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HARWELL

U.K. NUCLEAR DATA PROGRESS REPORT For the period April 1975 to March 1976

Editor: D.B. Gayther
Nuclear Physics Division
AERE Harwell, Oxfordshire
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PREFACE

This report is prepared at the request of the United Kingdom Nuclear Data Committee. It brings together reports on nuclear data from Harwell, Winfrith, Aldermaston, Dounreay, the National Physical Laboratory, the Berkeley Nuclear Laboratory of the Central Electricity Generating Board, British Nuclear Fuels Limited, the Universities of Aston, Edinburgh and Manchester, and the University of London Reactor Centre. Most of the reports are presented under a laboratory heading but it is more convenient to present those contributions on so-called chemical nuclear data under a heading of that name. Where the work is clearly relevant to requests in WRENDA 75 (INDC (SEC) - 46/U) the number of requests is given after the title of the contribution. A CINDA type index is included in the front of the document.

COMMITTEE ACTIVITIES

United Kingdom Nuclear Data Committee (Chairman: Dr. B. Rose)

The UK Nuclear Data Committee (UKNDC) has met twice during the period of this report. On the home front, the Committee has continued its role of co-ordinating the UK programme of nuclear data measurement, evaluation and compilation. The main emphasis remains on the provision of data for the fission reactor programme, this being the province of the Neutron Sub-committee and the Chemical Sub-committee (otherwise known as the Chemical Nuclear Data Committee). In the other fields of application, the Biomedical Sub-committee has begun to identify areas of data needs and a similar stage is now being reached in fusion and nuclear incineration. Reports on the activities of each of the five Sub-committees are given below.

There has been one change in the membership of the Committee. Following an invitation issued after the last meeting, the National Physical Laboratory has agreed to be represented and this should strengthen the Committee's links with laboratories and organisations concerned with nuclear data standards.

As in previous years, the Committee arranged for measurers, evaluators and users of nuclear data to get together for a day to discuss topics of current interest. The meeting, the 9th in the series of Nuclear Data Fora, was held at Harwell in December, with about 70 people attending. For the first time, the main themes were the nuclear data aspects of shielding and neutron therapy, and there was general agreement that the meeting had been a success.

In July, an AEA party of five spent 12 days in the USSR visiting the Kurchatov Institute (Moscow), the Nuclear Power Institute (Obninsk), the Research Institute for Nuclear Reactors (Dimitrovgrad), the Institute for Nuclear Research of the Ukrainian Academy of Sciences (Kiev) and the Leningrad Institute of Nuclear Physics of the Academy of Sciences of the USSR (Gatchina). A joint seminar was held at the Kurchatov Institute on nuclear data topics and valuable insight was gained into the state of neutron physics and data compilation and dissemination in the USSR. This visit was in return for a visit to the UK of a party of physicists from the USSR in 1974.

Much of the Committee's business has been concerned with its function as the formal link with other international data committees and organisations. Highlights of meetings attended by Committee members include proposals to form a European Nuclear Data and Reactor Physics Committee to replace the Joint Euratom Nuclear Data and Reactor Physics Committee (JENDRPC) as the forum for discussion in this geographical area and attempts to bring about greater co-ordination and co-operation in the evaluation and measurement of nuclear data within Europe. It has also been recognised that the effort on the evaluation and compilation of non-neutron nuclear data in the EEC countries has been insufficient in the past and steps are being taken to improve the situation. The UKNDC's attempts to stimulate more UK participation in this important work have been timely in view of recent moves by the USA to encourage a worldwide co-ordination in this field.

A proposal to regularise the series of international nuclear data conferences was well received by the various international committees which considered it. If the new scheme is

adopted, the first Western European meeting will be held in September 1978, with Harwell as a possible venue.

Under the auspices of the JENDRPC, a specialist meeting on inelastic neutron scattering was held at Harwell in April. Such gatherings of relatively few experts give a good opportunity to discuss problems in detail and the meeting formulated a number of recommendations for further studies in this topic and also on fission neutron spectra.

Neutron Sub-committee (Chairman: Dr. J.E. Lynn)

During the year the N.S.C. has considered data requirements for various fuel management codes, the collaboration of universities and U.K.A.E.A. laboratories on shielding data and iron benchmark experiments, integral experiments by Birmingham University on LiF, topics for the Nuclear Data Forum, and the possibility of providing very accurate total cross-section data for shielding. The request list for data for the U.K. Reactor Programme was also considered in detail, with respect particularly to the progress of work and the effort that may be made available to meeting requests on which no work is presently being done. The general conclusion from this review was a difficult one; the request list is very substantial in size and is being maintained by new requests, and the effort that is available to meet them is very limited. No substantial improvement of this situation can be foreseen in the near future.

Chemical Sub-committee* (Chairman: Mr. J.G. Cuninghame)

The Committee has held two regular meetings during the year, together with a number of other special meetings of all or part of the membership to discuss recommended documents and special topics.

Documents recommended during the year have been, a new evaluation of thermal and fast fission yield data by E.A.C. Crouch which takes account of physical conservation laws (AERE - R 8152) and an evaluation of all α-emitters by F.J.G. Rogers (AERE - R 8005).

The membership of the Committee has been strengthened and widened by the addition of Dr. P. Christmas of NPL.

The Committee's most important task after co-ordination of the measurement and evaluation effort continues to be the gradual assembling of the UK Chemical Nuclear Data File and the Data File Sub-committee (Chairman Dr. A.L. Nichols) has pursued this end; this is fully reported under "Evaluations and Compilations".

Bio-medical Sub-committee (Chairman: Mr. J.A. Dennis)

The Bio-medical Sub-committee met on 26th November 1975. Some uncertainty was expressed about the respective roles of this Sub-committee and the British Committee on Radiation Units and Measurements (BCRU). Although discussion with the Chairman of BCRU (Prof. F.W. Spiers) has indicated that the roles are complementary, a meeting between Mr. J.A. Dennis and the BCRU has been arranged to clarify the position.

At the November meeting the nuclear data needs for bio-medical applications were discussed. The principal needs appear to be for more accurate values for stopping powers,

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* Also known as the Chemical Nuclear Data Committee.

W values and neutron cross-section data to improve dosimetry in the use of neutron beams for cancer therapy. Some data on the production of isotopes by charged particles with very high bombarding energies would be useful. Photon attenuation coefficients for energies below 1 keV are required for internal dose calculations and certain cellular radiobiological research. It is thought that requirements for isotope decay scheme data may be satisfied by forthcoming ICRP publications.

The Committee undertook to prepare a paper explaining the sources of data for users in the bio-medical field.

Fusion Sub-committee (Chairman: Dr. C.A. Uttley)

The need to investigate the sensitivity of tritium breeding to cross section uncertainties in blankets with stainless steel structure was indicated in the last Progress Report. This work is being carried out at Birmingham University under the supervision of Dr. Beynon. Initially work has concentrated on the effects of iron cross section uncertainties. The sensitivity analysis is also relevant to sensitivity problems involved in deep penetrations in iron shields and has resulted in collaboration with the Winfrith Shielding Group.

The spectral distribution of tritium breeding in ^{6}Li and ^{7}Li in a typical blanket indicates that breeding in ^{6}Li is important for neutron energies below 2 MeV, and that breeding, on average, is shared about equally between the two isotopes. The energy range of importance in ^{6}Li has received considerable attention in recent years with no comparable experimental effort on the $^{7}Li(n,n'\alpha t)$ reaction. The latter reaction is at least as important, however, since it produces most of the breeding near the first wall and the inelastic neutrons considerably influence the neutron spectrum. For this reason, and also to interpret data from integral experiments, measurements of both the secondary neutron spectral distribution and the tritium production cross section as a function of incident neutron energy are being planned.

Work on the safety and environmental aspects of fusion reactors arising from activation of structural components is being actively encouraged and supported by Culham. It is first necessary to specify a blanket model based on a selected structural composition and gather together a data library of the cross sections which can lead to induced activity, including those of likely impurities. The calculations of the activity are performed using a computer code which allows for decay and the effects of sequential reactions.

Nuclear Incineration Sub-committee (Chairman: Dr. M.G. Sowerby)

The Sub-committee has met three times during the period of this report and has discussed a variety of topics related to Nuclear Incineration which are indicated below:

1. The long term potential hazards of the actinides and the relative hazards of different reactor systems.
2. Nuclear Incineration as a method of reducing the potential hazards of the actinides.
3. Inventory codes and the calculation of higher actinide build up.
4. The needs for nuclear data for the above topics.
5. Reports on international conferences.

The Sub-committee is still informing itself on the relative advantages and disadvantages of nuclear incineration and it is beginning to see where the data are inadequate at the present time (see this report page 26). It does not, however, expect to be able to draw up a formal request list for some time.

CINDA TYPE INDEX

Element S	Element A	Quantity	Type	Energy Min.	Energy Max.	Documentation Ref.	Vol.	Page	Date	Lab.	Comments
H	1	DIFF ELASTIC	EXPT-PROG	2.7 7		UKNDC	P80	12	7/76	HAR	COOKSON+ ANG DIST
Li	6	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ RES ENERGY
Li	7	DIFF ELASTIC	EXPT-PROG		1.4 7	UKNDC	P80	57	7/76	BIA	COX+ GRPH
C	12	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ RES ENERGY
Mg	24	N PROTON	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Al	27	N PROTON	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Al	27	N ALPHA	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
K	39	DIFF ELASTIC	EXPT-PROG		1.4 7	UKNDC	P80	57	7/76	BIA	COX+ GRPH
Ti	46	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ GRPH TRANS
Ti	46	N GAMMA	EXPT-PROG	2.0 2	8.0 5	UKNDC	P80	5	7/76	HAR	THOM+
Ti	47	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ GRPH TRANS
Ti	47	N GAMMA	EXPT-PROG	2.0 2	8.0 5	UKNDC	P80	5	7/76	HAR	THOM+ GRPH
Ti	48	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ GRPH TRANS
Ti	48	N GAMMA	EXPT-PROG	2.0 2	8.0 5	UKNDC	P80	5	7/76	HAR	THOM+
Ti	49	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ GRPH TRANS
Ti	49	N GAMMA	EXPT-PROG	2.0 2	8.0 5	UKNDC	P80	5	7/76	HAR	THOM+
Ti	50	TOTAL XSECT	EXPT-PROG	1.0 2	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+ GRPH TRANS
Ti	50	N GAMMA	EXPT-PROG	2.0 2	8.0 5	UKNDC	P80	5	7/76	HAR	THOM+
Cr	Nat	N GAMMA	EXPT-PROG	2.0 0	8.0 5	UKNDC	P80	4	7/76	HAR	GAYTHER+ WORK IN PROGRESS
Fe	Nat	TOTAL XSECT	EXPT-PROG	1.0 4	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+
Fe	Nat	N GAMMA	EXPT-PROG	2.0 0	8.0 5	UKNDC	P80	4	7/76	HAR	GAYTHER+ WORK IN PROGRESS
Fe	Nat	DIFF ELASTIC	EXPT-PROG		1.6 7	UKNDC	P80	59	7/76	EDG	GALLOWAY+ POLARISATION+ ANG DIST
Fe	56	N PROTON	EXPT-PROG	1.4 7	1.8 7	UKNDC	P80	48	7/76	NPL	RYVES+ PRELIMINARY DATA
Fe	56	N PROTON	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Co	59	TOTAL XSECT	EXPT-PROG	1.0 4	1.0 7	UKNDC	P80	6	7/76	HAR	BOWEN+
Ni	Nat	RESON PARAM	EXPT-PROG	2.0 4	3.0 5	UKNDC	P80	10	7/76	HAR	SYME+ SHAPE FIT
Ni	Nat	N GAMMA	EXPT-PROG	2.0 0	8.0 5	UKNDC	P80	4	7/76	HAR	GAYTHER+ WORK IN PROGRESS
Ni	58	N PROTON	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Cu	Nat	DIFF ELASTIC	EXPT-PROG		1.6 7	UKNDC	P80	59	7/76	EDG	GALLOWAY+ POLARISATION+ ANG DIST
Cu	63	N 2N	EXPT-PROG	1.4 7	1.8 7	UKNDC	P80	48	7/76	NPL	RYVES+ PRELIMINARY DATA
Cu	65	N 2N	EXPT-PROG	1.4 7	1.8 7	UKNDC	P80	48	7/76	NPL	RYVES+ PRELIMINARY DATA
In	115	DIFF ELASTIC	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
I	127	DIFF ELASTIC	EXPT-PROG		1.6 7	UKNDC	P80	59	7/76	EDG	GALLOWAY+ POLARISATION+ ANG DIST
Au	197	N GAMMA	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Hg	Nat	DIFF ELASTIC	EXPT-PROG		1.6 7	UKNDC	P80	59	7/76	EDG	GALLOWAY+ POLARISATION+ ANG DIST
Pb	Nat	DIFF ELASTIC	EXPT-PROG		1.6 7	UKNDC	P80	59	7/76	EDG	GALLOWAY+ POLARISATION+ ANG DIST
Th	232	PHOTO FISSN	EXPT-PROG			UKNDC	P80	18	7/76	HAR	NAIR+ ANG DIST FISSN
UO_2	Nat	TOTAL XSECT	EXPT-PROG	1.0 1	1.0 5	UKNDC	P80	11	7/76	HAR	HASTE+ STUDY OF DOPPLER EFFECT TBD
U	234	RESON PARAM	EXPT-PROG		1.5 3	UKNDC	P80	16	7/76	HAR	JAMES+ FISSN WIDTHS GRPH
U	235	FISSION	EXPT-PROG			UKNDC	P80	16	7/76	HAR	JAMES+
U	235	FISS BETA	EXPT-PROG			UKNDC	P80	32	7/76	WIN	MURPHY+ BETA DECAY POWER FROM FISS PROD
U	235	ETA	EXPT-PROG	THR		UKNDC	P80	21	7/76	HAR	MOXON+ TBD
U	235	SPEC FISS N	EXPT-PROG	5.2 5		UKNDC	P80	14	7/76	HAR	ADAMS+ TOF SPEC FISSN
U	235	SPEC FISS N	EVAL-PROG			UKNDC	P80	14	7/76	HAR	ADAMS COMPARES MEASURED FISS N SPEC
U	235	FISS YIELD	EXPT-PROG			UKNDC	P80	38	7/76	HAR	CUNINGHAME+ DIFFERENT FAST REACTOR SPECTRA
U	235	F NEUT DELAY	EXPT-PROG			UKNDC	P80	52	7/76	ALD	BESANT+ DELAYED N YIELD

Element S	A	Quantity	Type	Energy		Documentation				Lab.	Comments
				Min.	Max.	Ref.	Vol.	Page	Date		
U	238	FISSION	EXPT-PROG			UKNDC	P80	16	7/76	HAR	JAMES+ RATIO TO U-235(n,F)
U	238	PHOTO FISSN	EXPT-PROG			UKNDC	P80	18	7/76	HAR	NAIR+ ANG DIST FISS N
U	238	N GAMMA	EXPT-PROG	8.0 4	1.6 6	UKNDC	P80	2	7/76	HAR	PEARLSTEIN+ ACTIVATION XSEC
U	238	F NEUT DELAY	EXPT-PROG			UKNDC	P80	52	7/76	ALD	BESANT+ DELAYED N YIELD
U	238	FISSION	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Np	237	FISSION	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Pu	239	FISS BETA	EXPT-PROG			UKNDC	P80	32	7/76	WIN	MURPHY+ BETA DECAY POWER FROM FISS PROD
Pu	239	SPEC FISS N	EVAL-PROG			UKNDC	P80	14	7/76	HAR	ADAMS COMPARES MEASURED FISS N SPEC.
Pu	239	FISS YIELD	EXPT-PROG	1.3 5	1.7 6	UKNDC	P80	38	7/76	HAR	CUNINGHAME+ 6 NEUTRON ENERGIES
Pu	239	FISS YIELD	EXPT-PROG			UKNDC	P80	38	7/76	HAR	CUNINGHAME+ DIFFERENT FAST REACTOR N SPEC
Pu	239	HALF LIFE	EXPT-PROG			UKNDC	P80	41	7/76	HAR	GLOVER. NDG
Pu	239	FISSION	EXPT-PROG			UKNDC	P80	61	7/76	LON	HANNAN+ FAST REACTOR SPEC N RATIO TO U-235(n,F)
Pu	240	FISSION	EXPT-PROG			UKNDC	P80	32	7/76	WIN	SWEET AVERAGE FAST REACTOR
Pu	241	FISSION	EXPT-PROG			UKNDC	P80	32	7/76	WIN	SWEET AVERAGE FAST REACTOR
Pu	241	HALF LIFE	EXPT-PROG			UKNDC	P80	41	7/76	HAR	MCKEAN+ RATIO TO Pu-240
Am	241	N GAMMA	EXPT-PROG			UKNDC	P80	32	7/76	WIN	SWEET AVERAGE FAST REACTOR
Am	241	N GAMMA	EXPT-PROG	5.0 1	8.0 5	UKNDC	P80	3	7/76	HAR	GAYTHER+ LARGE LIQUID SCINTILLATOR GRPH
Am	241	EVAL	EVAL-PROG			UKNDC	P80	25	7/76	HAR	LYNN EVALUATION OF DATA + CALCULATED XSECTS.
Am	242^{m}	EVAL	EVAL-PROG			UKNDC	P80	25	7/76	HAR	LYNN EVALUATION OF DATA + CALCULATED XSECTS
Am	243	N GAMMA	EXPT-PROG			UKNDC	P80	32	7/76	WIN	SWEET AVERAGE FAST REACTOR
Am	243	EVAL	EVAL-PROG			UKNDC	P80	25	7/76	HAR	LYNN EVALUATION OF DATA + CALCULATED XSECTS
Am	243	N GAMMA	EXPT-PROG			UKNDC	P80	38	7/76	HAR	GLOVER+ Cm-244 PROD FAST REACTOR AVERAGE
Cm	244	FISSION	EXPT-PROG			UKNDC	P80	24	7/76	WIN	SWEET AVERAGE FAST REACTOR
Many		N GAMMA	EXPT-PROG			UKNDC	P80	32	7/76	WIN	TAYLOR ACTIVATION AVERAGE FAST REACTOR
Many		N 2N	EXPT-PROG			UKNDC	P80	32	7/76	WIN	TAYLOR ACTIVATION AVERAGE FAST REACTOR
Many		N PROTON	EXPT-PROG			UKNDC	P80	32	7/76	WIN	TAYLOR ACTIVATION AVERAGE FAST REACTOR
Many		N ALPHA	EXPT-PROG			UKNDC	P80	32	7/76	WIN	TAYLOR ACTIVATION AVERAGE FAST REACTOR

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

(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 beams, individual research items are labelled with a single letter indicating on which machine the experiments were performed. These labels are as follows:

B. 3 MV pulsed Van de Graaff IBIS (A.T.G. Ferguson)

E. 45 MeV Electron Linac (J.E. Lynn)

H. Synchrocyclotron (C. Whitehead)

D. 14 MeV Tandem Generator (J.M. Freeman)

The new machine for the electron linac laboratory (J.E. Lynn, M.S. Coates, P.P. Thomas and B.P. Clear)

The envisaged linac project was outlined in UKNDC(75)P71, page 2. There have been no major changes to this plan and during the last year most time has been spent on detailed design considerations. Contracts have been let for the provision of the machine (Radiation Dynamics Ltd.), for the provision of klystrons (Thomson-CSF), and for the construction of the new linac hall and the two experimental cells for fast neutron and condensed matter studies (W.E. Chivers). At this stage it seems that the present machine will be able to operate until the end of 1976. The new building work, which started in March 1976, should be completed by the end of 1977 and the new linac installed by the spring of 1978. The machine is expected to be available for experimental use by the summer or early autumn of 1978.

B. Neutron capture cross-section of ^{238}U (S. Pearlstein (Brookhaven National Laboratory) and M.C. Moxon) [Relevant to 10 requests]

The analysis of the ^{238}U capture measurements[1] carried out on IBIS using activation techniques is now complete and is being written up for publication.

The measured capture cross-section is shown in Fig. 1 and compared with the evaluation of M.G. Sowerby et al[2]. In the region below 500 keV there is reasonable agreement with the evaluation but above this energy the measurement indicates a lower capture cross-section.

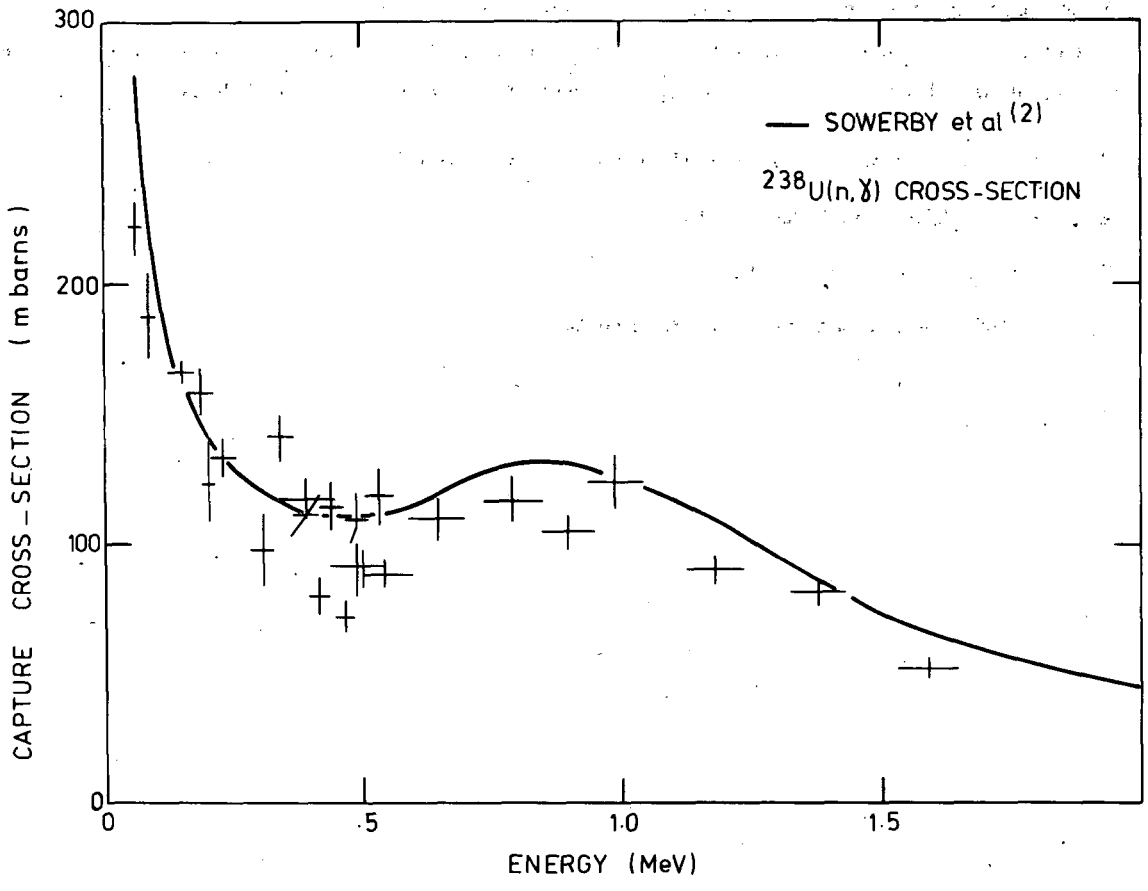

Fig. 1 The neutron capture cross-section of ^{238}U

(1) S. Pearlstein and M.C. Moxon, UKNDC(73)P53, page 4

(2) M.G. Sowerby, B.H. Patrick and D.S. Mather, Annals of Nuc. Sci. Eng. 1 (1974) 409

E. Measurement of the neutron capture cross-section of ^{241}Am using a large liquid scintillator (D.B. Gayther, B.W. Thomas, D.A.J. Endacott and J.E. Jolly) [Relevant to 15 requests]

Neutron capture in ^{241}Am has important consequences for reactor fuel handling and waste management. Previous measurements of the capture cross-section consist of a recent differential measurement[1] and a few integral measurements.

The present measurement was made with the 230 l liquid scintillator which is used mainly for work on the structural materials (UKNDC(75)P71, page 6). The sample consisted of 12 gm of ^{241}Am in oxide form, doubly canned in nickel and aluminium. It was manufactured at CBNM, Geel with the collaboration of Mrs. K.M. Glover of Chemistry Division, AERE. The major impurities in the sample were a mixture of plutonium isotopes totalling 1.5% by weight, the principal isotope being ^{239}Pu.

The high radioactivity of the sample (~ 40 Ci) created severe background problems due to the pile-up of soft gamma-ray pulses and detection of neutrons from (α,n) reactions in the oxide sample. The pile-up problem was largely overcome by placing an additional Pb tube (6 mm wall thickness) around the sample. Both backgrounds were also reduced by imposing a lower limit on pulses from the scintillator tank equivalent to the detection of a 3 MeV gamma-ray.

Data were collected in an identical manner to that used for the structural materials (page 4 of this report), except that in this case only coincidence events were recorded. This mode of running was chosen to further limit the background counting rate and avoid large losses at the data recording stage. In order to obtain as high a signal to background as possible, the linac was run with a pulse width of 0.5 μsec instead of the usual 0.15 μsec. The nominal resolution of the measurement was 5.8 ns/m.

The measurements covered the incident neutron energy range from 50 eV to 800 keV. Figure 1 shows the observed time-of-flight spectrum at the lower energies for gamma-ray events in the interval 3 to 13 MeV. The larger resonances observed by Derrien[2] in a recent measurement of the total cross-section are clearly visible. Events due to the detection of fission gamma-rays contribute to the observed spectrum. However, at energies below several hundred keV neutron capture is the dominant process. A preliminary attempt has been made to identify the fission yield in the present experiment by placing a high energy window on the pulse height distribution (8 to 13 MeV) where only background or fission gamma-rays would contribute. The time-of-flight spectrum so obtained appears to be devoid of the structure seen in Fig. 1 but at the higher energies genuine fission events are evident. Analysis of the measurements to obtain cross-sections is now under way.

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(1) L.W. Weston and J.H. Todd, Proc. Washington Conf. on Nuclear Cross Sections and Technology I (1975) 229

(2) H. Derrien and B. Lucas, Proc. Washington Conf. on Nuclear Cross Sections and Technology II (1975) 637

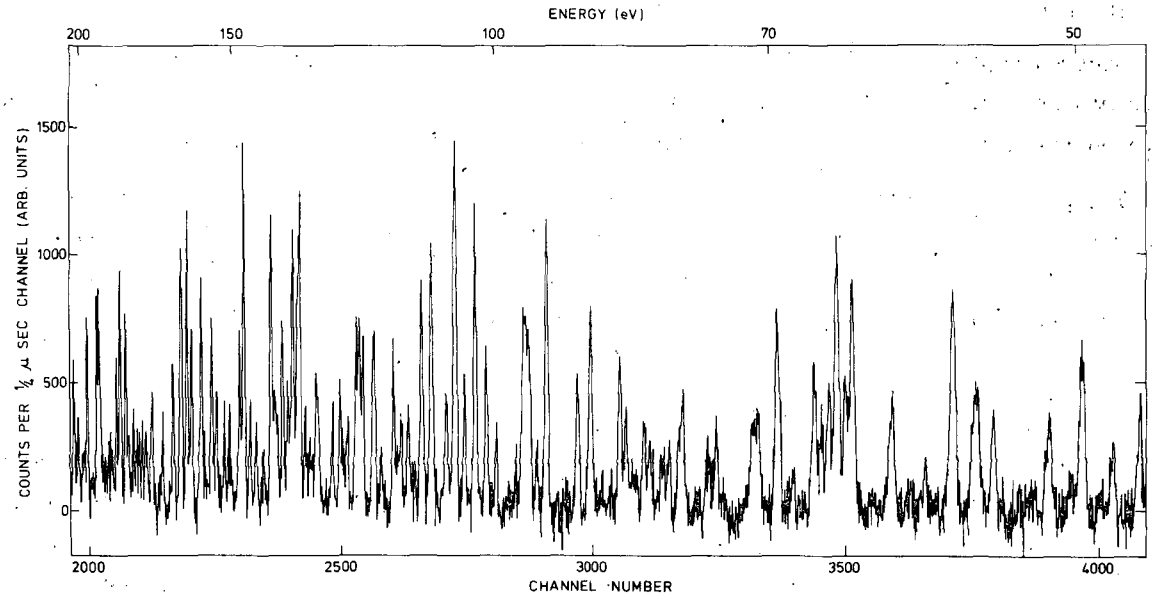

Fig. 1 The observed time-of-flight spectrum with a 12 gm oxide sample of ^{241}Am in the liquid scintillator for detected gamma-rays in the energy range 3 to 13 MeV

E. Neutron capture cross-section measurements on structural materials (D.B. Gayther, B.W. Thomas, B. Thom (Queen Mary College), M.C. Moxon, J.E. Jolly and D.A.J. Endacott) [Relevant to 28 requests]

During the past year a large quantity of data has been accumulated for each of the reactor structural materials, Fe, Ni and Cr, using the large liquid scintillator at the 100 m station of the Harwell Linac (UKNDC(75)P71, page 6). The scintillator is divided into two halves, enabling a reduction in natural background to be achieved by operating the halves of the tank in coincidence. An existing two-parameter data collection system has been used to obtain both pulse-height and time-of-flight information for each recorded event. Dynamic coding has also been used to facilitate the sorting of coincidence and anti-coincidence events.

Measurements have been made for three sample thicknesses of each material and also for a gold sample. The gold measurements provide reference data taken throughout the series of measurements, and monitor the neutron flux spectrum incident on the capture samples as well as the performance of the detector system. The capture measurements cover the neutron energy range from 50 eV to 800 keV with a time-of-flight resolution of ~ 1.7 ns/m. The energy spectrum of the incident neutron beam has been measured by comparison with standard reference cross-sections. These were the $^{6}Li(n,\alpha)$ cross-section for energies below 50 keV, the detector consisting of a 1 mm thick ^{6}Li-glass, and at higher energies the $^{235}U(n,f)$ cross-section, the fission neutrons being detected.

The reason for recording pulse height spectra is that in order to derive cross-sections from the scintillator tank measurements, some knowledge of the gamma ray cascades which follow neutron capture is necessary. A Monte Carlo program, which predicts the shape of the gamma-ray spectra for different cascade schemes, is used in the interpretation

of the data. This program has been used to generate pulse-height spectra for various cascade modes of ^{57}Fe based on the known level scheme and available high-resolution capture gamma-ray data. It is not yet possible to construct the complete spectra for resonances, but the coincidence/anti-coincidence ratio has been determined as a function of cascade multiplicity. A preliminary analysis of the iron data has yielded a range of coincidence/anti-coincidence ratios for a set of known resonances. The average multiplicities inferred from the calibration are found to be consistent with published gamma-ray data[1] (low multiplicity is obtained for resonances with strong ground-state transitions).

The collection of data has now stopped and current effort is concerned with processing the results using the Harwell central computer. The first step in the process will be to check the internal consistency between individual experimental runs prior to analysis.

Cross-sections obtained from the large tank are difficult to place on an absolute scale, and the measurements will yield essentially the shape of the capture cross-section as a function of neutron energy. In order to normalize the data, identical samples of the structural materials are presently being measured with the Moxon-Rae detector at the 32 m station of the linac. This detector has an efficiency for detecting capture events which is proportional to the neutron binding energy, and is consequently independent of the gamma-ray decay scheme.

The Moxon-Rae data are being collected on the PDP 11-45 computer; this enables us to use 16K time-of-flight channels, covering a neutron energy range from ~ 200 keV to ~ 2 eV with a nominal timing resolution of 5 ns/m. Although the resolution is poorer than that of the large liquid scintillator it will be possible to compare the average capture cross-sections obtained with the two systems up to an energy of ~ 100 keV.

E. Neutron capture measurements on the titanium isotopes (R.B. Thom (Queen Mary College), M.C. Moxon and D.B. Gayther) [Relevant to 3 requests]

Although the relevant abundances of the elements below iron are generally accounted for by nuclear fusion in stellar matter, the importance of neutron capture in the nucleosynthesis of some medium mass nuclei is not fully understood. Cross-section measurements in the energy range 1 to 100 keV on the separated isotopes of certain elements (including titanium) are required in order to resolve this problem.

Capture and transmission measurements have been completed at the Harwell Linac on separated isotope samples of titanium on loan from Oak Ridge National Laboratory. The bulk of the capture data were obtained from the Moxon-Rae detector on a 32 metre flight path covering an energy range from 5 eV to 100 keV. Additional data from the 230 l liquid scintillator at 100 m have extended these measurements to 800 keV with a region of overlap between 1 and 100 keV, allowing comparison to be made between the two sets of data.

A programme of total cross-section measurements, required in the analysis of capture data, over the same energy range, has proceeded in parallel at the Harwell synchrocyclotron (this report page 6). Supplementary low energy total cross-section information, of coarser resolution but higher statistical accuracy, has also been obtained at the Linac, using the Li-glass detector at 14 metres. A Moxon-Rae detector was also used on a 4.5 m flight path to make thermal capture measurements on the isotopes ^{47}Ti and ^{49}Ti.

(1) Nuclear Data Tables 11, No.6 (1973) 482

The ^{48}Ti was a 99% pure metallic powder while the other isotopes in the form of oxide powders were ~ 70% isotopic purity, the main impurity being ^{48}Ti, present to the extent of about 20% in each. The samples were compressed into 76 mm diameter cans and then sealed under vacuum after the extraction of the surplus air.

Many small, narrow resonances, most of which are previously unreported, are visible in the capture data in addition to the known broad levels observed in total cross-section data. Existing capture data on these isotopes are scarce, there being no reported capture measurements on the isotopes 46, 49 and ^{50}Ti. Ernst[1] has extracted capture areas for a few resonances in ^{47}Ti in the energy region 3-21 keV while measurements on the natural element (predominantly ^{48}Ti) have been reported by Allen[2].

A portion of the observed capture events from both detectors as a function of time-of-flight is shown in Fig. 1. The energy region covered is from 13 to 2 keV. The liquid scintillator data, in the upper half of the figure, shows that due to the increase in path length, many of the resonances observed in the Moxon-Rae data have been resolved into doublets. New resonances are marked with an asterisk.

Analysis of the data is now under way.

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(1) A. Ernst, F.H. Fröhner and D. Kompe, Proc. Helsinki Conf. on Nuclear Data for Reactors I (1970) 633

(2) B.J. Allen and R.L. Macklin, Bull. Amer. Phys. Soc. 15 (1970) 1667

H. Total cross-section measurements on the synchrocyclotron (P.H. Bowen, A.D. Gadd, G.D. James, D.B. Syme, B. Thom (Queen Mary College) [Relevant to 20 requests]

During 1975 a small-sample flight path was set up on the Harwell synchrocyclotron to measure total cross sections for nuclear reactor structural materials and for separated titanium isotopes which are of interest in the theory of astrophysical nucleosynthesis. The flight path is operated with an Ne 110 detector (with dynamic bias) at 100 m or with a Li glass detector at 50 m. The neutron beam diameter at the position of the sample can be 1 cm, 2 cm or 3 cm. The brass collimation system installed provides converging-diverging geometry for the detector at 50 m. Normally, operation at 100 m covers the energy range 10 keV-10 MeV and operation at 50 m covers the energy range 0.1 keV-100 keV.

Measurements on this flight path started in July 1975 and up to February 1976 transmission measurements for the following samples have been obtained: $^{46}TiO_2$, $^{47}TiO_2$, ^{48}Ti, $^{49}TiO_2$, $^{50}TiO_2$ at 50 m and 100 m (these isotopes are of both astrophysics and reactor interest); ^{6}Li and C at 100 m (these are required for accurate energy determinations); 30 mm Co and 10 mm Co at 100 m (cobalt is also of reactor interest) and 3 cm Fe at 100 m (this additional measurement on Fe is required to resolve statistical discrepancies in the data obtained in 1974). Resonance analyses of these data will be undertaken using the Harvey-Atta area analysis program and also using the shape analysis program FANAL[1] which has recently been brought into operation. The results obtained for the separated titanium isotopesare shown in Figs. 1a and 1b.

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(1) F.H. Fröhner, Report KFK 2129 (1976)

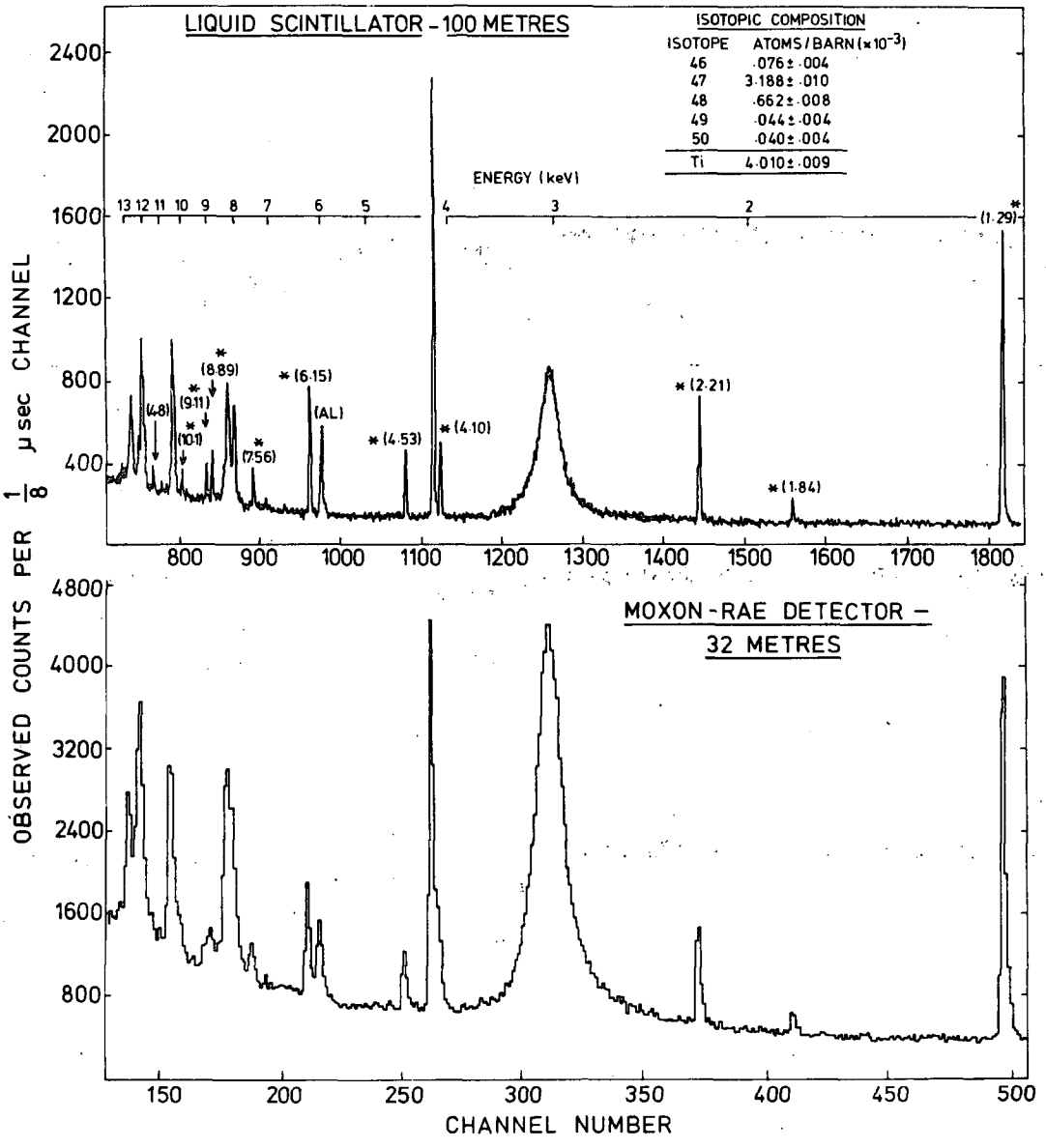

Fig. 1 Time-of-flight capture spectra from an oxide sample of ^{47}Ti. New resonance energies are marked by asterisks

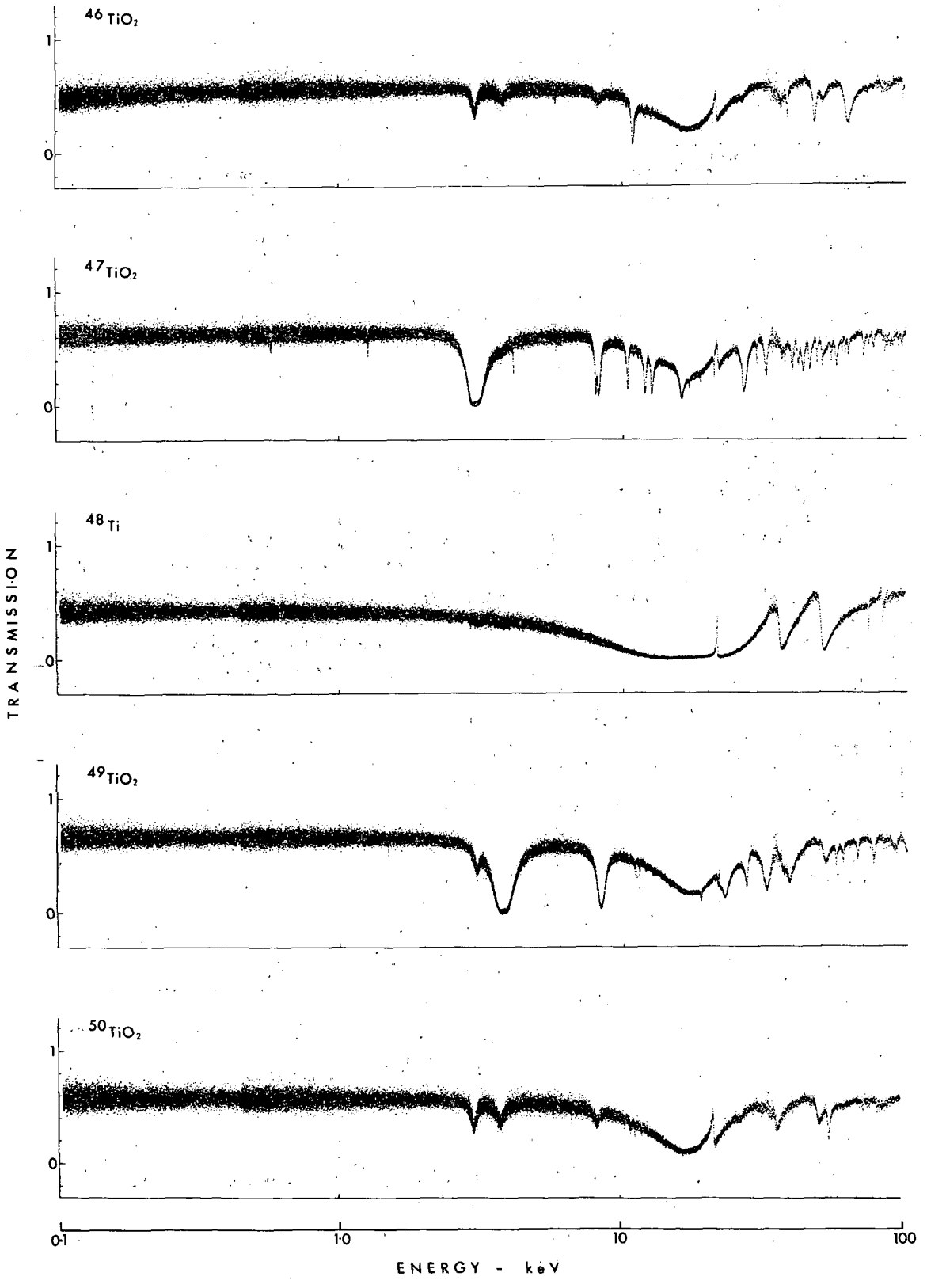

Fig. 1a Transmission for five separated titanium isotopes over the energy range 100 eV to 100 keV measured with a Li glass detector on a 50m flight path. All the major samples used, except for ^{48}Ti, are oxides

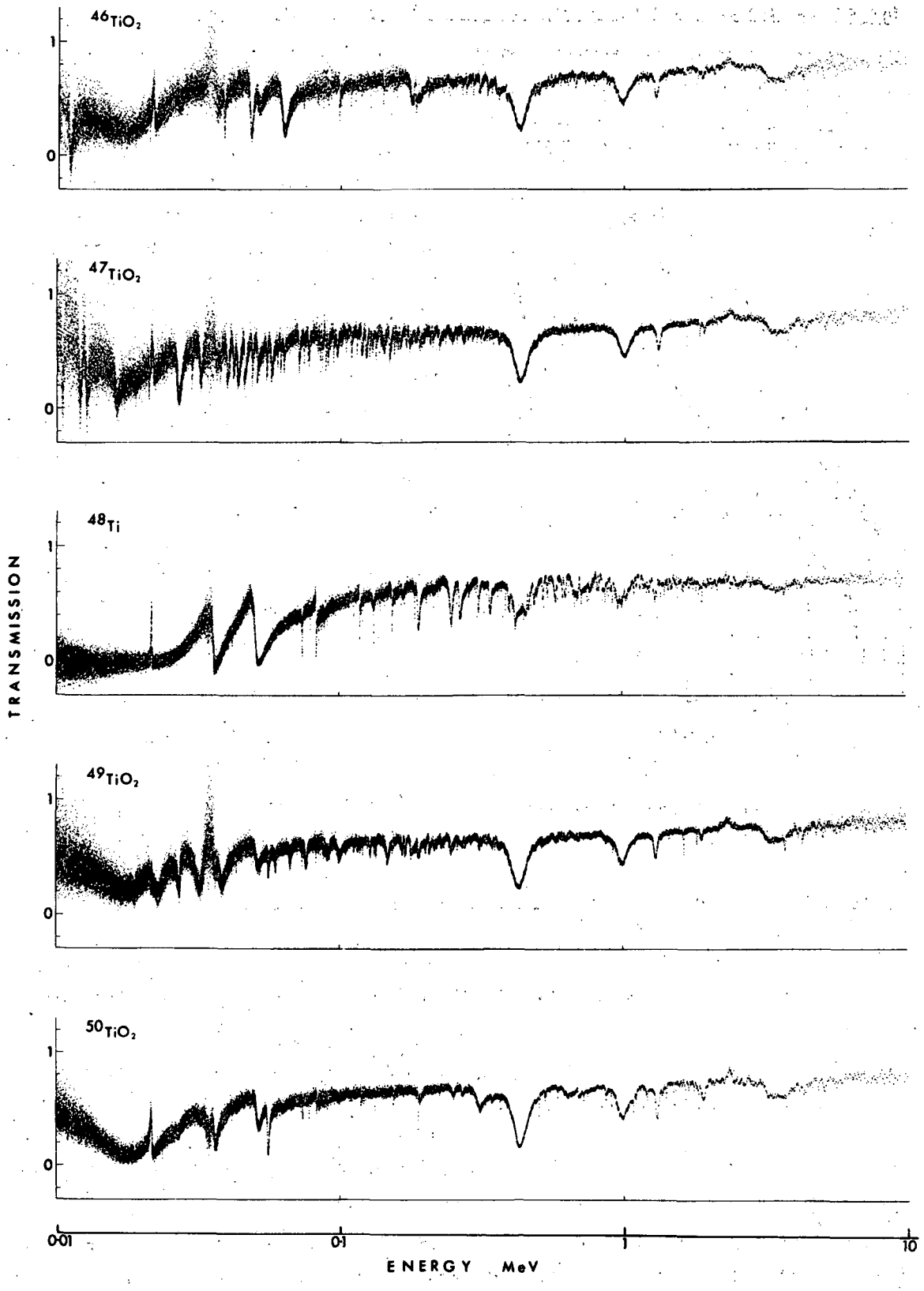

Fig. 1b Transmission for five separated titanium isotopes over the energy range 10 keV to 10 MeV measured with a dynamically discriminated NE110 detector on a 100m flight path. All the samples used, except for ^{48}Ti, are oxides

H. Design and use of a dynamic discriminator (D.B. Syme and P.E. Dolley)

Hydrogenous scintillators should be much more efficient detectors of neutrons in the 1 - 1000 keV region than ^{6}Li glass detectors because the hydrogen scattering cross section is about ten times larger than that for ^{6}Li(n,α) in this energy range. Neutrons with energy down to the noise limit of about 10 keV can be detected by using a plastic scintillator (Ne 110) coupled to a low noise, high efficiency photomultiplier (RCA 4522); the low threshold however allows detection of increased background at higher energies and of small after-pulses which sometimes follow the real events. These effects have been drastically reduced at the Synchrocyclotron neutron time-of-flight facility by the use of a dynamic discriminator in which the threshold decreases with the neutron energy. Such a discriminator has been in use now for more than a year and has proved reliable. Fig. 1 shows the small price paid in loss of fast neutron efficiency for a large reduction in background. The background component from time independent radioactivity has a time dependence caused by the changing discriminator threshold.

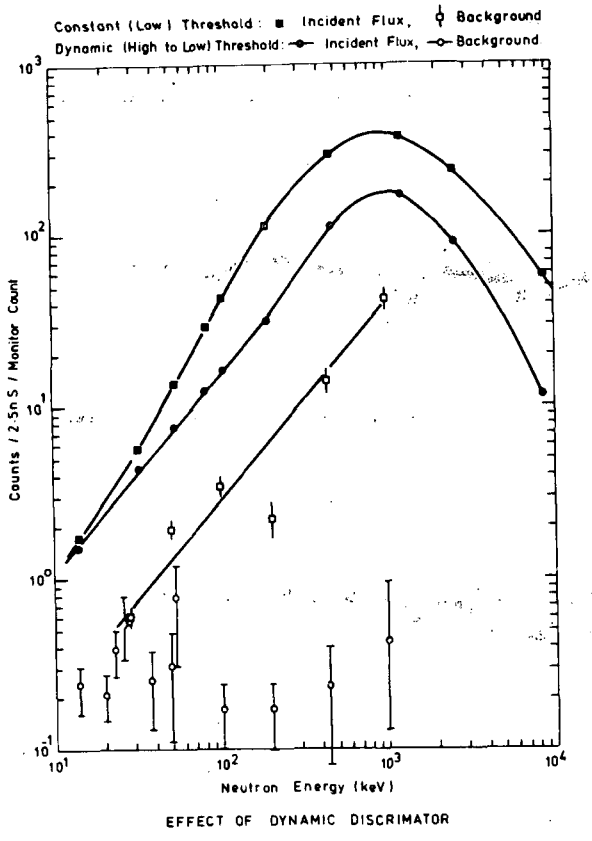

Fig. 1 The effect of a dynamic discriminator on neutron detection efficiency

H. Neutron resonance area analysis of nickel transmission data (D.B. Syme and P.H. Bowen)
[Relevant to 8 requests]

Transmission data (UKNDC(75)P71) for two thicknesses of nickel (0.6 cm and 1.8 cm) are being analysed over the energy range 20 keV to 300 keV using the Harvey-Atta computer code.

The neutron widths obtained for well separated s-wave resonances are in agreement with previous data. So far, about half the eighty analysable narrow resonances (l >0) in this energy range have been analysed. The good resolution of the present data reveals errors in some of the existing parameter assignments. For example, the resonance at 36.1 keV is clearly shown to be l = 0 whereas the previously accepted value was l = 1.

Another example of the analysis is given in Fig. 1 which shows three resonances in the transmission of nickel near 83 keV. The weakest resonance may be an s-wave level and has not been included in the fit to the two stronger levels which are regarded as l > 0 resonances in ^{60}Ni. This fit, however, is not necessarily unique. Previous data on natural nickel[1] have worse energy resolution and show two resonances, at 82.8 keV and 83.8 keV, which were fitted as l = 0 resonances in ^{60}Ni. The energy scale of these results is in good agreement with the present measurement. The present data show no

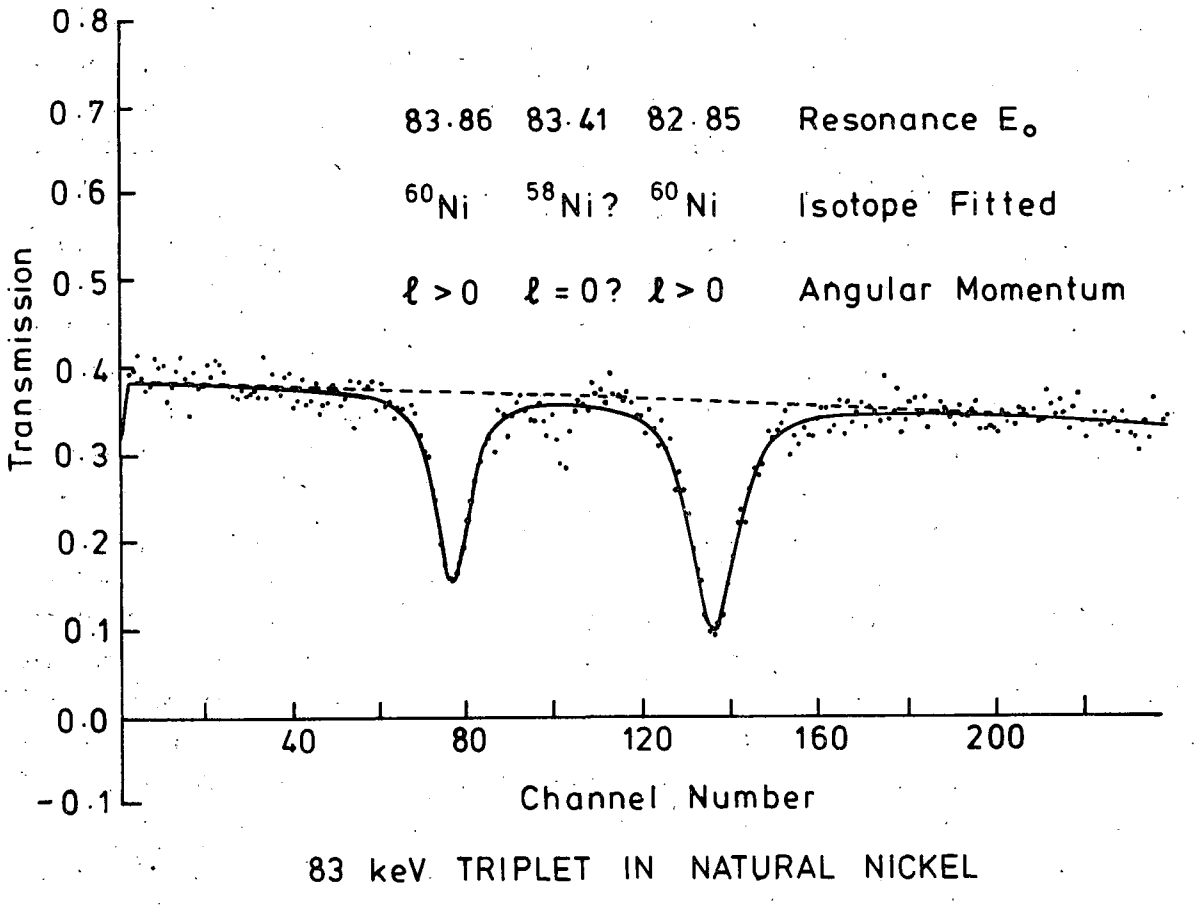

Fig. 1 A fit by Harvey-Atta analysis to the transmission of 1.8 cm nickel near 83 keV

obvious interference asymmetry and it seems unlikely that l = 0 for these resonances. Mono-isotopic data measured by Cho et al.[2] are presented as indicating one level in ^{58}Ni and one in ^{60}Ni within the energy range of Fig. 1. Unfortunately, a difference in energy scale prevents a clear cut comparison with these data.

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

(2) M. Cho, F.H. Fröhner et al. Report KFK 1230 (1970)

E. Doppler broadening studies on UO_2 (T.J. Haste, P.P. Thomas and M.G. Sowerby)
[Relevant to 6 requests]

Further progress has been made on the programme to study Doppler broadening effects in UO_2 samples heated up to ~ 2000°C - temperatures much higher than can be reached in reactor experiments. A vacuum furnace[1] has been constructed and installation is under way on an extensively modified flight path of the neutron booster. The furnace is mounted in the original detector station on a sample changer so that transmissions of identical hot and cold samples can be measured using a 2.5 cm thick Li glass scintillator mounted in a new 40 m detector station. A second sample changer, which is used to carry resonance filters for background measurements, is positioned between the booster and the furnace. By making both hot and cold measurements in the same run it is hoped to reduce the systematic errors.

The temperature of the hot samples will be monitored during the runs by an optical pyrometer; it is intended to determine the effective temperatures of the samples during analysis by fitting the low energy (eV range) resolved resonances. It is expected that preliminary measurements will be started in the near future.

Theoretical studies on the Doppler broadening effect in UO_2 have been continued. Attempts have been made to reproduce the results of earlier transmission measurements[2] on heated uranium samples, using an improved version of the computer code[1]. Average transmissions were calculated for samples up to 128 mm thick at 20°C and 800°C. Sets of resonances based on the average parameters of the GENEX[3] evaluation were chosen to reproduce the average transmission as a function of sample thickness at 20°C, using background terms to take into account the effect of distant levels. The same sets of resonances were used in the calculations for samples at 800°C. The effect of sample expansion was included. Agreement with experiment[2] was generally good, except for thicker samples (> 32 mm) where the observed effect was underpredicted for neutron energies greater than 10 keV. In addition the average transmission of the UO_2 samples to be used in the present measurements were calculated at 5 keV and 20 keV for various sample temperatures. The figures showed that the expansion effect could be of the same order as the Doppler effect, particularly at the higher energies for higher temperatures (≃ 1800°C), emphasising the need for accurate knowledge of sample expansion when evaluating the experimental results.

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(1) T.J. Haste et al., Progress Report UKNDC(75)P71, page 33

(2) A.A. Vankov, Yu.V. Grigoriev, M.N. Nikolaev, V.V. Filippov, B. Boehmer, S. Collatz and L.B. Pickelner, INDC(CCP-16/L (1971) p.49 (trans. by IAEA)

(3) M.F. James, private communication (1975); see also EANDC 90L

D. Scattering of 27 MeV neutrons by protons (J.A. Cookson, J.L. Fowler*, M. Hussain**, C.A. Uttley and R.B. Schwartz***)

Most of the data collection and a considerable part of the analysis has been completed on this experiment. As indicated previously (UKNDC(75)P71, page 18), the experiment is divided into two parts.

(a) Detector efficiency calibration. The neutron detector is a 10 cm diameter by 2.5 cm thick NE102A plastic scintillator which is calibrated in terms of absolute efficiency by the associated particle method over the neutron energy range 5-25 MeV. The neutron producing reactions between the hydrogen isotopes $T(p,n)^3He$, $D(d,n)^3He$ and $T(d,n)^4He$ are used, in which the angles for emission of a neutron and a helium particle with energy > 3 MeV are uniquely determined by reaction kinematics. Details of the gas target and helium reaction chamber have been published[1].

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* Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

** University of Dacca, Bangladesh.

*** U.S. National Bureau of Standards, Washington, D.C.

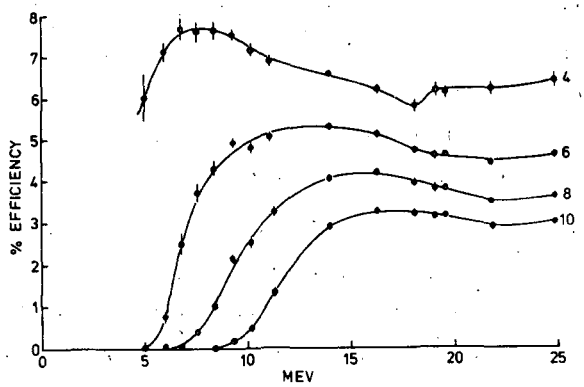

Fig. 1 Absolute efficiency of a 10 cm diam. by 2.5 cm thick NE102A plastic scintillator

The efficiency of the neutron detector for four proton thresholds is shown in Fig. 1. The energy range over which the efficiency has been measured is greater than the range of scattered neutron energies detected in this experiment. This has been done principally to afford a better comparison with predicted efficiencies using currently available computer codes.

(b) Angular distribution of scattered neutrons. 27 MeV neutrons are scattered by a small plastic scintillator into the calibrated neutron detector which is at a distance of about 85 cm. Neutrons scattered through six angles between 17^{o} and 50.8^{o} are measured, the time difference between pulses from the two detectors being recorded for each event together with the pulse amplitude from the neutron detector. A requirement placed on the small detector is that it should detect all proton recoils associated with primary neutrons scattered over the angular range studied. It is therefore necessary to detect recoils of energy ~ 0.9 MeV at 17^{o} when allowance is made for the finite angle over which scattered events can be detected, but higher thresholds are used as the angle of scattering is increased. In order to ensure that all recoils are detected, two discriminators with different thresholds are employed on the scatterer and the computer is coded to record events above the upper level and those lying between the two thresholds.

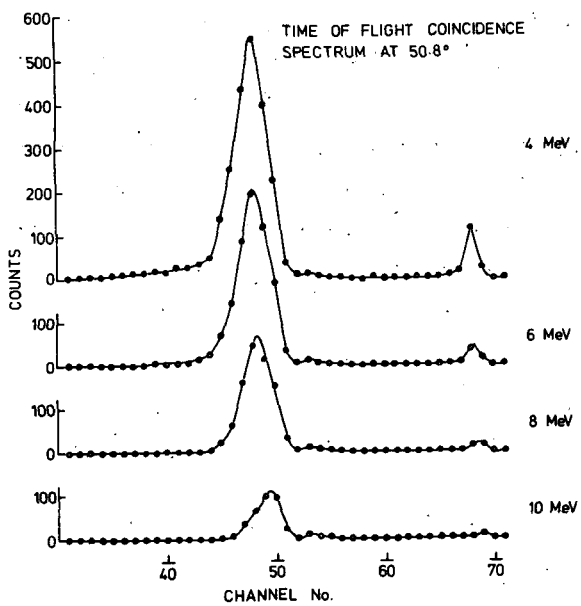

Fig. 2 Time-of-flight spectrum of scattered events at 50.8° (lab) for four proton thresholds on the neutron detector

An example of the time-of-flight spectrum of events scattered through 50.8^{o} is shown in Fig. 2 in which time-of-flight increases from the right. The first peak arises from events in the two detectors in which an incident γ-ray is Compton scattered from the small into the large detector and this is followed by the large elastically scattered neutron peak. Time-of-flight events for four different proton thresholds on the neutron detector are shown since it is instructive to analyse the data for different biases. One feature at 50.8^{o} not observed at the more forward angles is the occurrence of a small resolved peak above the elastic neutron peak. This may be due to $^{12}C(n,n^{1}\gamma)$ events in the

UKNDC(76)P80 8/76

scatterer in which the 4.44 MeV γ-ray is detected with the inelastic neutron of energy ~ 21 MeV detected in the large scintillator. Since the energy of the inelastic neutron varies only slowly with laboratory angle, these neutrons will merge into the main elastic peaks at the more forward angles and may be of sufficient number to cause a significant correction to the data. The effect of this reaction is being investigated.

The effects of flux attentuation and multiple scattering in the scatterer have been calculated using the Monte Carlo program MAGGIE[2,3]. Input data on hydrogen and carbon from the UK nuclear data files were extended from 20 MeV and 15 MeV respectively to 29 MeV. The result of this calculation is that the relative multiple scattering correction factor for events in the elastically scattered peaks varies by only ~ 1% over the angular range studied.

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(1) J.A. Cookson, M. Hussain, C.A. Uttley, J.L. Fowler and R.B. Schwartz, Proc. Washington Conf. on Nuclear Cross Sections and Technology I (1975) 66

(2) J.B. Parker, J.H. Towle, D. Sams and P.G. Jones, Nucl. Instr. and Methods 14 (1961) 1

(3) J.B. Parker, J.H. Towle, D. Sams, W.B. Gilboy, A.D. Purnell and H.J. Stevens, Nucl. Instr. and Methods 30 (1964) 77

B. Measurement of the fast neutron fission spectrum of ^{235}U at 0.52 MeV incident neutron energy (J.M. Adams and P.I. Johansson (Studsvik)) [Relevant to 3 requests]

As part of the comparison work of recent measurements of ^{235}U and ^{239}Pu fast neutron fission spectra (see below), considerably more analysis of these data has been carried out. In particular, account has been taken of the effect of the finite size of the ^{235}U sample used[1], which has had the overall effect of 'hardening' the shape of the fission spectrum, and thus increasing the average fission neutron energy, $\bar{E}$, from 1.986 MeV to 2.027 MeV[2]. This correction is of particular importance for data that extend over a fission neutron energy range from below 1 MeV to 10-15 MeV, and clearly indicates the necessity to employ smaller samples in measurements of the shape of the spectrum below 1 MeV. Further investigation of this finite sample size correction is in progress using the Monte Carlo code MAGGIE[3], in order to determine the correction uncertainties which was difficult to do with Knitter's analytical code[1]. It is planned to continue this collaborative work with Studsvik by a measurement of the ^{235}U fission neutron spectrum over the energy range from ~ 100 keV - 15 MeV in Studsvik this summer, using a thinner walled hollow cylinder of ^{235}U.

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(1) M.M. Islam and H.H. Knitter, Nuc. Sci. Eng. 50 (1973) 108

(2) J.M. Adams, Proc. Specialists Meeting on Inelastic Scattering and Fission Spectra, Harwell, 14-16 April 1975, to be published

(3) J.B. Parker, J.H. Towle, D. Sams, W.B. Gilboy, A.D. Purnell and H.J. Stevens, Nuc. Instr. Meth. 30 (1964) 77

Comparison of ^{235}U and ^{239}Pu fast neutron fission spectra (J.M. Adams) [Relevent to 5 requests]

As a result of the Specialists' Meeting on Inelastic Scattering and Fission Spectra held at Harwell, 14-16 April, 1975, the fast neutron fission spectra for ^{235}U and ^{239}Pu from

Cadarache[1], Geel[2], Harwell (^{235}U only)[3] and Studsvik[4] have been systematically intercompared. These data, corrected for finite sample size effects[2], have been fitted in terms of both Maxwell and Watt distribution formalisms. In all cases a preference for a Watt formalism[5] description was found, and consequently, these data have been intercompared on this basis. The results of the non-linear least squares fitting procedure to a Watt formalism are given in Table 1. There is reasonable agreement within the errors of

TABLE 1

Results of Watt distribution fitting

Data		Incident Neutron Energy (MeV)	Fission Neutron Energy Range of Data (MeV)	Watt Parameters		$\bar{E}$
				A	B	
^{235}U	Cadarache	0.01–0.058	0.5–13.946	0.977 ± 0.017	1.662 ± 0.162	1.970
	Geel	0.4	0.575–6.87	0.983 ± 0.028	2.046 ± 0.276	2.055
	Harwell	0.52	0.625–15.629	1.023 ± 0.016	2.440 ± 0.176	2.027
	Studsvik	0.53	0.225–14.4	1.019 ± 0.009	2.308 ± 0.092	2.027
	Weighted Mean			1.012 ± 0.011	2.189 ± 0.155	2.016
^{239}Pu	Cadarache	0.01–0.058	0.55–14.253	1.002 ± 0.021	2.033 ± 0.216	2.004
	Geel	0.215	0.28–13.87	1.005 ± 0.018	2.405 ± 0.163	2.088
	Studsvik	0.53	0.325–14.4	1.036 ± 0.008	2.873 ± 0.082	2.116
	Weighted Mean			1.029 ± 0.010	2.701 ± 0.204	2.097

the data in the fission neutron energy range from 1 – 10 MeV, but there is some evidence to suggest a 'hardening' of both spectra with increasing incident neutron energy. However, these data do not provide sufficient information with regard to the shape of the fission neutron spectrum below 0.5 MeV. A weighted mean of the Watt distribution parameters results in average fission neutron energy, $\bar{E}$, estimates of 2.016 MeV and 2.097 MeV for ^{235}U and ^{239}Pu respectively (cf. ENDF/B-IV evaluation estimates of 1.985 MeV and 2.06 MeV), leading to a $(^{239}\text{Pu}/^{235}\text{U})\bar{E}$ ratio of 1.04 (cf. ENDF/B-IV of 1.038). Although it is difficult to assess the absolute errors involved, since they depend on quantities whose uncertainties are not constant with energy, it is reasonable to consider that the estimated values for $\bar{E}$ are reliable to better than 2–3%, and the $(^{239}\text{Pu}/^{235}\text{U})\bar{E}$ ratio to better than 1–2%. This work, a report of which will be included in the proceedings of the above Specialists Meeting to be published shortly, will form the basis for a complete valuation of all available fission neutron spectral data to be undertaken at Harwell.

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(1) D. Abramson and C. Lavelaine, to be published

(2) M.M. Islam and H.H. Knitter, Nucl. Sci. Eng. 50 (1973) 108; and H.H. Knitter, Atomkernenergie 26 (1975) 76

(3) J.M. Adams and P.I. Johansson, Proc. Washington Conf. on Nuclear Cross-Sections and Technology II (1975) 631

(4) P.I. Johansson, B. Holmqvist, T. Wiedling and L. Jeki, ibid. p.572

(5) See UKNDC(75)P71, page 23 for definition

H. Fission cross-section measurements on the synchrocyclotron (G.D. James, G. Huxtable, P.A.R. Evans and M. Cooke) [Relevant to 10 requests]

In recent weeks the total cross section flight path collimation system has been raised by 3.5 cm to enable a back-to-back $^{235}U/^{238}U$ fission chamber placed at 26 m to receive neutrons directly from the proton target. This has greatly enhanced the neutron beam intensity and hence the yield from the fission chambers; this has enabled the $^{235}U/^{238}U$ fission cross-section ratio to be determined and these results are being processed. Experiments to investigate the behaviour of an absolutely calibrated knock-on proton detector are now in progress on the flight path at 13 m.

H. Maximum likelihood analysis of ^{234}U fission widths (G.D. James and P.A.R. Evans (Oxford University)) [Relevant to 1 request]

It is known that resonances in the fission cross section of ^{234}U below 1500 eV[1] comprise at least one narrow intermediate structure resonance. These data, which are shown in Fig. 1, contain two large fission widths at 1092.5 eV and 1134 eV which may indicate the presence of a second structure resonance at about this energy. A definitive

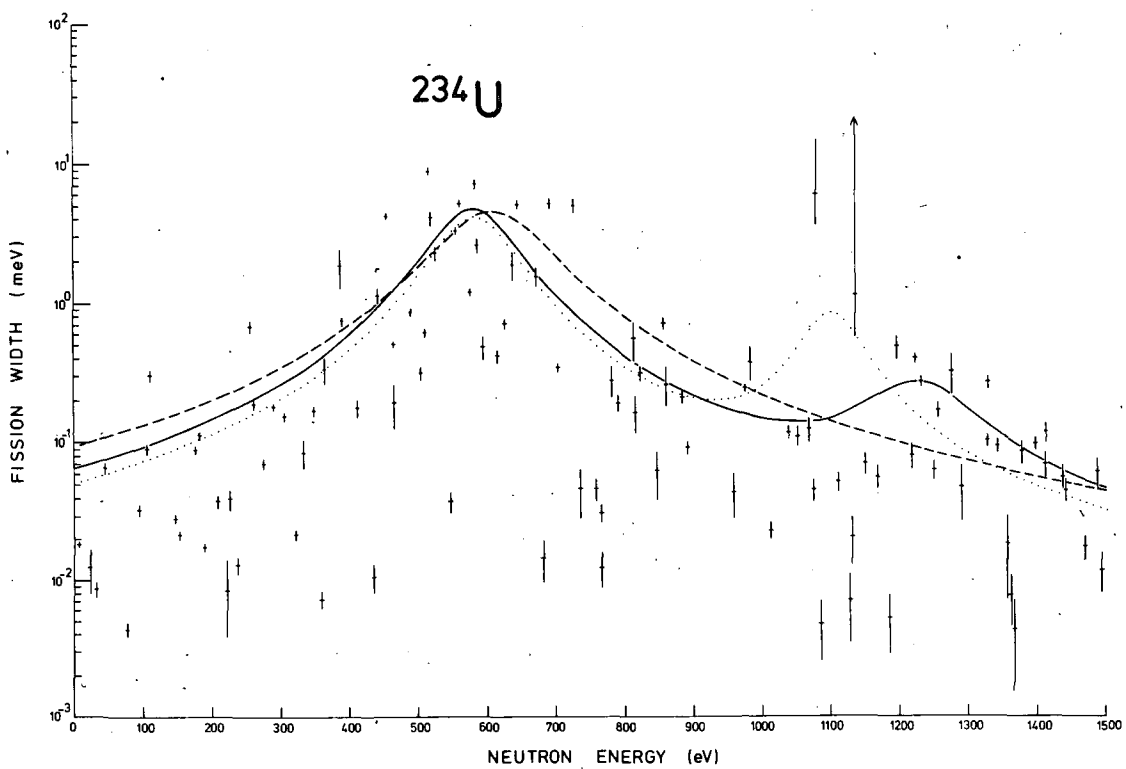

Fig. 1 Energy dependence of class I fission widths for resonances in the fission cross section of ^{234}U below 1500 eV. The curves represent the energy dependence of the mean fission widths defined by Lorentzian functions with the parameters given in Table 1. The solid line is the preferred fit. It shows the sum of two non-interfering Lorentzian curves with parameters deduced by a weighted maximum likelihood method. The dashed curve represents a single Lorentzian with parameters deduced in the same way. The dotted curve shows the sum of two Lorentzians derived by an analysis in which the likelihood was not weighted

test, using the likelihood ratio, confirms this possibility. Within a narrow intermediate structure resonance, the fission widths are expected to undergo a Porter-Thomas distribution about a Lorentzian energy dependent mean value. This distribution has been assumed in formulating a likelihood function which has been used to determine the parameters E_1, W_1 and K_1 in the equation

$$\langle \Gamma_f \rangle_i = K_1 / \left((E_i - E_1)^2 + W_1^2/4 \right) \quad \ldots\ldots (1)$$

and also the parameters E_1, W_1, K_1, E_2, W_2 and K_2 in the equation

$$\langle \Gamma_f \rangle_i = K_1 / \left((E_i - E_1)^2 + W_1^2/4 \right) + K_2 / \left((E_i - E_2)^2 + W_2^2/4 \right) \quad \ldots\ldots (2)$$

Here, $\langle \Gamma_f \rangle_i$ is the average fission width for resonance i at energy E_i.

The results obtained by maximum likelihood analysis are given in Table 1 and illustrated for eq. (2) by the dotted curve in Fig. 1. This analysis takes no account of the

TABLE 1

Lorentzian fit to ^{234}U fission width data

Method	Number of Class II levels	E (eV)	W (eV)	K (eV^2 MeV)
Maximum likelihood	1	645 ± 26	137^{+23}_{-19}	48460^{+6800}_{-5800}
Maximum likelihood	2	582 ± 17	64 ± 14	17200^{+3100}_{-2400}
		1101 ± 21	52 ± 15	2110^{+780}_{-570}
Weighted maximum likelihood	1	608 ± 18	89 ± 14	36090 ± 4500
Weighted maximum likelihood	2	580 ± 16	68 ± 10	22140^{+3400}_{-2750}
		1227 ± 65	87^{+17}_{-13}	1700^{+1200}_{-650}

errors of measurement and appears unreasonable in view of the large errors in the two high values of fission width which dominate the structure resonance near 1100 eV. A second analysis, using a likelihood function in which the fission width probability distribution functions are weighted inversely as the square of the errors in the fission widths, has been carried out and the results are also given in Table 1 and illustrated by the solid line in Fig. 1. It will be seen now that the second structure resonance arises from a cluster of high fission widths above 1100 eV and a preponderance of low values just below

this energy. The two large values near 1100 eV are largely ignored. In this weighted maximum likelihood test, let L_3 be the maximum likelihood obtained using the three parameter fit of eq. (1) and let L_6 be the value obtained for the six parameter fit of eq. (2). It is found that the likelihood ratio $\lambda = L_3/L_6 = \exp(-5.41)$ which, according to Wilke's theorem, enables us to reject the three parameter fit at the 1.27% significance level.

(1) G.D. James, J.W.T. Dabbs, J.A. Harvey, N.W. Hill and R.H. Schindler, UKNDC(74)P63, page 39

Fission neutron and fragment angular distributions from the threshold photofission of ^{232}Th and ^{238}U (S. Nair (University of Oxford), D.B. Gayther, B.H. Patrick and E.M. Bowey)

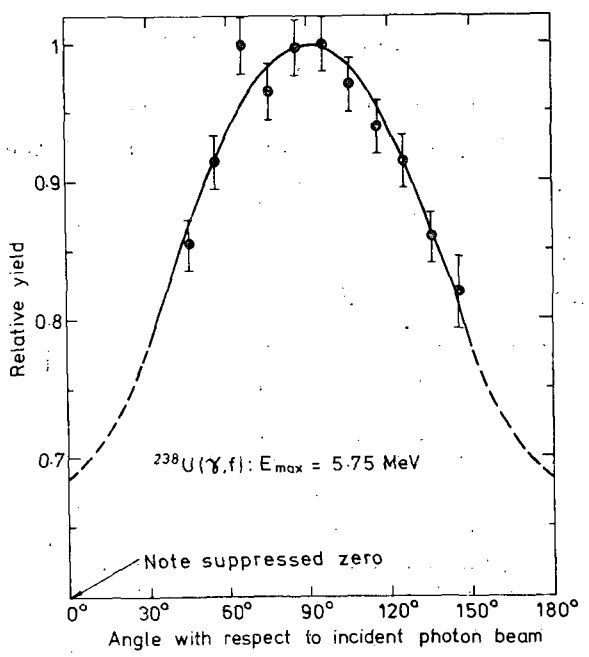

Fig. 1 Measured neutron angular distribution from photofission of ^{238}U by bremsstrahlung of end-point energy 5.75 MeV. The solid line is a least squares fit to the data of a Legendre polynomial expansion modified by the experimental angular resolution

The measurements of fission neutron angular distributions from bremsstrahlung induced fission have now been completed. Data have been obtained at end-point energies of 6.35 and 7.1 MeV for ^{232}Th and 5.75 and 6.15 MeV for ^{238}U. The angular distribution obtained in the 5.75 MeV end-point measurements is shown in Fig. 1, the results of preliminary measurements at the other energies were given in the previous report[1]. The neutrons were detected in a sandwich of Makrofol and depleted uranium foil[2] arranged in cylindrical geometry[1]. A least squares fit to the experimental points was made by assuming the angular distribution to have the form $N(\phi) \propto 1+N_2P_2(\cos\phi)+N_4P_4(\cos\phi)$ with an allowance for the experimental angular resolution.

The main purpose of these measurements is to establish if there is a component of the fission neutrons which cannot be accounted for by evaporation from the fragments after they have been fully accelerated. The assumption is made that this "scission" component is emitted isotropically in the rest system of the target nucleus, and its value is determined by comparing the observed neutron angular distribution with that calculated for the case of emission solely from the fragments. The method requires an anisotropic fragment angular distribution (measured with respect to the incident beam) and the moments of the distribution must be accurately known. Threshold photofission provides suitably large anisotropies for this type of measurement.

In the previous report a preliminary value for the scission neutron component of ~ 16% was given. This was derived from the preliminary data obtained at three end-point energies combined with the published fragment angular distributions of Rabotnov et al[3].

To rely on published data can lead to error, however, because of slight differences in energy calibrations (particularly near threshold where angular distributions can change rapidly) and differences in bremsstrahlung targets which produce different photon spectra. The fragment angular distributions have therefore been measured on the linac with the same target, end-points and geometry as those used in the fission neutron angular distribution measurements. The fissile samples were coated on thin aluminium cylinders to a thickness of ~ 1 mg/cm^2, and were mounted at the centre of a vacuum chamber. The fragments were registered in Makrofol foil which was attached to the wall of the chamber. Figure 2 shows the measured distributions for both targets at the lower end-point energies. The curves through the experimental points are least squares fits of the form $W(\alpha) \propto 1 + W_2P_2(\cos\alpha) + W_4P_4(\cos\alpha)$ modified by the experimental angular resolution; as in the neutron distributions the dipole component is the dominant term. Figure 3 shows the present values for W_2 in comparison with the data of Rabotnov et al[3]. The Russian measurements were made with a 1 mm thick tungsten bremsstrahlung target, while the target used in the present measurements was one-tenth of this thickness. The good agreement between the two sets of data is probably explained by the steeply rising photofission cross-section at the present energies which results in the observed fissions occurring mainly at the very tip of the bremsstrahlung spectrum.

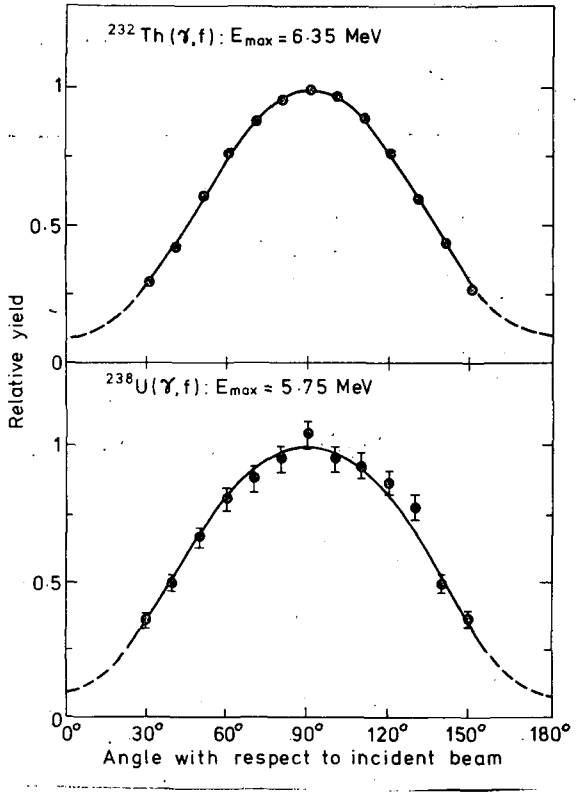

Fig. 2 Measured fragment angular distributions from bremsstrahlung-induced photofission of ^{232}Th at end-point energy 6.35 MeV and ^{238}U at end-point energy 5.75 MeV. The solid lines are least squares fits to the data of Legendre polynomial expansions modified by the experimental angular resolution

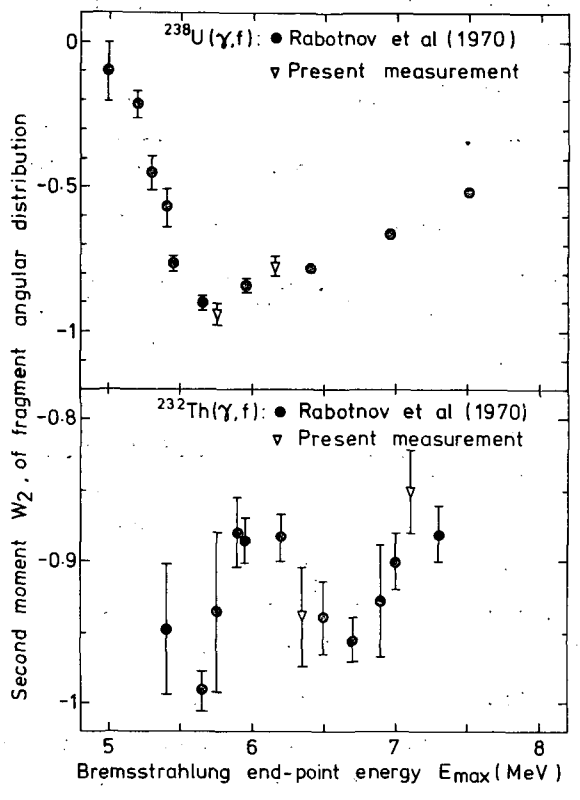

Fig. 3 Comparison of the present measurements of fission fragment angular distributions with the data of Rabotnov et al (1970)

The scission neutron component at each end-point energy was derived from the moments N_2 and W_2 of the Legendre polynomial fits to the data, combined with calculated expressions for the neutron distributions to be expected for emission solely from the fully accelerated fragments[4]. For the purpose of the calculation a simplified model of fission was used in which the process was represented by a typical light fragment and a typical heavy fragment, each moving with its own characteristic velocity. The neutrons were assumed to be emitted isotropically in the fragment rest systems and in equal numbers from both fragments. Inputs to the calculation consisted of the Watt spectrum temperature characterising the laboratory energy spectrum of prompt neutrons and the effective fission fragment kinetic energies per nucleon for the light and heavy fragments. No perceptible variation of the derived scission neutron component with end-point energy was noticed, and the weighted mean of the results gave fractional values of:

0.13 ± 0.05 for $^{232}Th(\gamma,f)$

and 0.11 ± 0.06 for $^{238}U(\gamma,f)$

It is to be emphasised that these figures apply only to those neutrons observed with the present system, the detection efficiency of which is proportional to the $^{238}U(n,f)$ cross-section. Roughly half of the experimental uncertainties are due to counting statistics, the remainder being made up of systematic uncertainties principally caused by uncertainties in the values used for the Watt spectrum temperatures and fragment kinetic energies per nucleon.

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(1) D.B. Gayther et al. report UKNDC(75)P71, page 26

(2) B.H. Patrick and E.M. Bowey, Nucl. Inst. Meth. 120 (1974) 245

(3) N.S. Rabotnov, G.N. Smirenkin, A.S. Soldatov, L.N. Usachev, S.P. Kapitza and Yu.M. Tsipenyuk, Sov. J. Nucl. Phys. 11 (1970) 285

(4) S. Nair, D.Phil. thesis, Univ. of Oxford (1975) unpublished

E. Photofission and photoneutron cross-section measurements (E.M. Bowey, E.W. Lees and B.H. Patrick)

A BF_3 detector assembly has been designed and constructed to measure $\sigma(\gamma,f)$, $\sigma(\gamma,n)$ and the ratio of these two cross-sections in the photon energy range 5-10 MeV. The motivation for this experiment is to deduce some systematics for the double-humped fission barrier by studying various actinides.

The relevant cross-sections will be deduced from the measured neutron multiplicity at counting rates such that pile-up is negligible. Therefore, it is necessary to use a detector which possesses both a high efficiency and, equally important, an efficiency which is almost independent of neutron energy. BF_3 detectors have been chosen because in the linear accelerator environment their inherent low sensitivity to γ-rays is a distinct advantage. Similar detectors used by previous researchers[1,2] have possessed a marked variation in neutron efficiency as a function of energy and the present work is trying to improve upon this situation. Reproducing by calculation the measured efficiency of the Livermore BF_3 detector assembly as a function of neutron energy[1] was tried first, since it had a

cylindrical geometry similar to the one planned for this work. Using the Aldermaston neutron transport code STRAINT[3] which is based on spherical geometry, the absolute efficiency of the Livermore detector is overestimated by the program. This is to be expected since corrections for neutron streaming, end effects etc. are neglected, and the difference between the actual geometry and its spherical approximation may also explain the enhanced calculated efficiency. However, the measured slope of the efficiency is reproduced very well as shown in Fig. 1 where the calculated efficiency has been normalised to the datum point at 2.1 MeV.

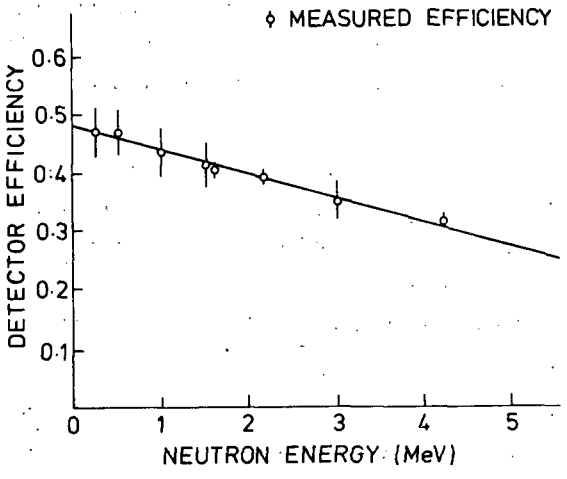

Fig. 1 The calculated efficiency of the Livermore BF_3 detector assembly normalized to the measured efficiency at 2.1 MeV

Enough confidence was therefore generated to use STRAINT as a means of extrapolating from the Livermore arrangement to one which improves the constancy of the efficiency curve. The adopted solution based on 56 $^{10}BF_3$ counters each 5 cm in diameter and with an active length of 107 cm immersed in an oil bath, has a predicted efficiency variation of 7% from 0.5 to 6.0 MeV neutron energy (c.f. Figure 1). Such a detector has been constructed and its efficiency will be measured by calibrated neutron sources in the near future. The lifetime of a neutron in the detector will also be measured shortly using a ^{252}Cf source mounted on an ion chamber.

(1) B.L. Berman, J.T. Caldwell, R.R. Harvey, M.A. Kelly, R.L. Bramblett and S.C. Fultz, Phys. Rev. 162 (1967) 1098

(2) E.J. Dowdy, J.T. Caldwell and G.M. Worth, Nucl. Instrum. Meth. 115 (1974) 573

(3) K. Dugan and J.A. Price, AWRE Report O 42/73 (1973)

E. Eta measurement (M.C. Moxon, M.G. Sowerby and B.W. Thomas [Relevant to 6 requests]

The U.K. thermal reactor data requests for the energy variation of η, relative to its value at 0.0253 eV, to an accuracy of ± 0.5% between 0.01 and 0.4 eV for ^{235}U and ± 0.75% between 0.01 and 0.5 eV for ^{239}Pu have not been met by any previous measurements. Before undertaking such measurements at Harwell it has been necessary to make a study of the feasibility of meeting the requested accuracy.

It is proposed to carry out measurements of eta on the Harwell 45 MeV electron linac neutron time-of-flight facility. This will require the following measurements and correction codes:-

(a) The measurement of the number of neutrons emitted from a thick fissile sample as a function of incident neutron energy. This will be carried out using a liquid scintillator with pulse shape discrimination to separate the neutrons

and γ-rays emitted from the sample. It is hoped to record both neutron and γ-ray pulse height as a function of incident neutron energy.

(b) The measurement and monitoring of the relative number of incident neutrons as a function of neutron energy. Measurements have already been carried out on ^{6}Li loaded glass scintillators, examining the ^{6}Li content and its distribution in the glass. Other types of neutron detector suitable for flux measurement are also being examined at present.

(c) Accurate values of the total cross-section are also required to carry out corrections to the observed fission neutron yields. The implies that accurate transmission measurements are required. Here various types of neutron detector have been examined to see their suitability for these accurate measurements. The presence of ^{238}U and ^{234}U in the ^{235}U samples also required accurate measurements on samples of these isotopes to be made.

(d) Accurate values of the scattering cross-section of ^{235}U are also required to carry out corrections to the observed fission neutron yields and as the present data are not accurate enough, requests for measurements have been made to the laboratories at Geel and Mol in Belgium.

(e) Correction procedures to allow for multiple scattering of the incident neutrons taking into account solid state effects. This may require further modification to the present Monte Carlo program used for these types of calculation above a neutron energy of 0.5 eV.

(f) Correction procedures to calculate the interaction of the fission neutrons produced in the sample. These may be carried out with some of the reactor computer codes that already exist or by modifying the Monte Carlo program.

The various measurements that have been carried out to test the feasibility of the eta measurements indicate that statistically the required accuracy can be obtained. However, until the main measurements are completed, it is not known to what extent the systematic uncertainties caused by the background and flux measurements will affect the result.

At present various pieces of equipment are being manufactured and a test is to be carried out on the Linac to see if it is possible to run the electron beam into three targets simultaneously; this is important because these rather time consuming measurements have to be carried out on the Cell III target rather than the Booster or Cell II target normally used.

B. Standard Harwell Long Counter (J.M. Adams)

A recent intercomparison of the standard Harwell and NPL Long Counters[1] has revealed an apparent inconsistency between them, which will necessitate further investigation. Independent calibrations, using these two standard long counters, of an intermediary de Pangher Long Counter has resulted in a maximum discrepancy of ~ 14% in the neutron energy range 0.35 - 0.5 MeV, decreasing to ~ 6% at 0.1 MeV, and to ~ 2% above 1 MeV. It is 8 years since the standard Harwell Long Counter was completely re-calibrated[2], but a comparison with another type of flat response detector was made in 1972 (PR/NP 19,20) and it is planned to repeat this intercomparison in order to check the possibility of a change in the original calibration. Although only used occasionally for calibration purposes in the last 8 years there is no indication that the calibration should be incorrect.

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(1) J.M. Adams, Nuclear Physics Division Progress Report, Harwell, AERE - PR/NP22, page 46

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

E. Nuclide distribution in lithium glasses (M.C. Moxon, J.D. Downes (University of Bath) and D.A.J. Endacott)

The rather slow neutron-energy dependence of the neutron reaction cross-sections of ^{3}He, ^{6}Li and ^{10}B make them possible reactions for use as standards for neutron flux measurements on slow and intermediate energy neutrons (up to 1 MeV or more).

^{6}Li loaded glass scintillators have been used for some time as neutron detectors, but only in recent years have they been used to measure the cross-section for neutron-induced break-up of ^{6}Li into an alpha-particle and triton, and as standard neutron flux measuring instruments based on this reaction. Discrepancies in the results of the more accurate measurements of this cross-section have indicated possible errors in the ^{6}Li content and also possible variations in the spatial distribution of ^{6}Li in the glass scintillators.

The simple energy dependent form (inversely proportional to neutron velocity) of the $^{6}Li(n,\alpha)T$ reaction cross-section below a neutron energy of ~ 10 keV can be used to determine the ^{6}Li content of a scintillator. This is simply carried out by measuring the fraction of neutrons transmitted through the glass as a function of neutron energy. Neutron energy is determined from time-of-flight over the distance between the pulsed neutron source (the target of the Harwell electron linac) and the glass detector.

The results of such a measurement are shown in Fig. 1. The ^{6}Li content can be

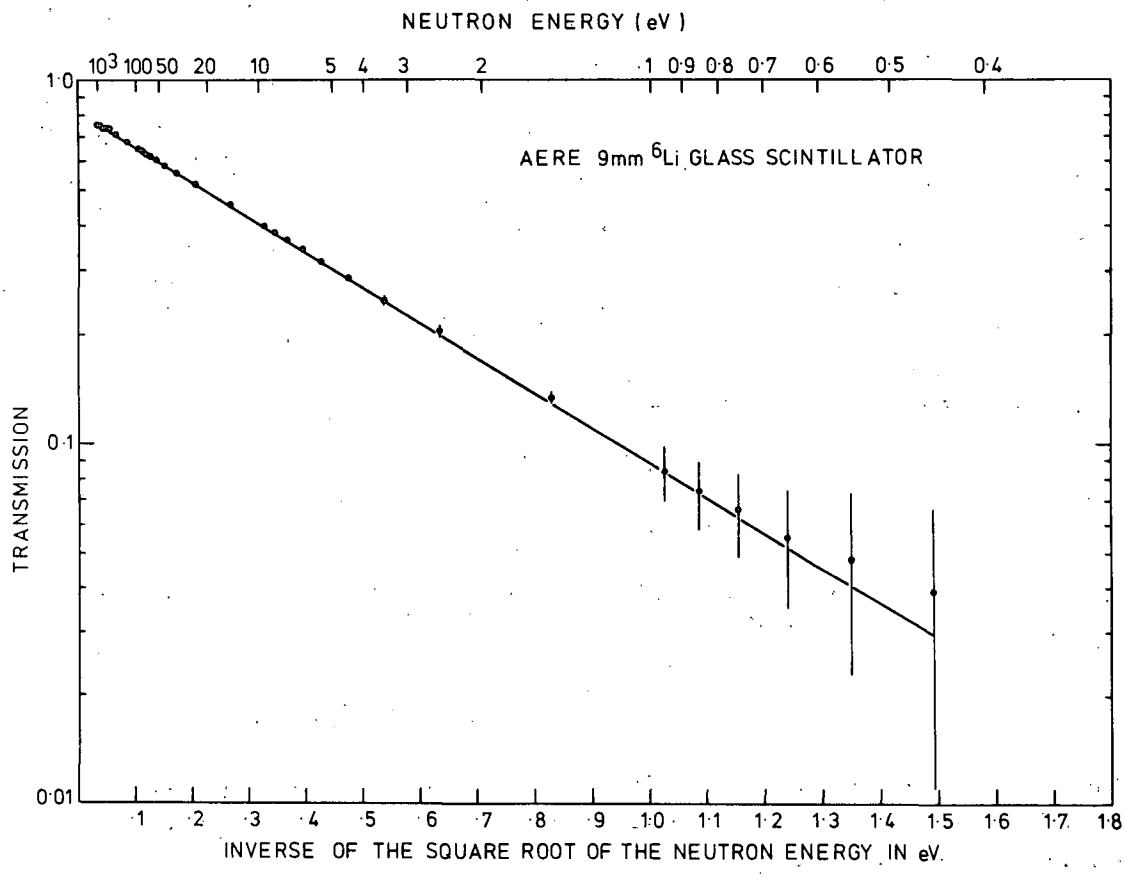

Fig. 1 The measured neutron transmission of a 9 mm thick ^{6}Li loaded glass scintillator as a function of neutron velocity

determined from the slop of the curve and the known values of the reaction cross-section at low energies. It turns out that the lithium content is always less than the value quoted by the manufacturers of the glass. The intersection of the curve of the ordinate axis gives us some qualitative checks on the other constituents of the glass. By using a narrow neutron beam (5 mm) and scanning across the glass the spatial variation of the ^{6}Li content can be found. A scan across a diameter of a 9 mm thick glass is shown in Fig. 2. From these measurements it is found that the ^{6}Li content is constant to within an accuracy of 1-2% in the central region of the glass, but falls rapidly to almost zero within 1 to 2 mm of the circumference. The check on the other constituents is not so accurate but indicate that the region around the circumference that is depleted in lithium is enhanced in material with a high energy-independent cross-section.

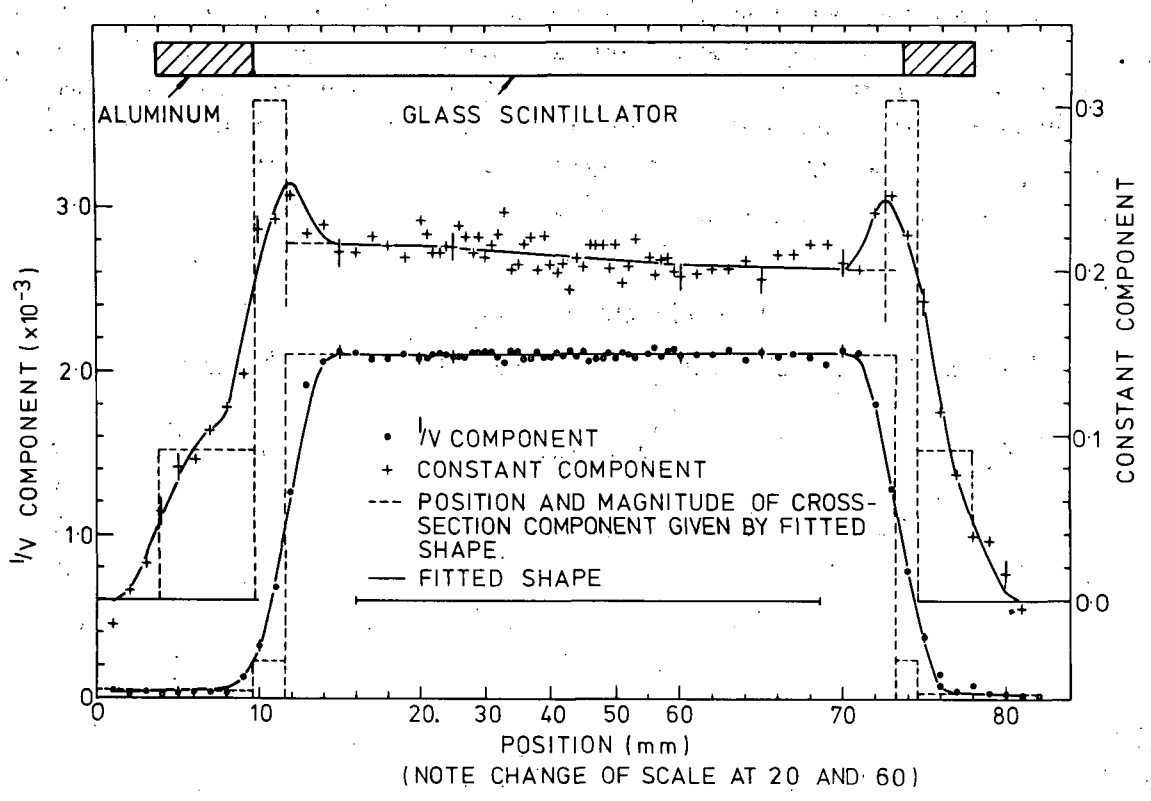

Fig. 2 Least squares fits to a transmission measurement from which the spatial distribution of the ^{6}Li content in a Li glass scintillator is obtained

Chemical tests proved that lithium could be easily leached out of the glass by water. This possibly explains the observed distribution and depletion of the lithium in the glasses, because they are ground and polished under water. The enhancement of the constant cross-section at the circumference could be caused by the absorption of water or OH^{+} radicals; hydrogen has a cross-section of 21 barns which is about one order of magnitude greater than the constant cross-section component of the known constituents of the glass.

This is an example of the use of neutron beams in non-destructive determination of the content of certain isotopes in a given material.

Nuclear data format conversion (M.S. Ridout, E.M. Bowey and M.G. Sowerby)

The MISSIONARY computer programme, which translates files of evaluated neutron cross-section data in ENDF/B format to the U.K. format has been obtained from AWRE and is now working on the Harwell 370/168 computer. Since the conversion is not completely automatic a number of other programmes (e.g. CHECK, CRECT, LISTF4), which are needed, have also been commissioned at Harwell. The first trial conversions on Ti will be made under the guidance of Dr. A.C. Douglas (AWRE). This will be followed by converting the French files on Hf, the even A isotopes first.

The conversion of the resonance parameter data is not done particularly well by MISSIONARY. An alternative approach is to use the parameters directly in the programme SIGAR which outputs the calculated cross-sections in U.K. format. A version of this programme is operational on the Harwell computer but this is not suitable for calculations where fission is a possible reaction.

Evaluation and theoretical calculation of nuclear data for higher actinides (J.E. Lynn)

The differential nuclear data on higher actinides required for fast reactor projects, particularly for various aspects of fuel burn-up and its later treatment, are only available from experiment to a very limited extent. The possibility of calculating many of the required cross-sections from nuclear theory has therefore been examined. The various parameters needed for such calculations have been deduced from many kinds of information on nuclear reactions with the actinides, and the systematic behaviour of the important parameters is now believed to be known; this work is reported in AERE - R 7468.

These methods have now been employed for the three most important americium nuclei (^{241}Am, ^{242m}Am, ^{243}Am). The experimental data available are limited to some thermal and low energy resonance cross-sections (total and fission) and to the fission cross-sections up to about 3 MeV neutron energy (but in the ^{242m}Am case these data seem virtually worthless above about 0.5 MeV, and in the ^{241}Am case data from different workers are highly discrepant below about 50 keV). These data have now been supplemented by calculations of the capture cross-section (up to about 4 MeV), the fission, inelastic scattering, (n,2n) and (n,3n) cross-sections up to about 20 MeV.

The calculations of the capture cross-section of ^{241}Am below about 50 keV neutron energy are dependent to some extent on the measured behaviour of the fission cross-section, on which there is disagreement by up to a factor of 30. The most likely behaviour of the fission and capture cross-section has been chosen as that giving best agreement with the integral cross-section measurements made on ZEBRA.

Assessment studies on nuclear incineration (M.G. Sowerby, Miss R. Rainey and F. Duggan (Imperial College))

The assessment studies reported previously (UKNDC(75)P71, page 27) showed that nuclear incineration appears to be a possible way of reducing the long term potential hazards from the higher actinides. This conclusion was based on the calculations of the irradiation of one actinide mixture in a conventional sodium cooled oxide fuelled fast reactor (CFR) and in a hard spectrum fast reactor (DFR). Similar calculations have now been made for a number of other actinide mixtures and these show that the previous conclusions are only weakly dependent on the nature of the isotopic mixture.

Some calculations have been performed on the production of higher actinides in a given fast reactor spectrum at different neutron fluxes or power densities. As one might expect the higher the flux the higher the production of the higher actinides, though a change of a factor 20 in flux (10^{15} to 2×10^{16} n/cm^2/sec) only increases the amount of higher actinides by a factor of ~ 1.3. These results also show that for a given reactor power output the total amount of higher actinides produced is lowest when the power density in the fuel is highest. This conclusion is not unexpected but it does indicate the way fast reactor design should go if one wishes to minimise the long term hazards from the actinides. These calculations also show that accurate production rates of higher actinides can only be obtained if detailed fuel management calculations are made.

A significant effort has been expended on sensitivity calculations in CFR and DFR spectra to identify where nuclear data are inadequately known at the present time. One of the problems in interpreting this work is the identification of the critical parameters and their required accuracy. It has been assumed at the present stage of assessment that we require to know at all irradiation times the following items:-

(1) "Eta" (defined here as the number of neutrons produced per neutron absorbed in heavy elements and fission products) to ± 10%

(2) Fission rates to ± 15%.

(3) Spontaneous fission rates to ± 20%

(4) Number of actinide atoms in the fuel to ± 10%

(5) The potential hazard from the heavy elements in the fuel at long times (10^3 years and greater) after the incineration is complete to a factor 2.

It is concluded from this work that the most important actinide data are the fission and capture cross-sections of ^{241}Am, ^{243}Am and ^{244}Cm. This might be expected since the Am isotopes are dominant isotopes at the start of incineration and ^{244}Cm becomes the dominant higher actinide during incineration. Though a request list for data measurements has not been formulated it appears that, for the isotopes given above, the fission cross-sections need to be known to ~ ± 10% and the capture cross-sections to ~ ± 20% to meet the accuracy criteria specified.

If incinerated fuel is held in the reactor until high burn-up is achieved then the capture in fission products seriously affects the neutron balance. The average capture cross-section of the fission products needs to be known to ~ ± 15% when the fuel is 90% burnt up for "eta" to be accurate to ± 10%. This implies needs for data on higher actinide fission yields as well as for capture cross-sections of the fission products.

The final conclusion from the sensitivity studies is that nuclear data are adequately known for potential hazard calculations.

A number of improvements have been made to our version of the HYLAS code to enable it to be used more easily for this type of work. In particular a graphical output facility has been incorporated in the programme. This has been written so that it should be a fairly easy modification to add the facility to other inventory codes.

There is a vast literature on waste disposal options - including nuclear incineration.

One of the authors (F.D.) is gradually working through this so that we have a good overall view of the present position.

D. Neutron yield from light elements under α-particle bombardment (D. West and A.C. Sherwood)

The actinides present in the active waste from nuclear fuel processing present a problem even when encapsulated in glass since they generate neutrons in light elements as a result of (α,n) processes. To minimise the neutron production it is necessary to have comprehensive information to determine those light elements which must be excluded or kept below specified concentrations when in contact with the α-emitters. Few measurements of the thick target yield of neutrons from light elements have been made since the days of the Manhattan project when yields were determined for 5.3 MeV α-particles. These measurements do not extend to high enough energies to embrace all the actinide α-emitters of importance (up to 7.2 MeV).

Other cross-section measurements, while numerous, are rarely sufficiently extensive in energy or angle to cover the practical requirements.

The light isotopes of interest (among those with exothermic (α,n) reactions or endothermic reactions with thresholds below 7.2 MeV) number between 10 and 20 ranging from ^{2}D to ^{30}Si and produce neutrons ranging in energy from 0 to 12.5 MeV.

The requirement to measure neutrons in this wide energy range with uniform efficiency places a severe constraint on the detector. It is planned to use a 1 metre right cylinder of polythene, which according to the neutron moderation programme STRAINT, is large enough to reduce the neutron leakage at its surface to no more than 6% for 12.5 MeV neutrons originating at the centre. To integrate the thermal neutron density distribution and hence to obtain a neutron intensity measurement independent of primary neutron energy it is planned to use 8 BF^3 or He^3 proportional counters located at different radii and extending throughout the length of the cylindrical block. The detector will be calibrated using ^{241}Am-Be and ^{241}Am-F neutron sources previously calibrated in a $MnSO_4$ bath against the NPL standards. Preparations to construct the detector and to carry out initial survey runs are in hand.

Criticality assessment (B.W. Hooton)

The design of nuclear fuel reprocessing plant calls for a careful assessment of the possibility of a criticality excursion. The MONK criticality program is a Monte-Carlo code which calculates most of the neutronics parameters needed to assess system safety and methods of improving it. Models of some of the geometries typical in fuel reprocessing have been established and work has started on a number of specific problems.

One of the major safety problems associated with reprocessing nuclear fuel is the possibility of a criticality excursion in the dissolver. The situation can be made critically safe by introducing a soluble neutron poison into the dissolver liquid. Gadolinium would be a suitable poison but the amount should be minimised in order to save on the cost of gadolinium and because of the penalties involved in incorporating it into the highly active storage glass. This problem is being investigated to see if savings on the amount of gadolinium can be achieved.

H. Cross-section measurements for isotope production by spallation reactions (D.B.C.B. Syme, E. Wood and M.C. Bowen)

Evaluation has continued of production feasibility for isotopes of medical interest by detailed measurements of excitation cross sections. Results for ^{52}Fe production by $^{55}Mn(p,4n)$ are given in Figure 1. Yields of some 200 μCi/μA hr of high purity isotope should be possible. Preliminary data for production of ^{204}Bi by proton spallation in thin natural lead targets indicate useful possible yields up to 5 mCi/μA hr although impurity ^{203}Bi is also present. Further measurements to determine thick target yields and define purity levels are under way.

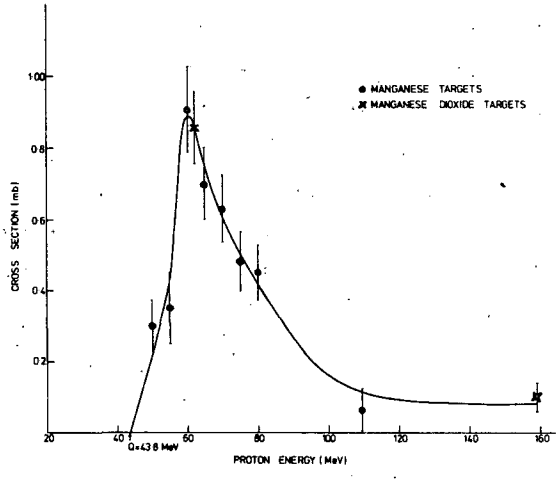

Fig. 1 The $^{55}Mn(p,4n)^{52}Fe$ cross section

There is great medical interest in ^{81}Rb and its daughter ^{81}Kr for pulmonary and other studies and investigation has begun of a possible high purity production route by $^{85}Rb(p,5n)^{81}Sr$ and $^{87}Rb(p,7n)^{81}Sr$ (the ^{81}Sr decaying to ^{81}Rb). Our preliminary results indicate possible ^{81}Rb yields of some tens of mCi/μA hr. More detailed work is now in progress where the yields from the competing direct reactions ($^{85}Rb(p,p4n)^{81}Rb$ for example will be ascertained simultaneously with those via the ^{81}Sr route.

H. Cross-sections for proton spallation reactions in iodine (D.B.C.B. Syme, E. Wood and M.C. Bowen)

Measurements of excitation curves are complete for production of the isotopes of mass 121, 123, 125, following proton spallation reactions in natural iodine (^{127}I). (Fig. 1). These data contain the limitations on production of the medically useful ^{123}I by $^{127}I(p,5n)^{123}Xe \rightarrow (\beta) \rightarrow {}^{123}I$. To minimise contamination by other isotopes only proton energies between about 47 and 77 MeV should be used, while the scale of the cross-section curve allows yields of order 20 mCi/μA hr to be predicted for this energy range. A more detailed report with final values is in preparation as AERE - R 8276.

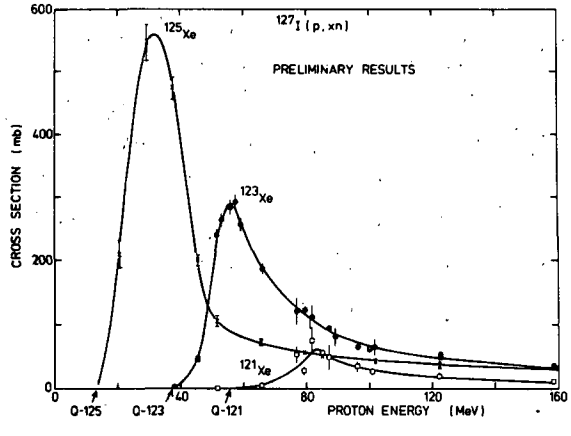

Fig. 1 The cross-sections for the production of ^{121}I, ^{123}I and ^{125}I following proton spallation reactions in ^{127}I

H. ^{123}I production target (D.B.C.B. Syme, E. Wood and A. Leatham)

For large scale production of ^{123}I on the Harwell Synchrocyclotron by $^{127}I(p,5n)^{123}Xe \rightarrow (\beta) \rightarrow ^{123}I$ it is necessary to use an iodine-bearing target inside the cyclotron vacuum to maximise the available proton current. We have developed such a device for the Harwell synchrocyclotron. The current utilisation is enhanced by deflecting the whole proton bunch down from its plane of circulation onto the target, this method being in routine use here for production of pulsed neutron beams.

To optimise the ^{123}Xe yield (and thus the ^{123}I yield) it is necessary to extract the Xe gas continuously during production and afterwards so that a flowing liquid target loop with Xe extractor must be used. The liquid is selected for high iodine concentration to be di-iodo methane (CH_2I_2) and this is contained in a target of doubly-encapsulated titanium plate (to avoid corrosion difficulties). Xe extraction is by helium bubbling through a portion of the target loop outside the cyclotron and Xe collection is by liquefaction.

These components are contained in one assembly, where the target probe can be inserted into the cyclotron through an air lock. Tests with a smaller scale prototype in the external beam have been successful and full scale testing of the final assembly is about to begin.

PUBLICATIONS

Investigations of resonance capture gamma-ray spectra in the $^{93}Nb(n,\gamma)^{94}Nb$ reaction. T.J. Haste and B.W. Thomas, J. Phys. G: Nuclear Physics 1 (9) (1975) 967

Non-statistical aspects of resonance neutron capture in ^{103}Rh. T.J. Haste and B.W. Thomas, J. Phys. G: Nuclear Physics 1 (9) (1975) 981

The photodisintegration of ^{13}C through excited states of ^{12}C and ^{12}B. B.H. Patrick, E.M. Bowey, E.J. Winhold, J.M. Reid and E.G. Muirhead, J. Phys. G: Nuclear Physics 1 (1975) 874

REPORTS

AERE - R 8082 NEANDC Topical Conference on capture cross-section measurements. Harwell, 9th April 1975. Edited by G.D. James

AERE - R 8210 (p,n) Threshold measurements for accelerator calibration and the problem of Q-value deductions. J.M. Freeman

IN COURSE OF PUBLICATION

Neutron angular distributions from fast neutron-induced fission in ^{232}Th and ^{238}U. S. Nair and D.B. Gayther

Neutron angular distributions from threshold photofission in ^{232}Th and ^{238}U. S. Nair, D.B. Gayther, B.H. Patrick and E.M. Bowey

The neutron capture of ^{151}Eu and ^{153}Eu in the energy range 0.1 to 100 keV. M.C. Moxon, D.A.J. Endacott and J.E. Jolly

The measurement of the ^{6}Li content of Li loaded glass scintillators. M.C. Moxon, J.D. Downes and D.A.J. Endacott

The photodisintegration of ^{15}N through excited states of ^{14}N, ^{14}C and ^{12}C. B.H. Patrick, E.M. Bowey and E.G. Muirhead

CONFERENCE PAPERS

Invited papers

Third All Union Conference on Neutron Physics, Kiev, June 1975

Intermediate structure studies of ^{234}U cross sections. G.D. James, J.W.T. Dabbs, J.A. Harvey, N.W. Hill and R.H. Schindler

IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data, Karlsruhe, November 1975

Theoretical calculation of transactinium isotope nuclear data for evaluation purposes. J.E. Lynn

Status of neutron cross sections of transactinium isotopes in the resonance region - Linear accelerator measurements. G.D. James

IAEA Consultants Meeting on the Use of Nuclear Theory in Neutron Nuclear Data Evaluation, Trieste, December 1975

Fission theory and its application to the compilation of nuclear data. J.E. Lynn

Australian Institute of Nuclear Science and Engineering, 6th AINSE Nuclear Physics Conference, University of Melbourne, 9-11 February 1976

Photodisintegration of p-shell nuclei by particle emission to specific residual states. B.H. Patrick and E.M. Bowey

Contributed papers

Third All Union Conference on Neutron Physics, Kiev, June 1975

Fast neutron fission spectrum of ^{235}U at 0.52 MeV incident neutron energy. J.M. Adams and P.I. Johansson (Studsvik) (Presented by C.A. Uttley)

Measurement of the ^{239}Pu fission cross-section and its ratio to the ^{235}U fission cross-section in the energy range from 1 keV to 1 MeV. D.B. Gayther (Presented by C.A. Uttley)

Total cross section measurements on Fe, Ni and Ti from 10 keV to 1 MeV. G.D. James, D.B. Syme, P.H. Bowen, I.L. Watkins and S.T. Box

Precise energy determination for three peak cross sections in ^{23}Na and ^{27}Al and for the 250 keV resonance in ^{6}Li. G.D. James, D.B. Syme, P.H. Bowen, P.E. Dolley, I.L. Watkins and M. King

Joint Seminar on Nuclear Data, Kurchatov Institute, Moscow, July 1975

Nuclear incineration. M.G. Sowerby

Nuclear data programme at Harwell. M.G. Sowerby

Nuclear Data Forum, A.E.R.E., Harwell, December 1975

Activation levels in concrete shielding after neutron irradiation for long periods. M.S. Coates

Neutron Interlab Seminar, Geel, 12-14 November 1975

Appraisal of fast neutron spectral measurements on ^{235}U and ^{239}Pu. J.M. Adams

Energy calibration of neutron time-of-flight spectra using (d,n) reactions. J.M. Adams

Tests on the new Harwell n-γ pulse shape discrimination system. J.M. Adams

Proposal for cross-section measurements on ^{241}Am. D.B. Gayther and M.G. Sowerby

The measurement of the ^{6}Li content of Li loaded glass scintillators. M.C. Moxon, J.D. Downes and D.A.J. Endacott

Background measurement techniques employed at the Harwell Linac. B.W. Thomas, M.C. Moxon and M.G. Sowerby

Absolute efficiency of an organic scintillator between 5 and 25 MeV neutron energy using the associated particle method. C.A. Uttley

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

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

MEASUREMENTS

Several integral measurements have been, or are being, analysed.

Beta-decay energy from fission products (M.F. Murphy, W.H. Taylor and D.W. Sweet)

The beta-decay power from fission products has been measured using a Ne-102 scintillator. ^{239}Pu and ^{235}U samples were irradiated in ZEBRA for 28 hours (10^5 sec) and measurements began about 20 seconds after removal of the sample from the reactor; the maximum cooling time so far achieved has been about 3×10^7 seconds. Some preliminary comparisons with the predictions of Tobias have been made.

Average cross-sections of structural materials (W.H. Taylor)

Activation measurements have been made in ZEBRA of the absolute values of fast reactor average cross-sections for some (n,2n), (n,γ), (n,p) and (n,α) reactions in the constituents of stainless steel and other potential primary circuit materials. Results have been compared with calculated values based on the FD5 data set.

Cross-sections of actinides (D.W. Sweet)

Fast reactor spectrum average values for the capture cross-section of ^{241}Am and the fission cross sections of ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{243}Am and ^{244}Cm have been measured in ZEBRA, and comparisons made with calculated values based on FD5. Radiochemical work on an irradiated ^{243}Am sample is in progress at Harwell which, it is hoped, will provide the capture cross-section for ^{244}Cm production.

DATA EVALUATION AND UK NUCLEAR DATA LIBRARY

Neutron cross-sections (A.L. Pope and J.S. Story)

The UKNDL and its associated computer programmes have been maintained and improved; new evaluations include one of data for gadolinium (DFN-949). A new edition of the request list for nuclear data has been issued, AEEW - M 1369. Re-edition of the UKNDL master data tapes from KDF-9 binary storage to the ICL-470 continues at a rather slow pace; however it is hoped that the tape of activation detector files will shortly be completed.

The most important computer programmes are now available in Fortran-4 on the ICL-470 computer (see WNDG-154), while CHECK-2 and SIGAR-5(RMP) are also available on the IBM-370 at Harwell. The programme SIGAR for calculating neutron cross-sections from resonance parameters has been improved considerably; a Reich-Moore option is available for non-fissile materials, and a fission channel has been added to the multi-level Breit-Wigner option.

A provisional evaluation has been made of the resonance parameters of gold, and the resonance integral recalculated - a fundamental reference standard. This work continues.

Further work has been done on the ^{239}Pu half-life, on thermal neutron scattering by ^{233}U and ^{235}U, and on the average energies of fission-spectra, for contribution to the IAEA Consultant's panel.

Decay data from fission-products and actinides

Two different libraries of fission-product decay data are now available in ENDF/B-IV format (the ENDF/B data themselves, and Tobias' (CEGB) data), and are being compared with each other and with current experimental data. Because of the great number of fission-products involved (of the order 800) a computer programme (CFLIBS) is being used for this purpose. For a start the half-life data were compared; half-lives differing by more than 20% between the two libraries were identified and examined. Similar comparisons of average decay energies- Q-values and branching ratios are being made.

A preliminary note is available (WNDG-143) comparing calculations of fission-product decay heat following thermal neutron fission of ^{235}U. Calculations using the Risley (Sidebotham), CEGB, American and French data libraries are compared with available integral measurements for a preliminary assessment of accuracies.

PAPERS

Actinide fission rate measurements in ZEBRA-14. D.W. Sweet (4 June, 1975) NEACRP-L-132

A preliminary note on the preparation of thermal neutron scattering data for uranium dioxide. A.T.D. Butland and Mrs. C. Taubman (Apr. 1975) WNDG-137

The production of data for decay heat calculations. M.F. James (May 1975) WNDG-139

Notes on the decay of ^{244}Cm. M.F. James (May 1975) WNDG-140

A user's guide to SIGAR, a Fortran-4 programme. A.L. Pope (June 1975) WNDG-141

Simple comparisons between three neutron data files for ^{241}Pu; DFN-60A, DFN-403B and MAT-1266. J.S. Story (June 1975) WNDG-142

Fission-product afterheat. A preliminary comparison between calculations and experiments. M.F. James (Sept. 1975) WNDG-143

Developments in Doppler broadening programmes. M.F. James (Sept. 1975) WNDG-147

The least-squares fit to a set of data when their sum has been measured. M.F. James (Oct. 1975) WNDG-148

Notes on the scattering amplitude at low energies in R-matrix theory. M.F. James (Sept. 1975) WNDG-151

Nuclear data requirements for the reactor programme in the United Kingdom - August, 1975. A.L. Pope (Oct. 1975) AEEW - M 1369, NEANDC(UK) - 164AL, INDC(UK) - 26G

CINDA coverage work in the United Kingdom. (Note prepared for the CINDA Reader's meeting, Saclay, 17-18 November, 1975). A.T.D. Butland and J.S. Story (Nov. 1975) WNDG-153

Computer programmes of interest to the Winfrith Nuclear Data Group. A.L. Pope (Nov. 1975) WNDG-154

CHEMICAL NUCLEAR DATA

Introduction

Chemical Nuclear Data experiments and evaluations are closely co-ordinated by the Chemical Nuclear Data Committee (Chairman: J.G. Cuninghame, AERE) of the U.K. Nuclear Data Committee. The committee has no executive powers but is prepared to advise on measurements, and consider in detail compilation and evaluation reports. The evaluation publications bear the slogan "the contents of this paper have been examined and recommended by the United Kingdom Chemical Nuclear Data Committee".

The committee deals with two aspects of nuclear data:

(i) the measurements of new data

and (ii) the compilation and evaluation of world-wide measurements in order to product best values of available data.

This section has been compiled by Dr. A.L. Nichols and brings together reports from Harwell (AERE), Winfrith (AEEW), Aldermaston (AWRE), Dounreay (DERE), BNFL and CEGB.

MEASUREMENTS

1. YIELDS OF FISSION PRODUCTS FORMED IN A WIDE VARIETY OF NEUTRON SPECTRA

Mass-spectrometric fission yields and alpha measurements in DFR (I.C. McKean, E.A.C. Crouch (AERE)

Progress in this work was delayed by the necessity of replacing obsolescent ion-counting electronic equipment. The Laben multiscaler and the pulse derandomiser which fed it have been removed and replaced by a secondhand PDP8 computer controlling very fast CAMAC scalers. Before this apparatus was finally working the PDP8 ferrite core store and several of the logic modules had been replaced.

Attention is now focussed on the ^{235}U analyses already done and no more chemical separations will be done until those calculations are complete.

Mass-spectrometric measurements of alpha in PFR (I.C. McKean, E.A.C. Crouch, J.G. Cuninghame, H.H. Willis (AERE), with V.M. Sinclair (DERE) and D.G. Vallis (AWRE))

The irradiation samples for this collaboration were delivered in 1973 and they have now been loaded into irradiation rigs and will be irradiated as soon as PFR reaches full power.

Fission yield measurement work at DERE (W. Davies, E.W. Etherington, V.M. Sinclair (DERE))

No further progress has been made during the past year with this work entailing the reactor irradiation of uranium and plutonium isotopes, which is described on pages 43 and 44 of the 1974-1975 UKND Progress Report. The work is still in hand, but it has been reprogrammed. It is now expected that the PFR irradiations will commence during Autumn 1976, and that the dissolution and analysis of the capsules already irradiated in DFR will be completed early in 1977.

The effect of change of angular momentum and excitation energy on the scission point properties of the fissioning nucleus $^{208}Po^{*}$ (J.G. Cuninghame, J.A.B. Goodall (AERE) with I.S. Grant and others (Manchester University Physics) and G.W.A. Newton and others (Manchester University Chemistry))

All the measurements for both the physics and chemistry parts of this experiment are now complete except that chemistry runs with ^{192}Os as target have had to await the arrival of sufficient ^{192}Os, which is now in our possession; we expect to complete these runs by autumn 1976.

The processing codes for calculation of the physics results are now, after much modification, working well and final data reduction is under way. Figures 1 and 2 are some examples of a small part of the results we expect to obtain. They show $\bar{\nu}$ as a function of fission fragment mass and of fragment total kinetic energy. In Figure 1 we have indicated how $\bar{\nu}$ would be expected to vary with A according to three rival hypotheses of the breakup of the compound nucleus. These hypotheses are Unchanged Charge Distribution (UCD), Equal Charge Distribution (ECD) and Maximum Excitation-Energy Without Shells (MEEWS). Results calculated so far seem to favour MEEWS, but we await the completion of the calculations before making a final choice.

In the chemical part of the work, mass dispersion curves (i.e. the distribution of A for constant Z of fission fragments) and charge dispersion curves (distribution of Z for constant A) have been prepared from the experimental data for all the ^{196}Pt and ^{204}Pb target runs. Such results give us further information about the way in which the nucleons of the compound nucleus are divided at scission and provide spot values of $\bar{\nu}$ versus A, which are used to normalise the physics measurements. Similarly the full fragment mass distribution curves from the physics part of the experiment are used in calculation corrections used in the chemistry calculations. Table 1 lists some of the chemistry results found so far.

Three parameter fission experiment using a highly fissile compound nucleus (J.G. Cuninghame, J.A.B. Goodall (AERE) with I.S. Grant and others (Manchester University Physics and G.W.A. Newton and others (Manchester University Chemistry))

This experiment, analogous to that with ^{208}Po, is intended to show up differences between scission point effects when the compound nucleus has a structure which is far from a closed shell, as compared with the near closed shell structure of ^{208}Po. It is not possible to select three suitable nuclear reactions leading to any one such compound nucleus, so we have chosen three in which the fissility parameters are virtually identical, viz:-

$$^{232}Th + {}^{1}H \rightarrow {}^{233}Pa^{*} \qquad \text{(fissility 0.7509)}$$

$$^{209}Bi + {}^{15}N \rightarrow {}^{224}Th^{*} \qquad \text{(fissility 0.7503)}$$

$$^{206}Pb + {}^{18}O \nearrow$$

So far, we have taken sufficient high quality data for the physics part of the $^{232}Th + {}^{1}H$ measurements.

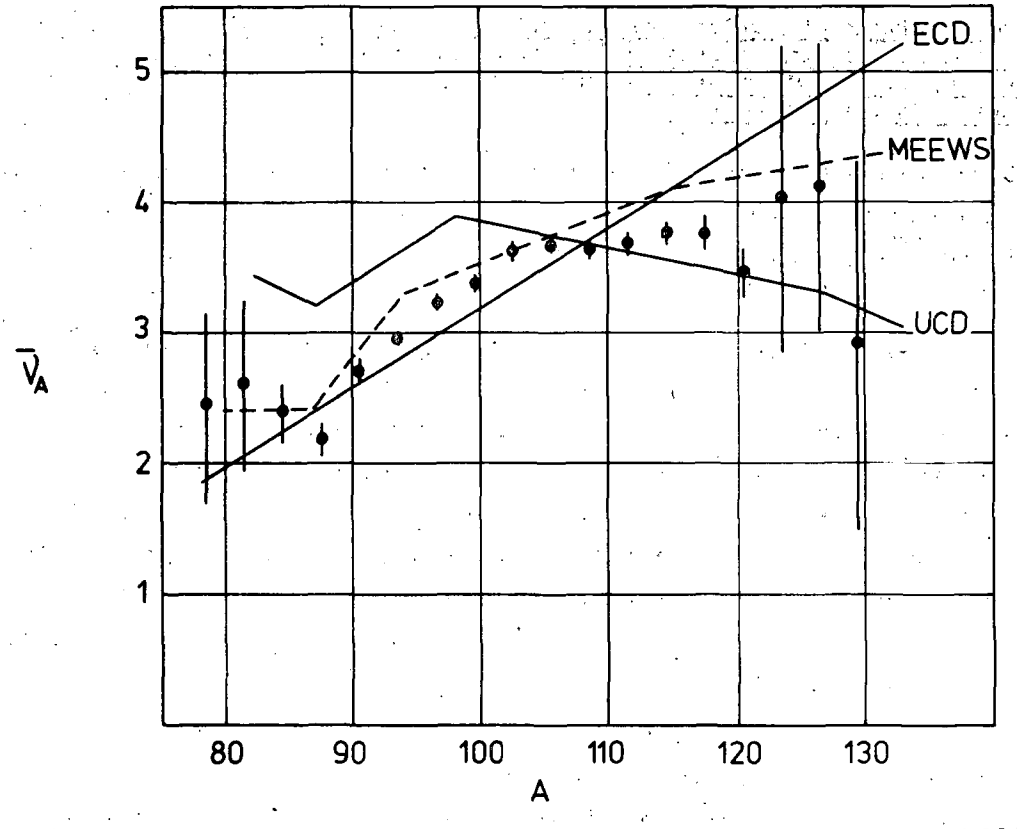

Fig. 1 ν as a function of fragment mass, A. Reaction $^{12}C + ^{196}Pt \rightarrow ^{208}Po^*$ at $E_x = 70$ MeV

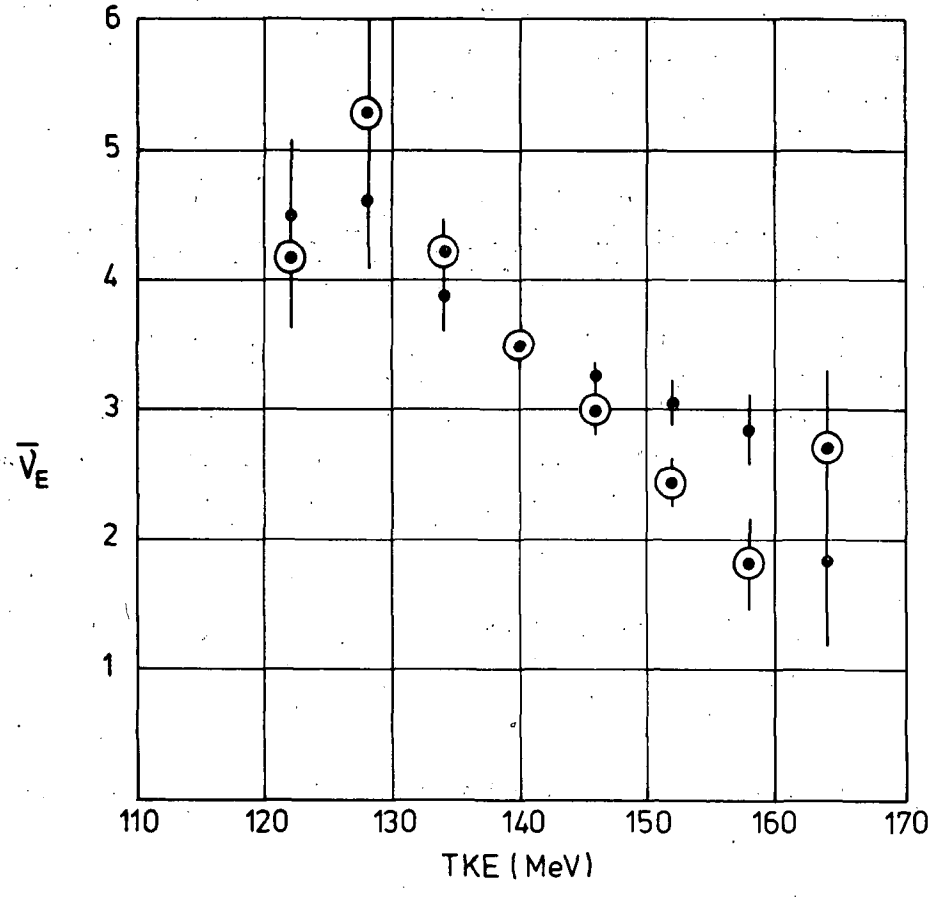

Fig. 2 ν as a function of fragment total kinetic energy. Reaction $^{12}C + ^{196}Pt \rightarrow ^{208}Po^*$ at $E_x = 70$ MeV

TABLE I

Examples of some radiochemical results

These tables show the measured average fragment mass, $\bar{A}$, for Z = 39 (yttrium) and 51 (antimony) after prompt neutron emission, together with the mass dispersion widths; the charge dispersion widths for Y and Sb and their neighbouring isotopes are also shown.

Z	Ex(MeV)	$\bar{A}$	Dispersion widths		Ex(MeV)	$\bar{A}$	Dispersion widths	
			A	Z			A	Z
39(Y)	60	92.71 ± .02	2.97 ± .04	1.25 ± .02	40	93.44 ± .14	2.41 ± .18	1.01 ± .08
	70	92.28 ± .09	3.01 ± 0.16	1.27 ± 0.6	55	92.97 ± .13	2.90 ± .21	1.22 ± .09
	85	92.49 ± .04	3.14 ± .07	1.32 ± 0.3	70	92.69 ± .20	3.05 ± .33	1.28 ± .14
51(Sb)	60	123.87 ± .14	3.84 ± .16	1.58 ± .07	55	124.29 ± .12	3.80 ± .13	1.56 ± .05
	70	123.35 ± .06	3.76 ± .07	1.56 ± .03	70	123.78 ± .30	4.40 ± .33	1.81 ± .14
$^{196}Pt + {}^{12}C \rightarrow {}^{208}Po^*$					$^{204}Pb + {}^{4}He \rightarrow {}^{208}Po^*$			

Fission-spallation competition in fission of $^{208}Po^{*}$ (J.G. Cuninghame, J.A.B. Goodall (AERE) with I.S. Grant and others (Manchester University Physics) and G.W.A. Newton and others (Manchester University Chemistry))

$^{208}Po^{*}$ is produced by using any of the nuclear reactions in the fission experiment and relative amounts of all the Po isotopes from ^{200}Po to ^{208}Po found in the target are measured. We have used off-line α and γ measurements, both with and without chemical separation of Po from the fission products, and on-line counting of prompt γ-rays from the Po isotopes. We also propose to make use of a helium jet separator. Fig. 3 is an example of an off line α-spectrum from a run at fairly high excitation energy in which the lighter Po isotopes can clearly be seen. Fig. 4 is an example of an on-line γ-spectrum at lower excitation energy showing some of the heavier Po isotopes.

^{239}Pu fission yields in fast monoenergetic neutron fluxes (J.G. Cuninghame, H.H. Willis (AERE) [Relevant to 4 requests]

The experimental work is now complete and final results are expected during 1976. Yields have been measured at 6 different neutron energies from 130 to 1700 keV; three irradiations have been carried out at each of these energies.

Effect of change of reactor neutron spectrum on fission yields; ZEBRA experiment (J.G. Cuninghame, J.A.B. Goodall, H.H. Willis (AERE))

Eight irradiations, each of three samples, were made in ZEBRA, five with ^{235}U as target and three with ^{239}Pu. The samples were irradiated in different core positions so as to give a wide variety of neutron spectra. Preliminary results of the data analysis are not as good as we had hoped, largely due to the fact that the irradiations had to be carried out before we had proved the method, due to the imminent shut-down of ZEBRA. However, improvements resulting from the lessons learned will be applied to a second series of irradiations to be made in the BIZET core when ZEBRA starts up again in 1977.

Effect of change of reactor neutron spectrum on fission yields; PFR experiment (J.G. Cuninghame, J.A.B. Goodall, A.L. Nichols, H.H. Willis (AERE))

We hope to be allowed to irradiate samples during a low power run by PFR during 1976. 48 samples (16 each of ^{235}U, ^{238}U and ^{239}Pu) have been prepared and 4 of each isotope will be irradiated in each of 4 different reactor positions. After irradiation we shall prepare a total of 208 counting samples and analyse them for a large number of fission products by both β and γ counting.

2. NEUTRON CROSS-SECTIONS

Measurement of the integral cross sections of ^{241}Am and ^{243}Am (Mrs. K.M. Glover, R.A.P. Wiltshire, F.J.G. Rogers (AERE))

Progress in this area has been severely limited due to lack of effort. Processing of the irradiated ^{243}Am samples for the measurement of the integral cross sections of ^{243}Am leading to the production of ^{244}Cm was begun during 1975, but has not yet been completed due to pressure of other activities.

Measurement of neutron cross-sections in PFR (W. Davies, E.W. Etherington, V.M. Sinclair (DERE))

No further progress has been made during the past year on the work outlined on pages 53-55 of the 1974-75 UKND Progress Report. It is now expected that the PFR irradiations will commence during autumn 1976, and that the dissolution and analysis of capsules already irradiated in DFR will be completed in 1977.

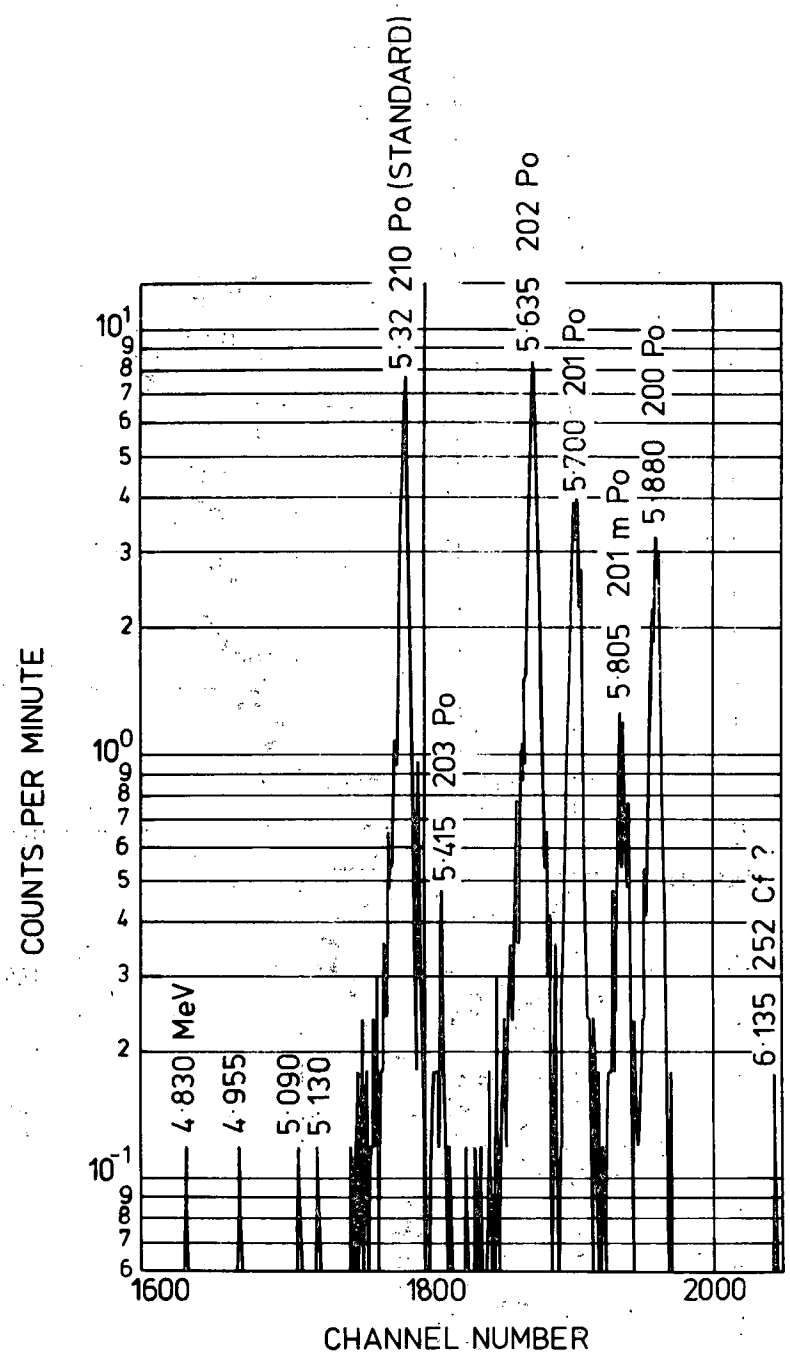

Fig. 3 Off-line α-spectrum of Po isotopes; $^{196}Pt + ^{12}C \rightarrow ^{208}Po^{*}$ at 116 MeV

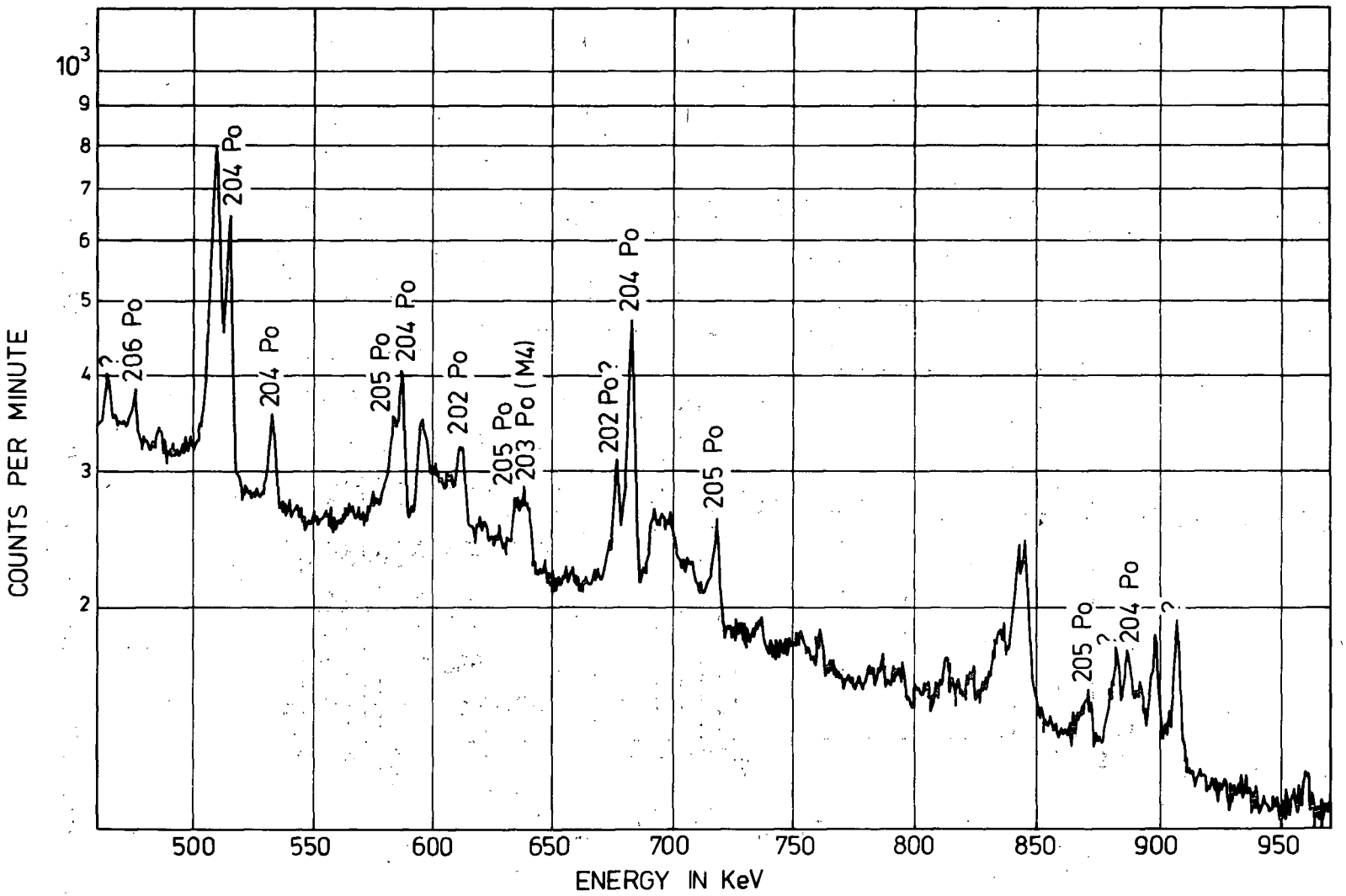

Fig. 4 On line γ-spectrum of Po isotopes; $^{204}Pb + {}^{4}He \rightarrow {}^{208}Po^{*}$ at 58 MeV

3. HALF-LIVES

^{239}Pu half-life (Mrs. K.M. Glover, R.A.P. Wiltshire, F.J.G. Rogers and M. King (AERE)) [Relevant to 1 request]

A further set of measurements on the half life of ^{239}Pu were made during the autumn of 1975. It is anticipated that when the analysis of all the half-life results is complete, the half-life value will be reported.

^{237}Np half-life (Mrs. K.M. Glover, D. Brown (AERE))

There is no progress to report on this measurement due to lack of effort.

Half-life of ^{241}Pu (I.E. McKean, E.A.C. Crouch (AERE)) [Relevant to 1 request]

^{241}Pu prepared at AERE by pile irradiation of separated ^{240}Pu and used by James, Rose and Whitehead[1,2] to investigate the possible existence of a short-lived isomer of ^{241}Pu, has been monitored by mass-spectrometry. There were two preparations made and the ^{241}Pu/^{240}Pu ratio together with the ratio of ratios (241/240)/(242/241) have been measured over ~ 2100 days (see decay plots, Figures 5 and 6). At February 1976 the observed half-life was:-

Sample A	Ratio of Ratios	14.53 ± .12 yrs
	Ratio	14.24 ± .12 yrs
Sample B	Ratio of Ratios	14.32 ± .10 yrs
	Ratio	14.34 ± .13 yrs

These results are still at variance with Wilkins'[3] findings using another ^{241}Pu sample. Portions of these disparate preparations have been sent to Geel for measurement there.

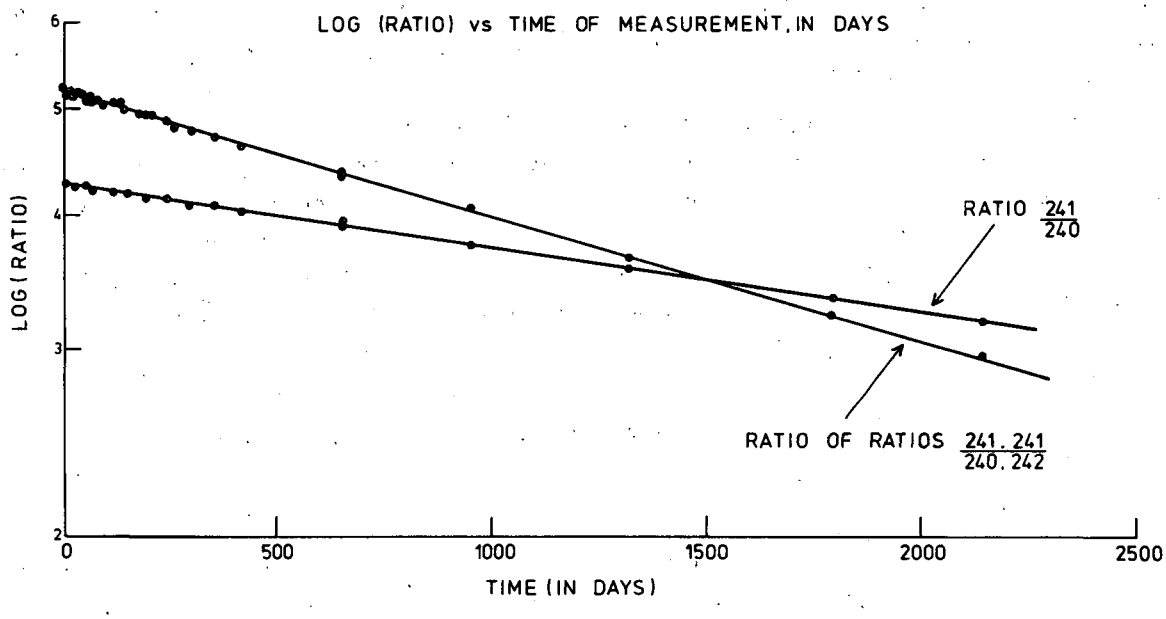

Fig. 5 The half-life of ^{241}Pu: sample A

(1) C. Whitehead, A.C. Sherwood and B. Rose, AERE PR/NP 18 (1972)

(2) G.D. James, J. Nucl. Ener. 26 (1972) 99

(3) M. Wilkins, AERE - R 7906 (1974)

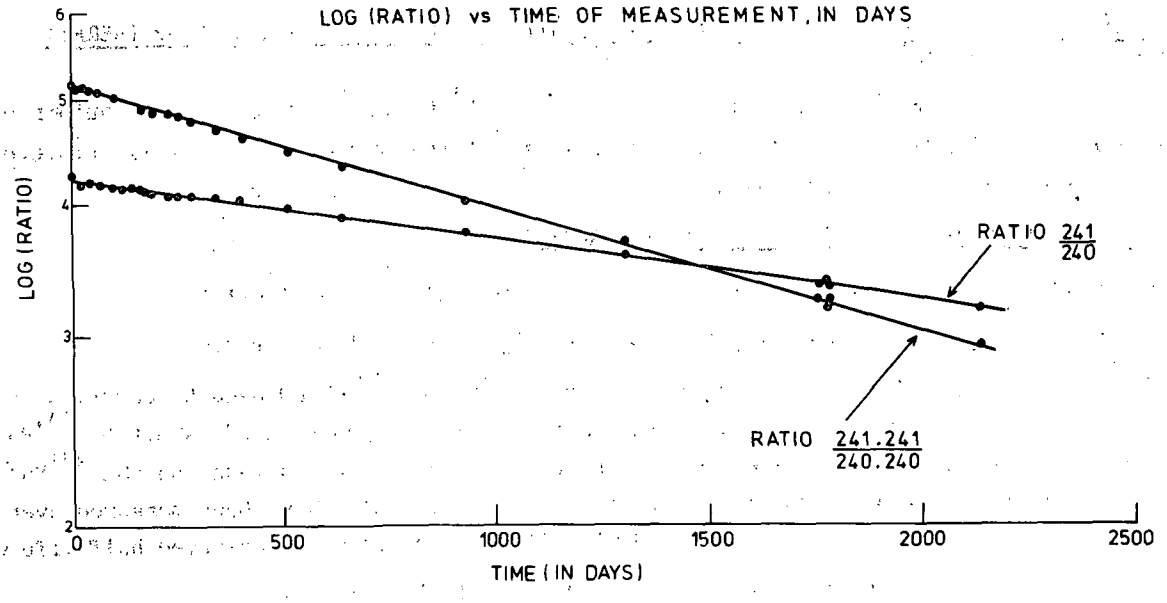

Fig. 6 The half-life of ^{241}Pu: sample B

EVALUATIONS AND COMPILATIONS

1. DATA FILE (DECAY SCHEMES) SUB-COMMITTEE (A.L. Nichols (AERE), B.S.J. Davies, A. Tobias (CEGB), V. Barnes (BNFL), D.G. Vallis (AWRE), M.F. James (AEEW))

There have been a number of changes in the sub-committee personnel during 1975, with a strengthening of the man power effort available for nuclear data evaluation. Progress has been made toward producing a decay scheme data file in ENDF/B format. An approximately 1.5 man power programme of evaluation work is under way to compile and evaluate data of a high priority, specifically defined by the sub-committee and determined by the needs of the U.K. reactor programme. This concentrated effort is upon fission product mass-chain evaluations, using the usual reference materials (e.g. Nuclear Data Sheets and Recent References). The decay schemes of nuclides arising from the activation of reactor structural materials are also being undertaken, and it is hoped that this first series of evaluations will be completed by the end of 1977. Whilst this work is underway the Tobias fission product library[1] and the US ENDF/B-IV[2] files are available.

A detailed inter-comparison is also being made of a number of published γ-libraries[3]. It is hoped that this comparison of more general nuclides, coupled with recent literature, will provide the data file with some non-reactor related nuclear data.

The file is slowly being constructed and it will be several years before a satisfactory, comprehensive UK data file is available (see Table 2). At present the Rogers' α-library[4] and the Tobias[1] library are available, whilst a second round of fission yield evaluations

(1) A. Tobias, CEGB RD/B/M2669 (1973)

(2) T.R. England and R.E. Schenter, LA-6116-MS (1975)

(3) (a) C. Meixner, Jul-1087-RX (1974); (b) G. Erdtmann and W. Soyka, Jul-1003-AC (1974); (c) W.W. Bowman and K.W. MacMurdo, Atomic Data and Nuclear Data Tables 13 (2-3) (1974); (d) N.R. Large and R.J. Bullock, unpublished data

(4) F.J.G. Rogers, AERE - R 8005 (1976)

by Crouch (see below) will be incorporated into the file when the evaluation is completed.

TABLE 2

U.K. Chemical Nuclear Data File

Item	Data	Present position	Insertion into file
1	α-library (Rogers)	Completed in non-ENDF format	If effort is available, Dec. 1976
2	Fission product decay schemes, including those nuclides produced by activation of stable FPs	The main effort of the sub-committee members is on this item, especially for fission products having half lives > 1 hr and fission yields > 0.1%	June 1977
3	Activation products of structural materials decay schemes	Some effort is also on these items	Some by Dec. 1976, completion by end 1977
4	Actinide decay schemes		
5	Decay schemes of other nuclides	Little effort available until items 2, 3, and 4 completed	Some of the more important by end 1977
6	Fission yields	Crouch evaluation in use	June 1976
7	Delayed neutrons	Tomlinson data in use	No effort available
8	Spontaneous fission data	May be covered by evaluator who maintains the α-library	--
9	X-ray energies and intensities	No effort available	--
10	β^+/EC ratios	No effort available	--
11	Internal conversion coefficients	No effort available	--
12	Cross sections of fission products etc.	No effort available	--

2. FISSION YIELDS (E.A.C. Crouch (AERE))

Fission Product Yields; consistent set

As previously reported (UKNDC(75)P71) an adjusted set of chain and independent yields was deduced and reported in AERE - R 7785. This work was based on the adjustment of the yields for any given fission reaction by means of the relations

$$\Sigma_A Y(A) = 2 \qquad \text{(i)}$$

$$\Sigma_A Y(A).A = A_F + 1 + \bar{\nu}_r = \bar{A} \qquad \text{(ii)}$$

where $\bar{\nu}_r$ is the total neutron emission per fission

and $$Y(A) = y(A)(\alpha + \beta y(A).\sigma(A)) \qquad \text{(iii)}$$

where Y(A) is the adjusted chain yield at mass A, y(A) is the experimentally determined yield at mass (A) with $\sigma(A)$ the experimental error, α and β are constants for a given fission reaction. (iii) was an arbitrary choice which was thought to reflect the dependence of the adjustment on the size of the yield and its error. The adjustments so found were in many cases greater than the experimental errors and in some cases the adjustment (which was a multiplying factor) was negative. These adjustments were reported in AERE - R 7785. Later, however, it was realised that fitting of the experimental yields to (i) and (ii) by means of least squares might prove better and this proved correct. The procedure was that of Deming, as follows:

Using (i) and (ii) above it is necessary to minimise the weighted square of the residual S as in

$$S = \sum_A \left[(Y(A) - y(A))/\sigma(A) \right]^2 \qquad \text{(iv)}$$

If V(A) = Y(A) - y(A), (iv) becomes:

$$S = \sum_A (V(A)/\sigma(A))^2$$

and S must be minimised subject to the constraints (i) and (ii) in the form:

$$f_1 = \sum_A [y(A) + V(A)] - 2 = 0$$

and $$f_2 = \sum_A [A.(y(A) + V(A))] - \bar{A} = 0$$

then

$$\frac{\partial S}{\partial V(A)} + \lambda_1 \frac{\partial f_1}{\partial V(A)} + \lambda_2 \frac{\partial f_2}{\partial V(A)} = 0 \quad \text{for each A.}$$

Hence, $$V(A) = -\frac{\sigma^2(A)}{2} (\lambda_1 + \lambda_2 A) \text{ for each A,}$$

and V(A) is an additive adjustment to the experimentally observed chain yield at A. The results of this procedure were reported in AERE - R 8152 and it was this consistent set which was used to construct the ENDF/B formatted fission yield file (see below).

ENDF/B formatted Fission Yield File for the UK Nuclear Data File

The consistent set described above was used to prepare a magnetic tape file for the UK Nuclear Data File (M.F. James at Winfrith), in the format of the American ENDF/B files. This was done by outputting the results of AERE - R 8152 on cards which were input to a specially written program.

Fission yield assessment

Since the publication of the last evaluations (AERE - R 7209, R 7394, R 7680), there have been over 90 papers published which have been included in the fission product Library. In order to include this work another evaluation was begun in October 1975, and is now almost complete. It includes thermal, fast and 14 MeV fission yields in one volume rather than separately, and the independent yields will be included also. It is hoped to publish this evaluation along with the derived consistent set in Atomic Data and Nuclear Data Tables.

3. α-DECAY SCHEMES (F.J.G. Rogers (AERE))

Document AERE - R 8005, describing this data available on magnetic tape in non-ENDF/B format, should be available during 1976.

4. RELATED COMPILATION STUDIES

CASCADE - Computerised analysis of evaluated decay schemes (D.G. Vallis (AWRE))

The CASCADE program converts a data set representing an evaluated radionuclide decay scheme into another data set describing the radiation emissions from that nuclide. The latter set consists essentially of a tabulation of the energies and intensities of radiations arising from primary disintegration processes, e.g. α, $\beta^{\pm}$ or EC and those produced by transitions between excited states of the daughter product(s): γ, X-ray, conversion electron and Auger electron.

The program can supplement the input decay scheme data with purely theoretical data, e.g. Hager and Seltzer internal conversion coefficients, as an input option. Relative intensities of coincidences between specified emissions can also be computed with due regard to the lifetimes of metastable levels and the resolving time of a counter. Thus the decay model is easily checked against the experimental data from which it is deduced.

CASCADE works by carrying out a systematic examination of all possible decay pathways through the intermediate levels from the initial state of the parent nuclide to the ground state(s) of the daughter nuclide(s). During this process the types, energies and intensities of radiations from only those pathways with significant probability are stored.

CASCADE is only one program in a suite of programs which is usually run as one computer job. During job execution several decay schemes are analysed serially and the radiation emission data thus produced stored on disc. In the final stages of the job the new data can be merged into existing data sets already stored on disc, thereby expanding or updating them. Also, during this phase, data can be listed in optical categories and priorities, e.g. γ-rays in order of decreasing energy within nuclides in order of increasing mass. An editing program allows obsolete data to be over-written.

The objective is to use these output data sets as input for many other computer programs used in the nuclear energy field, e.g. calculating heat output of reactors, assessing reactor shielding requirements, designing irradiated fuel containers, and so on.

Previously this type of data set has been constructed laboriously by detailed compilation and evaluation of the published literature usually only in the context of one type of

radiation at a time. The advantage of the CASCADE approach is that it results in data sets for different types of radiation which are derived from the same reference set of evaluated decay schemes. They are therefore internally consistent and very easily updated as soon as new evaluations of decay schemes are published, either singly or in major reviews.

Work is in hand to extend the scope of CASCADE and to remedy the main limitations previously reported. These were:

(a) the input data set was limited to about 70 decay schemes based on the 1967 Table of Nuclides and therefore obsolete;

(b) the program could only cope with decay schemes with less than 30 levels;

(c) it was unable to deal with decay by spontaneous fission or neutron emission;

(d) the uncertainties of the output data were not computed.

An AERE extramural research contract with Imperial College was initiated during 1975 and as a result a postgraduate research student (G. Evangelides) is now working to make the necessary improvements and to create an up-to-date file of evaluated fission product decay schemes as input.

In addition, we have obtained the current Nuclear Structure Data File produced by D.J. Horen and co-workers at Oak Ridge. Evangelides is writing a code to convert the parts of these files containing evaluated decay schemes into a format suitable for CASCADE input. For at least the fission products and actinides it will be desirable to produce the radiation data sets from CASCADE in a format compatible with the proposed UK Fission Product Data File; therefore he is also working on the problem of modifying the program to output data in ENDF/B format. It will then be possible to compare easily radiation data produced via two routes: from evaluated decay schemes using CASCADE and from the primary literature sources.

Some progress has already been made to extend the capability of the program to deal with very complex decay schemes without incurring intolerable penalties in computer storage. At present CASCADE uses a purely deterministic method of computing transition routes the process being reiterated if storage overflows. Evangelides has written a Monte Carlo code to give a prior probabilistic estimate of storage requirements; this has been run successfully as a subroutine.

UK - French Collaboration

A second meeting with representatives from the CEA was held at Harwell in March 1976. It was agreed in principle that more closely defined co-operation should occur, following the previous year's exchange of specific data and other information. Meetings to review progress take place once a year, and it is hoped that a sharing of the decay scheme evaluation load will occur.

PUBLICATIONS

Chain and independent fission product yields adjusted to conform with physical conservation laws. Part 2.
E.A.C. Crouch, AERE - R 8152 (1976)

E.A.C. Crouch (1975) Unpublished Information

CONFERENCE PAPERS

High energy fission of the nucleus $^{208}Po^{*}$
J.G. Cuninghame, J.A.B. Goodall (AERE) with I.S. Grant, G.W.A. Newton and others (Manchester University). 1st Iraqi Scientific Conference, Baghdad (April 1975).

The measurement by γ-counting of complete mass yield curves for fission of ^{235}U in several different fast reactor neutron spectra
J.G. Cuninghame, J.A.B. Goodall, H.H. Willis, 1st Iraqi Scientific Conference, Baghdad (April 1975)

DIVISION OF RADIATION SCIENCE, NATIONAL PHYSICAL LABORATORY

(Superintendent: Dr. W.A. Jennings)

CALIBRATION SERVICES

The NPL maintains standards of neutron flux density and facilities for the calibration of neutron sources. Extension and improvement of the standards available, including international intercomparisons with other national laboratories is a continuing process. Details of services available and their cost are described in a booklet entitled Measurement Services, available free of charge from the Division of Radiation Science, National Physical Laboratory.

STANDARDS OF NEUTRON FLUX DENSITY

Various methods of measuring neutron flux density are being developed and intercompared as a means of improving the accuracy of the existing standards.

Intermediate Energy (J.B. Hunt)

The long counter calibration has been checked using a proton recoil telescope of conventional design and the measurements are in excellent agreement from 2.5 MeV to 5.5 MeV. Above this energy there is a discrepancy of up to 7% and further measurements are planned to resolve this using a 2.5 cm diameter gas cell target.

The hydrogen proportional counter is built and together with the high vacuum gas transfer system, vacuum tests and filling procedures are about to be carried out. Tests using a collimated X-ray source will then be made to measure the effective length and volume of the proportional counting region between the two field tubes.

Measurements are continuing of the long counter efficiency in the energy range 500 keV to 1.2 MeV using the associated target activity method, employing the $^{57}Fe(p,n)^{57}Co$ reaction.

Fast Neutron Energies (T.B. Ryves, K.J. Zieba and P. Kolkowski) [Relevant to 7 requests]

The proton recoil telescope for measuring neutrons in the 12-20 MeV energy range has been commissioned. Preliminary measurements have been made on the $^{56}Fe(n,p)^{56}Mn$ reaction between 14 and 18 MeV, and the measured cross-sections are approximately 10% above the evaluation in the ENDF/B-IV data file. It is planned to continue these measurements, and also to measure the cross-sections for the $^{63}Cu(n,2n)^{62}Cu$ and $^{65}Cu(n,2n)^{64}Cu$ reactions.

NEUTRON SOURCE CALIBRATIONS (E.J. Axton and A.G. Bardell)

A low efficiency detector is to be added to the NPL manganese bath system in order to extend the facility to measure neutron emission rates of the order of 10^9 sec^{-1}.

Recently there has been an increase in the demand for the calibration of low intensity neutron sources (10^2 - 10^5 $n.sec^{-1}$). To meet this demand a high efficiency detector, the original AERE boron pile is being re-built at the NPL. The pile will be calibrated with a range of neutron sources which have been calibrated in the manganese bath. It is expected that this equipment will result in improvements in the accuracy and cost of the calibration of low intensity sources.

PROGRESS IN THE B.I.P.M. INTERNATIONAL INTERCOMPARISON OF NEUTRON FLUX DENSITY

Since last year's report, measurements have been made by the National Bureau of Standards, Washington and by Physikalisch-Technische Bundesanstalt (P.T.B.), West Germany, but results are not yet at hand.

For 14 MeV neutrons, the intercomparison using the $^{56}Fe(n,p)$ reaction as a transfer instrument continues. During the past year measurements have been completed by NPL, BCNM (Geel), and ETL, Japan. Foils have also been dispatched to B.I.P.M. (Sèvres) and I.M.M. Russia. The P.T.B. (West Germany), N.B.S. (USA) and N.R.C. (Canada) are expected to take part later.

The NPL is willing to supply iron foils on loan to other laboratories which are not involved in the B.I.P.M. intercomparison but which have a calibrated 14 MeV flux facility and the capability for low level $4\pi\beta$ counting of the activated foils.

REFERENCE STANDARD FOR NEUTRON THERAPY DOSIMETRY (E.J. Axton, V.E. Lewis, A.G. Bardell, D. Thomas and D. Young))

At the meeting of the BCRU neutron sub-committee of 12 March 1973 it was agreed that a National reference standard for the measurement of neutron absorbed dose should be established as soon as possible in order to promote uniformity and continuity in the dose measurements at the various field centres. In the interests of high precision and reproducibility, and ease of operation, twin cavity chamber systems are the most promising. The total dose is measured with a polyethylene-ethylene chamber or some form of tissue-equivalent chamber whilst the X- and γ-ray component is measured with a carbon-carbon dioxide chamber of similar design. One of the major problems is the estimation of the response of the X- and γ-ray chamber to neutrons. It will therefore be necessary to apply other techniques such as the use of Geiger counters, TLD or fission chambers to help resolve the X- and γ-ray component.

A 3 MV Van de Graaff accelerator and a 150 kV Sames accelerator are available for neutron production and a prototype gas-flow chamber-stem assembly has been built. The design caters for interchangeable wall and electrode material and counting gas, as well as for ease of measurement of the volume, and materials were selected to minimise neutron interactions.

The absolute response of the system can be determined in four possible ways.

1. Determination of dose from charge measurement by measurement of the chamber volume and assumption of W, and various wall correction factors, stopping power ratios etc.
2. Calibration against 2 MV X-ray standard. This is done at present at the centres through the medium of Farmer secondary standard chambers.
3. Calibration in standard neutron fluxes and assuming Bach-Caswell (1968) or other kerma-fluence relationships.
4. Comparison with a direct measurement of the kerma in hydrogen using a proton recoil telescope.

Comparison of results from the four methods should shed light on the validity of the various assumptions. The system should produce fairly quickly a 'working rad' which would

be available as a reference during the time that research would be under way to establish its absolute validity.

It is hoped that target emission rates of about 10^{11} neutron/sec will be achieved with the $^{3}H(d,n)$ reaction at 14 MeV and with the $^{9}Be(d,n)$ reaction which gives neutron groups in the 2-6 MeV range with 3 MeV deuterons. In addition $^{7}Li(p,n)$, $^{3}H(d,n)$, $^{2}H(d,n)$ reactions may be used to produce mono-energetic neutrons over a large part of the energy range from about 50 keV to 20 MeV but the dose rates available will be considerably lower since the requirements of high yield and good resolution are incompatible.

The source strengths referred to above are equivalent to dose-rates at 50 cm of 1.3 and 0.8 "rads in tissue, measured in air" per min for the $^{3}H(d,n)$ and $^{9}Be(d,n)$ reactions respectively. At 80 cm the dose rates would be 0.5 and 0.3.

The requirement of high dose rate and large field size are also incompatible. In the present design of collimator 5 circular field sizes are available providing beam diameters of 3.3, 4.6, 6.6, 9.2 and 14 cms at 50 cms distance, or 4.8, 6.8, 10, 14.2 and 21.8 cm at 80 cm.

Shielding problems preclude the use of the wider apertures at the higher dose rates.

The construction of the dosimetry laboratory is now complete, and the collimator and 150 kV accelerator have been installed. Neutron emission rates of the order of 10^{10} $n.sec^{-1}$ have been achieved in preliminary tests which have shown that some additional shielding is necessary. Some progress has been made towards transporting the particle beam from the Van de Graaff accelerator through two 90^{o} magnets to reach the wall collimator.

NEUTRONS IN THE 1-1000 eV ENERGY RANGE (E.J. Axton and A.G. Bardell)

To meet requirements in the field of environmental and personnel monitoring a calibration system covering this energy range has been built and is awaiting test. Neutrons are produced by bombarding a thick lithium target with protons from the Van de Graaff accelerator. The proton energy is carefully controlled to limit the neutron energy in the forward direction to 100 keV. The target is surrounded by a water moderator and the neutrons escaping from the moderator in the direction at 90^{o} to that of the proton beam are collimated and attenuated through boron filters. Difference measurements between the transmissions through various filter thicknesses produce broad spectra with maxima in the range of interest. The neutron spectra and intensities will be derived from measurements with a long counter and a small BF3 counter in combination with Monte-Carlo computational techniques.

Although the difference dose equivalent rates will be small, it is hoped that the facilities will go some way towards providing calibration facilities in this energy region.

NUCLEAR DECAY SCHEME MEASUREMENTS (P. Christmas, P. Cross, M.J. Woods, R.A. Mercer and S. Brown)

Work continues on the measurement of the L and K internal conversion coefficients of ^{133m}Xe. A value of 0.4589 has been obtained for the number of γ-rays per disintegration in ^{115m}In and measurements are being made of the γ branching ratio in ^{86}Rb.

W VALUE MEASUREMENTS (P. Christmas and M. Burke)

A contract is being placed with the University of Birmingham for the measurement of W values for protons in the energy range 700 keV to 3 MeV in hydrogen, acetylene, ethylene and Tissue-equivalent gas.

Work has been started on a complementary programme at NPL to extend the energy range down to 100-300 keV.

APPLIED PHYSICS DIVISION, AWRE, ALDERMASTON.

The following material was presented to a US/Japan Seminar in January 1976. A fuller version is in preparation for publication in the BNES Journal during 1976 and it is hoped to include ^{239}Pu data as well as improve the accuracy of the ^{235}U and ^{238}U data given here.

Absolute yields of delayed neutrons in the fast fission of ^{235}U and ^{238}U (C.B. Besant*, P.J. Challen**, M.H. McTaggart**, P. Tavoularidis* and J.G. Williams*) [Relevant to 6 requests]

Existing delayed neutron data are based primarily on Keepin's measurements in Godiva[1]. Recent reviews by Tomlinson[2], Cox[3] and Tuttle[4] include a variety of measurements, some direct, some values relative to ^{235}U and others in which the time dependence is not specifically extracted. By combining appropriately weighted values Tuttle produces recommended values which for ^{235}U and ^{238}U have an associated standard deviation of 1.3%. The present measurements using the VIPER pulsed reactor have as their objective, independent absolute measurements of ^{235}U, ^{238}U and ^{239}Pu delayed neutron yields to an accuracy ultimately of 3%, 4% and 3% respectively. The method adopted includes their time dependence since the decay following a millisecond duration reactor irradiation is recorded directly.

This study was started in 1970 by Clifford[5] who was responsible for the basic features of the system and carried out an initial set of measurements. No correction for the decrease in delayed neutron fraction above 4 to 5 MeV which is attributed to second chance fission[6] has been made. Tuttle[4] applies a 1.3% increase for ^{235}U and 2.3% for ^{238}U in the Godiva spectrum which is somewhat harder than in VIPER.

Experimental arrangement

The sample transport system comprises a tube and a pneumatic supply which fires a steel rabbit to the detector position in 35 milliseconds. There it is arrested in a polyurethane foam cylinder. Reproducibility of its rest position is ± 2 cm. The detectors are thermal neutron scintillation counters and the rabbit tube at the rest position is surrounded by a 2 inch thick lead cylinder as a gamma shield and a polythene cylinder to act as a neutron moderator. Two detector channels were used, one being a ^{6}Li loaded zinc sulphide scintillator (Nuclear Enterprises NE422) and the other a ^{10}B loaded glass disc (Nuclear Enterprises NE402). They were both enclosed in a constant temperature enclosure ± 0.5°C to ensure stability and a standard source calibration was made before and after each pulse.

Data acquisition was by an on-line ARGUS 500 computer which provided a multiscaled output in 10, 100 and 1000 millisecond channels chosen to suit the irradiation. Since the range of neutron count rates was wide it was necessary to combine the results of three pulsed irradiations to obtain the complete decay curve, using appropriate sizes of samples. To avoid saturating the detectors when large samples were used, a delay of up to 50 seconds before sample transfer could be incorporated.

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* Imperial College, London, UK

** AWRE Aldermaston, Berks, UK

Neutron detector calibration

A number of absolutely calibrated neutron sources were used to obtain the neutron efficiency curve. The result for channel 2 is shown in Fig. 1. The spontaneous fission ^{240}Pu source was used as the standard for day-to-day calibration. The two mono-energetic sources La(γ,n)D_2O at 140 keV and La(γ,n)Be at 747 keV were calibrated by a vanadium bath[7]. The Am(α,n)Li source calibrated at NPL by Bardell[8] has a broad spectrum and a mean neutron energy of 500 keV[9], similar to the Batchelor[10] spectrum though somewhat harder than the more recent Sloan Woodruff[11] results. For the results of this measurement the neutron efficiency given by the Am-Li source was taken to be the efficiency for delayed neutron detection. Its quoted accuracy is a standard deviation of 0.5%.

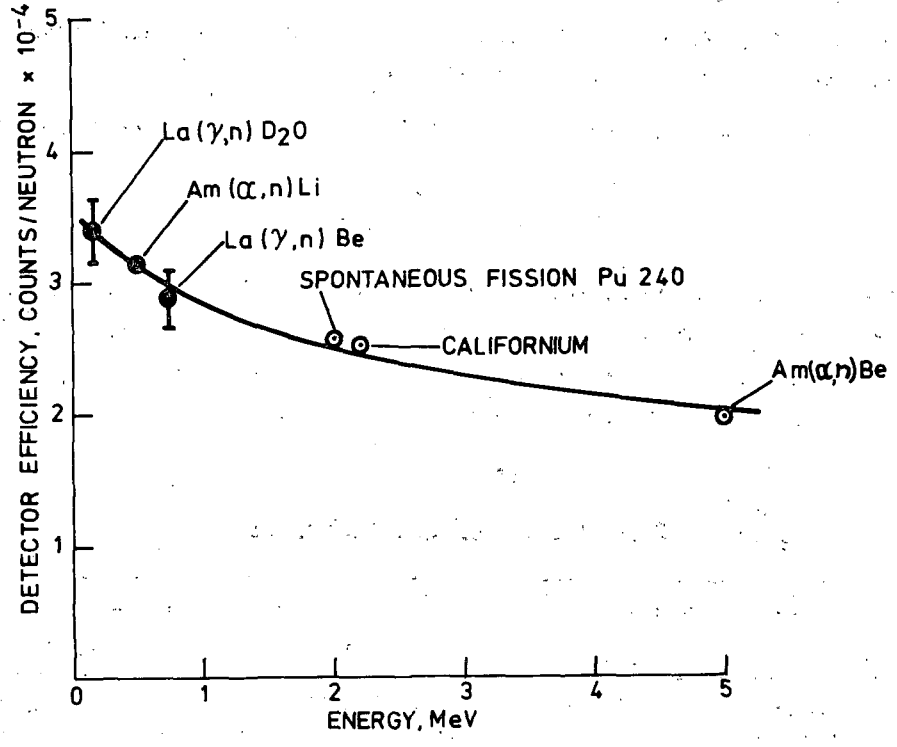

Fig. 1 Neutron detector efficiency to a point source at the sample rest position (channel 2)

Fission determination

Foils of the same material as the sample were irradiated in the rabbit and after completing the neutron counting were subsequently counted for ^{140}La activity, starting 10 days after irradiation, using a Li drifted germanium detector. By irradiating identical foils within a fission chamber containing a known mass fissile deposit during high steady power VIPER operation, a comparison ^{140}La source was obtained in which the fission density was established by the ratio of its mass to that of the fissile deposit. The pulse and steady state irradiations were done within the same period and their ^{140}La activity counted alternately to eliminate drift in gamma detector efficiency.

The basic foil masses had a standard deviation of 1½% and the accuracy of corrections for bias, loss of fission fragments, impurity fissions etc. added 0.5%.

^{235}U measurements

Data for ^{235}U were obtained from channel 2 from a total of five pulses, three with small samples contributing 71% of the detected neutrons, an intermediate size (0.35 g) contributing 21% and a large sample (8.3 g) contributing 3%. A correction of 4.4% based on Keepin's data was added for neutrons emitted between the pulsed irradiation and the start of neutron counting. The small samples consisted of a single foil, which was counted subsequently for ^{140}La activity. Similar foils inside the rabbit with the larger samples showed that the variation of fission rate within the sample was small. The match between the neutron output per fission from the small, intermediate and large samples in the time regions where overlap was valid (i) because both sets were statistically accurate and (ii) where dead time corrections were less than 3%, showed that the maximum differences did not exceed 5 ± 2% though the results generally were within 2 ± 1%.

The total yield, based on the detector efficiency for the AmLi source for channel 2 was

$$0.0162 \pm 0.0011 \text{ neutrons per fission}$$

To analyse the time-dependence of this data a composite smooth decay curve was generated by renormalising the data from the intermediate and large pulses to give an exact match in the overlap region. Using Keepin's data as an initial estimate a six group fitting procedure was applied. The results are given in Table 1.

TABLE 1

^{235}U group abundances and decay constants

i	Keepin values		Fitted values	
	a_i	λ_i (s^{-1})	a_i	λ_i (s^{-1})
1	0.038 ± 0.004	0.0127 ± 0.0003	0.035 ± 0.002	0.0129 ± 0.0001
2	0.213 ± 0.007	0.0317 ± 0.0012	0.234 ± 0.003	0.0323 ± 0.0002
3	0.188 ± 0.024	0.115 ± 0.004	0.278 ± 0.037	0.147 ± 0.005
4	0.407 ± 0.010	0.311 ± 0.012	0.292 ± 0.031	0.344 ± 0.028
5	0.128 ± 0.012	1.40 ± 0.12	0.146 ± 0.022	1.43 ± 0.17
6	0.026 ± 0.004	3.87 ± 0.55	0.015 ± 0.014	8.6 ± 5.8

^{238}U measurements

Data for ^{238}U were obtained also from channel 2 from a total of four pulses, two with small samples contributing 63%, one with an intermediate sample (2.9 g) contributing 23% and one with a large sample (11.2 g) contributing 5%. A correction of 7.6% using Keepin's data was added for neutrons emitted between the pulsed irradiation and the start of neutron counting. The small samples (0.25 g) comprised seven fission foils and ^{140}La counting done on three (Nos. 1, 4 and 7) from one sample showed that the ^{238}U fission rate was

uniform. The low fission rates in ^{238}U meant that the fission distribution in the larger samples could not be measured by the ^{140}La technique and a less accurate total fission gamma activity method was adopted to relate the total fissions in each sample to the fission rate in the one foil which was selected for ^{140}La counting. The measured ratios were 0.95 ± 0.04 and 0.94 ± 0.04 for the 11.2 g and 2.9 g samples respectively. Examination of the overlap regions of the neutron emission curves based on the ^{140}La measured fissions gave corresponding ratios of 0.901 ± 0.012 and 0.928 ± 0.010.

The total yield was therefore based on the small sample results and the intermediate and large sample results renormalised by the neutron overlap ratios giving a total yield of

$$0.0410 \pm 0.0025$$

The same composite curve was analysed to give the six group time dependence representation. The result is given in Table 2.

TABLE 2

^{238}U group abundances and decay constants

i	Keepin[1] values		Fitted values	
	a_i	λ	a_i	λ_i (s^{-1})
1	0.013 ± 0.001	0.0132 ± 0.0004	0.01296	0.0132
2	0.137 ± 0.003	0.0321 ± 0.0009	0.144 ± 0.003	0.0316 ± 0.0002
3	0.162 ± 0.030	0.139 ± 0.007	0.182 ± 0.03	0.148 ± 0.008
4	0.388 ± 0.018	0.358 ± 0.021	0.372 ± 0.024	0.369 ± 0.018
5	0.225 ± 0.019	1.41 ± 0.10	0.257 ± 0.026	1.83 ± 0.12
6	0.075 ± 0.007	4.02 ± 0.32	0.031 ± 0.030	11.2 ± 6.6

Discussion

The total delayed neutron yields derived from these measurements using only one of the two neutron detector channels recorded, indicate agreement with Keepin's original values, within the accuracy achieved at the present state of analysis. The errors arise mainly from the assumed neutron efficiency and from the internal consistency of the neutron emission data. The fission determinations give rise to an error of 2.5% (^{235}U) and 1.6% (^{238}U), the t = 0 correction contributes 0.4% (^{235}U) and 0.7% (^{238}U), the uncertainty in impurity corrections is virtually negligible for ^{235}U but amounts to 0.6% for ^{238}U. Combining these in quadrature gives 2.6% for ^{235}U and 2% for ^{238}U. The possibility of a systematic error of 2% in neutron efficiency and of a further 2% from the possible lack of internal consistency in the neutron emission data has to be added (not in quadrature) giving the final yield values of

$$^{235}U \text{ yield} = 0.0162 \pm 0.0011 \quad (\pm 6.6\%)$$

$$^{238}U \text{ yield} = 0.0410 \pm 0.0025 \quad (\pm 6\%)$$

The results of the second detector channel with its slightly different neutron energy

sensitivity and a more accurate calibration of the La(γ,n) sources to improve the accuracy of both detector channels should allow the systematic errors to be reduced and bring the overall errors close to the 3–4% target accuracy.

These results agree with Keepin's[1] original data, but are somewhat lower than Tuttle's[4] current recommended value for fast fission of ^{235}U of 0.01714 ± 0.00022, though just within the standard deviation; the ^{238}U results similarly agree well with Keepin's though are lower than Tuttle's value of 0.04510 ± 0.00061.

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(7) M. Scott, Journal of Nucl. Energy 25 (1971)

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PHYSICS DEPARTMENT, UNIVERSITY OF ASTON IN BIRMINGHAM

(Department head: Prof. S.E. Hunt)

Differential cross-sections for the elastic scattering of 14 MeV neutrons on ^{39}K and ^{7}Li (A.J. Cox and D. Holland) [Relevant to 4 requests]

Measurements have been made of the differential cross-sections for the elastic scattering of 14.1 MeV neutrons by ^{39}K and ^{7}Li. The neutrons were produced using the $T(d,n)^{4}He$ reaction with the incident deuterons accelerated to 130 keV by a SAMES type J accelerator. The neutrons were detected by a cylinder of plastic scintillator (NE 102A) (100 mm diameter × 50 mm) mounted on to a 56AVP fast focussed photo-multiplier tube. The energy of the detected neutrons was determined by a neutron time-of-flight system, based on taking as a zero time, the instant of detection of the α-particle associated with the production of a given neutron. The flight path used was 2 m. The α-detector was a sheet of NE102A 0.5 mm thick mounted again on a 56AVP photo-multiplier tube. The neutron efficiency of the system was measured by elastically scattering neutrons from the hydrogen in a polythene slab. The timing accuracy of the system was ± 1 nS. and the angular resolution was ± 4°. In each case the scattering sample consisted of elemental material cast into a slab 25 mm × 120 mm × 140 mm and contained in a stainless steel box of wall thickness 1 mm. Measurements were taken for scattering angles in the laboratory of between 20° and 100°. The potassium results are shown in Fig. 1, and are seen to confirm the results of Frasca et al.[1]. These latter results were taken with cylindrical geometry. The results for Li are shown in Fig. 2 together with those of Armstrong[2] and Wong[3] where it will be seen that all the results are in agreement up to scattering angles of 75°; above this however discrepancies occur with our results tending to support the measurements of Armstrong. In both Fig. 1 and Fig. 2 the line shown is an optical model fit performed using the computer code RAROMP[4].

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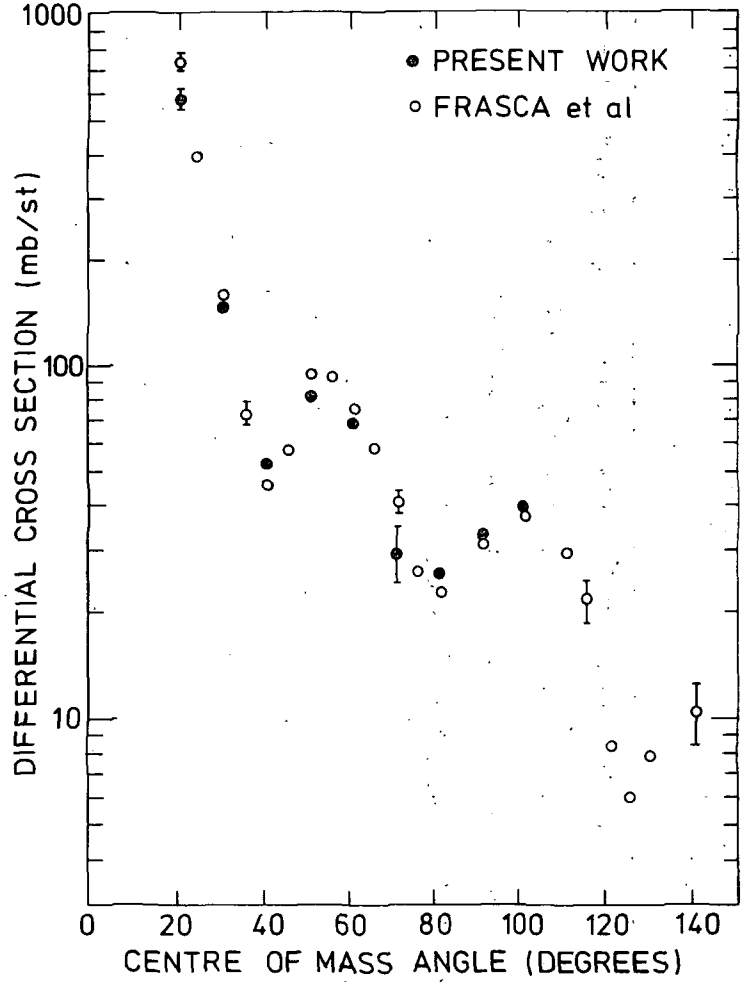

Fig. 1 Comparison of the measurements of the differential elastic scattering cross section from ^{39}K at 14.1 MeV

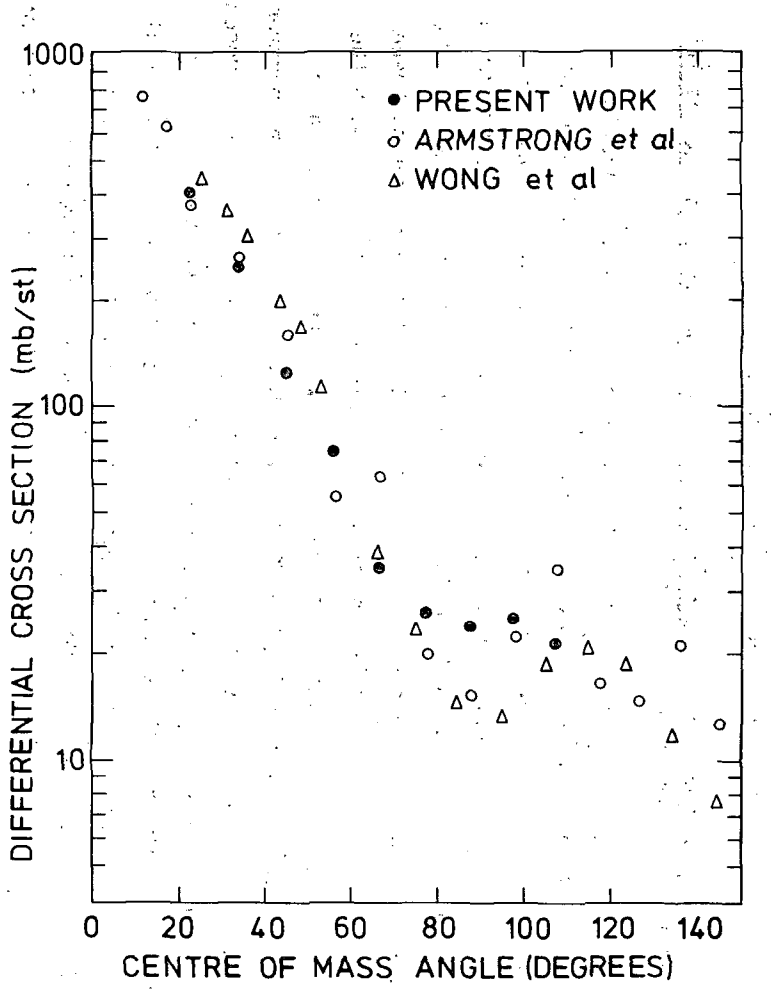

Fig. 2 Comparison of the measurements of the differential elastic scattering cross section from ^{7}Li at 14.1 MeV

PHYSICS DEPARTMENT, UNIVERSITY OF EDINBURGH

(Department head: Prof. W. Cochran)

Polarization and differential cross-section for fast neutron elastic scattering (R.B. Galloway and F. McN. Watson) [Relevant to 6 requests]

Work is in progress on the elastic scattering of 2.9 and 16 MeV neutrons by medium and heavy nuclei. An associated particle time-of-flight system with the $^{2}H(d,n)^{3}He$ reaction is employed to provide 2.9 MeV neutrons with 15% polarization at 45^{o} to a 300 keV deuteron beam[1] while 16 MeV neutrons with 24% polarization are obtained from the IBIS accelerator at AERE, Harwell. A preliminary report on polarization and measurements for the scattering of 2.9 MeV neutrons through 20^{o} - 160^{o} by Fe, Cu, I, Hg and Pb and of 16 MeV neutrons through 20^{o} - 90^{o} by Cu and Pb has been given to the Zurich 1975 Conference[2]. A major part of the work during the past year has been the development of the fast neutron polarimeter[3] from a six detector to a twelve detector system and the associated replacement of the multi-channel analyser data collection system by a CAMAC-PDP11/05 system. The resulting more efficient polarimeter and data collection system has been used for measurements on 16 MeV neutron scattering through 90^{o} - 160^{o} by Fe, Cu and Pb. These most recent data are still subject to multiple scattering and finite geometry corrections.

The polarization of neutrons from the $^{2}H(d,n)^{3}He$ reaction by Mott-Schwinger scattering (R.B. Galloway and R. Martinez Lugo) [Relevant to 1 request]

The Mott-Schwinger scattering fast neutron polarimeter reported last year[4] has been employed to determine the polarization of neutrons emitted at 45^{o} from $^{2}H(d,n)^{3}He$ reaction over the deuteron energy range 106 to 436 keV. Significant discrepancies exist in this energy region between different sets of measurements obtained using scattering by ^{4}He as polarization analyser, so the intention was to obtain a set of values based on a quite different polarization analysing process. The resulting polarization values, to an accuracy of $\pm$ 0.01, are in good agreement with the recent ^{4}He scattering results obtained in this laboratory[5] and by Sikkema and Steendam[6].

Incidentally to the main work neutron total cross-sections and small angle elastic differential cross-sections for Pb were obtained for neutron energies from 2.2 to 3.0 MeV.

The polarization of neutrons from the $^{2}H(d,n)^{3}He$ reaction by ^{4}He scattering (A. Alsoraya, R.B. Galloway and A.S. Hall)

The study of polarization of the neutrons from the $^{2}H(d,n)^{3}He$ reaction for deuteron energies from 1 to 5.5 MeV[7] is being continued for deuteron energies less than 500 keV[8]. Measurements of neutron polarization with an accuracy of about $\pm$ 0.005 for deuteron energies down to 35 keV have been made and below 200 keV are in good agreement with the theory of Boersma[9]. The angular dependence of the neutron polarization has also been determined at 290 and 460 keV deuteron energy. The data is being considered in relation to the models of the reaction which have been proposed.

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UNIVERSITY OF LONDON REACTOR CENTRE

(Director: Mr. M. Kerridge)

Compilation of nuclear data relevant to thermal neutron activation analysis (T.D. MacMahon)

A table[1] has been compiled to assist in the identification of, and quantitative determination of, the elements present in a sample which has been subjected to bombardment by thermal neutrons. The table lists, in order of energy, the gamma-rays emitted by radionuclides produced by the (n,γ) reaction; also included are background gamma rays and gamma-rays emitted by the main radionuclides produced by fast neutron reactions in a reactor neutron spectrum.

For each of 713 gamma rays the following data are listed

(i) the energy of the gamma ray

(ii) the name of the radionuclide

(iii) a reference to the most intense gamma ray of the radionuclide

(iv) the absolute intensity of the gamma ray

(v) the product of the thermal neutron absorption cross-section and the natural abundance of the target nuclide

Decay scheme studies (T.D. MacMahon, M. Thein, A.K. Entwistle, J.S. Tay) [Relevant to 6 requests]

Gamma ray absolute intensity measurements have been carried out for ^{133}Ba[2] and for ^{226}Ra and its daughters. Relative gamma ray intensities have been determined in the decay of ^{110m}Ag.

A study of gamma ray absolute intensities in $^{140}Ba/^{140}La$ and $^{144}Ce/^{144}Pr$ has just been commenced.

Evaluation (T.D. MacMahon)

Data is being collected for an evaluation of the decay scheme properties of ^{22}Na. This evaluation will be a contribution to the international collaboration described by Grinberg et al.[3]

Average cross section ratios in reference fast neutron fields (A.H.M.A. Hannan and J.G. Williams)

Measurements have been made by activation techniques using a calibrated Ge(Li) spectrometer and by absolute double fission chambers of average cross section ratios in the NISUS[4] spectrum. The results are compared in Table 1 with values calculated from data given by Fabry[5,6] for the $\Sigma\Sigma$[7] spectrum, which closely resembles that of NISUS. Decay scheme data for the present measurements were the same as those given by Fabry in ref. (7) except for ^{115m}In for which the values of ref. (5) were used.

Also shown in Table 1 are calculated cross section ratios using cross section data sets (identified in the table) derived from differential measurements, and neutron spectra evaluated from various spectrometry techniques and S_N transport theory calculations. Two evaluations of neutron spectrum were used: the $\Sigma\Sigma$ evaluated spectrum[7], and the NISUS evaluated spectrum (unpublished), which was derived from measurements with proton recoil

proportional counters[8] and ^{6}Li sandwich spectrometers[9], joined above 7.4 MeV and below 67 keV, to the same S_N transport theory spectrum used for the high and low energy tails in the ΣΣ evaluated spectrum. The two spectrum evaluations differ by approximately 20% in the energy range 2 MeV - 6 MeV, the NISUS values being higher. This difference is not attributable to any real difference between the two fields. At other energies the differences between the evaluations are small (< 8%) and are probably not significant in the context of the present comparison of average cross sections.

Satisfactory agreement is found between the NISUS experimental cross section ratios and those calculated using the NISUS evaluated spectrum (C/E values given in column 7 of Table 1). Such is not the case if the ΣΣ evaluated spectrum is used (column 8). Differences between the NISUS and ΣΣ measured cross section ratios are in most cases small, with the exception of the two ^{27}Al reactions.

Measurements are about to be made (April 1976) by the present authors of cross-section ratios in ΣΣ and the Mol ^{235}U fission spectrum cavity[10] in order to provide further data for comparisons of the kind described above.

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TABLE 1

Cross section ratios for NISUS and ΣΣ relative to $^{235}U(n,F)$

1	2	3	4	5	6	7	8
Reaction	Measured cross section ratio		Cross section set used	Calculated cross section ratio		Calculation / Experiment (cols. 2 & 5)	Calculation / Experiment (cols. 2 & 6)
	NISUS Present work	ΣΣ Fabry (5 & 6)		NISUS Evaluated spectrum (see text)	ΣΣ Evaluated spectrum (7)		
$^{197}Au(n,\gamma)^{198}Au$	0.26992 (± 2.5%)	0.2650 (± 3.5%)	ENDF/B-III (Mat.1166)	0.2532	0.2532	0.940	0.927
$^{235}U(n,F)F.P.$	1.0000 (ref.)	1.0000 (ref.)	ENDF/B-III (Mat.1157)	1.0000 (ref.)	1.0000 (ref.)	1.0000 (ref.)	1.0000 (ref.)
$^{239}Pu(n,F)F.P.$	1.1793 (± 2.0%)	1.1750 (± 2.5%)	ENDF/B-III (Mat.1159)	1.141	1.144	0.970	0.970
$^{237}Np(n,F)F.P.$	0.3751 (± 2.3%)	0.3800 (± 2.9%)	McElroy(11) (1970)	0.3893	0.3869	1.040	1.031
$^{115}In(n,n')^{115m}In$	0.03731 (± 2.5%)	0.03707 (± 3.5%)	McElroy(11) (1970)	0.03674	0.03517	0.985	0.943
$^{238}U(n,F)F.P.$	0.05664 (± 1.5%)	0.5640 (± 1.70%)	ENDF/B-III (Mat.1158)	0.0555	0.05300	0.980	0.936
$^{58}Ni(n,p)^{58}Co$	0.01718 (± 3.1%)	0.01756 (± 4.0%)	McElroy(11) (1970)	0.01697	0.01498	0.988	0.872
$^{27}Al(n,p)^{27}Mg$	0.0006148 (± 5.5%)	0.000650 (± 10%)	McElroy(11) (1970)	0.000600	0.000526	0.976	0.856
$^{56}Fe(n,p)^{56}Mn$	0.0001686 (± 3.5%)	0.000172 (± 4.5%)	McElroy(11) (1970)	0.000168	0.0001547	0.996	0.920
$^{24}Mg(n,p)^{24}Na$	0.0002471 (± 5.1%)	-	McElroy(12) (1967)	0.000247	0.0002320	0.999	0.939
$^{27}Al(n,\alpha)^{24}Na$	0.0001041 (± 3.3%)	0.0001145 (± 4.5%)	McElroy(11) (1970)	0.0001009	0.00009615	0.969	0.924