}U to ^{235}U fission cross sections over the energy range 1 to 14 MeV(4).

(3) This report page 23 and AERE - R 7425.

(4) This report page 27.

H A measurement of the neutron total cross-section of iron from 24 keV to 1000 keV
(N.J. Pattenden, I.T. Belcher, I.M. Blair, P.H. Bowen, G.C. Cox, P.E. Dolley, (AERE) and W.R. McMurray (SUNI, South Africa)).

A measurement of the total cross-section of natural iron covering the energy range 24 to 1000 keV has been made on the Harwell synchrocyclotron and the results published(1). Fig. 8 shows the data between 200 and 300 keV. The measurements, which have a best resolution of ~ 0.07 ns/m, are preliminary, since (1) machine modifications which are at present being carried out on the synchrocyclotron should enable much higher neutron

(1) Pattenden N.J., Belcher I.T., Blair I.M., Bowen P.H., Cox G.C., Dolley P.E., and McMurray W.R., AERE - R 7425 (1973).

intensities to be reliably produced at the source, (2) a new data collection program which more fully utilizes the capacity of the on-line computer will enable the measurements to cover a longer time range, extending the results to lower energies. Hence it should be possible to repeat and improve on these measurements with higher statistical accuracy, better background determinations and using samples of several different thicknesses.

In the energy region below 350 keV, the only other recent measurements are those of Garg et al[2], for which the resolution was almost an order of magnitude worse than for the present measurements. Thus it is not surprising that their results do not show many of the narrow resonances observed in our data. In some regions where resolution is not important, our results appear to be systematically lower than theirs, by 10-15%.

Above 350 keV, our results may be compared with those of Barnard et al[3], and above 500 keV also with Cierjacks et al[4], Schwartz et al[5] and Carlson and Cerbone[6]. Inspection of the cross section curves shows that the Cierjacks and Carlson sets of data were made with considerably better resolution than ours, the Schwartz data with poorer resolution than ours and the Barnard data with similar or slightly poorer resolution than ours. In the latter case, the published curve is on too small a scale for close comparison. Thus the curve shapes agree with the quoted resolutions with the exception of Barnard et al. The absolute values of observed cross section above 350 keV are strongly resolution-dependent, and so it is difficult to compare magnitudes. On the whole, there appears to be reasonable agreement between our values and the other published values to within the quoted errors.

The narrow resonances observed in our data, which are superimposed on the well known large s-wave resonances, may be compared with those observed in radiative capture measurements by Hockenbury et al[7] and Ernst et al[8]. Area analysis of our data should enable

---

(2) Garg J.B., Rainwater J., and Havens W.W., Phys. Rev. C3, 2447, (1971).

(3) Barnard E., De Villiers J.A.M., Engelbrecht C.A., Reitmann D., and Smith A.B., Nucl. Phys., A118, 321 (1968).

(4) Cierjacks S., Forti P., Kopsch D., Dropp L., Nebe J., and Unseld H., KFK 1000 (1968); also Cierjacks S., Nuclear Data for Reactors, 2, 219, IAEA Vienna (1970).

(5) Schwartz R.B., Schrack R.A., and Heaton H.T., unpublished (1969).

(6) Carlson A.D., and Cerbone R.J., Nuc. Sci. and Eng. 42, 28, (1970).

(7) Hockenbury R.W., Bartoleme Z.M., Tartarczuk J.R., Moyer W.R. and Block R.C., Phys. Rev. 178, 1746, (1969).

(8) Ernst A., Fröhner F.H., and Kompe D., Nuclear Data for Reactors 1, 633, IAEA Vienna (1970).

values of fg Γ_n to be obtained, where f is the isotopic abundance, g is the spin statistical weight factor and Γ_n is the resonance neutron width. These values combined with the values of fg $\Gamma_n \Gamma_\gamma/(\Gamma_n + \Gamma_\gamma)$ obtained from the area analysis of the capture cross-section measurements will allow values of Γ_γ, the radiation width, to be obtained in favourable cases.

The radiative capture measurements made to date on resolved resonances have covered a rather lower energy range than is covered by the total cross section measurements reported here, due to poorer resolution. Therefore, it is proposed to extend the present measurements down to lower energies, and at the same time to repeat them with better statistical accuracy and background determinations, covering a range of sample thicknesses.

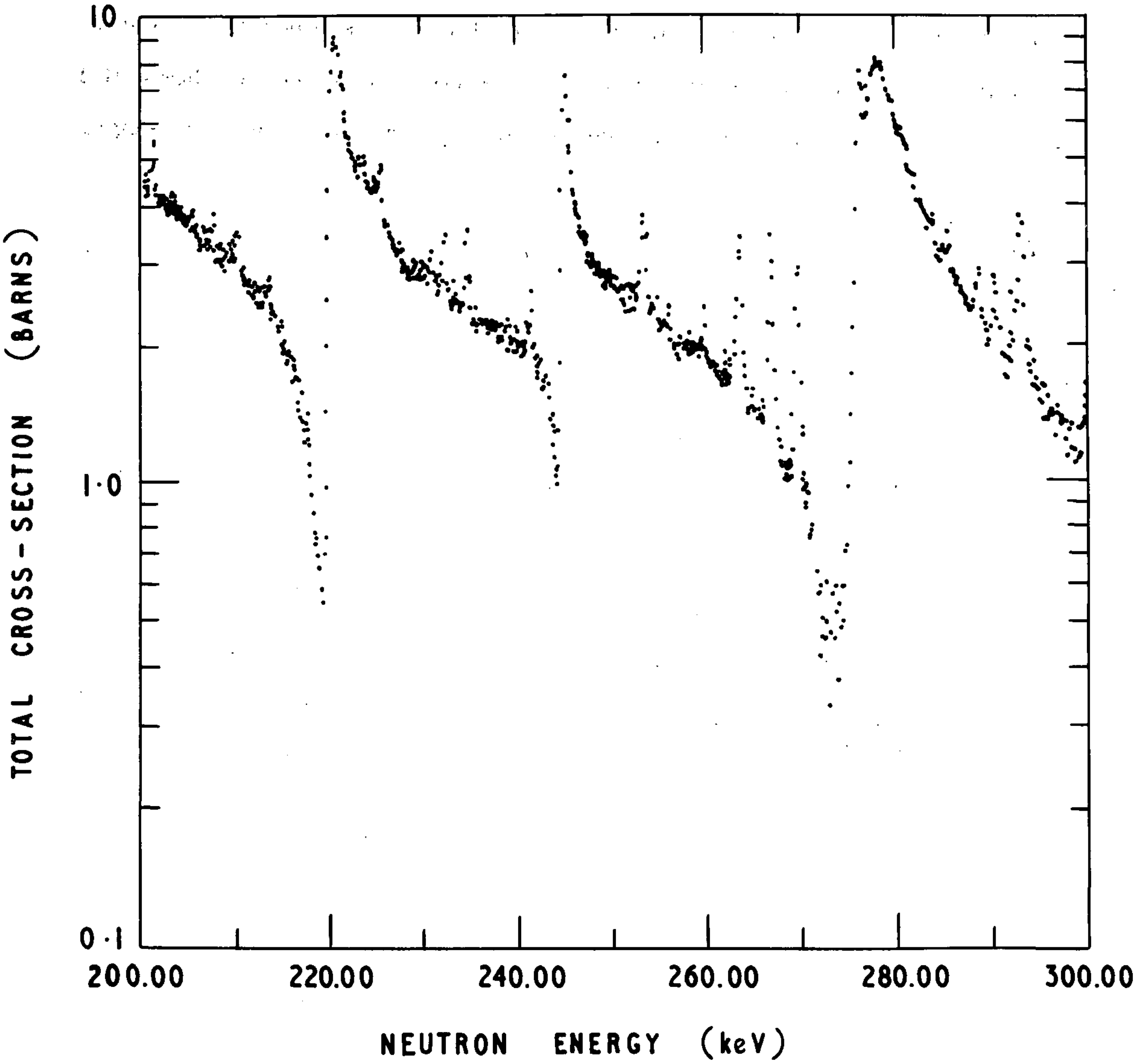

Fig. 8

The Fe total cross-section between 200 and 300 kev.

H <u>The ^{238}U/^{235}U fission cross-section ratio</u> (M.S. Coates, D.B. Gayther, N.J. Pattenden, D.A. Boyce, I.T. Belcher, P.H. Bowen, J.B. Brisland, G.C. Cox and P.E. Dolley)

The ratio of the neutron induced fission cross-sections of ^{238}U and ^{235}U has been
1014 measured by the time-of-flight method in the energy range from the ^{238}U(n,f) threshold to
1015 ~ 20 MeV. Fission fragments were detected in a gas scintillation chamber in which 0.5
1016 mgm/cm^2 foils of each material were mounted back-to-back and perpendicular to the incident
1017 beam. The detector was placed 12 m from the synchrocyclotron neutron target to give an
1018 overall resolution of ~ 0.4 nsec/m. In order to eliminate the effect of incident neutron
1019 momentum (which causes preferential fragment emission in the forward direction), measurements were made alternately with the ^{235}U and then the ^{238}U foil facing the target and the data from the two sets of runs were averaged. The energy scale was calibrated by placing carbon samples in the beam and observing the positions of the well-known resonances above 2 MeV. These runs also served to give an indication of the time dependent background based on the known carbon total cross-section.

The cross-section ratio was not measured absolutely and Fig. 9 shows our preliminary data normalized at 14 MeV to the recent evaluation of Sowerby et al[1]. A correction for the time dependent background has not yet been applied, but indications are that this should not distort the observed ratio by more than 2% at any energy. The statistical error (standard deviation) on all points is less than ± 1.5%. It can be seen from the figure that overall shape agreement is good, the experimental values always lying within ± 5% of the evaluated ratio.

(1) Sowerby M.G., Patrick B.H. and Mather D.S., AERE Report R-7273 (1973).

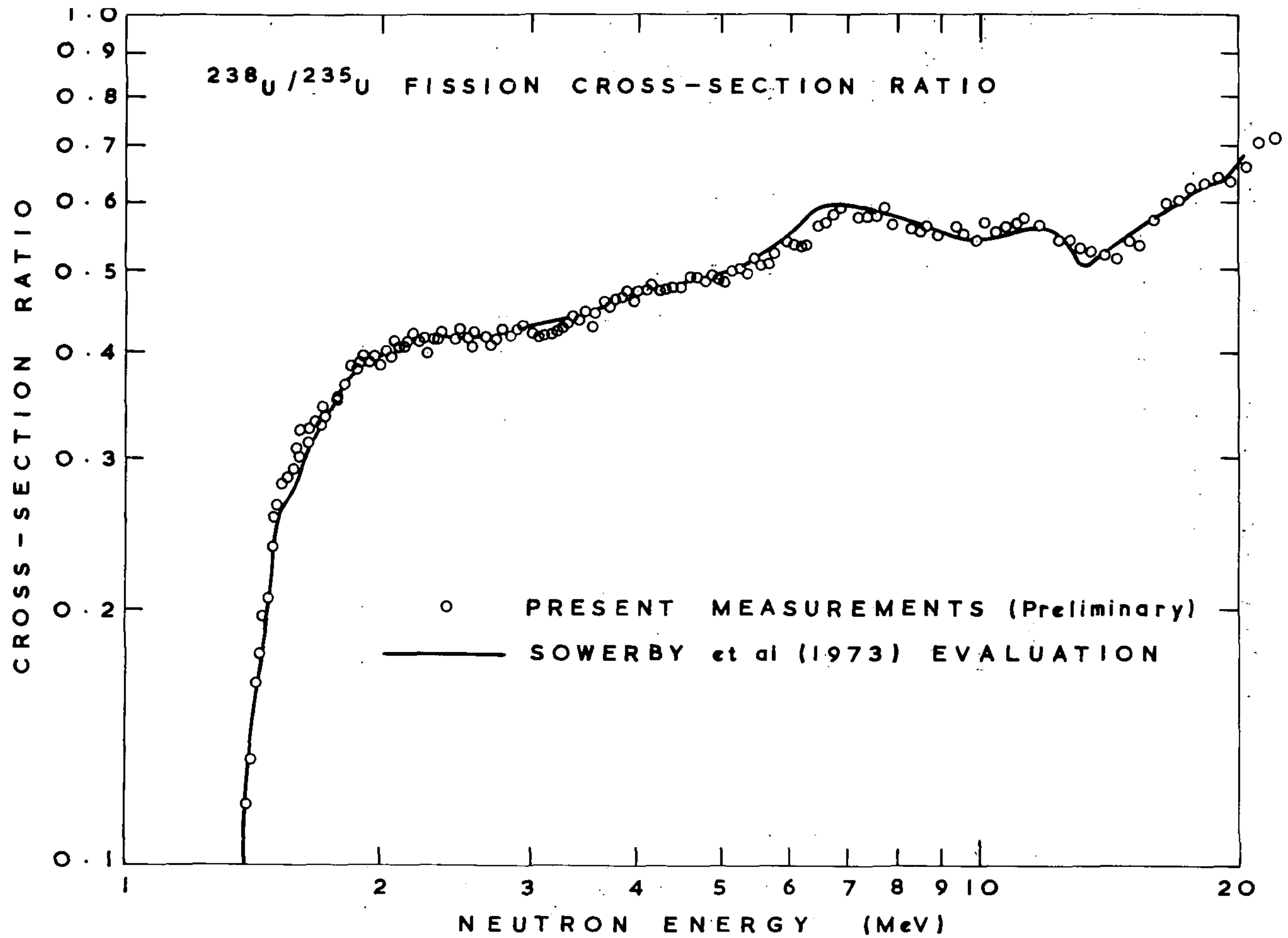

Fig. 9

The ratio of the ^{238}U and ^{235}U fission cross-sections.

Evaluations of the cross-sections of actinides (M.G. Sowerby, B.H. Patrick, Mrs. R. North, Miss E.M. Bowey)

903 to The simultaneous evaluation of the fission cross-sections of ^{235}U, ^{238}U and ^{239}Pu and
921 1013 the capture cross-section of ^{238}U reported in the previous progress report[1] has been
to 1019 fully documented and issued as report AERE-R 7273. As well as containing the recommended
1033 to cross-sections the report includes a compilation of all the experimental data accepted for
1040 1102 the evaluation together with details of any renormalisations. Also given are lists of
to 1116 unreliable experiments and the reasons for their rejection.

In January 1972 a meeting sponsored by the European American Nuclear Data Committee (EANDC) on the evaluation of ^{235}U, ^{238}U and ^{239}Pu cross-sections was held at A.E.R.E., Harwell. The report of the meeting (EANDC 90'L') contains details of the different national philosophies adopted in evaluation to reconcile the differences between measured and calculated fast reactor properties. The report also includes comparisons of the various sets of evaluated data (e.g. UKNDL, ENDF/B, KEDAK and SPENG).

1267 In order to calculate the build up of the higher actinides in fast reactor fuel it is
1278 1279 necessary to evaluate the cross-sections of the Am and Cm isotopes. Fission cross-section
1280 data are available for most isotopes but there is little information on capture cross-
1281 sections and these must therefore be obtained by calculation. Lynn (this report) has made
1282 1284 Hauser-Feshbach calculations (with fluctuations) of the fission cross-sections for a wide
1285 range of Z and A. Parameters (such as the number of fission channels and the level density
1286 distributions) have been adjusted to fit the experimental data which we have evaluated.
1292 1298 An important part of this work was the establishment of a consistent set of thermal cross-
1299 sections for the Am isotopes as these are frequently used for the normalisation of experi-
1300 mental data extending to higher energies. Table 4 gives the recommended values of these
1302 1305 thermal cross-sections.

1307 Data files in UKNDL format based on this work and suitable for fast reactor calcula-
1308 tions have been created for the following materials: ^{241}Am (DFN 1001), ^{242}Am (DFN 1002),
1310 1312 ^{243}Am (DFN 1003), ^{242}Cm (DFN 1004), ^{243}Cm (DFN 1005), ^{244}Cm (DFN 1007) and ^{245}Cm (DFN 1006).
1313 These files give fission and capture cross-section data from a keV to 10 MeV.

1315

1316

1317

---

(1) UKNDC (72) P37, EANDC (UK) 140 AL, INDC (UK) - 15G.

TABLE 4

Recommended Thermal cross-section data for Am

Quantity	Energy	Recommended value
σ_{nf} (Am-241)	0.0253 eV	3.16±0.16b
σ_{nT} (Am-241)	0.0253 eV	605±50 b
σ_{nA} (Am-241)	0.0253 eV	590±50 b
Fraction of $\sigma_{n\gamma}$ (Am-241) leading to Am-242m	0.0253 eV	10.1±3.0%
	"Resonance integral"	12.5±3.0%
	Fast Reactor Spectrum	15.9±3.0%
σ_{nf} (Am-242m)	0.0253 eV	6600±500 b
$\sigma_{n\gamma}$ (Am-242m)	0.0253 eV	700±700 b
σ_{nf} (Am-242gs)	0.0253 eV	2950±1000

Work has started on the evaluation of the cross-sections of ^{235}U and ^{239}Pu in the
923 energy range below ~ 1 eV. In addition to providing better cross-section data the work is
925 aimed at helping the assessment of the feasibility of making an experiment to measure the
1120 energy dependence of η below 0.5 eV. In most previous evaluations it has been assumed that $\bar{\nu}$ is constant in the thermal energy range and so the values of η have come from a combination of η measurements and values derived using the expression

$$\eta = \frac{\bar{\nu}\,\sigma_{nf}}{\sigma_{nT} - \sigma_{nn}}$$

where σ_{nf}, σ_{nT} and σ_{nn} are the fission total and scattering cross-sections. The measurements of Weinstein et al(2) suggested that $\bar{\nu}$ could be significantly changing in this energy range and so a better η evaluation should take this into account. Recently, however, Block(3) has reported improved measurements which indicate that $\bar{\nu}$ is constant and this probably indicates that improved data are unlikely to come from evaluation as there are few recent measurements in this energy range. However, before final conclusions are drawn the effects of revision of the 2,200 m/sec data recommended by the IAEA must be considered.

---

(2) Weinstein S., Reed R. and Block R.C., Physics and Chemistry of Fission, p. 477 IAEA Vienna, (1969).

(3) Block R.C. Private communication (1973).

Calculation of cross-sections of higher actinides (J.E. Lynn)

A survey of parameters of the fission barriers of actinide nuclei has been made (see Nuclear Studies in this Progress Report p. 33), and these have been used in conjunction with the dipole giant resonance model of the radiation process to calculate capture cross-sections of several important Am and Cm nuclei in the neutron energy range ~ 1 keV to ~ 2 MeV, for which differential capture cross-section measurements have not been made. Up to an energy of about 1 MeV (the exact value depending on the condition that the number of fission and inelastic scattering channels should not be too large) Hauser-Feshbach theory (with allowance for the fluctuations in individual resonance partial widths) was used in these calculations, while at higher energies a simpler statistical model was used. These calculations have been incorporated in the evaluations of Am and Cm nuclei made by Sowerby et al (this report p. 29).

E Resonance reaction measurements performed on Er isotopes (H.P. Axmann (University of Vienna))

Capture and transmission experiments on various enriched Er-isotope samples were carried out in the past two years. The information obtained from an area analysis of these measurements was combined to determine resonance parameters for the ^{167}Er s-wave resonances in the energy region from 5 eV to 130 eV. In addition resonance spin determinations were carried out using ratios of low energy gamma-ray transition probabilities.

From this work the resonance parameters J, Γ_n, and Γ_γ for some 30 resonances were obtained. However, the values of Γ_γ could not be determined very well in many cases from these data.

In order to improve the accuracy of the results, elastic neutron scattering cross-section measurements were performed on the rebuilt 50 m flight path facility. The data from these experiments are undergoing analysis at present. It is also hoped to obtain more accurate results with improved area analysis techniques.

In an attempt to round off the picture of the neutron resonance reactions, measurements of the de-excitation gamma-ray spectra (1.3 MeV < E_γ < 8 MeV) of ^{167}Er after neutron resonance capture were performed. These data are still awaiting analysis.

E Spin assignments for s-wave resonances in ^{133}Cs(n,γ) (P. Riehs (Institut fur Experimentelle Kernphysik an der Technischen Hochschule, Vienna) and B.W. Thomas)

Previous measurements(1) of low energy gamma-rays of ^{133}Cs(n,γ) have been continued for resonances at higher neutron energy in the region from 150 to 900 eV. It is intended to deduce further spin assignments from the population of low energy levels; the data are under evaluation at the present time. The fluctuations of population at low energy due to the random distribution of partial radiation widths are studied theoretically using a gamma-ray cascade model in analogy to the model by Poenitz.

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

Fission in nuclear reaction theory (J.E. Lynn)

In this work the incorporation of fission into the R-matrix nuclear reaction theory in a formal way was considered. By suitable definition of the fission variable in terms of the individual nucleon co-ordinates, and explicit expression of the kinetic energy term of the many-particle Schrödinger equation in terms of this variable, this incorporation can be achieved. The adaptation of this formalism to the double-humped fission barrier was then considered. A paper describing all this work has now been published in J. Phys. A:

Math., Nucl., Gen. Vol. 6, p.542 (1973).

Properties of fission barriers (J.E. Lynn)

An extensive survey and analysis of experimental data on fission of the actinide nuclei has yielded a set of fission barrier parameters for many nuclei from the thorium isotopes to those of curium. A notable feature of these parameters is a distinct odd-even effect in the height of the barrier peaks relative to the ground state; the inner barrier peaks of odd nuclei are of the order of 0.5 MeV higher than those of their odd-Z neighbours of the same charge, while a slightly smaller difference appears between the odd-N and even nuclei. The same study reveals that the density of intrinsic states at the deformation of the inner barrier approaches 5 times the density of states of normal deformation at excitation energies up to a few MeV. This is in disagreement with independent quasi-particle models of the level density, which indicate that the barrier densities should be slightly lower than those at normal deformation.

E Neutron resonance capture gamma-ray studies (B.W. Thomas and T.J. Haste (Oxford University))

(1) $^{240}Pu(n,\gamma)^{241}Pu$ reaction

A preliminary analysis of the high energy capture gamma-ray spectra of ^{240}Pu resonances has been discussed previously(1) in connection with the determination of the total binding energy. These data have now been extensively analysed to obtain the relative strengths of 48 transitions (range 2.5 to 5 MeV) for 9 s-wave resonances below 104 eV. The energies of ^{241}Pu excited states populated by primary transitions (Binding Energy - E_γ) are compared with those obtained from a (d,p) experiment(2) in Fig. 10. The overall features are similar, and bear a striking resemblance to those of the low lying excited states of ^{239}U which has the same number of neutrons.

The relative intensities of all transitions have been averaged over 9 resonances (< 104 eV) to investigate any bulk properties of the spectra. The uncertainties are large (~ 50%) because of the small sample involved, but the highest energy transitions suggest an E1/M1 ratio of 4 or 5.

The average intensities have been summed in energy bands of 100 keV, Fig. 11, and the histogram indicates a marked cut off at 4.5 MeV due to the fall in level density below 750 keV excitation and the absence of negative parity states near the ground state. An interesting feature is the marked absence of strength between 3 and 3.5 MeV which may

(1) UKNDC (72) P37, EANDC (UK) 140 AL, INDC (UK) - 15G.

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

indicate the existence of structure effects.

As can be seen in Fig. 12 there is an apparent strong correlation between the strength of gamma-rays at 3042, 3943, 4389 keV. These transitions are relatively strong in the average spectrum and seem to occur at the energies of the broad structural bumps in Fig. 11.

Gamma-ray spectra for the unresolved resonance cross-section (0.5 $\longrightarrow$ 2.0 keV) were examined for any significant structure, particularly in the 3 subthreshold fission regions. Common features in these regions were:-

(1) exceptionally strong single gamma-rays between 4 and 5 MeV and

(2) the existence of a small but significant bump near 3 MeV.

These features together with those of the resolved resonance region may point to a common structural phenomenon which is at present unexplained.

(2) $^{93}Nb(n,\gamma)^{94}Nb$ reaction

(a) Spin assignments for resonances in ^{93}Nb

Measurements have been made of the low energy neutron capture gamma-ray spectra for individual s-wave and p-wave resonances in ^{93}Nb, using a 30 cm^3 Ge(Li) detector at the 10 metre flight path of the Neutron Booster. A 30 gm sample of niobium pentoxide was used as the target. Data were collected by a two-parameter system on-line to a PDP-4 computer.

The results for the s-wave resonances studied are presented in Table 5, together with those of previous experiments. The results of Le Poittevin et al[3] were derived from cross-section measurements while those of Prestwich et al[4] and Chrien et al[5] were deduced from primary capture gamma ray studies. The gamma rays used in the present work are the 100 keV, 114 keV, 293 keV, 310 keV and 338 keV transitions. The ratios of the 293 keV and 100 keV transitions to the 114 keV transition are shown in Fig. 13. The level scheme constructed by Jurney et al[6] shows that these gamma-rays depopulate levels with spin and parity of 2^+, 2^- and 5^+ respectively.

Analysis of the data for p-wave resonances is in progress. Preliminary analysis indicates that the intensity ratios of the low energy gamma-rays may differ for s-wave and p-wave resonances with the same spin.

(3) Le Poittevin G., De Barros S., Huynh V.D., Julien J., Morgenstern J., Netter F. and Samour C., Nucl. Phys., 70 497 (1965).

(4) Prestwich W.V., Coté R.E. and Shwe H., Phys. Rev. 174 1421 (1968).

(5) Chrien R.E., Rimawi K. and Garg J.B., Phys. Rev. C3 2054 (1971).

(6) Jurney E.T., Motz H.T., Sheline R.K., Shera E.B. and Vervier J., Nucl. Phys., A111 105 (1968).

(b) Investigation of non-statistical effects associated with high-energy gamma-rays

An experiment is being performed to measure the high energy neutron capture gamma-ray spectra for individual s-wave and p-wave resonances in the $^{93}Nb(n,\gamma)^{94}Nb$ reaction, with the aim of investigating non-statistical effects. A 10 cm^3 Ge(Li) detector is being used at the 10 metre flight path of the Neutron Booster, and the data are being collected using the two-parameter on-line system linked to the PDP-4 computer.

TABLE 5

^{93}Nb s-wave resonance spin assignments

E_R (eV)	J			
	Le Poittevin et al (1965)	Prestwich et al (1968)	Chrien et al (1971)	Present experiment
105.8			4	4
119.2		4	(4)	5
193.8			(4)	5
335.5			4	4
378.4	(4)			5
460.3				5
640.8				5
741.4	(5)			4
934.7	4			5
1009.0				4
1147.7	5			5
1175.3	4			4
1393.1	4			4
1452.0	4			4

Parentheses denote an uncertain assignment

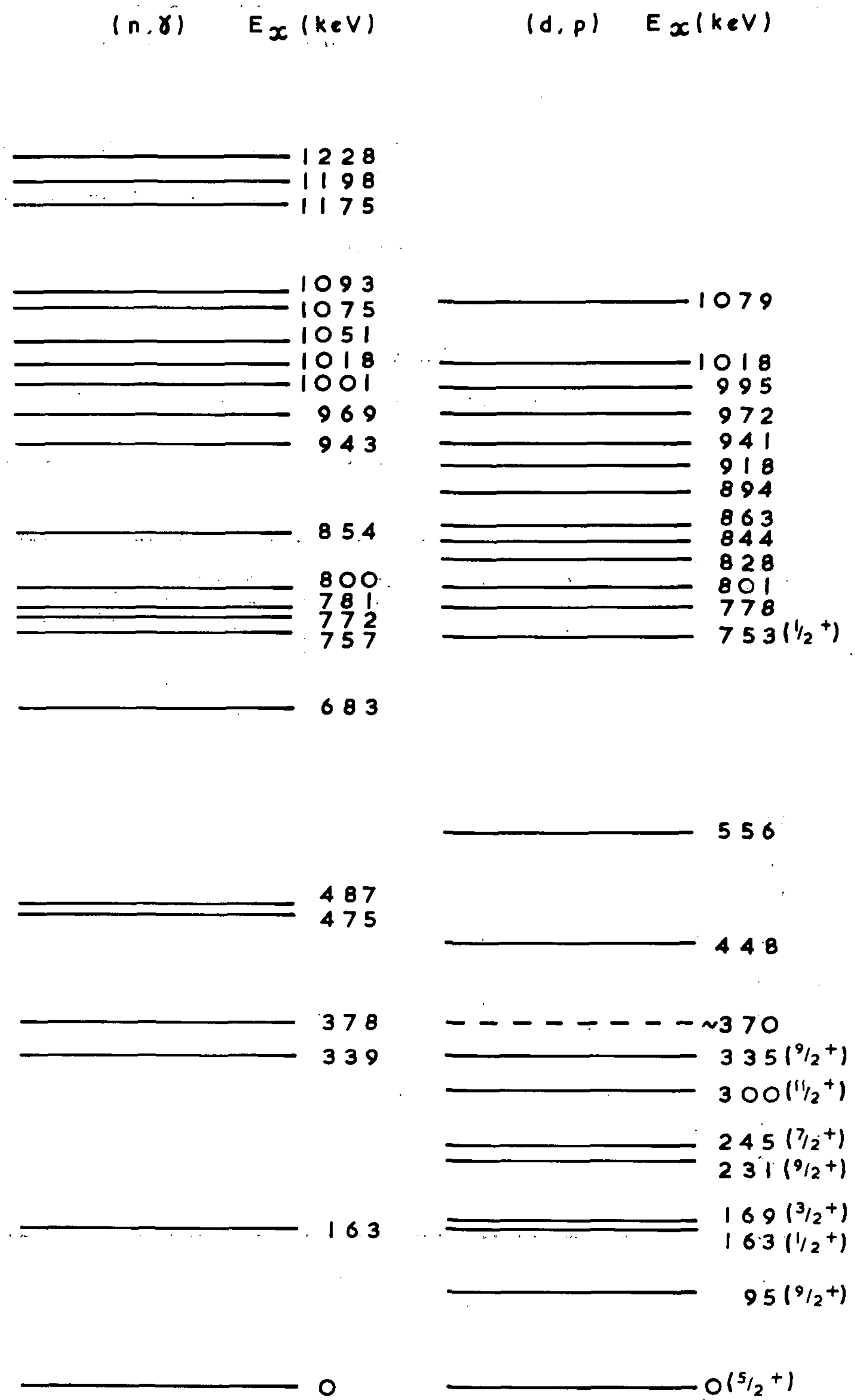

Fig. 10

The energies of the excited states of ^{241}Pu observed in the ^{240}Pu (n, γ) and ^{240}Pu (d, p) reactions.

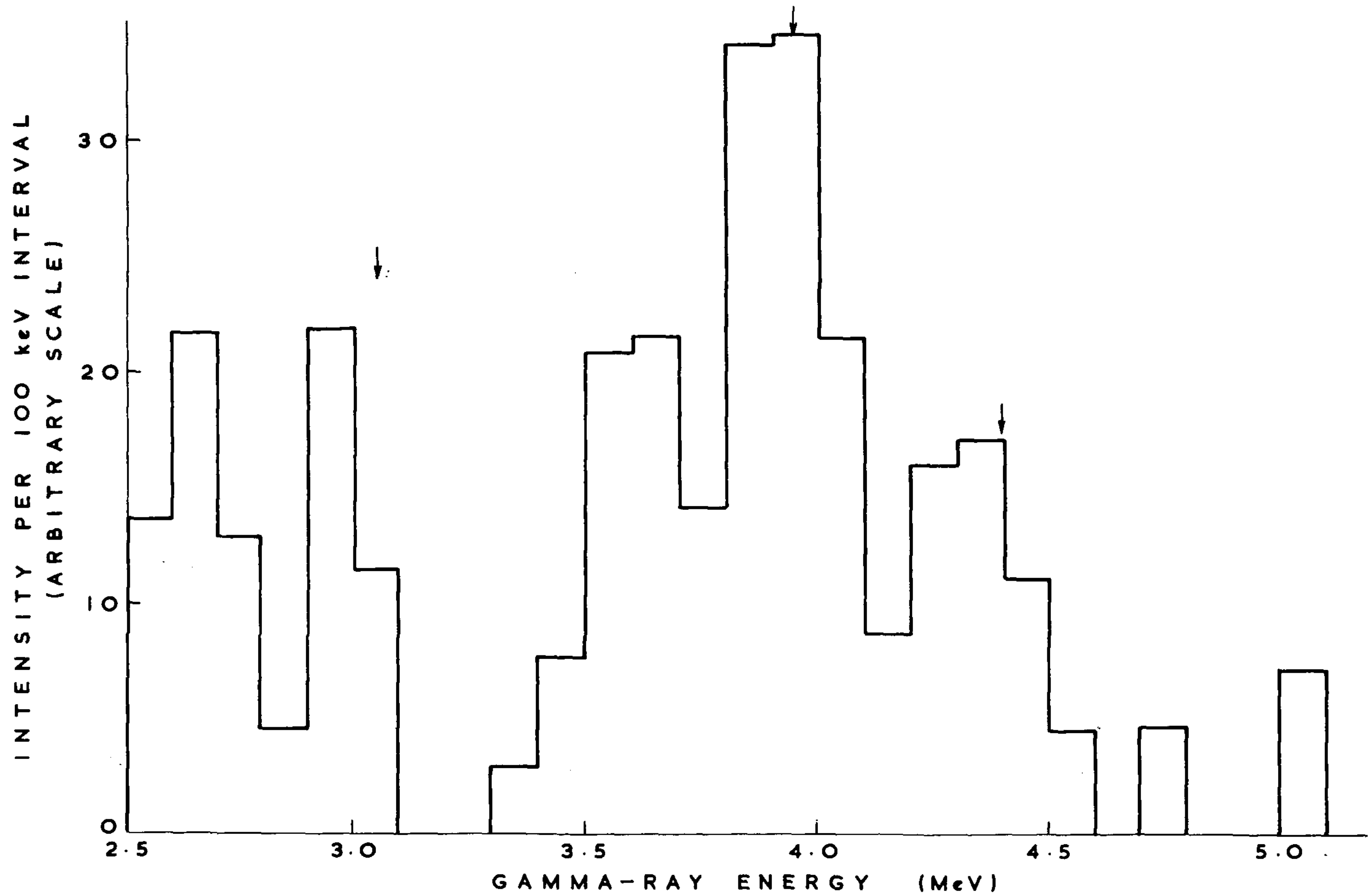

Fig. 11

Average capture gamma-ray spectrum for 9 s-wave resonances in ^{240}Pu.
The arrows mark the positions of the γ-rays at 3042, 3943 and 4389 keV.

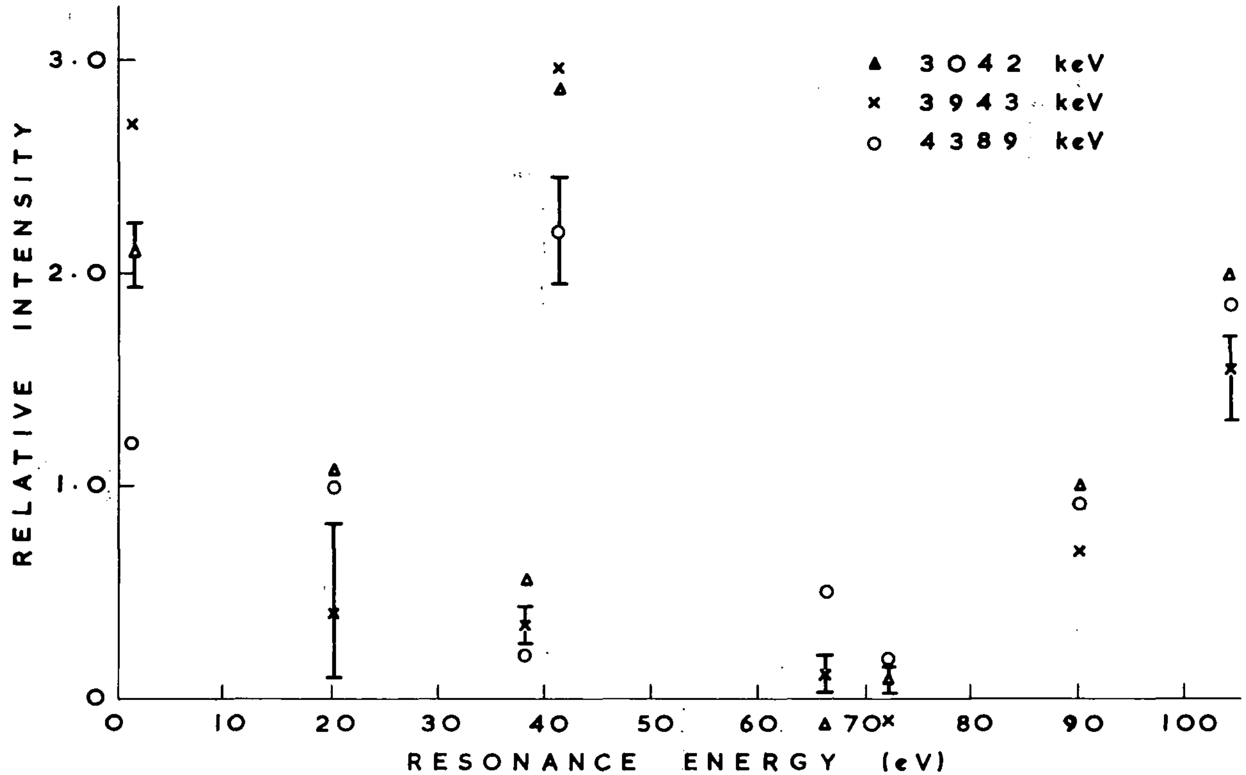

Fig. 12

Comparison of the intensities of the 3042, 3943 and 4389 keV γ-rays observed in resonances in $^{240}Pu\ (n, \gamma)$ below 104 eV.

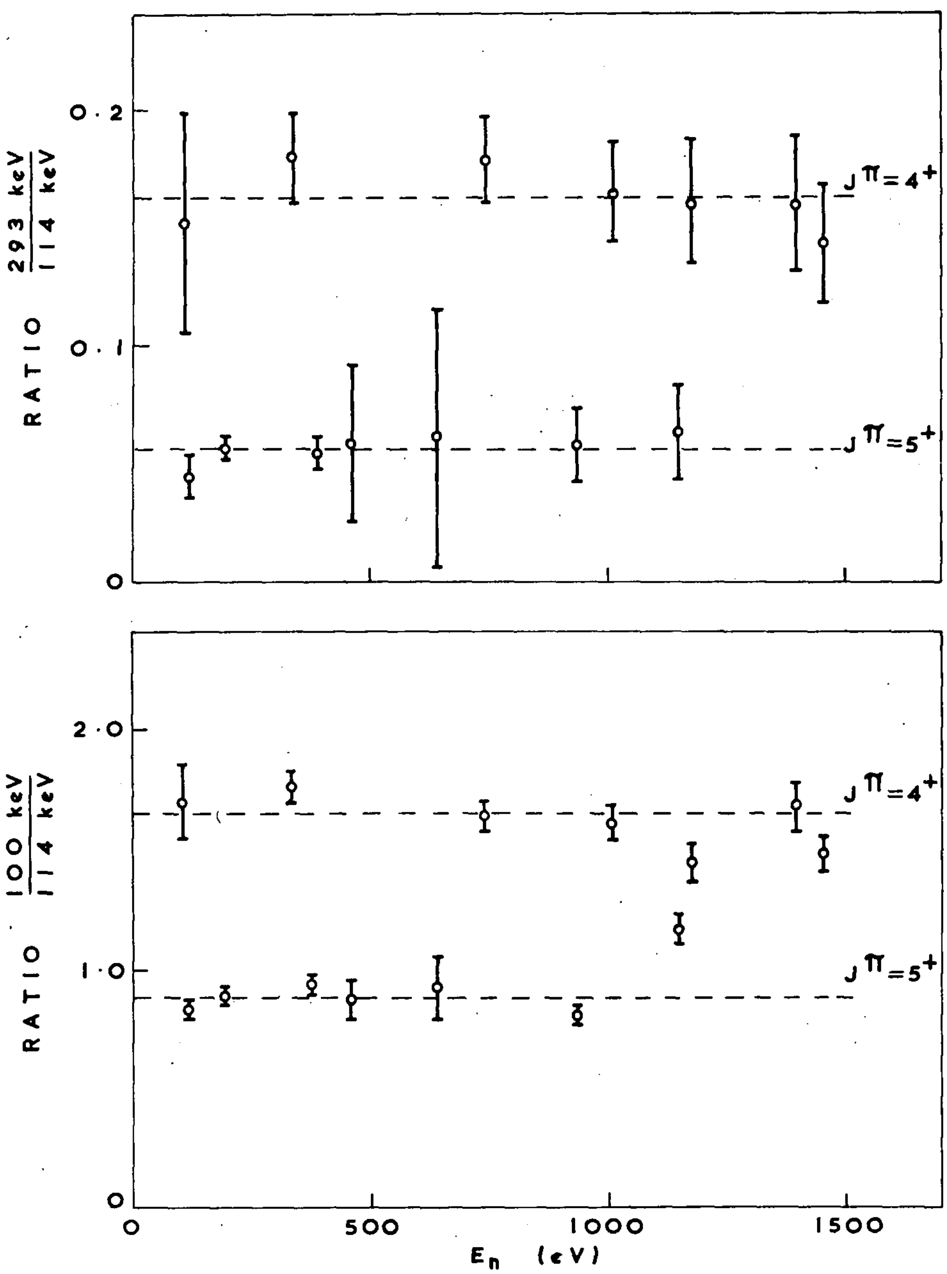

Fig. 13

Ratio of low energy γ-ray intensities observed in ^{93}Nb (n, γ).

NUCLEAR DATA FOR FUSION REACTORS

Introduction (A.T.G. Ferguson)

Experimental work in this area was initially oriented towards charged particle reactions (see for example measurements of the cross-section for the $^{6}Li(p,{}^{3}He)^{4}He$ reaction)[1]. The emphasis has now changed and, as can be seen from the work reported below, the main aim is to develop instrumentation and techniques so that the neutron cross-sections of importance can be measured in the energy range 6-15 MeV.

(1) Hooton B.W. and Ivanovich M. UKNDC (72) P36, EANDC (UK) 139 AL, INDC (UK) - 14G, page 31.

D Tandem Neutron Facility (J.M. Adams and T.W. Conlon)

A neutron facility is being set up for the producing of neutrons in the energy range 6-15 MeV which are available from the $D(d,n)^{3}He$ and $T(p,n)^{3}He$ neutron producing reactions. At this stage no attempt will be made to develop a pulsed-beam facility on the Tandem. At the incident energies that will be used, there will also be neutrons due to competing 3-body break-up reactions, as well as a background problem due to the gas target assembly etc. A series of experiments will be conducted to investigate the magnitude of these effects and help minimise the latter.

At the present time a beam line is being set-up for this work incorporating the necessary safety facilities for handling tritium. A neutron spectrometer is being developed for investigating the neutron energy spectra, which will also be used for neutron flux measurements. The spectrometer comprises two fast neutron scintillation detectors arranged in a conventional "hydrogen scattering" geometry, with one of the detectors acting as the "hydrogen scatterer" itself. Conventional fast neutron time-of-flight techniques will be employed to time the neutrons from the "scattering" detector to the larger "second" detector.

The initial experiments will include a study of the $^{19}F(n,2n)^{18}F$ reaction from the neutron threshold at 10.984 MeV, employing the $T(p,n)^{3}He$ reaction as the source of mono-energetic neutrons.

The AWRE Large Liquid Scintillator (A.T.G. Ferguson and T.W. Conlon)

The large liquid scintillator which has been used extensively for (n,2n) and $\bar{\nu}$ measurements is to be transferred to A.E.R.E. and will be set up on an accelerator as and when required.

REPORTS

AERE - R 7166 Neutron cross-sections for Li-7 in the energy range 10 keV to 15 MeV. T.W. Conlon.

AERE - R 7273 A detailed report on the simultaneous evaluation of the fission cross-sections of U-235, Pu-239 and U-238 and the U-238 capture cross-section in the energy range 100 eV to 20 MeV. M.G. Sowerby, B.H. Patrick and D.S. Mather.

AERE - R 7396 A Li-6 loaded glass detector for neutron cross-section measurements on the Harwell synchrocyclotron. W.R. McMurray, N.J. Pattenden and G.S. Valail.

AERE - R 7425 A preliminary measurement of the neutron total cross-section of iron from 24 keV to 1000 keV using the Harwell synchrocyclotron. N.J. Pattenden, I.T. Belcher, I.M. Blair, P.H. Bowen, G.C. Cox, P.E. Dolley and W.R. McMurray.

EANDC-90"L" Report on the Evaluation Working Group Meeting held on 26-28 January 1972 at A.E.R.E., Harwell, U.K. to discuss the evaluation of U-235, U-238, and Pu-239 cross-sections. Edited by B.H. Patrick and M.G. Sowerby.

PUBLICATIONS

JAMES G.D., LYNN J.E. and EARWAKER L.G. Nuclear spectroscopy of highly deformed Th-231. Nuc. Phys. A189, 225 (1972).

LYNN J.E. Fission in nuclear reaction theory. J. Phys. A, Gen. Phys. 6, 542 (1973).

SOWERBY M.G. and KONSHIN V.A. Review of the measurements of alpha for Pu-239 in the energy range 100 eV to 1 MeV. Atomic Energy Review, 10, No. 4, 453 (1972).

CONFERENCE PAPERS

Contributed

COATES M.S., HUNT G.J. and UTTLEY C.A. Measurements of the relative $^{6}Li(n,\alpha)$ cross-section in the energy range 1 keV ⟶ 500 keV. Proceedings of 2nd IAEA Panel on Neutron Standard Reference Data, Vienna, November 1972.

COATES M.S., HUNT G.J. and UTTLEY C.A. A preliminary measurement of the relative $^{10}B(n,\alpha\gamma)$ cross-section. Proceedings of 2nd IAEA Panel on Neutron Standard Reference Data, Vienna, November 1972.

COATES M.S., GAYTHER D.B., HUNT G.J. and BOYCE D.A. Experimental test of the calculated efficiency of the Harwell black detector at high neutron energies using the Harwell long counter. Proceedings of 2nd IAEA Panel on Neutron Standard Reference Data,

Vienna, November 1972.

FERGUSON A.T.G. Fission spectrum as a standard. Proceedings of the 2nd IAEA Panel on Neutron Standard Reference Data, Vienna, November 1972.

GAYTHER D.B., BOYCE D.A. and BRISLAND J.B. Measurement of the U-235 fission cross-section in the energy range 1 keV to 1 MeV. Proceedings of the 2nd IAEA Panel on Neutron Standard Reference Data, Vienna, November 1972.

CHEMISTRY DIVISION, A.E.R.E., HARWELL

(Division Head Dr. W. Wild (until 30th November 1972)
Dr. C.B. Amphlett (after 1st December 1972))

CHEMICAL NUCLEAR DATA

A. Measurements completed

1. Cross-section for the production of ^{242}Cm from ^{241}Am

(R. Wiltshire, H.H. Willis, F.J.G. Rogers, K.M. Glover, J.G. Cuninghame (AERE) D.W. Sweet (AEEW)).

This integral cross-section was measured by irradiation of 3 samples of purified $^{241}AmO_2$ in the Zebra MZB core, followed by chemical separation of the ^{242}Cm produced in the irradiation. The result was 1.49±0.09 barns (AERE - R 7363, May 1973).

B. Measurements in progress

1. ^{235}U fission yields in fast monoenergetic neutron fluxes

(J.G. Cuninghame, J.A.B. Goodall, H.H. Willis)

Absolute fission yields are being measured for five key fission products at
952 neutron energies of 130, 300, 700, 900 and 1300 keV. The work is nearly complete and present indications are that there is no change in fission yields of peak nuclides with neutron energy within the accuracy of the experiment. A paper on this work has been submitted to the Journal of Inorganic and Nuclear Chemistry.

2. Mass spectrometric measurements of alpha and of fission yields

(E.A.C. Crouch, I.C. McKean)

Measurements are being made of alpha for ^{235}U, ^{238}U and ^{239}Pu and of fission yields for "burn-up" nuclides by mass-spectrometry. Samples were irradiated in various regions of DFR. Results are expected during 1974.

3. Effect of change of angular momentum and excitation energy on the fissioning nucleus $^{239}Pu^*$

(J.G. Cuninghame, J.A.B. Goodall)

This work is now complete and the results are being evaluated. Preliminary indications are that mean total kinetic energy of the fission fragments goes down as excitation energy of the compound nucleus increases. The effect of increase in angular momentum is uncertain because it seems to be masked by the fact that, when the bombarding particle is ^{3}He, direct interactions take place. This is being investigated further.

4. Half-lives of ^{237}Np and ^{239}Pu

(K.M. Glover, F.J.G. Rogers)

These measurements, which should be accurate to ± 1% and ± 0.5% respectively, are expected to be completed in 1974.

C. Evaluations

1. Thermal fission chain yields

(E.A.C. Crouch)

The evaluation of thermal fission chain yields has been completed and published as AERE - R 7209.

2. Fast fission chain yields

(E.A.C. Crouch)

The evaluation of fast fission chain yields has been completed and will be published as AERE - R 7394.

3. Independent fission yields

(E.A.C. Crouch)

The evaluation of independent fission yields is continuing and it is hoped that the results will be published by the end of 1973.

4. Delayed neutron emission

(L. Tomlinson)

The data on delayed neutrons from fission are being re-evaluated and it is hoped to publish the results in mid 1973.

5. Gamma ray energy and intensity catalogue

(N.R. Large, R.J. Bullock)

The results of this work will be published in June 1973.

PUBLICATIONS

AERE - R 7209 Fission product chain yields from experiments in Thermal Reactors. E.A.C. Crouch.

AERE - R 7363 The cross-section for the production of ^{242}Cm from ^{241}Am in a fast reactor. R. Wiltshire, H.H. Willis, D.W. Sweet, F.J.G. Rogers, K.M. Glover and J.G. Cuninghame.

AERE - R 7394 Fission Product Chain Yields from experiments in reactors and accelerators producing fast neutrons of energies up to 14 MeV. E.A.C. Crouch.

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

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

Measurement of Delayed neutron yield (M.H. McTaggart)

Present Status

937 Clifford's measurements of the total yield of delayed neutrons from U-235 and U-238
938 as published in Tomlinson's review paper (AERE - R 6993) have been modified slightly due
1023 to recalibration of the U-238 fissile deposit he used (the foil thickness correction he
1024 applied was incorrect). The best values are:-

1041

U-235	0.0174±0.0008	neutrons per fission
U-238	0.0472±0.0025	neutrons per fission

(quoted as 0.049±0.005 in AERE - R 6993)

Future Programme

A programme of work has started to recheck the neutron detector, its energy response and efficiency and then repeat the Clifford measurements including Pu-239. This is expected to take 6-9 months.

A.E.E. WINFRITH, FAST REACTOR PHYSICS DIVISION

(Division Head: Dr. C.G. Campbell)

Evaluation of Neutron Data

1. The UK Nuclear Data Library

(J.R. Allen, A.L. Pope and J.S. Story)

Neutron data evaluation work in the UKAEA has been and is being reported regularly in the series of Neutron Nuclear Data Evaluation Newsletters (NNDEN), originally published by Ribon at Saclay and now by the CCDN. For the period under review, see NNDEN-6 to -10.

The main tape of the UK Nuclear Data Library, NDL-1, has been re-edited and an EBCDIC copy was sent to the CCDN in May. This contains some new data files, some files converted from the American ENDF/B, and many minor corrections which include up-dated Q-values and atomic weights. Next to be done are the data tapes containing activation detectors and other files with data for only 1 or 2 reactions.

Thermal neutron Maxwellian average cross-sections, resonance integrals and fission-spectrum averaged cross-sections have been derived for all reactions in all the main data files by use of the programme MINIGAL; the results are published in AEEW - M 1191 (Pope and Story).

Manipulation and editing programmes have been steadily improved over the last year and a half, and conversion to Fortran-4 is well advanced. The main ones have already been converted and are being thoroughly tested in use; for further details see NNDEN-10.

The programme SIGAR, for calculating Doppler broadened cross-sections from resonance parameters using the multi-level Breit-Wigner approximation has been converted to Fortran-4 and is available from the CPL at Ispra. A development of the earlier programmes MLBW and TEMPO, SIGAR has in particular a much improved energy selection routine with separate sets for the unbroadened and Doppler broadened peaks.

2. Thermal neutron scattering matrices

(A.T.D. Butland)

Graphite

The generation and partial testing of a set of thermal neutron scattering matrices for graphite at 14 temperatures in the range 293 to 3273^{o}K was completed during the period under review. The work may be described in the following steps:

(a) In order to ensure a realistic and progressive behaviour of the matrices with variation of temperature, a thorough evaluation was made of the specific heat data for reactor grade graphite at constant pressure and constant volume (Butland and Maddison 1972, AEEW - R 815). This evaluation was used to extend the Chalk River measurements of the graphite phonon frequency function at 1300 and 1800°K to lower and higher temperatures. Thence were derived phonon frequency functions in the form of a sum of "displaced gaussian" terms for 14 temperatures in the range 293-3273°K.

(b) These phonon frequency spectra were then divided into modes perpendicular and parallel to the graphite basal plane, so that the effect might be studied of the anisotropy of the graphite crystal on the thermal neutron scattering matrices.

(c) Group averaged inelastic cross-sections were derived using the code CY-LEAP (Butland 1973, AEEW - M 1201) to generate the scattering law $S(\alpha,\beta)$ as a first step, and SOLON (Butland 1973, to be published) and PIXSE (Macdougall 1963, AEEW - M 318) to calculate the cross-sections. The effects were studied of using different weighting spectra for the group averaging, and the best compromise was adopted.

(d) Group averaged elastic cross-sections were generated using the code HEXCOH (Butland 1969, AEEW - M 954) in order to include interference effects.

Care was taken throughout to ensure that the numerical techniques used were sufficiently accurate, and that the scattering matrices generated exhibit good agreement with measurements of the total scattering cross-section. First results of reactor calculations with the new scattering matrices are significantly better than the older data described by Butland 1972 in AEEW - R 813. Pu/U fission ratios are predicted within experimental error at 313°K and 655°K.

$\underline{H_2O}$

To test the validity of thermal neutron scattering models for H_2O, various integral
1349 characteristics of four H_2O moderated systems were calculated, using the WIMS multigroup transport programme. Six very different scattering models for H in H_2O were considered and the results of the work have been reported by Butland and Chudley 1972 in AEEW - R 814.

Thermal neutron scattering matrices have recently been prepared for H in H_2O over the temperature range 293°K to 600°K, using both Nelkin's and the effective width models. This work brought to light some defects in the code ADDELT used when there is a delta function in the phonon frequency spectrum, and errors in PIXSE; these have been rectified. It was found from this work that the Nelkin model overestimates the total scattering cross-section below 0.001 eV, and increasingly as the energy is decreased. The effective width model shows a similar fault, and to a lesser extent so too does the GGA modification of Haywood's model. It is probably caused by inadequate representations of the diffusive motion in H_2O.

Computer programmes

Some effort has been devoted to testing various computer programmes used in calculating the scattering law from phonon frequency functions (Butland 1972, AEEW - M 1136). Examination of the problems involved in computing group-to-group scattering matrices from scattering laws led to the new programme SOLON as a partial replacement for PIXSE.

3. GENEX data files; resonance data in resolved and unresolved regions

(M.F. James and J.D. Macdougall)

Data files for several materials have been prepared using the RESP/GENEX set of programmes. The tapes produced by RESP contain the resolved resonance parameters complemented by further parameters derived by random sampling from appropriate distributions in the unresolved resonance range. GENEX uses these parameters to produce computer files of Doppler broadened cross-sections at 125,000 energies from 25 keV downwards.

The materials for which GENEX data files are available are:-

Mo, Ta, and Th-232 based on resonance parameter data from ENDF/B2 and ENDF/B3.

U-235, U-238 and Pu-239; there is some discussion of the bases of these data files in EANDC-90L, section 3.3 (edited by Patrick and Sowerby, Sept. 1972).

Pu-240; a new evaluation by James (unpublished 1972) taking an average radiation width of 26.9 meV.

NATIONAL PHYSICAL LABORATORY

Division of Radiation Science
(Superintendent: Dr. P.J. Campion)

$\bar{\nu}$ for spontaneous fission of ^{252}Cf (E.J. Axton and A.G. Bardell)

The NPL measurements currently yield a value of 3.725 n/f for several Cf samples. However an earlier sample yielded 3.700. Another measurement is required to resolve this apparent discrepancy. The earlier sample contained only half the quantity of ^{252}Cf relative to the other californium isotopes present.

A critical evaluation of all absolute measurements of $\bar{\nu}$ for ^{252}Cf has been carried out at the request of the IAEA. The following is a summary of the evaluation the results being summarized in Table 6.

Moat et al[1] used a wax moderator containing BF_3 counters as the neutron detector, which was calibrated with reference to the Harwell standard ^{240}Pu spontaneous fission source. The fission rate was determined by 2π counting and gave an original result of 3.77 ± 0.07. This was revalued by Fieldhouse et al following recalibration of the standard source, to 3.675 ± 0.04, the reduced error reflecting the improvement in neutron source calibrations during the intervening period.

The 1969 panel revalued it to 3.725 ± 0.056[11] for the increase in the estimated difference of the mean energies of the ^{240}Pu and the ^{252}Cf fission neutron spectra, an additional ± 1% error being included to cover the uncertainty in this correction. This value and error is retained by the 1972 panel.

Colvin and Sowerby[2] used a large graphite moderator containing a lattice of BF_3 counters (the boron pile) as the neutron detector, neutrons being detected in delayed coincidence with pulses from a fission counter situated at the centre. Values of 3.700 ± 0.031 and 3.713 ± .015 were obtained with the pile calibrated with standard neutron sources and by counting of photoprotons from the ^{2}H (γ,n)p reaction respectively. These values and errors were retained by both the 1969 and the 1972 panels.

White and Axton[3] measured the fission rate of a sample in low geometry, the neutron rate being obtained from the NPL Manganese Sulphate bath. A value of 3.796 ± 0.025 was reported and retained by the 1969 panel. The 1972 panel retained the value but raised the error to 0.039 by increasing the estimated errors for solid angle uncertainty, spectrum uncertainty, and migration of fission material.

Early work at NPL by Axton, Bardell and Audric[4] on an old Cf sample gave a value of 3.700 ± .020 which was retained by the 1969 panel. Later work which is still in progress with several newer samples gives 3.725 ± .023. Further work with the original sample is required to determine whether the difference is significant. The error estimate is provisional, pending the resolution of this apparent sample-dependent discrepancy.

The liquid scintillator measurements of Hopkins and Diven[5] and Asplund-Nilsson, Condé and Starfelt[6] gave values of 3.780 ± .031 and 3.808 ± .037 respectively. These were revalued in 1969 to 3.793 and 3.830 following a new measurement of the ^{252}Cf mean energy. The 1972 panel reverted to the original values following further measurements of the energy spectrum. (5) was further reduced to 3.770 ± .031 after correction for the effects of delayed γ-rays, and (6) was reduced to 3.778 ± .060 after correction for the effect of delayed γ-rays and the "French" effect. The error estimate of (6) was enlarged in view of the rather large leakage corrections involved. Recent precise and well documented liquid-scintillator measurements by Boldeman[7] give a value of 3.744 ± .014 which was accepted by the 1972 panel. Manganese bath measurements by De Volpi and Porges[8] using a coincidence technique to determine the fission-counting efficiency gave a provisional value of 3.739 ± .017 which was accepted by the 1969 panel. The final value is reported as 3.729 ± .015. Pending the clarification of some features of the experiment the 1972 panel adopted a provisional error of ± .030 for this work, although the authors have confidence in their own estimate. Fortunately the resolution of this point does not significantly affect the estimate of the weighted average of all measurements since the latter is very close to the (8) value.

For the input to the least squares fit the 1969 panel, faced with such obviously discrepant results, applied equal arbitrarily increased errors of ± 0.024 to four values: the mean of the NPL bath-dependent group (3.713), the mean of the liquid scintillator measurements (3.807), and the Argonne (3.739) and Harwell (3.713) values. The weighted mean was 3.743 ± .016 which can be compared with the output value from the least squares fit (3.7653 ± .0104) and the value based on η, α, and $\bar{\nu}$ ratios but excluding all direct californium measurements (3.784 ± .014).

The situation confronting the 1972 panel is quite different. The weighted mean of the NPL bath dependent group is now 3.728 with internal and external errors of ± .0140 and .0169, indicating that this group forms a consistent set. The common NPL bath error of ± 0.0123 is then added and the result averaged with the other measurements to give a weighted mean of 3.733 with internal and external errors of ± 0.0083 and ± 0.0078 indicating that this group also forms a consistent set. This value, supported by

TABLE 6

Measurements of $\bar{\nu}$ for ^{252}Cf

Ref	Authors	Authors Original Value	1969 Value	1969 Input to LS fit	1972 Provisional Input to LS fit
Experiments Dependent on NPL Manganese Bath					
1	Moat et al	3.77 ± 0.07 (3.675 ± 0.04)	3.737 ± .056		3.727 ± .055 *
2	Colvin, Sowerby	3.700 ± .031	3.700 ± .031	3.713 ± .024	3.700 ± .028 *
3	White, Axton	3.796 ± .025	3.796 ± .025		3.796 ± .037 *
4	Axton, Bardell, Audric	3.700 ± .020	3.700 ± .020		3.725 ± .019 *
	Weighted mean				3.728 ± .0140 Internal error
					± .0169 External error
					Add ± .0123 Common bath error
All Experiments					
	NPL Bath Group (above)			3.713 ± .024	3.728 ± .0186
5	Hopkins, Diven	3.780 ± .031	3.793 ± .031	3.807 ± .024	3.770 ± .031
6	Asplund, Nilsson Conde, Starfelt	3.808 ± .037	3.830 ± .037		3.778 ± .060
7	Boldeman	3.744 ± .014			3.744 ± .014
8	Colvin, Sowerby	3.713 ± .015	3.713 ± .015	3.713 ± .024	3.713 ± .015
9	De Volpi, Porges	3.739 ± .017	3.739 ± .017	3.739 ± .024	3.729 ± .030 (.015)
	Weighted mean			3.743 ± .016	3.733 ± .0083 Internal
					± .0078 External

* These errors differ from those in the text because the common error has been excluded.

In accordance with the IAEA panel practice, the errors, including systematic errors, are assumed to be randomly distributed, and are estimated at the one standard deviation, or 68% confidence level.

independent reviews by De Volpi, by Conde, and by Ribon is to be compared with the values 3.749 ± .006 obtained as output from the least squares fit using provisional input data, and 3.784 obtained by omitting all absolute measurements for ^{252}Cf.

It is clear that there is conflict between the absolute measurements of $\bar{\nu}$ for ^{252}Cf and absolute measurements of η. The latter were weighted heavily by the Manganese bath measurements of Macklin and de Saussure[9] and Smith and Reeder[10], both of which involve rather large corrections for the complicated effects of fast neutron multiplication and scattering in the samples and thermal neutron capture in the cadmium shield. It is possible that the errors in these corrections have been underestimated. However a recent suggestion that the mean energies of the ^{235}U and ^{252}Cf spectra are nearly equal would explain part of the discrepancy.

(1) (a) Moat, A., Mather, D.S., McTaggart, M.H. J. Nucl. Energy, Parts A/B, 15, 102, (1961).

(b) Fieldhouse, P., Culliford, E.R., Mather, D.S., Colvin, D.W., McDonald, R.I., Sowerby, M.G. J. Nucl. Energy, Parts A/B, 20, 549, (1966).

(2) Colvin, D.W., Sowerby, M.G.

(a) Physics and Chemistry of Fission, 2, 25, IAEA, Vienna, (1965)

(b) Nuclear Data for Reactors, 1, 307, IAEA, Vienna, (1967).

(3) White, P., and Axton, E.J. J. Nucl. Energy, 22, 73, (1968).

(4) (a) Axton, E.J., Cross, P., Robertson, J.C. J. Nucl. Energy, Parts A/B, 19, 409, (1965).

(b) Axton, E.J., Bardell, A.G., Audric, B.N. J. Nucl. Energy, Parts A/B, 23, 457, (1969).

(c) Ryves, T.B., and Harden, D. J. Nucl. Energy, Parts A/B, 19, 607, (1965).

(5) Hopkins, J.C., and Diven, B.C. (2)

(a) Nuclear Physics 48, 433, (1963).

(b) Phys. Rev. 101, 1012, (1956).

(c) Phys. of Fast and Intermediate Reactors, 1, 149, IAEA, Vienna, (1962).

(6) Asplund-Nilsson, L., Conde, H., and Starfelt, N.

(a) Nucl. Sci. Engineering, 16, 124, (1963).

(b) Nucl. Sci. Engineering, 11, 397, (1961).

(c) Phys. of Fast and Intermediate Reactors, 1, 155, IAEA, Vienna, (1961).

(7) Boldeman, J., presented to IAEA Reference Standards Panel, 22 Nov 1972. To appear in Report of IAEA Panel on Neutron Reference Standards.

(8) De Volpi and Porges, K.G. Phys. Rev., C1, 683, (1970), Metrologia, 5, 128, (1969), ANL 7642, (1969).

(9) Macklin, R.L., DeSaussure, G., Kington, J.D., Lyon, W.S. Nucl. Sci. Eng. 8, 210, (1960) and ORNL 60-2-84.

(10) Smith, J.R., Reeder, S.D., Fluharty, R.G. IDO 17083, (1966). Also NBS, SP 299, 1, 589 and WASH 1093.

(11) Hanna, G.C., Westcott, C.H., Lemmel, H.D., Leonard, B.R. Jr., Story, J.S., Attree, P.M., Atomic Energy Review 7, No. 4, 3, (1969).

Half-life of ^{60}Co. (E.J. Axton)

A provisional value of 5.2565 ± 0.0022 (Standard error) years has been obtained. Possible systematic errors are being investigated. The value is based on measurements of 13 samples of spectroscopically pure cobalt foil over a period of 10 years.

Resonance Integral Measurements. (T.B. Ryves and K.J. Zieba)

A closely dE/E neutron slowing down flux was produced by the moderation of fast neutrons from the $D(^{9}Be,n)^{10}B$ reaction in a large water tank. Pairs of foils, together with standard foils of gold and manganese, were activated, bare and under cadmium, on a rotating wheel. The cadmium ratios gave a value for I'/σ_o (where I' was the reduced resonance integral, σ_o the 2200 ms^{-1} neutron capture cross-section) relative to gold (σ_o = 98.86 and I' = 1514 ± 60b) and manganese (σ_o = 13.23 ± 0.2b and I' = 7.8 ± 0.3b). This experimental method automatically corrected for small deviations in the slowing down neutron spectrum in the resonance region.

The following reduced resonance activation integrals have been measured.

Isotope	Activation Integral (Barns)	Uncertainty (99% Confidence)
^{63}Cu	2.79	0.18
^{65}Cu	1.22	0.06
^{107}Ag	79	4
^{159}Tb	390	24
^{164}Dy	-514	115
^{165}Ho	618	34

In the course of these measurements the following half-lives and 2200 ms^{-1} cross-sections were measured.

Isotope	Half-life	Uncertainty (99% Confidence Level)
^{64}Cu	5.13m	± 0.03
^{66}Cu	12.704h	± 0.006
^{166g}Ho	26.83h	± 0.03
^{108}Ag	2.37m	± 0.01

Isotope	Cross Section (Barns)	Uncertainty (99% Confidence Level)
^{159}Tb	23.2	± 0.5
^{107}Ag	37.6	± 1.2 (re-evaluated from the new half-life)
^{165}Ho	61.2	± 1.1

This work will be submitted for publication in the Journal of nuclear energy, and together with previous work (Ryves, T.B., 1969, J. Nuclear Energy 24, 35, and 1971, 25, 129) forms a consistent set of activation integrals suitable for the measurement of slowing down spectra.

<u>$^{238}U(n,\gamma)$ and $^{115}In(n,\gamma)$ ^{116m}In cross-section in the energy range 150 kev to 625 kev.</u>
(T.B. Ryves, J.B. Hunt, J.C. Robertson)

The neutrons were produced by the $^{7}Li(p,n)^{7}Be$ reaction. Sandwiches consisting of disc samples of ^{238}U and In were irradiated at 0^{o} close to the target, and the ratios of U/In capture cross-sections found by activation. The In foils were then irradiated separately at various distances of between 5 and 40 cm from the target at 0^{o}, and the absolute In capture cross-section found from a $1/r^2$ vs. activity plot, using a long counter to measure the neutron flux. This long counter was calibrated over the energy range with photoneutron sources of known disintegration rates (via the manganese bath), and a knowledge of the counter efficiency shape, derived from a collimated vanadium bath experiment.

These measurements have been submitted for publication in the Journal of Nuclear Energy. The following is a summary of the results.

En kev	$\sigma(n,\gamma)$ In(mb)	Total Uncertainty % 99% Confidence	68% Confidence
153 ± 14	238	4.8	1.9
184 ± 14	239	4.3	1.9
195 ± 11	217	4.3	1.9
231 ± 17	179	4.1	1.9
336 ± 15	144	5.7	2.1
548 ± 14	152	3.4	1.5
623 ± 14	154	3.4	1.5
	^{238}U(mb)		
157 ± 20	162	7.7	2.4
231 ± 18	128	8.1	2.5
559 ± 15	111	6.9	2.1
624 ± 14	119	7.4	2.1

PHYSICS DEPARTMENT, UNIVERSITY OF BIRMINGHAM

(Prof. J. Walker)

A fast neutron spectrometer for shielding studies (Work done by the author on attachment to the Fast Reactor Physics Division, A.E.E., Winfrith) P. Roberts.

In order to extend the range of shielding measurements a fast neutron spectrometer has been developed to cover the range between 2 MeV and 18 MeV.

The detector chosen for the basis of the spectrometer was an organic liquid scintillator type NE-213[+] coupled to a high gain photomultiplier tube. The scintillator was encapsulated in a cylindrical cell of dimensions 4.60 cms by 4.65 cms diameter. This size was chosen because it afforded a high neutron detection efficiency and also because a scintillator of this type and volume had been previously extensively calibrated by Verbinski[(1)]. It should be mentioned here that in situations where the high energy neutron flux is high, a smaller scintillator would be better as it would have a greater gamma tolerance and give more idealized response lines.

A basic property of NE-213 lies in the different pulse shapes which are produced by particles having different specific ionizations - the proportion of the total light output in the tail increasing with specific ionization. This property can be used to separate out these pulses due to neutrons from those due to gamma radiation. The method chosen was one developed by Owen[(2)] which is based on a space charge effect between the last dynode and the anode of the photomultiplier chain. The potential between these two points is kept to $\sim$ 4 volts. The initial fast rise of the scintillation pulse causes the voltage on the last dynode to go rapidly negative. As the remaining charge in the pulse is collected the dynode voltage increases and in the case of the heavier ionizing particles goes positive. Adjustment of the potential between the dynode and anode can optimize the separation between pulses induced by neutrons and gamma radiation. A gamma tolerance of 20 mR/hr was obtained at the expense of having a neutron detection threshold at 2 MeV.

In order to check that the differential data of Verbinski was suitable for use with this scintillator, various monoenergetic line shapes were measured on the 3 MV Van de Graaff, IBIS, at AERE Harwell. The measured lines compared well in shape and absolute

---

[+] Supplied by Nuclear Enterprises Ltd., Edinburgh, Scotland.

(1) Verbinski, V.V. and Burrus, W.R., Nucl. Inst. & Methods 65, 8, (1968).

(2) Owen, R.B., Nucleonics 17 (9), 92-95, (1959).

efficiency with those given by Verbinski though the resolution of the measured lines was slightly worse. The light output of NE-213 increases non-linearly with increasing neutron energy. From the measured line shapes a light function was fitted to

$$\log(y) = a_1 \log E + a_2 (\log E)^2 + a_2 (\log E)^3 + a_4$$

where y is the maximum light output for a given neutron energy E. This light-energy relationship was then used to linearize Verbinski's differential data.

A response matrix was constructed from the linearized line shapes by first fitting a logarithmic orthogonal polynomial across the top row elements and then subsequently fitting further logarithmic orthogonal polynomials down the diagonals. The justification for working in log-log space was the smoothly varying (n,p) scattering cross-section of hydrogen.

Measured recoil pulse height spectra were analysed using the unfolding code Radak (Goodfellow[(3)]) which was developed concurrently with this work. The complete spectrometer was tested by measuring the $^{241}Am - Be$ neutron spectrum and the result is compared with a previous measurement of Thompson and Taylor[(4)] and Bennett[(5)] in figure 14.

The spectrometer is now being used for measuring the transmitted neutron spectra through various shielding materials and also for measuring the high energy neutron spectra in the reflector and breeder of a mock-up fast reactor assembly.

(3) Goodfellow, M.R., to be published.

(4) Thompson, M.N., and Taylor, J.M., Nucl. Inst. & Methods 37, 305, (1965).

(5) Bennett, E.F., ORNL-TR-2415, p.93.

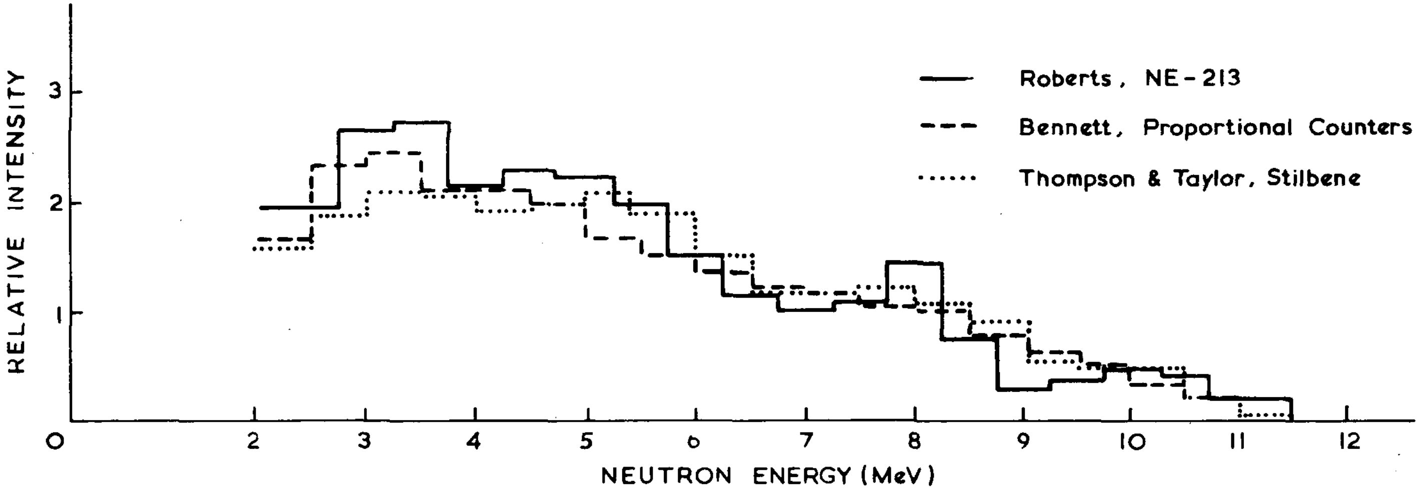

Fig. 14

The neutron spectrum produced by an ^{241}Am-Be neutron source.

KELVIN LABORATORY, UNIVERSITY OF GLASGOW

(Director: Prof. G.R. Bishop)

For administrative reasons the present report covers the period Mid 1971 to March 1973.

(n,n',γ) measurements (G.I. Crawford, J.D. Kellie and M.N. Islam)

Measurements have been made of the (n,n',γ) cross-sections of ^{27}Al, ^{28}Si, ^{32}S, ^{31}P and ^{56}Fe using the electron linac of the Kelvin Laboratory. The measurements typically cover the energy range 0.75 to 9 MeV and details of the experimental technique have been published(1). Considerable effort has been expended in writing and testing computer programmes to calculate the inelastic cross-sections from Hauser-Feshbach theory in both its original form and with Moldauers width fluctuation correction. In general the trend of the results agrees well with the calculations, which of course predict only average values and not the fine structure observed in the measurements.

Elastic Neutron Scattering (S.J. Hall, J. McKeown and H.R. Siddique)

Differential cross-sections for elastic scattering for three elements have been measured using the electron linac T.O.F. spectrometer. Two (^{28}Si and ^{32}S) were measured with a resolution of 0.16 ns/metre, and the third ^{40}Ca with a resolution of 0.24 ns/metre. The data were normalised to the Carbon differential cross-section and overall errors are estimated to be ± 6%.

Data were taken at eight angles for ^{40}Ca between 0.8 and 3.4 MeV and at twelve angles for ^{28}Si and ^{32}S between 0.6 and 3.5 MeV. In all cases the data are corrected for the effects of multiple scattering and finite angular resolution. The ^{40}Ca data are pure elastic scattering though the ^{28}Si and ^{32}S data include total scattering cross sections where the neutron energy is above the threshold for inelastic processes.

Averaging of the ^{40}Ca data over successively larger energy intervals showed two broad peaks centred on 1.1 and 1.8 MeV. A phase shift analysis of the differential cross-section data enabled J^{π} values of $\frac{1}{2}^{+}$ to be assigned to the peak at 1.1 MeV, consistent with its being a doorway state. A 2p-1h state with $J^{\pi} = \frac{1}{2}^{+}$ is expected at 1.56 MeV in ^{41}Ca, giving good agreement with the experimentally determined energy. No such assignment could be made to the state at 1.8 MeV. Further analysis showed the doorway state interpretation of the broad peak to be non unique since their amplitude was explicable in terms of statistical variations in level widths and spacings.

---

(1) Crawford G.I., Hall S.J., McKeown J., Kellie J.D. and Syme D.B.C.B., Nucl. Inst. and Meth. 109, 479 (1973).

Total cross-sections (D.B.C.B. Syme, J.D. Kellie, J. McKeown, S.J. Hall and G.I. Crawford)

A programme of total cross-section measurements has been carried out during the period covered by this report. Initially measurements on ^{40}Ca and ^{19}F were performed to complement the elastic scattering data described above. Measurements were then made on natural uranium and on 10 rare earths (e.g. Ho, Er, Gd, Dy, Nd, Pr, Sm, La, Ce and Yb) over an
40 energy range 0.8 to 9 MeV. Recently the energy range that can be covered in the measure-
983 ments has been lowered to 0.2 MeV and data obtained on ^{10}B, ^{11}B, ^{238}U, La, Ce, Yb. The
984 data on the latter sequence of measurements are still being analysed. We have attempted to fit the rare earth data using the optical model with, as one would expect, varying success and this work is almost ready for publication. A paper with the following abstract has been submitted for publication to the Journal of Nuclear Energy on the natural uranium data:-

"The total cross-section of natural uranium for fast neutrons in the energy range 0.8 - 9 MeV has been measured with good resolution and statistical precision, using a time-of-flight spectrometer based on an electron linear accelerator as neutron source. The results are compared with other recent data, with the recommended ENDF/B III compilation and with theoretical calculation".