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United Kingdom Atomic Energy Authority

HARWELL

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

Editor: D.B. Syme
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, and covers the nine month period from April to December 1976. Contributions on nuclear data topics are included from Harwell, Winfrith, the National Physical Laboratory, the Berkeley Nuclear Laboratory of the Central Electricity Generating Board and the Universities of Birmingham, Edinburgh and Glasgow.

As before, contributions on "chemical nuclear data" are grouped under that heading but other reports are presented under a laboratory heading. Where the work is clearly relevant to requests in WRENDA 76/77 (INDC(SEC)-55/URSF) the request numbers are 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 UKNDC met once during the period of this report, and continued its role of co-ordinating work on nuclear data in the U.K. and providing the formal link with other national and international nuclear data committees and organisations. Detailed nuclear data needs were dealt with by the five sub-committees, summary reports from which are given below.

At the meeting of the UKNDC it was agreed that the timing of the U.K. Nuclear Data Progress Report would be changed to cover the calendar year. The period covered by the Harwell Nuclear Physics Division Progress Report is to be changed in this way to rationalize the compilation of the varous progress reports which are required from the Division. Since these two reports contain a substantial amount of common material, the new timing will help to reduce further the amount of effort devoted to their production in the Nuclear Physics Division. The change will also bring the U.K. into line with the practice in other countries. The present report consequently covers the nine month period ending 31st December 1976, and subsequent editions will cover the calendar year.

A report on the function and activities of the UKNDC has been written. Its purpose is to publicize the work of the Committee by bringing its existence and activities to the attention of a wide audience with possible interests in nuclear data. It is intended to publish the main report in Atom and abridged versions are being prepared for submission to such publications as the Bulletin of the Institute of Physics, the Bulletin of the Hospital Physicists Association, the Radiological Protection Bulletin, etc.

An International Conference on Neutron Physics and Nuclear Data for Reactors and other Applied Purposes is to be held at Harwell in September 1978. This will be the first in a series of triennial European conferences which will be held alternately with similar conferences in the USA and the USSR to provide annual meetings.

The tenth Nuclear Data Forum was held in December at the Culham Laboratory. The theme for the morning session was fusion, and the main talks were on fusion reactor concepts and fusion blanket neutronics. The afternoon session was devoted to experimental and calculational techniques. About 70 people attended, including representatives from other laboratories of the UKAEA, the National Physical Laboratory, the Central Electricity Generating Board, and several universities. It was generally considered to have been a successful meeting.

In the autumn the attention of several members of the Committee was drawn to an EEC Directive which requires member countries of the EEC to cease authorizing the use of the barn not later than 31st December, 1979. It is generally considered that there are no advantages and considerable disadvantages in doing this and the chairman of the UKNDC is co-ordinating a vigorous campaign to save the barn. The support of the scientific community will be canvassed in the open literature.

Neutron Sub Committee (Chairman: Dr. J.E. Lynn)

The committee met once in this period. Data items on the request list were reviewed if they arose in progress reports received from Birmingham Radiation Centre, N.P.L., Winfrith, the University of Glasgow, the CEGB Berkeley Nuclear Laboratories and from the Harwell Divisionsof Chemistry and Nuclear Physics. The BIPM flux comparison and the arrangements for the 1978 International Conference at Harwell on "Neutron Physics and Nuclear Data for Reactors" were also discussed.

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

The sub-committee has met once during the period covered by this report. As nuclear incineration is still being assessed as a possible disposal option for the higher actinides, the sub-committee has not drawn up a formal request list for nuclear data. However, it is now in a position of being able to identify some of the data requirements that would be necessary if nuclear incineration were adopted.

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

During the period of this report the fusion sub-committee has had two formal meetings and was also concerned with the organisation of the Nuclear Data Forum held at Culham in December.

The main area of concern, which is common to both the neutronics and sensitivity calculations, is the unreliability and lack of documentation of UKNDL compared with the American data file ENDF/BIV. A comparison of the two files for the structural materials Fe, Ni and Cr indicates that in some instances the data base and the assumptions used in UKNDL to produce the elemental cross sections are outdated. The disagreement in sensitivity calculations using the ANISN code between ENDF/BIV and UKNDL via GALAXY suggest that more reliance should be placed on calculations using ENDF/BIV in view of the frequent update and effort devoted to the American evaluation. A similar situation exists in neutronics calculations on fusion blankets for which it would be desirable to use ENDF/BIV data with the Monte Carlo code SPECIFIC via a MISSIONARY conversion.

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

In 1976 the committee held three meetings and the Data File Sub-Committee (Chairman: Dr. A.L. Nichols, AERE) held two.

The U.K.C.N.D.C. produces a U.K. Chemical Nuclear Data Request List every two years and the preparation of the 6th edition of this document has been underway during 1976. Although a large number of requestsfrom the 5th edition (CNDC(75)P2) have been deleted either as satisfied or as no longer required, the total number has increased, mainly as new requests from BNFL. The efforts of the committee to reduce the duplication of the work in the U.K. have been successful, and it has also been satisfying to see a continued increase in international collaboration in the data field.

* Also known as the Chemical Nuclear Data Committee

Bio-Medical Sub-Committee (Chairman: Mr. J.A. Dennis)

The Bio-Medical Sub-Committee held its third meeting on 10th January 1977. A request list for nuclear and atomic data measurements for use in the biomedical field has been prepared. This covers excitation functions for the production of radioisotopes, neutron cross-section data, stopping powers for electrons and other ions, W values in gases, electron slowing down and bremsstrahlung spectra and photon attenuation coefficients. The Sub-Committee has had difficulty in determining the exact requirements for decay scheme data, although these requirements undoubtedly exist. The preparation of a publication on the available sources of nuclear and atomic data for bio-medical applications is well advanced.

The Sub-Committee has maintained contacts with the British Committee on Radiation Units and Measurements (B.C.R.U.), through which it is aware of the activities of the International Committee on Radiation Units and Measurements (I.C.R.U.).

CINDA LISTINGS

ELEMENT S	A	QUANTITY	TYPE	ENERGY MIN.	ENERGY MAX.	REF	VOL	PAGE	DATE	LAB	COMMENTS
H	1	DIFF.ELASTIC	EXPT-PROG		2.7 7	UKNDC	P86		7/77	HAR	COOKSON + angular distribution fitted to theory.
Li	6	N ALPHA	EXPT-PROG	2.0 3	8.0 5	UKNDC	P86		7/77	HAR	GAYTHER + relative to U-235 (n-f)
Li	7		EVAL-PROG	0	1.4 7	UKNDC	P86		7/77	BIR	BEYNON+ R matrix fit to all available data
Li	7	NN ALPHA	EXPT-PROG		1.4 7	UKNDC	P86		7/77	HAR	UTTLEY+ work just starting
C	12	RESON PARAM	EXPT-PROG		2.06	UKNDC	P86		7/77	HAR	JAMES Res energy 2.078 ± .00016 MeV
Ti	NAT	TOTAL X SECT	EXPT-PROG	1.0 4	1.0 7	UKNDC	P86		7/77	HAR	BOWEN+ ToF Synchro-cyclotron
Ti	NAT	N, GAMMA	EXPT-PROG	5.0 0	8.0 5	UKNDC	P86		7/77	HAR	GAYTHER+ ToF LLS
Ti	46	RESON PARAM	EXPT-PROG		1.0 5	UKNDC	P86		7/77	HAR	THOM+ Main S wave.
Ti	47	RESON PARAM	EXPT-PROG		3.0 4	UKNDC	P86		7/77	HAR	THOM+ Main S wave
Ti	48	RESON PARAM	EXPT-PROG		1.0 5	UKNDC	P86		7/77	HAR	THOM+ Main S wave
Ti	49	RESON PARAM	EXPT-PROG		3.0 4	UKNDC	P86		7/77	HAR	THOM+ Main S Wave
Ti	50	RESON PARAM	EXPT-PROG		1.0 5	UKNDC	P86		7/77	HAR	THOM+ Main S Wave
Cr		N, GAMMA	EXPT-PROG	5.0 0	8.0 5	UKNDC	P86		7/77	HAR	GATHER+ ToF LLS
Cr		N ALPHA	EXPT-PROG	2.0 6	2.0 7	UKNDC	P86		7/77	HAR	UTTLEY+ Work due to start 77-78
Fe	NAT	TOTAL X SECT	EXPT-PROG	1.0 4	1.0 7	UKNDC	P86		7/77	HAR	BOWEN+ ToF Synchrocyclotron
Fe	NAT	N, GAMMA	EXPT-PROG	5.0 0	8.0 5	UKNDC	P86		7/77	HAR	GAYTHER+ ToF LLS
Fe	NAT	N, ALPHA	EXPT-PROG	2.0 6	2.0 7	UKNDC	P86		7/77	HAR	UTTLEY+ Work due to start 77-78.
Fe	56	N, PROTON	EXPT-PROG	1.4 7	1.9 7	UKNDC	P86		7/77	NPL	RYVES+
Ni	NAT	N, GAMMA	EXPT-PROG	5.0 0	8.0 5	UKNDC	P86		7/77	HAR	GAYTHER+ ToF LLS
Ni	NAT	N, ALPHA	EXPT-PROG	2.0 6	2.0 7	UKNDC	P86		7/77	HAR	UTTLEY+ Work due to start 77-78
Ni	58	TOTAL X SECT	EXPT-PROG	1.0 4	1.0 7	UKNDC	P86		7/77	HAR	BOWEN+ ToF Synchrocyclotron
Ni	58	RESON PARAM	EXPT-PROG	2.0 4	3.0 5	UKNDC	P86		7/77	HAR	SYME+ Area Analysis $\ell > 0$
Ni	60	RESON PARAM	EXPT-PROG	2.0 4	3.0 5	UKNDC	P86		7/77	HAR	SYME+ Area Analysis $\ell > 0$
Ni	62	RESON PARAM	EXPT-PROG	2.0 4	3.0 5	UKNDC	P86		7/77	HAR	SYME+ Area Analysis $\ell > 0$
Cu	63	N2N REACTION	EXPT-PROG	1.4 7	1.9 7	UKNDC	P86		7/77	NPL	RYVES+
Cu	65	N PROTON	EXPT-PROG	1.4 7	1.9 7	UKNDC	P86		7/77	NPL	RYVES+
Cu	65	N2N REACTION	EXPT-PROG	1.4 7	1.9 7	UKNDC	P86		7/77	NPL	RYVES+
Y	89		EVAL PROG	3.0 5	9.0 6	UKNDC	P86		7/77	GLS	CRAWFORD+ TBL
Au	NAT	N, GAMMA	EXPT-PROG	5.0 0	8.0 5	UKNDC	P86		7/77	HAR	GAYTHER+ ToF LLS
Th	232	PHOTO FISSN	EXPT-PROG			UKNDC	P86		7/77	HAR	LEES+ Photo fission near threshold
U	235	FISSION	EVAL PROG	1.0 4	4.0 4	UKNDC	P86		7/77	HAR	JAMES Analysis of structure

CINDA LISTINGS

ELEMENT S	A	QUANTITY	TYPE	ENERGY MIN.	ENERGY MAX.	DOCUMENTATION REF.	VOL.	PAGE	DATE	LAB	COMMENTS
U	235	ETA	EXPT-PROG	1.0 2	1.0 0	UKNDC	P86		7/77	HAR	MOXON+ Shape measurement
U	235	SPEC FISSN	EXPT-PROG		1.05	UKNDC	P86		7/77	HAR	ADAMS+
U	235	FISS YIELD	EXPT-PROG			UKNDC	P86		7/77	HAR	MCKEAN+ Work delayed irrad DER.
U	235	BETA FISS	EXPT-PROG			UKNDC	P86		7/77	WIN	MURPHY+ Beta decay energy after irradiation in fast reactor spectrum.
U	235	N FISS	EXPT-PROG	3.0 5	9.0 6	UKNDC	P86		7/77	GLS	CRAWFORD+ Gas Scintillator
U	238	TOTAL X SECT	EXPT-PROG	4.0 0	1.5 5	UKNDC	P86		7/77	HAR	HASTE+ High temp. ToF measurements on UO_2
U	238	DIFF INELAST	EXPT-PROG	1.1 6	2.4 6	UKNDC	P86		7/77	HAR	ARMITAGE+ Angle 90^o only
U	238	FISSION	EXPT-PROG	1.2 6	2.0 6	UKNDC	P86		7/77	HAR	EVANS+ Fission ratio U238/U235
U	238	N FISS	EXPT-PROG	3.0 5	9.0 6	UKNDC	P86		7/77	GLS	CRAWFORD+ Gas Scintillator.
U	238	FISS YIELD	EXPT-PROG			UKNDC	P86		7/77	HAR	MCKEAN+ Work delayed. irrad. DFR
U	238	FISS YIELD	EXPT-PROG			UKNDC	P86		7/77	HAR	CUNNINGHAME+ Work started.
U	238	RESON PARAM	EXPT-PROG	1.0 2	2.6 3	UKNDC	P86		7/77	HAR	JAMES 5 Reson energies
U	238	PHOTO N	EXPT-PROG			UKNDC	P86		7/77	HAR	LEES+
U	238	PHOTO FISSN	EXPT-PROG			UKNDC	P86		7/77	HAR	LEES+ Photo fission near threshold
Pu	239	FISS YIELD	EXPT-PROG			UKNDC	P86		7/77	HAR	MCKEAN+ Work delayed. irrad. DFR
Pu	239	FISS YIELD	EXPT-PROG			UKNDC	P86		7/77	HAR	CUNNINGHAME+ published in J. Inor. Nucl. Chem. Grph.
Pu	239	BETA FISS	EXPT-PROG			UKNDC	P86		7/77	WIN	MURPHY+ Beta decay energy after irradt. in fast reactor spectra
Pu	239	HALF LIFE	EXPT-PROG			UKNDC	P86		7/77	HAR	GLOVER+ awaits final evaluation
Pu	241	HALF LIFE	EVAL.PROG			UKNDC	P86		7/77	HAR	MCKEAN+ different values quoted.
Am	241	ABSORPTION	EXPT-PROG	1.0 3	2.5 5	UKNDC	P86		7/77	HAR	GAYTHER+ ToF LLS
Am	241	FISSION	EXPT-PROG	5.0 0	2.0 4	UKNDC	P86		7/77	HAR	GAYTHER+ ToF Fast Neutron Detector
Am	243	N GAMMA	EXPT-PROG			UKNDC	P86		7/77	HAR	GLOVER+ Product of CM244 Progress Limited
MANY		DIFF.ELAST	EXPT-PROG	2.9 6	1.6 7	UKNDC	P86		7/77	EDG	GALLOWAY+ polarisation and differential elastic 20^o-160^o
MANY		FISS YIELD	EVAL.PROG			UKNDC	P86		7/77	HAR	CROUCH assessment for many fission nuclei made.

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)

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

The construction programme for the new linac project has so far essentially kept to the schedule required to meet the key dates given in UKNDC (76) P80,p2. Much of the contrete linac hall has been built, by Chivers Ltd. to the design and specification of the Building Design and Construction Group of Engineering Division, and the shells of associated buildings, including the modulator and control rooms, have been erected. Clearance work connected with the construction of the new experimental cells has begun. Two accelerator sections, a modulator tank, and other associated equipment are in the final stages of production at Radiation Dynamics Ltd., and Thomson-CSF (U.K.) Ltd. have manufactured and delivered the first two klystrons to the firm. Works tests at Radiation Dynamics Ltd. with an accelerated electron beam are due to begin in March 1977.

The old 45 MeV linac was shut down at the end of November 1976. The last four of the seven accelerator sections have been removed to allow building work to proceed but the capability to produce a low energy ($\lesssim$ 13 MeV electrons) beam from the first three sections has been retained. Use of this beam will be restricted to the silent hours and it is envisaged that it will be used primarily for irradiation work.

E. Measurements of the neutron cross sections of ^{241}Am (D.B. Gayther, B.W. Thomas, D.A.J. Endacott and J.E. Jolly)

Capture cross-section [Relevant to request numbers 1042-7, 1049, 1051-2]

The last report gave details of a measurement of the absorption cross-section of ^{241}Am using the 230 l liquid scintillator (UKNDC (76) P80, p.3). A two parameter data collection system was used (pulse amplitude and time-of-flight). Sorting and summing of individual runs has been completed, and a preliminary determination of the average absorption cross-section is shown in Fig. 1 for gamma-ray events in the range 3 to 7 MeV. Although both capture and fission gamma-rays were detected in this measurement, the result is essentially a capture cross-section since this process dominates below a few hundred keV (see section on fission below). The measurement of the neutron spectrum incident on the sample is described in the contribution on the capture cross-sections of structural materials (this report p. 3). In the present work, the shape of the absorption cross-section is determined, and in Fig. 1 the result has been normalized in the 30 to 40 keV interval to the recent measurements of Weston and Todd [1] Also shown in the figure are the values in the American data file ENDF/BIV. No corrections to the data have been applied for multiple scattering in the sample or for the variation of detection efficiency with neutron energy, but it is thought that these effects will be of

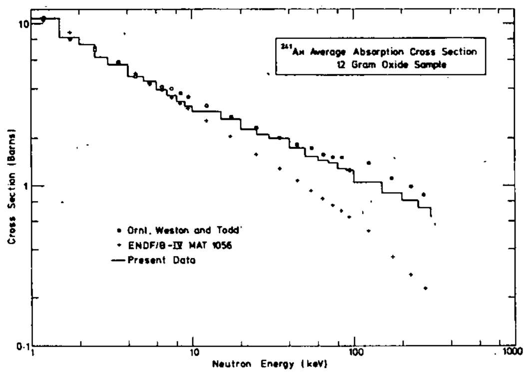

Fig. 1 Comparison of a preliminary analysis of a measurement of the neutron absorption cross-section of ^{241}Am with other data in the energy range 1 to 300 keV.

minor importance. The next stage in the analysis will be to establish an independent normalization to the gold cross-section.

Fission cross-section [Relevant to request numbers 1054-8]

The need for fission cross-section measurements on ^{241}Am below threshold is of prime importance for resolving a major discrepancy (up to a factor of 40) in the available data.

The present measurement was made in the energy range from a few eV to 20 keV using the 12 g $^{241}AmO_2$ sample on a 13 m linac flight path. Fission events were recorded with a fission neutron detector equipped with a pulse shape discriminator to eliminate events caused by gamma-rays. The measurement was difficult because of the low fission yield and the high background resulting from (α,n) reactions in the sample. The spectrum of incident neutrons was measured with a ^{6}Li-glass detector. Fission measurements were also made with a ^{235}U sample to provide a normalization for the ^{241}Am data.

Although the analysis of the results is still at an early stage, it is already possible to place an upper limit of 100 mb for the value of the average fission cross section of ^{241}Am in the energy range 1 to 10 keV. This is almost an order of magnitude smaller than the data from the 1966 bomb shot(2).

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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) P.A. Seeger, A. Hemmendinger and B.C. Diven, Nucl. Phys. A96 (1976) 505

E. Neutron capture cross-sections of structural materials (D.B. Gayther, B.W. Thomas, B. Thom (Queen Mary College), M.C. Moxon, D.A.J. Endacott and J.E. Jolly)

[Relevant to request numbers: 184-193, 233-8, 140-5]

During the past nine months, the original two-parameter measurements taken with the large liquid scintillator (UKNDC (76) P80,p4) for Fe, Ni, Cr and the Au reference sample have been sorted, and similar runs have been summed. Individual runs were examined for consistency at the summing stage and rejected when counting losses or poor monitoring introduced errors in normalization. As a result of this processing, data for each sample have now been archieved as two dimentional arrays of pulse amplitude and time-of-flight.

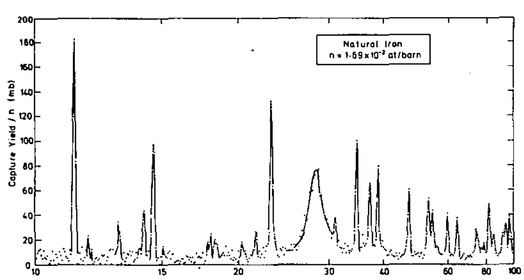

Fig. 2(a) Capture yield for natural iron from 10 to 100 keV (preliminary result)

The measurement of the neutron spectrum incident on the capture sample in the large liquid scintillator used a detector based on $^{6}Li(n,\alpha)$ cross-section below 50 keV, and a detector based on the $^{235}U(n,f)$ cross-section at higher energies (UKNDC (76) P80, p4). These data have now been analysed. This has enabled the next stage in the analysis to be made, that of determining the capture yield (number of capture events per incident neutron). The preliminary results of such an analysis for a 2 mm Fe sample are shown in Fig. 2 (a,b).

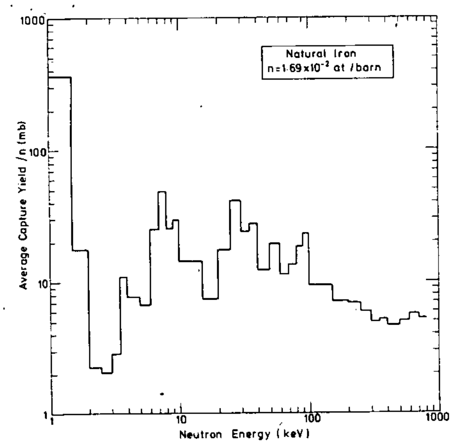

Fig. 2(b) Average capture yield for natural iron from 1 to 800 keV (preliminary result)

In the examples shown, pulse amplitudes were selected which corresponded to the detection of gamma-rays in the energy range 4 to 9 MeV The capture yield has been normalized at the 1 keV resonance in ^{56}Fe to absolute measurements made on the same sample with a Moxon-Rae detector (UKNDC (76)P80,p5). The final stage in the determination of capture cross-sections will be achieved in the near future, when the effects of multiple scattering and variation of detector efficiency with neutron energy have been evaluated.

A similar stage has been reached in the analysis of the Au reference data. The shape of the average capture yield is in excellent agreement with the recent measurements of Macklin et al[(1)] when normalized at 30 keV. In this case, the effects of multiple scattering and detector efficiency variation are expected to be small.

(1) R.L. Macklin, J. Halpern and R.R. Winters, Phys. Rev. C11 (1975) 1270

H. Area analysis of neutron resonances in nickel transmission data (D.B. Syme and P.H. Bowen) [Relevant to request numbers: 256, 261, 266]

Area analysis is almost complete for 87 narrow (ℓ>0) resonances between 20 and 300 keV in high resolution neutron transmission data (UKNDC 76 (P80),p10) for two thicknesses of natural nickel.

Transmission data of similar quality on separated ^{58}Ni were obtained on the Harwell Synchrocyclotron and these have been invaluable in isotopic identification of resonances in the natural data. We have determined $g\Gamma_n$ for 53 (ℓ>0) resonances in ^{58}Ni, 31 in ^{60}Ni and 3 in ^{62}Ni from the natural sample data. (Resonances from low abundance isotopes are unlikely to be observed, and losses due to resonance overlap occur above about 250 keV). In this energy range, neutron widths were previously known for 5 (ℓ>0) resonances in ^{58}Ni and 15 in ^{60}Ni[(1)] so that the resonance parameter data have been much extended. The few well-separated s-wave resonances are being analysed at present. Both sets of resonance parameters will be used as starting values for multilevel shape analysis, which in conjunction with capture yield data will yield Γ_γ values.

(1) M.C. Moxon, AERE R7568 (1974)

Doppler broadening studies on UO_2 (T.J. Haste and M.G. Sowerby) [Relevant to request numbers : 775, 776-8, 823, 852, 854, 856]

The programme of work to study Doppler broadening effects in heated UO_2 (UKNDC(76)P80, p 11) has been continued. Following initial tests of the vacuum furnace up to the design temperature of 2300K, modifications were made to the radiation shielding, and in addition a voltage stabiliser was installed in the heater tube power supply. Transmission measurements were made on depleted UO_2 samples from 1 cm to 6 cm in thickness at temperatures of 293, 1093 and 1730K and also on 4 cm samples at 2100K. Some raw data for 4 cm samples are shown in Fig. 3, where the increased Doppler broadening at 1730K is clearly seen. At the higher temperature the thickness of the sample is reduced owing to expansion, hence the off-resonance transmission is greater in this case. Hot and cold sample measurements were made in the same run, with the hope of reducing systematic errors. The temperature of the hot sample was monitored regularly during the runs using an optical pyrometer. The voltage applied to the heater tube, the current flowing through the heater tube, and the temperature of the cold sample were recorded continuously.

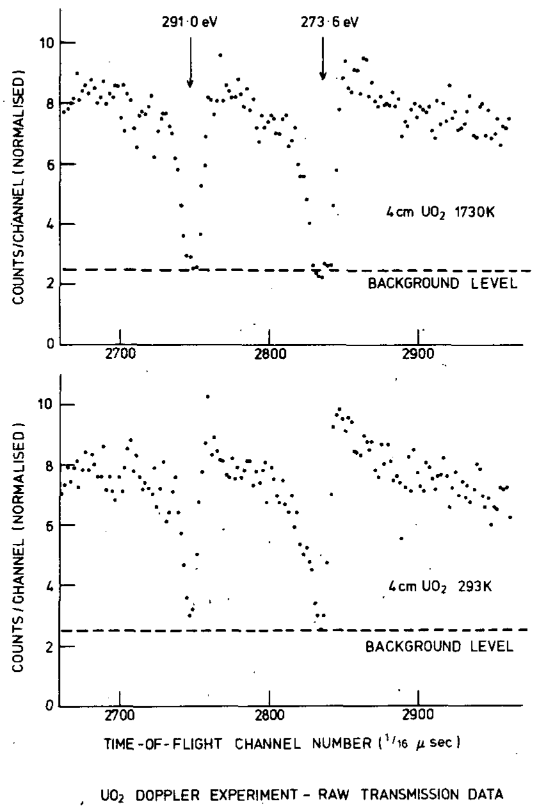

***Fig. 3** Raw transmission data for 4 cm UO_2 samples at 293K and 1730K*

Examination of the furnace following the highest temperature run indicated the need for further improvements to the tantalum radiation shields and to the cooling system. Evaporation of the UO_2 samples at 1093 and 1730K was negligible. However, at 2100K substantial loss of UO_2 did occur (over a period of about 5 days). This loss was contained within the vacuum vessel. The feasibility of canning samples for use at temperatures over 1700K is to be studied.

The uniformity of the UO_2 samples was investigated at Harwell by neutron radiography (M.J. Prictoe) and marginal range proton radiography (D. West). The latter technique proved more sensitive; a large area defect of about 0.1% of the sample thickness was noted in one case. Following these tests the most uniform samples were selected for the transmission measurements.

The transmission data are in the preliminary stages of analysis. Computer programs to assist in the analysis are being developed.

H. Transmission and spectrum measurements on the synchrocyclotron (P.H. Bowen, M.C. Cooke (Queen Mary College), A.D. Gadd, G.D. James, D.B. Syme and I.L. Watkins) [Relevant to request numbers: 165-7, 212, 222, 256, 266]

The small sample flight path has been used to make neutron transmission measurements on 1.2cm Fe, 0.6cm Ti, 1.8cm Ti and ^{58}Ni. These measurements supplement the data taken previously and will help in the task of resonance analysis. The results for ^{58}Ni taken at 50 m with a Li-glass detector and at 100m with an NE110 detector are shown in fig 4.

In order to select suitable material for the construction of the neutron producing target for the new Linac, high resolution transmission measurements have been carried out on zircalloy, Mo, Ta, Hg and U, and high resolution measurements of neutron spectra have been made for assemblies of uranium sheets in water placed directly in front of the tungsten proton target in such a way that some protons were stopped in the uranium. Similar spectrum measurements were made for a water cooled assembly of tantalum faced with a thin sheet of zircalloy. This target was provided by M.S. Coates and represents a possible Linac target assembly. The effect of the 13m of air normally present in the 100m flight path was successfully removed by making an additional measurement with 26m of air.

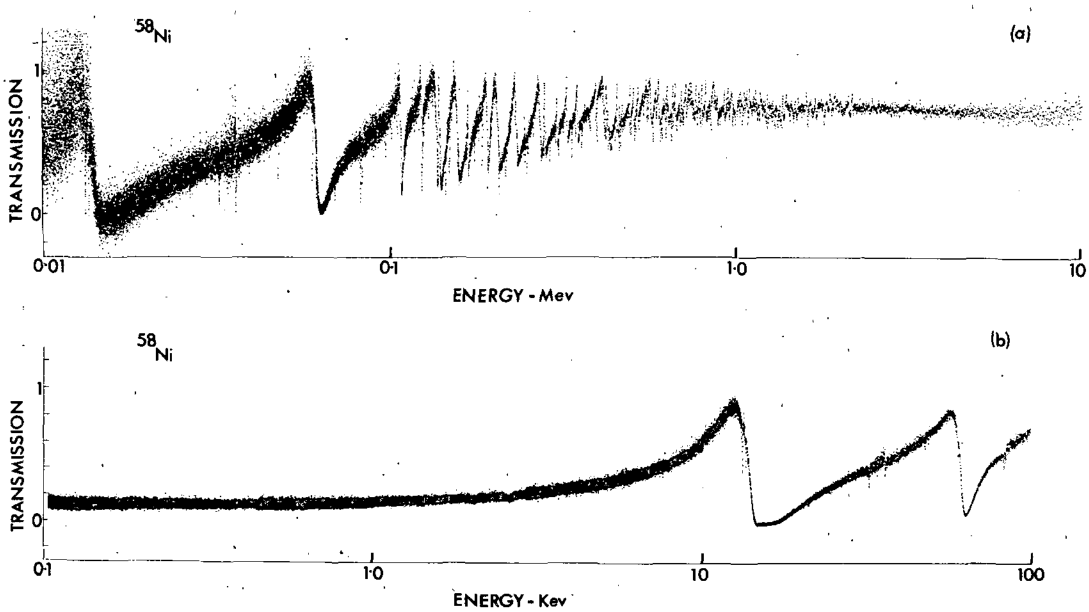

Fig. 4 The neutron transmission of ^{58}Ni from 0.1 keV to 10 keV measured with a Li-glass detector on a 50 m flight path and from 0.01 MeV to 10 MeV measured with a dynamically discriminated NE110 detector on a 100 m flight path.

H. Synchrocyclotron time of flight data taking program (J.P. Argyle and M.C. Cooke (Queen Mary College)

The neutron time-of-flight data taking program GCTX06 which runs on a Honeywell DDP516 has been modified to increase the rate of data taking from 1500 s^{-1} to 2000 s^{-1} and to reduce the computer core usage. The six scaler modules have been replaced by a single width module containing twelve 100 MHZ scalers. A new program records certain monitor counts. These ratios are plotted on a line printer at the end of a run and enable monitor stability to be examined. Another new routine enables the user to check the position and width of the gamma flash at any time during the experiment. Up to eight different spectra can now be recorded within the 32,000 channels available. The VDU cursor can how be positioned by three thumb wheels which give the channel reading.

H. Neutron energy standards (G.D. James)

As part of a collaborative effort between several laboratories to compare and improve neutron energy standards, the energy at the peak of several neutron cross section resonances in ^{238}U and at 2078 keV in carbon have been determined on the synchrocyclotron.

The results are given in table 1 for four separate measurements on the carbon resonance, three at 100m using an NE110 detector and one at 50m using a Li-glass detector. The table also gives the energies obtained by subtracting the 50m flight path and flight time from the 100 flight path and flight time. This method is designated as $\Delta L/\Delta t$. It enables the slowing down time delay, the estimation of which introduces the greatestsinglé uncertainty, to be removed from the equations. To be correct, the same detector should be used at both flight path lengths but the failure to do this introduces only a minor uncertainty in the data. Table 1 also shows the data available from six other laboratories. The measurements of Heaton et al [2] and by Meadows [3] were made on Van de Graaff accelerators by the mono-energetic beam technique. All the other measurements were made by neutron time-of-flight experiments. The excellent agreement between the two methods is clear. The three central values are quoted more precisely than the others. Taken alone these values have an average of 2078.11 ± 0.16 keV. The average for all seven values is 2078.05 ± 0.32 keV. In both cases the error in the mean is quoted.

Table 1

Measured peak energy for the resonance in carbon at 2078.05 + 0.32 keV

Reference	Date	Energy (keV)
Harwell 50m	Aug' 76	2079.2 ± 1.1
" 100m	Aug' 76	2078.31 ± 0.44
" $\Delta L/\Delta t$	Aug' 76	2077.45 ± 0.84
" Average*		2078.33 ± 0.89
Davis & Noda [1]	1969	2079 ± 3
Heaton et al [2]	1975	2079 ± 3
James	1977	2078.33 ± 0.89
Meadows [3]	1977	2078.2 ± 2.8
Perey et al [4]	1972	2077.8 ± 1.5
Böckhoff et al [5]	1976	2077 ± 1
Cierjacks et al [6]	1968	2077 ± 1
Average**		2078.05 ± 0.32

* Error in individual reading derived from spread of the data.

** Error in the mean derived from spread of the data.

The first part of table 2 gives the results of four measurements of energies at the peak of five resonances in the total cross section of ^{238}U. All these measurements were made using a Li-glass detector on the Harwell Synchrocyclotron time-of-flight spectrometer. A measurement on a 50m flight path was made in August 1976. For other reasons, the flight path was then raised by 3cm and the source geometry was altered so that the water

Table 2

Measured peak energies for five resonances in ^{238}U

Origin	Energy (keV)	Energy (keV)	Energy (keV)	Energy (keV)	Energy (keV)
Harwell 50m Aug' 76	145.634 $\pm$ 0.037	463.23 $\pm$ 0.12	708.44 $\pm$ 0.19	1420.12 $\pm$ 0.45	2590.16 $\pm$ 0.40
" 50m Nov' 76	145.578 $\pm$ 0.051	462.93 $\pm$ 0.15	708.62 $\pm$ 0.27	1419.56 $\pm$ 0.35	2489.96 $\pm$ 1.1
" 100m Nov' 76	145.593 $\pm$ 0.033	463.09 $\pm$ 0.12	708.09 $\pm$ 0.13	1419.80 $\pm$ 0.34	2489.26 $\pm$ 0.79
" $\Delta L/\Delta t$ Nov' 76	145.606 $\pm$ 0.071	463.24 $\pm$ 0.25	707.59 $\pm$ 0.29	1420.02 $\pm$ 0.46	2488.61 $\pm$ 1.54
Harwell average*	145.603 $\pm$ 0.024	463.12 $\pm$ 0.14	708.18 $\pm$ 0.45	1419.88 $\pm$ 0.25	2489.50 $\pm$ 0.71
Oak Ridge (7)				1419.76 $\pm$ 0.19	2489.18 $\pm$ 0.43
Geel (5)	145.68 $\pm$ 0.10	463.62 $\pm$ 0.20	708.59 $\pm$ 0.25	1420.7 $\pm$ 0.3	2490.8 $\pm$ 0.4
Columbia (8)	145.57 $\pm$ 0.15	462.8 $\pm$ 0.4	707.9 $\pm$ 0.4	1419.2 $\pm$ 0.3	2488.4 $\pm$ 0.7
Average**	145.617 $\pm$ 0.033	463.18 $\pm$ 0.24	708.22 $\pm$ 0.20	1419.88 $\pm$ 0.32	2489.47 $\pm$ 0.5
G	4412	1929	3541	4437	4978

* Error quoted here is that in an individual reading derived from the spread of four values

** Error in the mean derived from the spread is quoted.

moderator stood in front of the proton target instead of underneath it. Energy measurements of ^{238}U resonances were then made, in November 1976, both at 50m and at 100m flight path lengths. From these two measurements the results given by the $\Delta L/\Delta t$ method were also computed. The correct method of deriving the best value from these four estimates remains to be formulated. For the present, the four results obtained for each resonance are regarded as independent and the average value is given. However the error quoted in the average value is that for an individual reading derived from the spread of the measurement.

Table 2 also shows measurements from three other laboratories. Results from Oak Ridge for three of the resonances were not available when the table was prepared. An unweighted average from all Laboratories together with an error in the mean derived from the spread is also given. The agreement between Harwell and Oak Ridge[7] is well within the quoted errors and all the Harwell values are within the quoted range of the average from all laboratories. The discrepancy between Geel[5] and Columbia[8] has already been noted[5]. The accuracy of the measurements at present is illustrated by G, the ratio of the average value to its error.

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H. The $^{238}U/^{235}U$ fission cross section ratio over the energy range 1.2 MeV to 2 MeV (P.A.R. Evans, G.B. Huxtable and G.D. James) [Relevant to request numbers: 833-4, 837, 841-2]

A measurement of the $^{238}U/^{235}U$ fission cross section ratio over the energy range 1.2 to 2 MeV has been made mainly to help resolve an energy discrepancy between the measurements of Coates et al[1] and the measurements of Behrens et al[2] and Cierjacks et al[3]. Coates et al[4] have revised their method of establishing the energy scale and their results are now in better agreement with the data of Behrens et al. Although the present experiment was, in a sense, a repeat of that carried out by Coates et al[1], none of the experimental details was the same except that the same foils and gas scintillation chamber were used. In particular, all factors concerning the determination of neutron energy were different in that a different flight path length and a different time digitizer[5] were used. Also, in the time between the two experiments the energy scale of the time-of-flight system was carefully assessed[6]. The data obtained

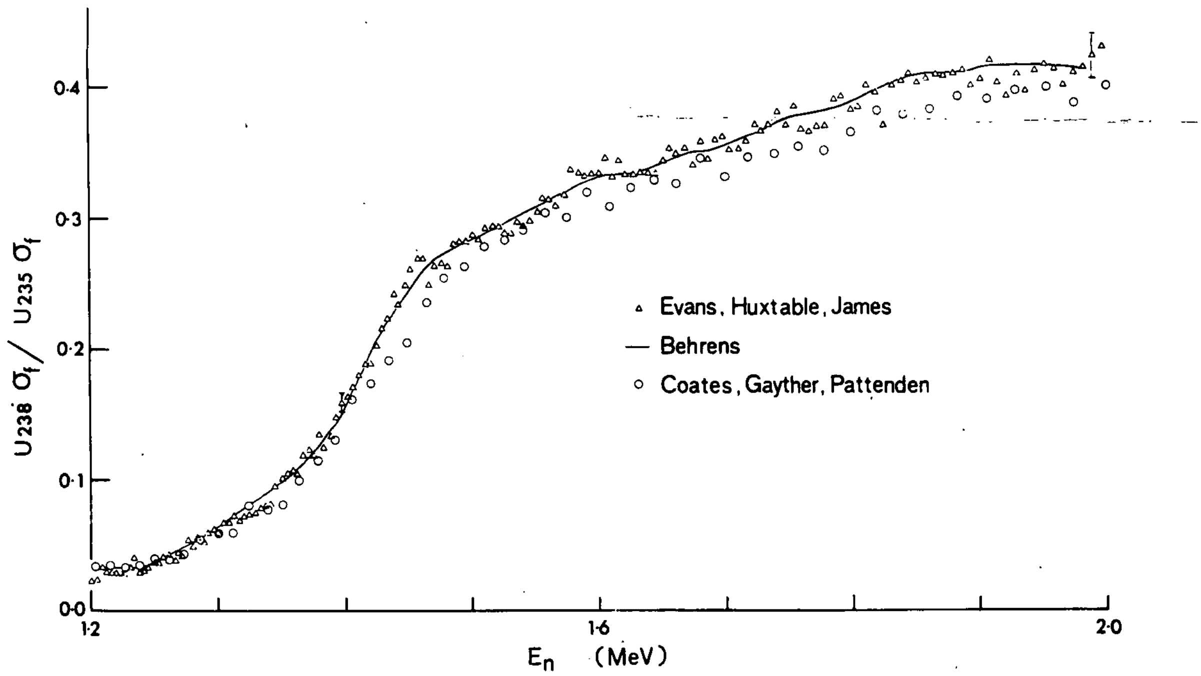

Fig. 5 The ratio of the ^{238}U to ^{235}U fission cross sections over the energy range 1.2 to 2 MeV. The results of the present experiment (Δ) are compared with the solid line derived from the data of Behrens et al. and with the renormalised data of Coates et al. (O)

(Fig. 5) give an energy scale in close agreement with the results of Behrens et al[(3)]. The re-analysed data of Coates et al[(1)] are also shown. This work has now been published.

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(5) J.P. Argyle, P.E. Dolley and G. Huxtable, Proc. 2nd ISPRA Nuclear Electronic Symposium (Euratom, Luxembourg) EUR 537oe (1975) 421

(6) G.D. James, D.B. Syme, P.H. Bowen, P.E. Dolley, I.L. Watkins and M. King, AERE-R7919(1975)

(7) P.A.R. Evans, G.B. Huxtable and G.D. James, Report ANL-76-90 (1976) 149

Simulation of structure in ^{235}U cross sections (G.D. James)

It has been shown in collaboration with G. de Saussure and R. Perez[(1)] that the fission and capture cross sections of ^{235}U when averaged over 100 eV intervals over the energy range 10 keV to 40 keV show structure established as significant by the Wald and Wolfowitz runs test. This work has been extended by the application of a more powerful correlation test due to Wald and Wolfowitz[(2)] and also by a simulation of these cross sections which closely reproduces the observed runs and correlation statistics. This simulation used a modulation of the 3^- sequence of resonances only. The modulated value of the 3^- fission width is given by the equation:-

$$\Gamma_{\lambda f} = \Gamma_{\lambda f} + \sum_{\mu} \frac{A^2_{\lambda\mu} \cdot \Gamma_\mu}{(E-E_\mu)^2 + \Gamma^2_\mu/4}$$

where $\Gamma_{\lambda f}$ is an energy independent component associated with the class I levels, Γ_μ and E_μ are the fission widths and level energies for the class II levels and $A_{\lambda\mu}$ is the coupling between the two potential wells. The energy dependence of the structure was best fitted by the following average modulation parameters

$$\langle A^2_{\lambda\mu} \rangle = 18.7 \pm 7.1 \text{ eV}, \quad \langle \Gamma_\mu \rangle = 1000 \pm 380 \text{ eV and } \langle D_\mu \rangle = 2000 \pm 800 \text{ eV}.$$

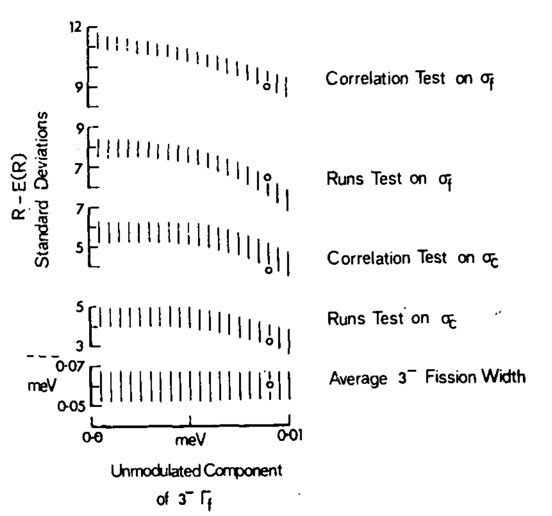

Fig. 6 Structure statistics for ^{235}U (O) compared with simulated data shown by vertical bars which extend over two standard deviations. Both experimental and simulated results are obtained by applying the correlation test and the runs test to 100 eV average values of the ^{235}U fission and capture cross sections over the energy range 10 keV to 40 keV

Here D_μ is the average modulation level spacing.

Structure statistics obtained from both the simulated and the experimental cross sections are shown in fig. 6 as a function of $\Gamma_{\lambda f}$, considered a free parameter. At the optimum value of $\Gamma_{\lambda f}$ (=0.009 eV) the experimental and simulated cross sections give consistent values for all four structure statistics, i.e. the runs and correlation statistics for capture and fission cross sections. The numerical values for this case are given in table 1 in terms of a parameter 'F' defined as the difference between a statistic and its expectation value in the absence of structure, expressed in units of standard deviation. The technique is successful in producing F values from simulated cross sections which are within 0.6 standard deviations of those from the experimental data. This work has been published[3].

TABLE 1

Simulated and experimental F values for ^{235}U

	Simulated F	Experimental F	Difference/SD
σ_F Correlation	9.35 $\pm$ 1.54	8.94	0.27
σ_F Runs	5.95 $\pm$ 1.67	6.48	0.32
σ_c Correlation	4.85 $\pm$ 2.01	3.75	0.55
σ_c Runs	3.45 $\pm$ 2.06	3.27	0.09
Average Γ_{f3}	0.060 $\pm$ 0.021 eV	0.060 eV	0.00

1. G.D. James, G. de Saussure and R. Perez, Trans. Am. Nucl. Soc. 17 (1973) 495 and AERE-PR/NP21, p19.

2. A. Wald and J. Wolfowitz, Annals. Math. Stat. 14 (1943) 378

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E. The measurement of the energy dependence of eta in the neutron energy range below 1 eV (M.C. Moxon and J.E. Jolly) [Relevant to request numbers: 757-9]

To meet the U.K. thermal reactor data requests for the energy variation of η in ^{235}U and ^{239}Pu, a series of measurements on the Harwell 45 MeV linac and necessary correction procedures were proposed in (UKNDC (76) P80, p21). During the period covered by this report transmission measurements on four samples of ^{235}U were completed and a preliminary analysis started.

The liquid scintillator used for detecting fast neutrons was set up with pulse shape discrimination equipment to distinguish between fast neutrons from fission events and gamma-rays from both fission and capture events. Time-of-flight measurements were carried out on four samples of ^{235}U. Measurements were also carried out on samples of ^{Nat}Ta, ^{Nat}Hf, ^{197}Au and ^{Nat}U to check the cross talk between the gamma-ray output and the neutron output. In each run four sets of time-of-flight data were recorded:- (a) a neutron flux monitor (this was to enable the count loss correction to be carried out more accurately), (b) the output from two thin ^3He counters placed in the beam between the neutron source and the ^{235}U sample (enabling a check to be kept on the neutron spectrum), (c) the fast neutron and (d) gamma-ray outputs from the liquid scintillator. The last two were required for count loss correction which depends on both outputs; they also enable an accurate correction to be carried out for the gamma-ray cross talk in the neutron spectrum and the neutron energy dependence of alpha may be obtainable from their ratio.

Measurement of the fast neutron fission spectrum of ^{235}U at 0.1 MeV incident neutron energy (J.M. Adams, B. Trostell (Studsvik) and L. Eriksson (Studsvik)) [Relevant to request numbers: 767, 769]

This measurement was conducted using the 6 MeV pulsed Van de Graaff accelerator of AB Atomenergi, Studsvik, Sweden, which delivers 1.5 ns pulses of protons or deuterons at a repetition frequency of 1 MHz on to a neutron producing target. The objective of the measurement was primarily to study the low energy portion of the fission neutron spectrum in order to investigate whether there was any evidence to suggest a departure from a Watt formalism, which has been shown to provide a good description of the shape of the ^{235}U and ^{239}Pu fast neutron fission spectra at higher fission neutron energies (UKNDC(76)P80,p14).

The experimental arrangement comprised two fast neutron detectors (12.5 cm diameter by 5 cm thick NE213 organic scintillators coupled to 11.4 cm RCA8854 photomultipliers) employing the new Harwell n-γ PSD system.* Both detectors were housed in a large shield, which could be rotated automatically about a fixed point, and each detector could be collimated to look either at the neutron producing target or the ^{235}U sample by suitable adjustment of the target position itself. All data were recorded at a flight path of 3 metres, and the angular separation between the detectors was 5^{o}. For each detector, the fast neutron fission neutron spectra were recorded at a "mean" laboratory angle of 90^{o} using a hollow cylindrical sample of ^{235}U (42g, 93% enriched, 2.95 cm long, 2.5cm outer dia., 1.8cm inner dia.)$^{+}$, positioned 5.5cm from a 10 keV thick Li metal target producing neutrons of approximately 100 keV. The relative detector response functions were measured using conventional techniques and checked by thick target Cu(p,n) neutron time-of-flight spectra during the course of the experiment. This also confirmed the neutron energy calibration at the lower neutron energies. The energy calibration of the neutron time-of-flight scale was obtained using monoenergetic neutrons up to about 1 MeV, and using the neutron groups from the $^{9}Be(d,n)^{10}B$ reaction at higher neutron energies. At present the data are being analysed.

* On loan from AERE Harwell

\+ Supplied by AERE Harwell

B. Neutron scattering from ^{238}U (B.H. Armitage and W. Spencer) [Relevant to request numbers 800, 802, 804, 807]

Measurements made on the inelastic scattering of neutrons from natural U are now complete and are in the process of being prepared for publication. The measurements, which involve the use of time-of-flight techniques, have been made at seven neutron energies between 1.12 and 2.37 MeV, and have been carried out at the single observation angle of 90^{o}.

The energy dependence of the detector efficiency was measured by comparison with the calibrated Harwell long counter during the course of each series of measurements. The detector efficiency has also been determined by J.L. Rose using known angular distribution data for the $^{7}Li(p,n)^{7}Be$ and the $^{3}H(p,n)^{3}He$ reactions. Furthermore the detector efficiency was measured by comparison with the calibrated boron vaseline plug[1] detector. Finally a calculation of the detector efficiency was obtained from the Lucifer program[2].

The cross-sections for the excitation of the 45 keV (2^+) and 148 keV (4^+) members of the ground state rotational band have been measured and are shown in Fig. 7 where a comparison is made with the results of other workers[3,4]. Since the inelastic groups corresponding to the states are not adequately resolved at the primary neutron energies involved, a sample of Bi was used to obtain a reference peak. The Bi peak shape (free from the presence of unresolved inelastic groups) was then used to deduce the cross section of the two low lying states in ^{238}U.

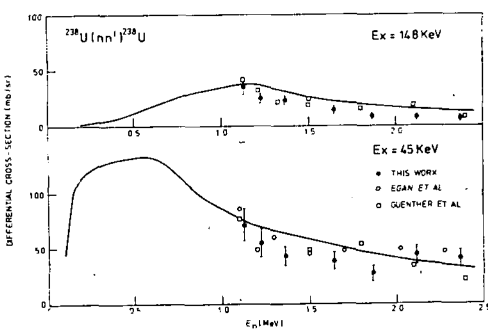

Fig. 7 Cross-sections for the excitation of the 45 keV (2^+) and the 148 keV (4^+) state of ^{238}U compared with the results of other measurements. The solid curves correspond to calculations made by Guenther et al[4] using a combination of the optical model and direct interaction theory.

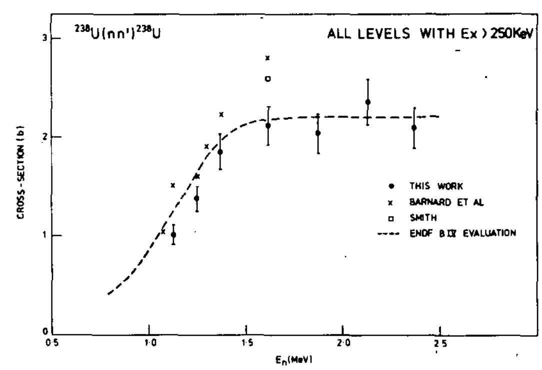

Fig. 8 Measured cross-sections for the inelastic scattering of all levels above an excitation energy of 250 keV, compared with the results of other workers and with the ENDF/BIV evaluation

No further attempt has been made to obtain cross-sections for individual levels in ^{238}U. Consequently the measured inelastic scattering cross-sections have been expressed as integrals over a number of bands of excitation energy. In Fig. 8 the cross-sections for all excited states above 250 keV are given as integral cross-sections, it being assumed that the inelastic scattering cross-sections are isotropic. The cross-sections appear to be significantly lower than those obtained by others but their departure from the ENDF/BIV evaluation is not great except perhaps at the lower end of the primary neutron energy range.

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3. J. Egan et al, Fourth Inter. Conf. on Nuclear Cross-Sections and Technology, Washington (1974)

4. P. Guenther, D. Havel and A. Smith, ANL/NDM-16 (1975)

5. E. Barnard, A.T.G. Ferguson, W.R. McMurray and I.J. Van Heerden, Nuclear Physics 80 (1966) 46

6. A.B. Smith, Cited by W.P. Poenitz in Proc. Inter. Conf. on Nuclear Data for Reactors, Helsinki (1970)

E. Test of a resonance detector for eV range neutron spectroscopy using pulsed neutron sources (R.N. Sinclair, M.C. Moxon and J.M. Carpenter (Argonne National Laboratory))

For neutron scattering measurements which require the definition of final energies in the eV range a resonance capture detector has been successfully tested. Such a detector is needed to make possible the efficient use of the high flux of epithermal neutrons provided by pulsed neutron sources. Scattering samples were placed in a neutron beam of the Harwell 45 MeV electron linac pulsed source, within the Moxon-Rae total capture gamma ray detector. Around the sample, a 0.00127 cm ^{181}Ta foil was arranged at a scattering angle of 90°. Neutrons scattered to 4.28 eV were detected through the capture gamma-ray cascade, while the probability of scattering as a function of incident energy was established by time of flight. The scattering from samples of lead and of graphite was determined in a few hours with reasonable statistical accuracy and in agreement with Monte Carlo simulations of the measurements, between the time of arrival of 10.34 eV and 4.28 eV neutrons. The test indicates that efficient spectrometers can be designed having final energy resolution of the order of 0.02 eV and final neutron energies of 1 to 10 eV.

Assessment of transmutation, activation and afterheat in fusion reactor structures (O.N. Jarvis)

The investigation of the effects of nuclear reactions on materials expected to be used in fusion reactor construction is conveniently separated into two distinct calculations. First, Monte Carlo or discrete ordinate codes are used to derive the neutron fluxes and energy spectra at various locations in the reactor using known cross-section data for the original constituents of the structure (the neutron blanket being of greatest interest). Transmutation, activation and afterheat effects can then be studied in detail for various periods of postulated operation of the reactor, taking several generations of reaction and decay products into account, using codes such as FISPIN and ORIGEN (although these codes were written specifically for fission reactor calculations). Either code constitutes a satisfactory basis for future CTR investigations; their use has been investigated using a partial data library prepared for a niobium structure using a Fast Breeder Reactor neutron spectrum and the results were found, as expected, to be in excellent numerical agreement.

There is no complete multi-group nuclear data library in existence which can be applied directly to general CTR applications. Many qualitative survey investigations have been performed for specific fusion reactor structures but the present need is to prepare a library which includes all likely structural materials and in which the decay and reaction chains are not truncated too abruptly. Indeed, the quantitative value of future activity calculations will be assessed in terms of the extent and quality of the nuclear data incorporated into the library. As an example of the complexity of the data requirement one can do no better than to refer to an unpublished report by W. Danner(1) who has shown that a full activation analysis for stainless steel would require cross-sections for no fewer than 378 nuclear reactions, involving a total of 104 nuclides of which 73 are radioisotopes (for which few experimental results are available). The present approach is to generate a basic multigroup library for all nuclides and reactions of interest by the combined use of nuclear models, partial libraries prepared elsewhere and the various nuclear data compilations. This master library will then be spectrum averaged before being recast into secondary libraries suitable for access by FISPIN or ORIGEN.

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(1) W. Danner, Unpublished report No. 6 Max-Planck-Institut fur Plasmaphysik, Garching, W. Germany (1975)

D,B <u>Measurement of cross sections for fusion reactor applications (C.A. Uttley, J.A. Cookson, M. Swinhoe* and C. Wise*)</u>

(1) <u>The $^{7}Li(n,n'\alpha\ t)$ reaction</u> [Relevant to request numbers: 1240-5]

The tritium production cross section and the secondary neutron spectrum are to be measured as a function of incident neutron energy from near threshold to 14 MeV. The method being used for measuring this reaction cross section is based on that discussed by Dierckx[1]. A sample of Li_2CO_3, enriched to 99.97% in ^{7}Li, is irradiated in a measured flux of monoenergetic neutrons from suitable targets on the 12 MeV Tandem generator or the Birmingham Dynamitron. The tritium produced is converted to HTO and measured by β-counting after mixing with a suitable liquid scintillator. Work is underway on the preparation of lithium carbonate samples and the chemistry involved in producing the tritiated water in a solution miscible with a liquid scintillator.

Neutronics calculations show that the energy distribution of the inelastic neutrons from this reaction, particularly at 14 MeV, can have a significant influence on the tritium breeding gain in a fusion blanket and on the total energy deposited. These effects depend on the fraction of inelastic neutrons with energies above the threshold (2.8 MeV) for further inelastic interactions in ^{7}Li leading to tritium production. The measurement of the inelastic neutron energy distribution will be carried out principally on the 3 MeV pulsed Van de Graaff IBIS.

(2) <u>(n,α) cross sections</u> [Relevant to request numbers: 1369-71, 1394-6, 1417-9]

(n,α) cross sections of Fe, Ni and Cr are likely to be important in a stainless steel structured fusion reactor blanket both with respect to radiation damage and neutron economy. At present (n,α) data on these elements in the available libraries differ by up to a factor of two and the evaluations rely heavily on model predictions of the cross sections. Consideration of available neutron yields from the 12 MeV Tandem Generator, the 500 keV Cockcroft-Walton accelerator and the 3 MeV Van de Graaff IBIS suggest the following possible programme:

(a) elemental (n,α) cross sections of Fe, Ni and Cr at 14 MeV using either solid state track detection or electronic detection of the α particles,

(b) a measurement at 14 MeV on one or more isotopes which are also capable of study by activation. In these cases the energy dependence of the (n,α)

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cross section could also be measured by irradiations on the Tandem Generator in addition to the energy spectra and angular distribution of the α particles at 14 MeV.

Common to both sets of measurements outlined in (1) and (2) is the need to determine the incident neutron flux. For this purpose an NE213 liquid scintillator, 5 cm dia. by 3.8 cm thick coupled to an RCA 8850 photomultiplier, is presently being calibrated in terms of absolute efficiency over an energy range from 2 MeV to 20 MeV. The method of calibration is similar to that in UKNDC(76)P80,p13 except that for this detector a neutron-gamma pulse shape discrimination circuit is being used.

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(1) R. Dierckx, Nucl. Instr. and Methods, 107 (1973) 397

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

Survey runs have been carried out on the Tandem Generator and the information used to specify and design the equipment needed for the measurements.

^{3}He neutron counters 1m long and 20mm diameter have been chosen as the detectors. The gas filling consists of 52 torr ^{3}He and 730 torr of A/CH_4. This filling does not minimise the wall effect as it was found that the increased γ-ray sensitivity which results shortens the effective plateau of the counters too much. Twelve counters have been made and filled by E and A.P. Division.

The polythene moderator in which eight ^{3}He neutron counters are to be embedded at different radial positions has been designed and is being constructed. Two modifications have been made in the light of the survey runs.

1. The need to make special provision for gaseous targets such as D,N, O and F and possibly for insulating targets which include B, UO_2 and plutonium oxide (see later) conflicts with positioning the innermost counter as close to axis as is desired in the case of conducting solid targets. To accomodate these conflicting requirements it has been decided to have the central section of the moderator block removeable and to provide different centre pieces for the various targets. At present we contemplate two central blocks which will contain the axial hole for the target tube and the two innermost counter holes for, in the one case, metallic targets and in the other case gaseous and possibly insulating targets.

2. The neutron shield for the moderator was originally specified to contain borated wax. This has been changed to borated resin because of its greater mechanical rigidity.

Preliminary yield determinations using a single neutron counter in a 500mm diameter polythene block have been carried out over the energy region 2 - 7.5 MeV for B, C, Al, Mg, Fe and (for background purposes) Au and Ta. The yield from Al for instance varies by four orders of magnitude between 3 and 7.5 MeV. This sets severe limits on the required reproducibility of the beam energy since a 4 keV change in energy alters the measured yield from Al by 1%. It is known that the day to day reproducibility of the

Tandem is no better than 10 to 20 keV although the short term stability is very much better. To minimise errors from this source a beam energy monitor using Rutherford scattering from thin Au foils is being set up. A preliminary trial using a scattering angle of 45° indicates that energy determinations better than a few keV can be achieved with silicon surface barrier detectors. Tests of the efficiency of different Faraday cup arrangements are still in progress.

Consideration has been given to the means of deriving the thick target neutron yield of a chemical compound or mixture from the measured values of yield of the pure constituents. If the Bragg law of additivity of electron stopping powers in a compound applies, it is believed that only the relative stopping powers of the individual constituents will be involved rather than the variation as a function of energy. Measured values of stopping power indicate that the ratio of stopping powers for any two materials is constant within $\pm$ 2% provided the α-particle energy lies within the limits 3 to 8 MeV and the atomic numbers lie between 4 and 20. In some cases such as UC and UO_2 and plutonium oxide it will be necessary to measure the neutron yield in the actual compound of practical importance. Any serious departure from the Bragg additivity law will also require special treatment.

Finally a small polythene block for intercalibrating the neutron counters and special blocks for mounting neutron calibration sources in the large moderator block have been designed. Two neutron sources, an ^{241}Am - B and an ^{241}Am - F source have been calibrated at NPL in their $MnSO_4$ bath and will constitute the secondary standards of neutron intensity for the measurements.

E. A measurement of the ^{6}Li(n,α) cross-section (D.B. Gayther and J.E. Jolly) [Relevant to request numbers: 1212-3, 1216-7]

A useful by-product of the programme of neutron capture measurements on the linac (this report p3) has been a determination of the energy dependence of the ^{6}Li(n,α) ^{235}U (n,f) cross-section ratio. The energy spectrum of the neutron beam incident on the capture sample was determined with a 1 mm thick ^{6}Li glass detector and also by detecting the fission neutrons from a ^{235}U sample. The measurements were made by the time-of-flight method and allowed a determination to be made of the relative shape of the ^{6}Li(n,α)/^{235}U (n,f) cross-section ratio in the energy range 2 keV to 800 keV. The ^{6}Li(n,α) cross section was obtained by combining the measured cross-section ratio with an evaluation of the ^{235}U(n,f) cross-section. The relative cross-section so derived was normalized in the interval 2 keV to 10 keV where the ^{6}Li(n,α) cross section is accurately known.

Figure 9 shows the derived cross-section based on the U.K. evaluation of the ^{235}U(n,f) cross-section[1]. The accuracy of this result is limited mainly by the uncertainty in the evaluation which is estimated to be $\pm$ 3% ($\pm$ 1 s.d.) at energies below 800 keV. If the more recent ENDF/BV evaluation of the ^{235}U(n,f) cross-section had been used in the derivation, the resulting ^{6}Li(n,α) cross section would not have been changed by more than about $\pm$ 3%, since the shapes of the two evaluations are in broad agreement.

For neutron energies above 50 keV there are considerable discrepancies in the existing data. At the peak of the p-wave resonance at 240 keV, recently reported values

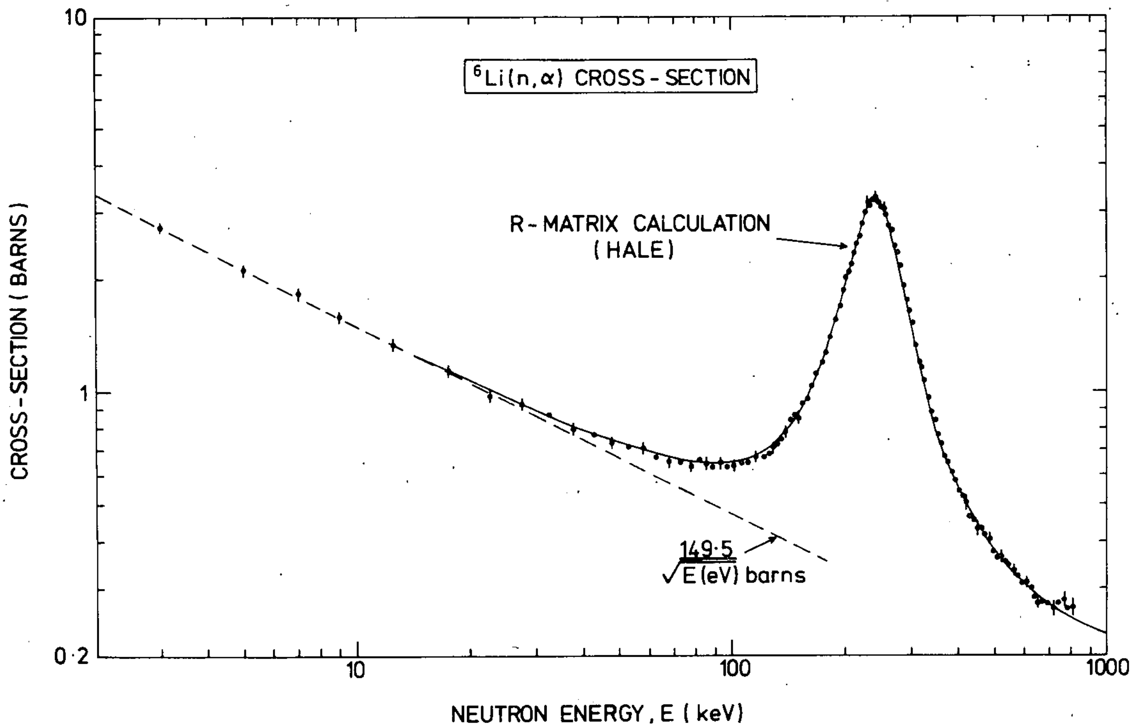

Fig. 9 Comparison of the measured ^{6}Li(n,α) cross-section in the energy range 2 keV to 800 keV with an R-matrix calculation

have ranged from 2.946b(2) to 3.776b(3). The present measurement gives a peak cross section of 3.29 ± 0.12 b. Also shown in Fig. 8 is a recent theoretical calculation of the ^{6}Li(n,α) cross section by Hale(4), in which R-matrix theory was applied to the ^{7}Li system. The parameters of the R-matrix were adjusted to obtain a best fit to known experimental data on the total neutron cross-section of ^{6}Li and the reactions ^{6}Li(n,n)^{6}Li, ^{6}Li(n,α)t and ^{4}He(t,t)^{4}He. It can be seen that the experimental values are in good agreement with the calculated cross-section.

A full account of this work will appear as the report AERE - R 8556.

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

(2) M.S. Coates, G.J. Hunt and C.A. Uttley, Proc. of Panel on Neutron Standard Reference Data, IAEA, Vienna (1974)

(3) S.J. Friesenhahn, V.J. Orphan, A.D. Carlson, M.P. Fricke and W.M. Lopez, Report INTEL-RT 7011-001 (1974).

(4) G.M. Hale (Los Alamos) - private communication to D.B. Gayther, December 16 1976.

D. Scattering of 27.3 MeV neutrons by protons (J.A. Cookson, J.L. Fowler*, M. Hassain**, C.A. Uttley and R.B. Schwartz***)

Measurements are now complete and the data are in the final stages of analysis.

The main problem left unresolved in the last report (UKNDC(76)P80,p12) was a possible contribution from the $^{12}C(n,n'\gamma)$ reaction to the time-of-flight spectrum. This effect has now been investigated by using an NE213 liquid scintillator in place of the NE102A previously used as the hydrogenous scatterer. This allowed neutron-gamma discrimination to be used to show that corrections to the relative hydrogen cross sections of between 0.8 and 2.2% are necessary to allow for this effect.

At the present stage of analysis, the indications are that the measured angular distribution will not disagree significantly with the calculations of Hopkins and Breit[1] from phase shift analyses.

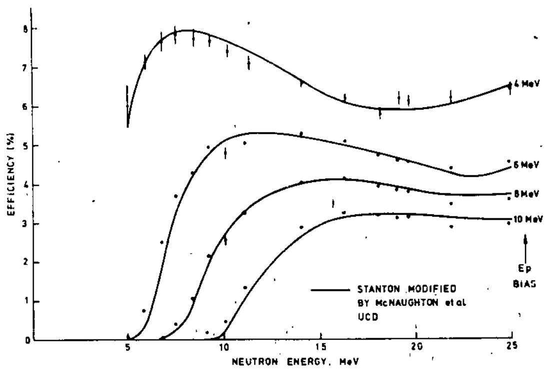

Fig. 10 A comparison of neutron detector efficiency measurements with Monte Carlo calculations for several different bias values (quoted in terms of the recoil proton energy)

A major part of this measurement has been the determination of the efficiency of a 10 cm dia. 2.5 cm thick, NE102A scintillator as a function of neutron energy. The measured efficiencies have now been compared with predictions of a Monte Carlo computer code originated by Stanton[2] and modified by McNaughton[3]. The results shown in Fig. 10 were obtained using neutron data supplied by McNaughton but a different relationship between proton and electron light outputs. Even at this preliminary stage, agreement between calculation and measurement is encouraging.

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

(2) N.R. Stanton, COO-1545-92 (1971)

(3) M.W. McNaughton, N.S.P. King, F.P. Brady and J.L. Ullmann, Nucl. Instr. and Methods 129 (1975) 241

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

The assessment studies on nuclear incineration previously reported (UKNDC (76)P80,p25) have been continued. During the period of this report particular emphasis has been placed on assessment of possible nuclear incineration strategies. Major contributions have also been made to the joint study being performed on behalf of the E.E.C. by Harwell and E.C.N., Petten to assess the state of the art of the removal of higher actinides from radioactive waste followed by their destruction by nuclear incineration.

Calculations of the nuclear incineration of higher actinides have been made by a number of authors. In general these have used different mixtures of isotopes which makes detailed comparisons difficult. In order to further understanding and to help in the selection of nuclear incineration strategies a programme of calculations of the incineration of "monoisotopic fuel" has been carried out. As an example of the results

* Oak Ridge National Laboratory, Tennessee, U.S.A., ** University of Dacca, Bangladesh, *** U.S. National Bureau of Standards, Washington D.C., U.S.A.

that can be obtained from these calculations, Table 1 shows the half-lives for the conversion of various actinides to fission products in four reactor spectra ("DFR" is a notional reactor with a spectrum similar to the Dounreay Fast Reactor [not PFR]). These results show that all the dominant higher actinides in waste, such as ^{237}Np, ^{241}Am, ^{243}Am and ^{244}Cm, burn more rapidly in a fast reactor than in a thermal reactor and this supports the normally held view that incineration should be performed in a fast reactor. The calculations also show that the dominant higher actinides burn more rapidly than normal Pu/U fast reactor fuel and this could cause a power rating problem if higher actinide fuel elements were put into a fast reactor.

TABLE 1

Half-lives for the conversion of actinides to fission products as functions of irradiation time in various reactor spectra

	Half-life $T_{\frac{1}{2}}$ (y), averaged over the irradiation time T+									
Reactor type	LWR		FBR			"DFR"*			HTR	
Irradiation time T (y)	10	20	10^{-3}	10	20	10^{-3}	10	20	10	20
Fuel at start of irradiation										
^{232}Th	66.3	54.1	200	5.1	4.9	100	10.8	10.3	97	87
^{321}Pa	14.9	10.5	5.5	1.8	2.4	3.1	2.8	2.8	18.1	13.3
^{234}U	10.1	9.9	7.1	3.7	4.0	4.4	3.7	4.0	14.1	13.7
^{236}U	49.9	25.5	22.7	5.6	4.8	11.0	6.7	6.3	100.9	51.6
^{238}U	97.2	90.5	46.7	9.1	8.5	24.1	11.0	10.7	70.2	69.8
^{237}Np	10.1	8.3	6.5	2.2	2.4	3.3	2.2	1.8	12.3	10.7
^{238}Pu	3.8	5.3	1.9	1.9	2.3	1.3	1.7	2.1	4.1	6.2
^{239}Pu	2.9	4.8	1.2	1.9	2.3	1.4	1.7	2.1	3.2	5.8
^{241}Am	5.4	6.9	5.4	2.4	2.6	3.9	2.6	2.8	6.7	8.7
^{243}Am	13.2	11.6	11.7	4.5	4.1	5.6	3.3	3.1	31.3	23.1
^{244}Cm	9.7	10.3	4.9	2.8	3.2	2.6	2.4	2.6	11.5	14.3
Fast reactor fuel	-	-	6.0	7.1	7.3	-	-	-	-	-

* The same flux (10^{16} n/cm^2/ s) was used for DFR and the FBR and this implies a lower power density for DFR by ca. 30%

\+ The fraction of all actinides (including products formed by capture and decay) left after irradiation of T years is given by $\exp(-0.693T/T_{\frac{1}{2}})$. The remainder have been converted to fission products.

From the work performed to date it is now believed that the following recycle strategies should be considered in detail:-

(1) higher actinides are moved uniformly in fast reactor core fuel

(2) higher actinides are contained in special fast reactor sub-assemblies designed to withstand high burn-up (∿90% desirable). Such sub-assemblies will need a diluent mixed with the actinides.

(3) higher actinides are mixed uniformly in thermal reactor fuel. The further selection of strategies requires detailed consideration of many factors such as

(a) reactor performance

(b) safety of reactors

(c) design and manufacture of suitable fuel and its cladding.

(d) the effect on reprocessing

(e) cost/risk/benefit studies

and (f) logistics.

It is clear that "losses" of actinides from the fuel cycle are particularly important. If these are small, then Strategy 1 appears attractive since there are fewer problems due mainly to the fact that the higher actinides will only at most represent a few per cent of the fuel. Larger losses will make Strategy 2 more desirable as this only requires ∿2 cycles to eliminate most of a particular batch of actinides. This strategy has the advantage that the potential hazards of the actinides are reduced before the first reprocessing of the special fuel. There are, however, many additional problems related to reactor operation and safety and fuel design. The use of Strategy 2 may also create logistic problems unless some isotopes are dealt with using Strategies 1 and 3.

Data files for the U.K. Nuclear Data Library (E.M. Bowey and C.M. Chaffey)

The version of the program SIGAR (UKNDC(76) P80,p25) has now been updated to include a Breit-Wigner calculation for fission cross-sections. The evaluation and theoretical calculation of nuclear data for higher actinides required for fast reactor projects are now available and it is intended to construct data files for the three most important americium isotopes.

In order to be able to produce these files and amend existing ones efficiently at Harwell, a suite of editing programs has been transferred from A.E.E. Winfrith to Harwell. Problems encountered in the transfer and implementation of these programs on the IBM 370 have caused serious delays. Thus an attempt to prevent duplication has been much more costly and time consuming than anticipated, but has highlighted the need for good comprehensive software documentation and adequate testing in order to be able to transfer programs between different computer systems.

A new file for ^{238}U which includes a recent extended evaluation of the fission cross-section is currently being tested. Files for ^{241}Am, ^{242}Am and ^{243}Am will be constructed thereafter.

Conversion of ENDF/B data to UKNDL format (M.S. Ridout)

The conversion of the data on 5 hafnium isotopes in ENDF/B format to the UKNDL format using MISSIONARY has now been completed. During the course of the conversion a number of errors and inconsistencies in the ENDF/B files were brought to light and corrected. The conversion of the two odd numbered isotopes was done without Doppler broadening to limit the computer time and space required to process the large numbers of resonances. For these two isotopes, the use of CHECK revealed some arithmetic inconsistencies in the resonance region, probably due to the use of varying interpolation methods in different parts of the program, but as it is intended to replace these sections of the files, no adjustments were made. Secondary neutron energy distributions were generated from the measured parameters using a program MAXPEC supplied by A. C. Douglas of A.W.R.E..

E. Analysis of neutron transmissions and capture yields of the titanium isotopes (R.B. Thom (Queen Mary College), D.B. Gayther and M.C. Moxon) [Relevant to request number: 106]

Analysis is in progress of the extensive body of neutron transmission and capture information accumulated for the separated isotope samples of titanium (UKNDC(76)P80, p. 5).

Accurate values of resonance energies and neutron widths have been derived for resonances observed in synchrocyclotron transmission data using a full R-matrix multi-level shape fitting code, developed at Harwell by Moxon. These parameters have been extracted for the principal s-wave resonances below 100 keV for the even isotopes 46, 48 and 50. For the odd isotopes 47 and 49, the analysis is more complex due to the increased level density and the increase in possible spin states; nevertheless many resonances have been studied, particularly in the region below ∿30 keV.

Capture yields (number of capture events per incident neutron) are obtained from time-of-flight data after subtraction of background and correction for the incident neutron flux shape. In the case of Moxon-Rae data[1] the yields are normalized using the saturated resonances in the low energy cross section of silver. Yields derived from large liquid scintillator data are calculated relative to the well established capture cross section of gold at 30 keV.

Shown in Fig. 11 is a portion of liquid scintillator data from a sample of $^{49}TiO_2$ in the region of the 3.82 keV (spin 3) s-wave resonance in ^{49}Ti. The open circles in the figure represent the fit to the data obtained with the capture analysis program FANAC[2]. This code takes account of multiple scattering and self shielding effects within the sample and iteratively adjusts the chosen parameters to best reproduce the capture yield shape. For the example shown, the radiation width was allowed to vary. The neutron width used was derived from transmission data.

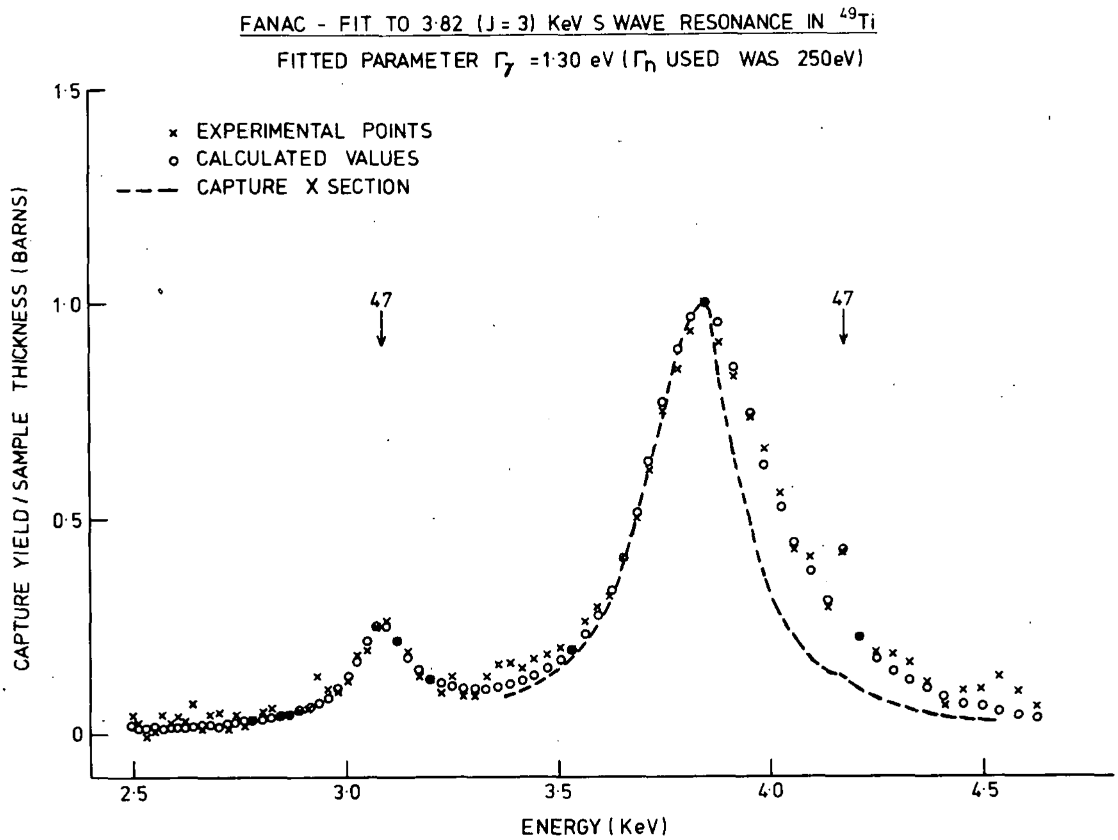

Fig. 11 Fit obtained to 3.82 keV (spin 3) s-wave resonance in ^{49}Ti from a $^{49}TiO_2$ sample (n = 0.006759 at/b). The crosses (x) are the experimental points, the open circles (O) are the calculated yields and the broken curve the actual capture cross section after multiple scattering and self-screening corrections have been applied

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(1) M.B. Moxon and E.R. Rae, Nucl. Instr. and Methods 24 (1963) 445

(2) F.H. Fröhner - private communication, (1976).

E. Photofission and photoneutron studies (E.W. Lees, B.H. Patrick and E.M. Bowey)

The $^{10}BF_3$ detector assembly described in UKNDC (76) P80,p20 has been positioned and suitably shielded, to use the low energy beam of the Harwell Linac. The absolute efficiency has been measured using calibrated AmLi, AmF, AmB and AmBe neutron sources and also a spontaneous ^{252}Cf source. The results are shown in Fig. 12 where it can be seen that the efficiency drops by 0.07 from 0.45 MeV to 4.2 MeV neutron energy in good agreement with the design calculations. The sources were also used to measure the ring ratios as a function of neutron energy i.e. the probability of neutron detection by each of the outer rings of counters relative to that for the innermost ring. The ring ratio calibration allows the evaluation of the average neutron energy for each experiment and hence defines the detector efficiency which should be employed. The neutron detection probability of the detector as a function of time was measured using a ^{252}Cf source and is shown in Fig. 13.

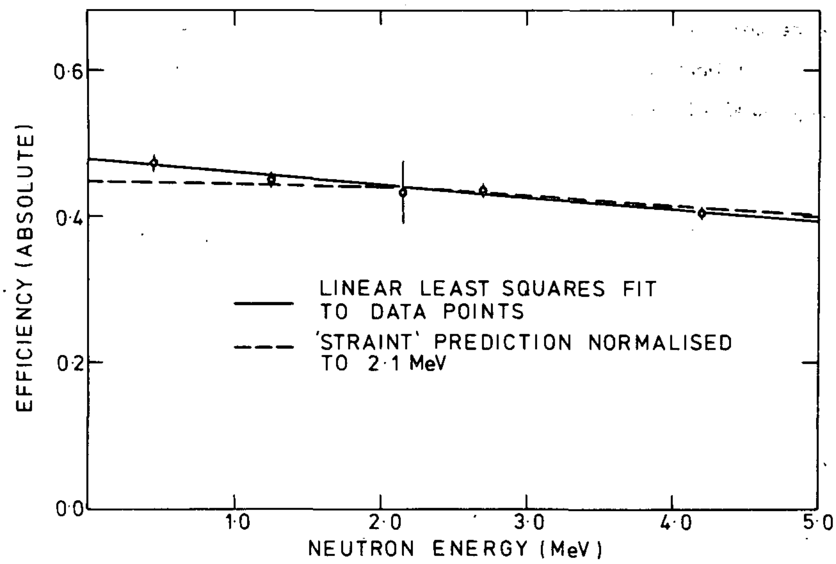

Fig. 12 The absolute efficiency of the Harwell $^{10}BF_3$ detector assembly as a function of neutron energy

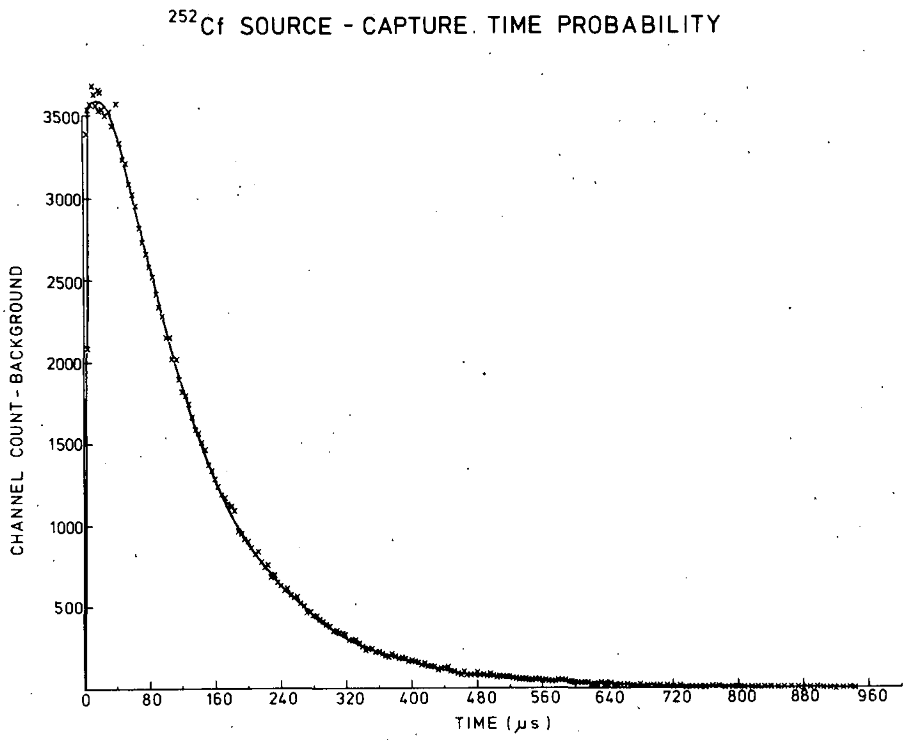

Fig. 13 The capture time probability distribution for the Harwell $^{10}BF_3$ detector with an internal ^{252}Cf spontaneous fission source. For the gate delay and width employed, the gated efficiency is 73% of the absolute efficiency

Measurements were made with end-point energies in the range 5 to 10 MeV using a collimated bremsstrahlung beam produced in a 0.05 mm thick tungsten foil. To reduce gamma-flash and background effects, an electronic gate was used which opened for 170 μs after an initial delay of 8 μs from the electron pulse. In order to separate (γ,n) and (γ,f) contributions, the neutron multiplicity was measured. Overlap of events was minimised by maintaining low counting rates. Typically, the event rate was 30 per 1000 machine cycles and the background was less than 3% of this rate. The data were sorted electronically and transferred on-line to a PDP 11/45 for storage. A computer program has been written to correct the raw data for the effects of background and residual gamma-flash, and for the possibility of event overlap in the measured neutron multiplicity distribution.

To check the overall experimental procedure, a measurement of $\bar{\nu}$ for spontaneous fission of ^{252}Cf was made. After correcting the data for the effects described above, $\bar{\nu}$ was evaluated by minimising the χ^2 function formed from the experimentally measured and theoretically predicted neutron multiplicity distributions for a given detector efficiency. This gave a value for $\bar{\nu}$ of 3.75 ± 0.08 which is in good agreement with the accepted value of 3.737 ± 0.008 [1]. The main contribution to the error in the measured value of $\bar{\nu}$ is due to the uncertainty in the detector efficiency. Alternatively, the gated detector efficiency for a ^{252}Cf source can be deduced to $\pm$ 0.3% by assuming the accepted value of $\bar{\nu}$.

Preliminary neutron yields have been obtained from the $^{238}U(\gamma,f)$ and $^{238}U(\gamma,n)$ reactions and from the $^{232}Th(\gamma,f)$ reaction. In addition, measurements of $\bar{\nu}$ for low energy photofission of these two actinides have been made. The computer program which evaluates ν is being modified to allow the extraction of the (γ,n) events from the (γ,f) events by fitting only those events with experimental multiplicities greater than or equal to 2. Analyses of all the data are now in progress.

The detector has also been used to measure the neutron production resulting from (α,n) reactions with the oxygen in an $^{241}AmO_2$ sample with a precision of $\pm$ 5%.

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(1) H.D. Lemmel, in "Nuclear Cross Sections and Technology" Washington, NBS Special Publication 425 (1975) 286

H. <u>Cross section measurements for isotope production by proton spallation reactions (D.B.C.B. Syme, E. Wood and M.C. Bowen*)</u>

We have begun analysis of gamma ray spectra from the activity induced in natural lead targets following high energy proton irradiation. The product radioisotopes of interest are ^{204}Bi (11.3h) and ^{206}Bi (6.2d) with potential applications in tumor diagnosis. The yield of ^{204}Bi has been found to peak in a broad range (30-65 MeV). ^{206}Bi production is significant through this range and radionuclides observed with lower yield include ^{201,202,203}Pb and ^{202,203}Bi. Further measurements are planned to investigate the region of interest in detail.

^{81}Rb and its daughter ^{81}Kr are of medical interest for pulmonary and other studies, and this interest would significantly increase if a product with high radionuclidic

* Physics Dept., University of Surrey.

purity could be obtained. Our initial studies of ^{81}Rb yields from high energy proton irradiation of RbCl targets (UKNDC(76)P80,p28) have been extended to include a detailed study of the time dependence of the activity of each product radionuclide, identified by gamma-ray spectroscopy. This should allow the yields of the competing direct and indirect production [eg. $^{85}Rb\ (p,p4n)\ ^{81}Rb$ or $^{85}Rb(p,5n)\ ^{81}Sr \xrightarrow{(\beta^+)} {}^{81}Rb$] to be determined and the route with best yield and purity selected.

For proton energies between 40 and 160 MeV the yield of ^{81}Rb activity (measured 120m after irradiation) from the sum of direct and indirect production routes is shown in Fig. 14. Several ^{81}Rb - ^{81}Kr minigenerators (about 20-25 mCi ^{81}Rb each) would be made in an eight hour period with a suitable target covering the peak energies. Our initial results indicate likely ^{82m}Rb impurities of the order of 10% by activity for this mixed

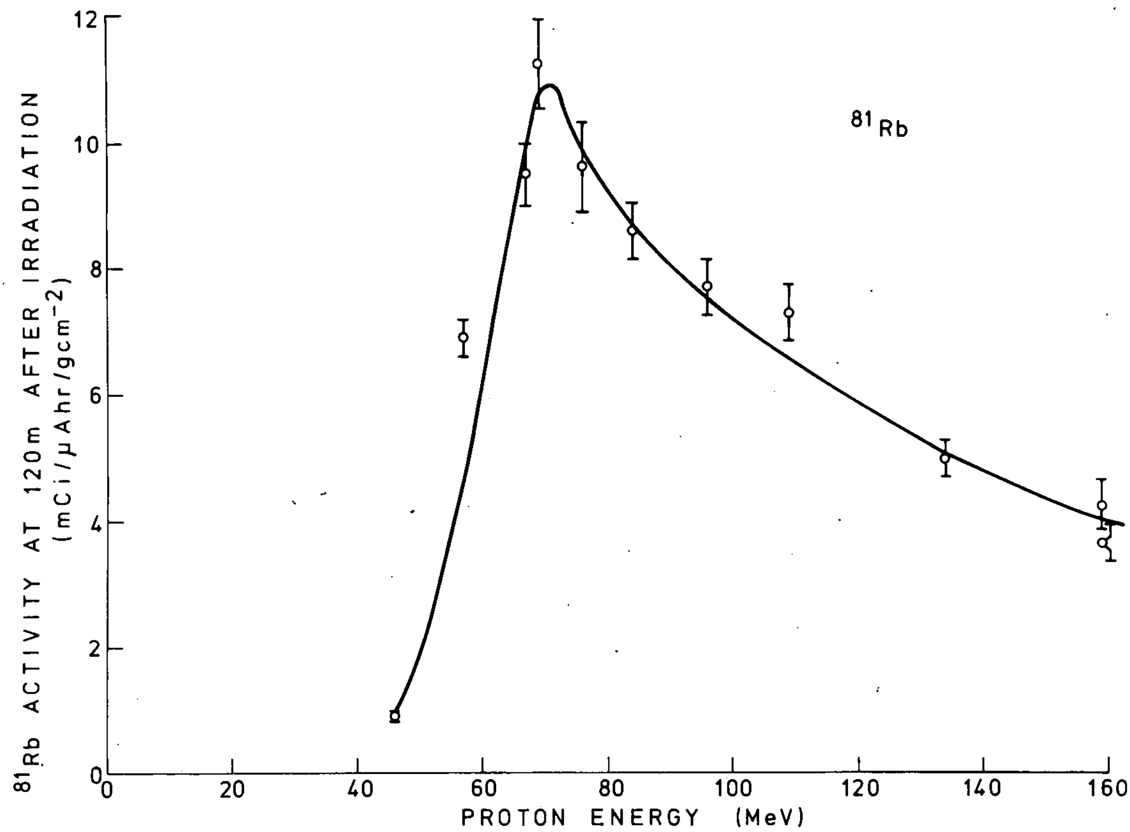

Fig.14 Yield of ^{81}Rb activity from proton irradiation of natural RbCl, measured 120 min after the irradiation

reaction route. In the ^{81}Rb presently available this is the most important impurity and is present at the 35% level.

Restriction to the indirect reaction route by initial separation of the strontium radioisotopes would largely remove ^{82m}Rb impurity at the expense of about 30% in yield.

Yield curves for other possible impurities (^{85m}Sr, ^{84m}Rb) are given in Figures 15 and 16. A more detailed analysis is in progress.

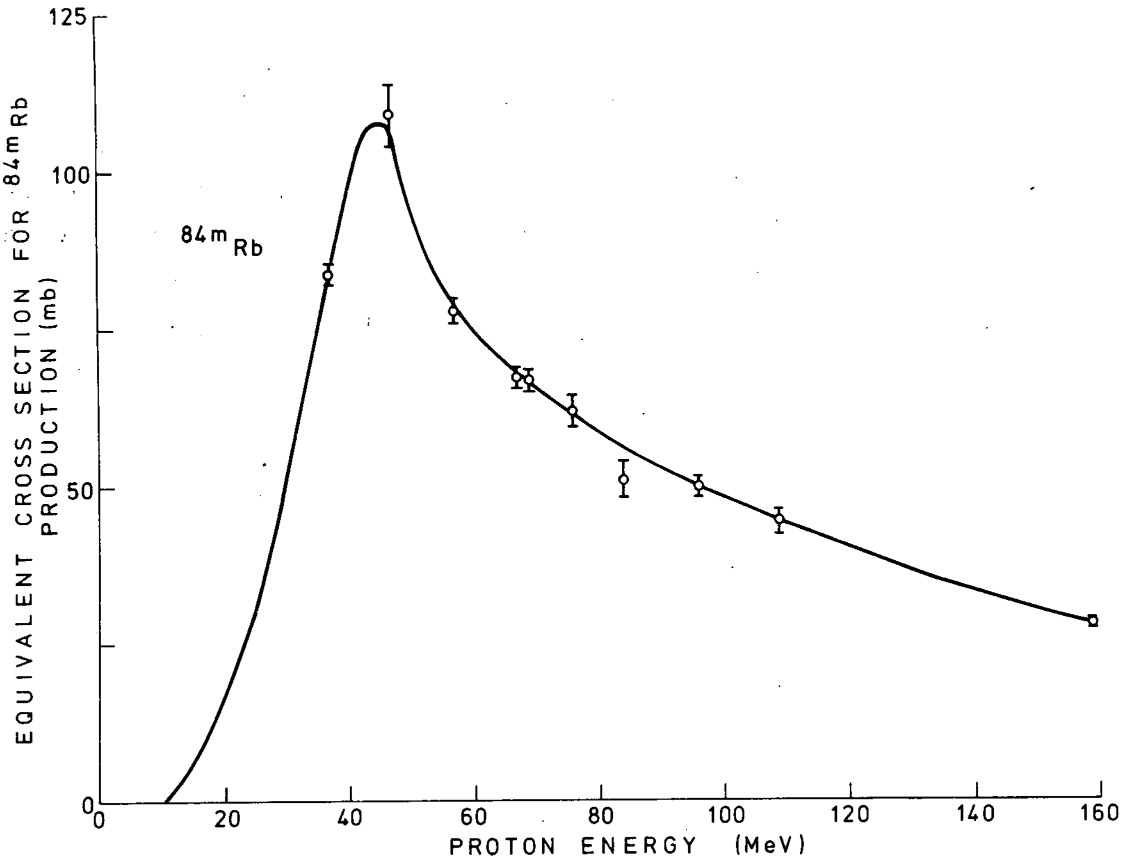

Fig. 15 Equivalent cross section (per atom) for the production of ^{84m}Rb by proton spallation reactions in natural Rb

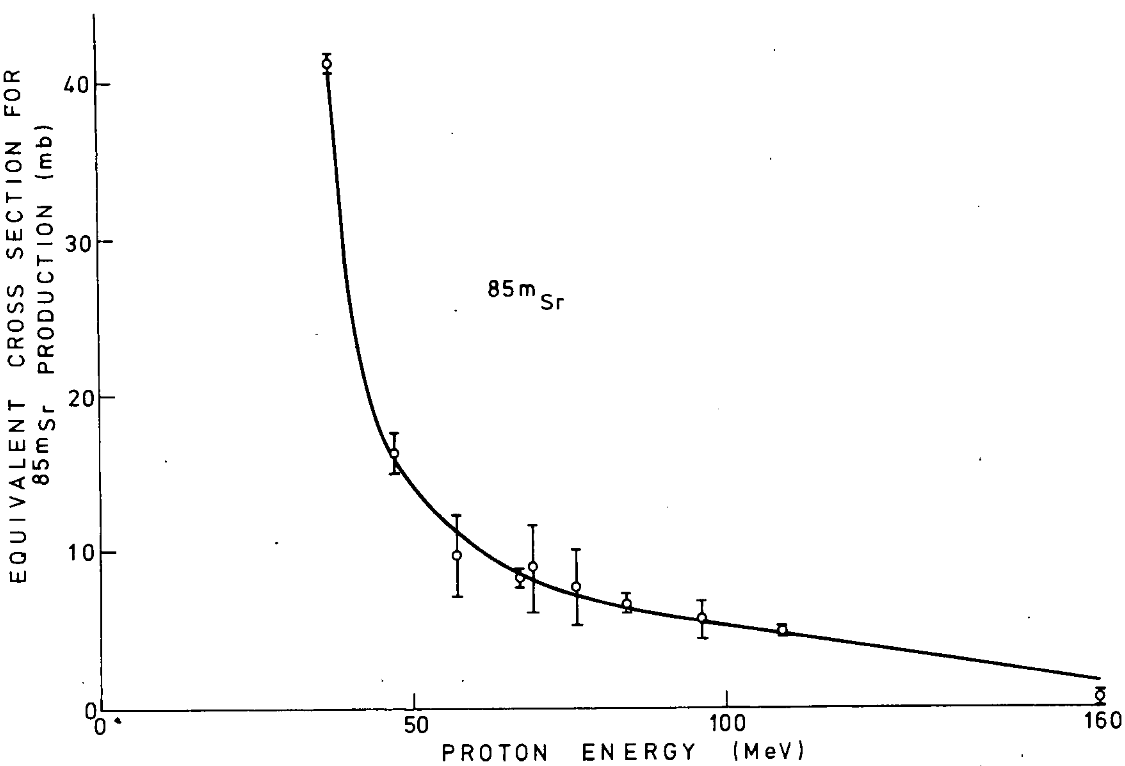

Fig. 16 Equivalent cross section (per atom) for the production of ^{85m}Sr by proton spallation reactions in natural Rb

PUBLICATIONS

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, J. Phys. G: Nuclear Physics, 2 (1976) No. 10, 751

REPORTS

AERE - R 8556 A measurement of the $^{6}Li(n,\alpha)$ cross section, D.B. Gayther

AERE - R 8728 Fast neutron fission measurement of ^{235}U at 0.52 MeV incident neutron energy, J.M. Adams and P.I. Johansson

AERE - R 8529 Estimates of the $(n,\gamma n')$ cross-section for ^{238}U, J.E. Lynn

AERE - R 8636 Inelastic Scattering and Fission Neutron Spectra - Proc. of a Specialist Meeting, Edited by B.H. Armitage and M.G. Sowerby

IN COURSE OF PUBLICATION

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

Fission neutron and fragment angular distributions from threshold photofission of ^{232}Th and ^{238}U, S. Nair, D.B. Gayther, B.H. Patrick and E.M. Bowey, accepted by Journal of Physics G

CONFERENCE PAPERS

Invited Papers

1976 International Conference on the Interactions of Neutrons with Nuclei, 6-9 June 1976, University of Lowell, USA

Research trends in neutron physics, J.E. Lynn

Fast neutron scattering, reaction mechanisms and nuclear structure, A.T.G. Ferguson (with I.J. van Heerden [Southern Universities Nuclear Institute] and P. Moldauer and A.B. Smith [Argonne National Laboratory].

Contributed papers

Third International Conference on Nuclei far from Stability, Cargese, Corsica, May 1976

The Harwell Buechner magnet/PSD system as a mass spectrometer for unslowed fission products, T.W. Conlon

International Conference on the Interactions of Neutrons with Nuclei, Lowell, USA, July 1976

Capture and transmission measurements on the titanium isotopes, R.B. Thom, J.A. Edgington, D.B. Gayther, G.D. James, M.C. Moxon and D.B. Syme

Nuclear Data Forum, Culham Laboratory, December 1976

Fusion blanket neutronics, G. Constantine

A measurement of the $^{6}Li(n,\alpha)t$ reaction, D.B. Gayther

Nuclear Data requirements for fusion reactor structure activity calculations, O.N. Jarvis

A proton recoil chamber for the absolute measurement of fast neutron flux, P.A.R. Evans

CONFERENCE PROCEEDINGS

The $^{238}U/^{235}U$ fission cross section ratio over the energy range 1.2 MeV to 2 MeV, P.A.R. Evans, G.B. Huxtable and G.D. James, Proc. NEANDC/NEACRP Specialist Meeting on the Fast Neutron Fission Cross Sections of U-233, U-235, U-238, and Pu-239, (W.P. Poenitz and A.B. Smith (Eds.)), ANL-76-90 (1976) 149

Simulation of the Structure in ^{235}U cross Sections, G.D. James, Proc. NEANDC/NEACRP Specialist Meeting on the Fast Neutron Fission Cross-Sections of U-233, U-235, U-238 and Pu-239, (W.P. Poenitz and A.B. Smith (Eds.)), ANL-76-90 (1976) 382

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, Neutron Physics (Proc. 3rd All Union Conference on Neutron Physics, Kiev. 9-13 June 1975) Vol. 4 (1976) 3.

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, Neutron Physics (Proc. 3rd All Union Conference on Neutron Physics, Kiev, 9-13 June 1975) Vol 5 (1976) 251

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, Neutron Physics (Proc. 3rd All Union Conference on Neutron Physics, Kiev, 9-13 June 1975) Vol. 4 (1976) 24

Inelastic scattering and fission neutron studies, J.M. Adams, (Proceedings of the Harwell specialist meeting, AERE - R 8636, Eds B.N. Armitage and M.G. Sowerby).

REACTOR PHYSICS DIVISION, AEE, WINFRITH

(Division Head: Dr C G Campbell)

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

A report on the results of measurements of β-decay energy from the fission of ^{239}Pu and ^{235}U in a typical fast reactor spectrum during the period 20 - 3 x 10^7 s (after a 10^5 s irradiation) was presented to the NEANDC during their topical discussions at Studsvik in September 1976. The paper NEANDC(UK)168A compared the preliminary experimental results with calculated predictions by A. Tobias (private communication, March 1976) and found encouraging agreement. Since that time a series of subsiduary experiments have been completed and analysed. The results of these experiments have confirmed the validity of the experimental technique, particularly the ability of an aluminised melinex foil to catch and retain all fission fragments. A final report on the whole work is presently being prepared.

Data evaluation and UK nuclear Data library (A.L. Pope & J.S. Story)

Re-editing of the main library tape NDL-1 and the detector file tape NDL-3 has continued. They now appear to be correct, and will shortly be distributed.

Summary documentation of some of the main file editing programs has been carried out. More detailed reports on the resonance cross-section program SIGAR-5 are in draft.

An interactive program has been written (DEEBAR), using the Dyson-Mehta "optimum" statistic for the mean-spacing of a set of observed s-wave resonances: the calculation is carried out successively for the first 2, 3, 4 ... observed resonances. The program has been extended in heuristic fashion to yield the a priori most probable energies of negative energy resonances and to indicate the numbers and most likely energies of missed resonances.

Decay data for fission-products and actinides (M.F. James)

A revised version of the Risley inventory code FISPIN-4 (Richardson, 1976) has been implemented at Winfrith. Further comparisons have been made of different libraries of fission-product decay data and fission-product yields. Detailed studies have been made of the fission yields in the ENDF/B4 library and the two sets produced by Crouch (AERE-8152 and Atom. Nucl. Data Tables, to be published); it is found that no set satisfies all the physical constraints:

$$\Sigma\, Y(A) = Z$$

$$\Sigma\, A\, Y(A) = A_F + 1 - \bar{\nu}$$

$$\Sigma\, y(A,Z) = \Sigma\, y(A,\, Z_F - Z)$$

summing over mass numbers A, in which the Y(A) are the chain yields and the y(A, Z) the independent yields

$$Y(A) = \sum_Z y(A,\, Z).$$

As a further useful test of the independent yields some work has been done on the calibration of delayed neutron yields from fission-product decay data and fission yield libraries.

PAPERS

Experiments to determine the rate of beta energy release from ^{239}Pu and ^{235}U fission fragments following an $\sim 10^7$ second irradiation in a commercial fast reactor - a preliminary report, Murphy, M.F., Taylor, W.H., Sweet, D.W. and March M.R. (Mar. 1976) NEANDC (UK) - 168A

Actinide fission rate measurements in Zebra, Sweet, D.W. (Jan. 1977) AEEW-R1090

User notes on some of the UKNDL editing programs, Pope, A.L. (Oct. 1976) WNDG-171

Heat deposition in a region of a nuclear reactor, James, M.F. (Jan. 1977) AEEW-M1433

A state-of-the-art commentary on fission-product decay data, James, M.F. (June 1976) NEACRP-A257

The present status of data and programs for fission-product and actinide inventory and heating calculations in the UK. James, M.F. (Sept. 1976) NEANDC(UK)-169A

CHEMICAL NUCLEAR DATA

Introduction

Chemical nuclear data experiments and evaluations are coordinated 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 of reports. The evaluation publications bear the solgan "the contents of this paper have been examined and recommended by the U.K. Chemical Nuclear Data Committee". The preparation of the U.K. CNDC nuclear data file is under the control of the Data File Sub-Committee (Chairman: A.L. Nichols, AERE). The committee held three meetings and the sub-committee two meetings in 1976.

The committee deals with two aspects of nuclear data:

(i) the measurement of new data

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

The UKCNDC produces a U.K. Chemical Nuclear Data Request List every 2 years, and the preparation of the 6th edition of this document has been underway during 1976. Although a large number of requests from the 5th edition (CNDC(75)P2) have been deleted either as satisfied or as no longer required, the total number has increased, mainly as new requests from BNFL. The efforts of the committee to reduce the duplication of work in the U.K. have been successful, and it has also been satisfying to see a continued increase in international collaboration in the data field.

This section has been compiled and edited 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 has been delayed, and results are being worked out as opportunity allows for $^{235,238}U$ and ^{239}Pu.

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 samples have been awaiting irradiation in PFR.

Tritium yields in thermal and fast fission (I.C. McKean and E.A.C. Crouch (AERE))

Apparatus and an experimental method have been devised which seem to allow the determination of ^{3}H yields in thermal fission of ^{235}U and ^{239}Pu. We have carried out neutron irradiations of polythene bottles having capillary necks and containing acid solutions of ^{235}U. The bottles were then inserted in a glass container upside down, the pressure reduced and the capillary neck melted.

Carrier solution for the fission monitor ^{140}Ba was similarly released and the combined solutions neutralised. The water was then decontaminated and isolated as neutral water. Blank runs showed no ^{3}H was entering the system in reagents, and addition of known quantities of ^{3}H to runs containing no ^{235}U showed recoveries of 100%. Further experiments are planned under conditions that produce more ^{3}H so that it can be more accurately determined quantitatively. (^{3}H counting was done in Nuclear Physics Division, AERE by the low background ^{14}C and ^{3}H analysis section).

Fission yield measurements at DERE (W. Davies, V.M. Sinclair (DERE))

No further progress has been made during the past year on the reactor irradiations described on pages 43 and 44 of the 1974-75 UKND Progress Report. The work schedule has been reprogrammed.

On-line measurements of the variation with energy and angular momentum of nubar ($\bar{\nu}$) and other scission-point properties for ^{208}Po* fission. (J.G. Cuninghame (AERE), J.L. Durell, G. Foote, I.S. Grant (Manchester University Physics))

The experimental work, described on page 35 of the 1975-76 UKND Progress Report, has been completed, but current calculation methods give unreal errors for nubar, particularly for very small and very large fragment masses. Attempts are being made to resolve this problem. Three parameters (the energies of both primary fission fragments and the time-of-flight of one of them) have been measured, allowing calculation of the number of prompt neutrons emitted as a function of mass ($\bar{\nu}$) as well as other scission point properties.

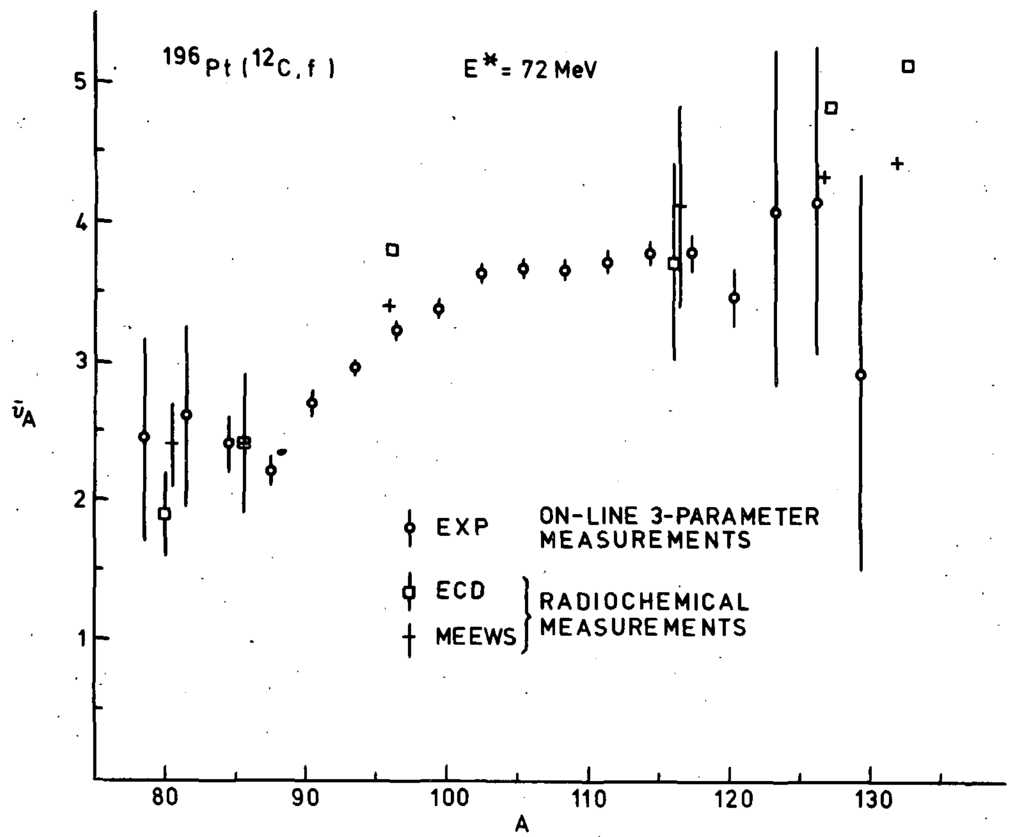

FIG.1. $\bar{\nu}$ AS A FUNCTION OF FRAGMENT MASS: COMPARISON OF $\bar{\nu}$ MEASURED BY PHYSICAL AND CHEMICAL METHODS.

Figure 1 shows a comparison of one set of results with those obtained from the radiochemical measurements (described below), calculated assuming two different hypotheses for the division of charge in fission. These hypotheses are Equal Charge Distribution (ECD) and Maximum Excitation Energy Without Shells (MEEWS).

On-line measurement of variation with energy and angular momentum of nubar ($\bar{\nu}$) and other scission-point properties for fission of highly fissile compound nuclei. (J.G. Cuninghame (AERE), J.L. Durell, G. Foote, I.S. Grant (Manchester University Physics)).

This work is analogous to that outlined above except that compound nuclei far from closed shells are being fissioned. Resolution of the data reduction problems of the earlier work is required before continuing.

Fission-spallation competition in ^{208}Po* fission. (J.G. Cuninghame (AERE), J.L. Durell, G. Foote, I.S. Grant (Manchester University Physics)).

Trials of three possible methods for measuring relative intensities of all the Po isotopes produced in spallation of ^{208}Po* have been made. Off-line α-counting is ineffective because of the low α-branching intensities, α or γ counting using a He jet separator presents too many technical problems to make it workthwhile, but prompt γ counting using a Ge(Li) detector is promising and the method is now being developed.

Measurement of elastic scattering and fission cross-sections of ^{208}Po* (J.G. Cuninghame (AERE), J.L. Durell, G. Foote, I.S. Grant (Manchester University Physics))

It is important to know the amount of multi-chance fission occurring in high energy systems under investigation, and this can only be determined by calculation of the competition between evaporation and fission. In order to select the best parameters for such calculations, measurements are being made of elastic scattering and fission cross-sections in the reactions (^{12}C + ^{196}Pt) and (^{16}O + ^{192}Os). The measurements at three different excitation energies for the second reaction have been completed. An investigation of the (^{4}He + ^{204}Pb) reaction will also be made.

Mass distribution and charge dispersion of ^{208}Po* fission measured by radiochemical methods. (J.A.B. Goodall (AERE), J.E. Freeman, J.D. Hemingway, G.W.A. Newton, V.J. Robinson (Manchester University Chemistry)).

This work is the radiochemical analogue of the on-line measurement of $\bar{\nu}$ for ^{208}Po* (see above) using the same targets and beams. Work on the systems (^{4}He + ^{204}Pb) and (^{12}C + ^{196}Pt) is now complete and is being prepared for publication, while the study of (^{16}O + ^{192}Os) has been held up because of target preparation problems, now resolved.

Relative mass yields have been measured for different isotopes of a number of elements and the most probable mass A_P and the isobaric width Γ_Z are derived from these; the results are given in table 1. The isobaric width must be the same for complementary elements at the moment of fission (complementary elements are pairs for which the sum of the atomic numbers is equal to the atomic number of the fissioning nucleus). The values of Γ_Z in the tables show a marked increase with Z, an increase which must be due either to neutron evaporation from the primary fragments or to multi-chance fission. Evaporation calculations show that neutron emission from the primary fragments does not, in fact, contribute much to Γ_Z but almost all the observed width can be accounted for by multi-chance fission. This implies that the charge dispersion of primary fragments must be extremely narrow, with Γ_Z comparable to the values found in spontaneous and thermal neutron induced fission.

TABLE 1: Charge Distribution Parameters

Particle Energy		Charge Distribution Parameters from $^{196}Pt(^{12}C,f)$ 79 MeV (I)	79 MeV (II)	93 MeV (I)	93 MeV (II)	105 MeV (II)	Charge Distribution Parameters from $^{204}Pb(^{4}He,f)$ 49 MeV	64 MeV	79 MeV
Arsenic	A_p	-	-	-	78.4 $\pm$ .3	78.2 $\pm$ .3	-	77.2 $\pm$ .5	77.1 $\pm$ .3
	Γ_Z	-	-	-	(1.2)*	(1.2)*	-	(1.0)*	(1.0)*
Bromine	A_p	-	83.8 $\pm$ .5	83.6 $\pm$ .5	-	83.3 $\pm$ .5	83.0 $\pm$ .4	83.7 $\pm$ .4	83.1 $\pm$ .3
	Γ_Z	-	(1.2)*	(1.2)*	-	(1.2)*	(1.1)*	1.03 $\pm$ .29	(1.1)*
Yttrium	A_p	92.80 $\pm$ .03	-	92.53 $\pm$ .10	-	92.64 $\pm$ .04	94.05 $\pm$ .35	93.07 $\pm$ .04	92.84 $\pm$ .08
	Γ_Z	1.29 $\pm$ .02	-	1.32 $\pm$ .08	-	1.27 $\pm$ .01	1.23 $\pm$ .06	1.18 $\pm$ .02	1.02 $\pm$ .05
Silver	A_p	112.6 $\pm$ .7	113.3 $\pm$ .6	112.8 $\pm$ 1.0	-	112.6 $\pm$ .7	113.5 $\pm$ .3	112.9 $\pm$ .3	112.2 $\pm$ .3
	Γ_Z	(1.4)*	(1.4)*	(1.4)*	-	(1.4)*	(1.2)*	(1.2)*	(1.2)*
Antimony	A_p	123.31 $\pm$ .04	-	122.72 $\pm$ .04	122.92 $\pm$ .08	122.63 $\pm$ .05	125.5 $\pm$ .5	123.75 $\pm$ .10	123.24 $\pm$ .13
	Γ_Z	1.47 $\pm$ .02	-	1.54 $\pm$ .03	1.50 $\pm$ .04	1.44 $\pm$ .02	(1.4)*	1.55 $\pm$ .04	1.40 $\pm$ .06
Iodine	A_p	-	128.80 $\pm$ .18	127.72 $\pm$ .06	128.24 $\pm$ .04	128.04 $\pm$ .13	130.6 $\pm$ .3	129.4 $\pm$ .3	128.4 $\pm$ .2
	Γ_Z	-	1.67 $\pm$ .10	1.74 $\pm$ .03	1.61 $\pm$ .01	1.68 $\pm$ .04	(1.5)*	1.53 $\pm$ .26	1.82 $\pm$ .2

*These Z widths were interpolated from the other data, they were not experimentally determined.

Mass distribution and charge dispersion in the fission of highly fissile compound nuclei measured by radiochemical methods (J.A.B. Goodall (AERE), J.D. Hemingway, G.W.A. Newton, V.J. Robinson (Manchester University Chemistry))

This radiochemical study has just begun, and is analogous to the on-line measurements of $\bar{\nu}$ described above.

An investigation of angular momentum distribution of primary fission fragments by radiochemical measurement of isomer ratios (J.A.B. Goodall (AERE), C. Branquinho, J.E. Freeman, H.D. Hemingway, G.W.A. Newton, rJ. Robinson (Manchester University Chemistry))

Information about angular distribution of primary fission fragments can be obtained by measuring the ratio of metastable to ground states for pairs of isomers formed in fission. The pairs studied in this work were in ^{82}Br, ^{83}Br, ^{84}Br, ^{120}Sb, ^{126}Sb, and ^{128}Sb, produced in the ^{208}Po fission experiment described above in separate VEC (^{4}He + ^{204}Pb) irradiations at Harwell, and in (^{12}C + ^{209}Bi) irradiations on the Manchester heavy ion linear accelerator (HILAC).

Isomer ratios have been predicted for fragments whose angular momentum distribution is taken from statistical theory assuming the the fissioning nucleus reaches the scission point along a low viscosity path, and table 2 gives examples of the predicted values compared with the experimental ones. This work is now being prepared for publication.

Table 2: Predictions of the Spin Distribution of Fission Fragments

For the ^{209}Bi (94 MeV ^{12}C, fission) Reaction				
Average Fragment Spin, n	Standard Deviation n	Calculated Isomer Ratio	Fragment Studied	Experimental Isomer Ratio
20	5.97	1.54 ± 0.41	^{120}Sb	2.13 ± 0.51
23	6.86	4.80 ± 0.95	^{126}Sb	5.02 ± 0.49
For the ^{209}Bi (85 MeV ^{12}C fission) Reaction				
Average Fragment Spin, n	Standard Deviation n	Calculated Isomer Ratio	Fragment Studied	Experimental Isomer Ratio
19	5.67	1.38 ± 0.35	^{120}Sb	1.62 ± 0.49
21	6.26	4.02 ± 0.7	^{126}Sb	4.40 ± 0.18

The average prompt neutron emission of fission fragments measured by radiochemical methods (J.A.B. Goodall (AERE), J.E. Freeman, J.D. Hemingway, G.W.A. Newton, V.J. Robinson (Manchester University Chemistry))

From the A_P values (see table 1) which are in this case average masses after prompt neutron emission, and assuming a relation for the most probable charge of primary fragments as a function of mass, it is possible to deduce the number of neutrons which must be emitted to lead to the observed A_P values. Thus there is a possible direct comparison between these radiochemical values and the values found in the on-line physical measurements. This comparison is being made throughout the VEC work by the Harwell-Manchester group.

^{239}Pu fission yields in fast monoenergetic neutron fluxes (J.G. Cuninghame, H.H. Willis (AERE))

This work has been completed and accepted for publication by J. Inorg. Nucl. Chem. The results are summarised in figure 2.

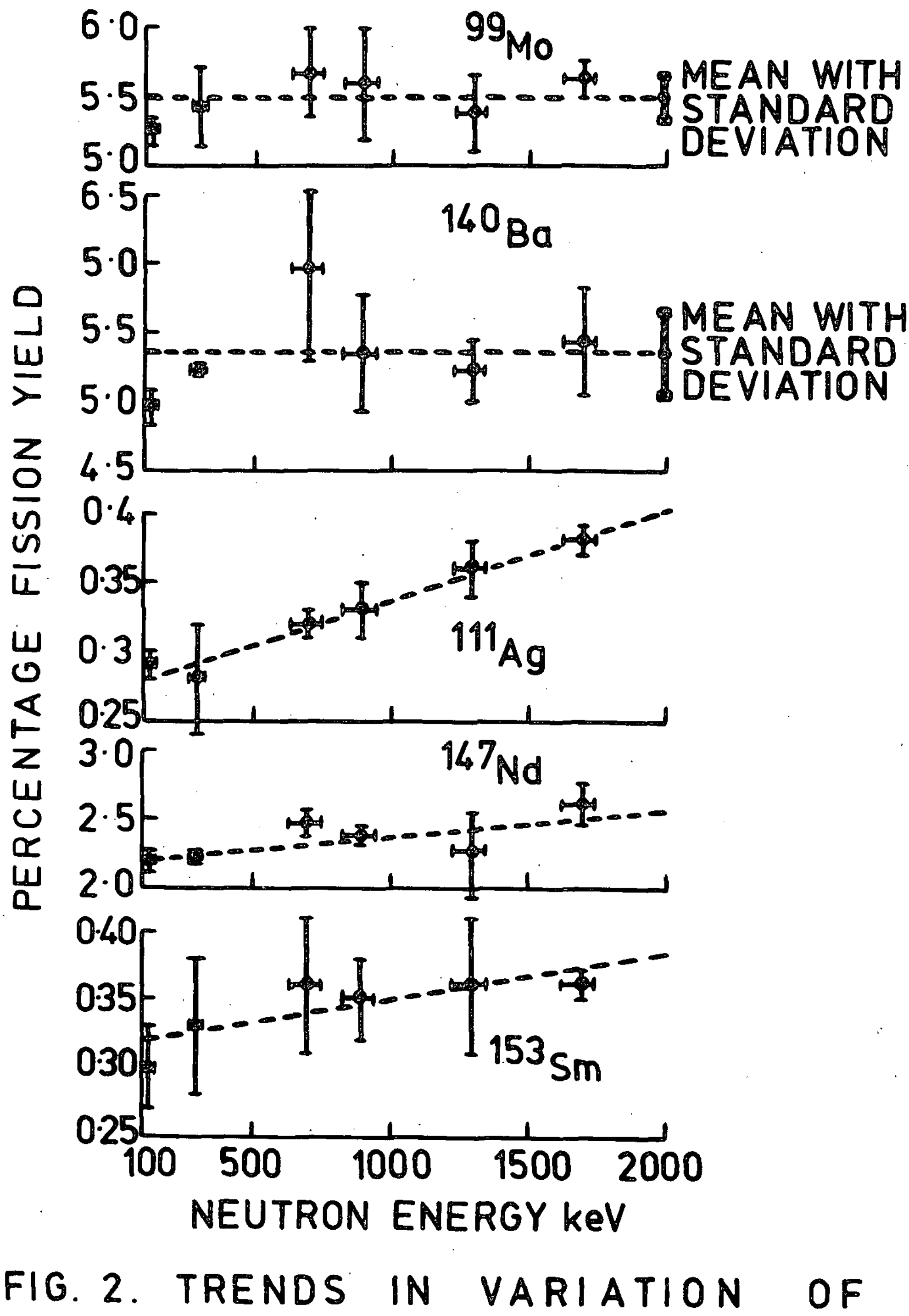

FIG. 2. TRENDS IN VARIATION OF FISSION YIELDS WITH NEUTRON ENERGY.

^{238}U fission yields in fast monoenergetic neutron fluxes (J.G. Cuninghame, H.H. Willis) (AERE))

This work has just started. When finished it will complete the current series of investigations into the effect of neutron energy change on fission yields using monoenergetic neutrons.

Development of a method for the simultaneous measurement of fission yields of a large number of fission products from a low flux irradiation of nuclear fuel (J.G. Cuninghame, H.H. Willis (AERE))

One of the principal problems facing those who wish to make measurements of fission yields and other fission product and actinide nuclear data for fast reactors, is the extreme difficulty of having samples irradiated to high total doses in the appropriate neutron spectrum. This means that the normal mass-spectrometric or high intensity γ-counting analytical procedures are frequently unavailable and the only irradiation facilities are accelerators or zero energy reactors for which the practical total neutron dose for a sample is in the range 10^{9}-10^{12}. Given such low neutron fluxes the usual analytical technique employed has been β-counting of thick sources prepared after laborious and time-consuming radiochemical separation and purification.

Techniques are being developed for γ-counting of fissile material with no chemical separation, so that all fission products with suitable γ-rays are measured simultaneously. The γ-spectrometers have been accurately calibrated and the ultimate aim is to be able to obtain absolute measurements of the yields of at least 15 fission products with γ-counting rates in the photo peaks sometimes as low as 1 count/min, with an absolute accuracy for a fission yield of from 3-10%, depending on count rate.

Several test runs have been carried out with natural uranium irradiated in Dido, with promising preliminary results. Data reduction involves the development of an improved version of the γ-analysis program GAMANAL (see below).

Development of a version of the GAMANAL computer program primarily applied to fission yield studies (J.G. Cuninghame, J.A.B. Goodall (AERE))

GAMANAL is a sophisticated computer program running on the IBM 370 for fitting all the photopeaks in a 4096 channel spectrum. The program first finds the peaks, fits them, applied appropriate calibration data, and finally lists all peaks found, together with their energies, count rates, error data.

The version we received from Kaufman of the Argonne National Laboratory performed only these functions and required input from cards or IBM magnetic tape. This program is being developed to provide the following additional facilities (some of which are optional):

(i) input from Dectape from both our PDP8 and PDP11 spectrometers;

(ii) input from floppy discs from our PDP11 spectrometer;

(iii) plotting of all peaks on the line printer with original data, fit and continuum;

(iv) full spectrum plot on the line printer with original data, fit and continuum;

(v) similar full spectrum plot on the Calcomp in 4 frames;

(vi) Calcomp plot of selected peaks in 1 frame to show all the separate Gaussian elements of the fit;

(vii) output on cards suitable for use as input to a decay curve analysis program;

and

(viii) as a long term measure, automatic decay curve fitting of all the peaks from a number of spectra taken in a time sequence. GAMANAL is now used for all our γ-analysis work.

ZEBRA-BIZET experiments to study the effect of change of reactor neutron spectrum on fission yields (J.G. Cuninghame, J.A.B. Goodall, H.H. Willis (AERE))

As feared the original ZEBRA experiments were unsuccessful because the reactor programme was such that the irradiations had to be carried out before the method had been developed. The intention is to repeat them when the BIZET core is operational, and when there has been enough progress with the development of GAMANAL and fissile γ-counting techniques (see above).

PFR experiments to study the effect of change of reactor neutron spectrum on fission yields (J.G. Cuninghame, J.A.B. Goodall, H.H. Willis, I.C. McKean, A.L. Nicholas (AERE))

The samples are now awaiting irradiation in PFR. If this takes place in the very near future, the original analytical procedures will be followed whereby the main emphasis will be on accurate β-counting after chemical separation and purification of fission products, with some γ-counting as back-up. However, should the irradiation be delayed, γ-counting procedures will be used as discussed above.

2. NEUTRON CROSS-SECTIONS

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

No further progress has been made in the past year on the work outlined on pages 53-55 of the 1974-75 UKND Progress Report.

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

Progress in this area has again been severely limited due to lack of effort. Processing of the ^{243}Am samples irradiated in ZEBRA to measure the production cross section of ^{244}Cm is still not completed, but it is hoped to complete this measurement and to carry out a second irradiation in ZEBRA during 1977.

3. HALF-LIVES

^{239}Pu half-life (Mrs K.M. Glover, R.A.P. Wiltshire, M. King, D. Brown (AERE))

The experimental measurements for the redetermination of the half life of ^{239}Pu are now complete. However, due to pressure of other work and lack of effort the final evaluation of the experimental data is still incomplete. It is anticipated that the half-life value will be reported during 1977.

^{239}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.C. McKean, E.A. Crouch, M. Wilkins, A.J. Fudge (AERE), P. De Bievre (CBNM Geel)).

A meeting was held on 20 December 1976 between Applied Chemistry Division, Chemistry

Division, Nuclear Physics Division of A.E.R.E. and Central Bureau of Nuclear Measurements, Geel, Belgium to discuss the current status of the measurements of the half life of plutonium-241. The following experiments have been identified:

(i) Lounsbury, Hall and Crouch. 240/241/242 ratio measurements on a highly irradiated plutonium sample were started in 1952 and in 1970 a further measurement was made. Two half lives have been obtained based on the changes in isotopic composition between 1952, 1953 and 1970 respectively. These are (14.25 $\pm$ 0.10) years and (14.31 $\pm$ 0.10) years.

(ii) Crouch. 240/241 ratio measurements have been made on an irradiated ^{240}Pu sample between 1970 (end of irradition) and 1976. The half-life values obtained on two separate samples are (14.44 $\pm$ 0.14) years and (14.31 $\pm$ 0.12) years.

(iii) Wilkins and Cabell. 240/241/242 measurements have been made on a synthetic mixture of enriched isotopes. This work was reported in AERE R-7906 (1974) and no subsequent measurements have been made. The latest half-life value from this experiment is (15.02 $\pm$ 0.15) years.

(iv) Whitehead. Measurements have been made at AERE of the growth of americium-241 on the same material as prepared by Crouch in (ii). The value obtained was (14.56 $\pm$ 0.15) years.

(v) De Bievre. 240/241 ratio measurements on an enriched ^{241}Pu sample have been made, also using 240/239 ratio as an internal standard, over a decay period of about eight months. The mean of two values for the half-life is 14.60 years.

No obvious cause for differences found could be decided upon. None of the measurements show the existence of an isomeric state. It was proposed that further measurements be carried out on (i) and (ii); this will give additional information on ^{241}Pu of differing dates of preparation. Measurements on material in experiment (iii) will again be made and other mass spectrometers used for the work. De Bievre will continue the mass measurements on the enriched material at fairly frequent intervals. De Bievre will also make measurements on samples (ii) and (iii), aliquots of which have been sent to CBNM. It was considered worthwhile continuing with (iv) since it represented a different technique. A re-analysis of all existing data will be made and compared with the new data in about one year.

E. 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))

Compilation and evaluation of nuclear decay data has continued with an effort of approximately 1.5 manpower. The priorities are defined by the sub-committee and linked to the requirements of the U.K. reactor programme. The UKCNDC data files are to be in ENDF/B4 format, an internationally accepted format[1,2] for consistency, ease of comparison and use. The data includes half-life, decay modes (energies, intensities and internal conversion coefficients), branching ratios, mean alpha, beta and gamma energies, Q-values, all with associated errors when possible.

The major effort continues to be upon fission product decay data evaluations. The fission product data of Tobias[3] for mass numbers A= 72 to 161 and A = 166 are now in the desired format. Barnes and Tobias are re-evaluating and updating data for this fission product file (see table 3).

Nichols has been evaluating decay data for a list of activation products provided by the CEGB. The preliminary file is half complete, this first section yet to be tested to trace any errors. Much use has been made of recent evaluation effort by other groups (e.g. Nuclear Data Sheets and CEA, Laboratoire de Metrologie des Rayonnements Ionisants). The production of the file is continuing.

The 1976 fission yields evaluation of Crouch (see below) is now on file in ENDF/B format, as is the non-ENDF alpha decay data of Rogers[4].

A great deal of published data is at hand and is being used to slowly construct the UKCNDC data files, but it will be several years before a satisfactory, comprehensive set of files is available. After some initial problems, satisfactory progress to achieve this mammoth task is now being made, and it is to be hoped that this degree of effort can be maintained, or even increased, over the forthcoming years.

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

(2) A. Tobias, CEGB report RD/B/M3733 (1976)

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

(4) F.J.G. Rogers, AERE-R 8005, submitted for publication

2. Fission Yields

Fission Yields Assessment (E.A.C. Crouch (AERE))

This assessment, which was briefly mentioned in UKNDC(76) P80, has been completed. It consists of:

(i) thermal fission cumulative yields of ^{227}Th, ^{229}Th, ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu ^{241}Am, ^{242}Am, ^{245}Cm, ^{249}Cm, ^{251}Cf, ^{254}Es and ^{255}Fm; thermal independent yields for ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu;

(ii) fast neutron fission cumulative yields for ^{227}Ac, ^{231}Pa, ^{232}Th, ^{233}U, ^{235}U, ^{237}Np, ^{238}U and ^{239}Pu; fast independent yields for ^{235}U and ^{238}U;

(iii) 14 MeV neutron fission cumulative yields for ^{231}Pa, ^{232}Th, ^{233}U, ^{235}U, ^{237}Np, ^{238}U and ^{239}Pu; independent yields for ^{232}Th, ^{233}U, ^{235}U, ^{238}U and ^{239}Pu;

and

(iv) 11 MeV fission; cumulative yields for ^{232}Th,
8 MeV fission; cumulative yield for ^{232}Th,
3 MeV fission; cumulative yield for ^{231}Pa, ^{232}Th and ^{238}U,
1.1 MeV fission; cumulative yield for ^{237}Np.

From these experimental yields the unknown independent yields have been deduced empirically for the thermal neutron induced fission of ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu; the fast neutron fission of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu; the 14 MeV neutron fission of ^{232}Th, ^{233}U, ^{235}U and ^{238}U.

TABLE 3: U.K. Chemical Nuclear Data File in ENDF/B4 format

(December 1976)

Item	Data	Present Status	File Development
1	α-library	Completed in non-ENDF format by Rogers	No effort at present available to convert this data into ENDF format
2	Fission product decay schemes, including those nuclides produced by activation of stable FPs.	This is the main effort of the sub-committee especially for FP having half-lives > 1 hr and fission yields > 0.1%. The major contributions are by BNFL (Barnes) and CEGB (Tobias). The data published by Tobias in RD/B/M2669 has been converted into ENDF/B4 format. Detailed beta radiation information has been included in the Hollerith section of the format (end-point energies, mean energies and forbiddeness). At BNFL new calculations are underway for ^{137}Cs, ^{137}Ba, ^{144}Ce, ^{144}Pr, ^{134}Cs, ^{136}Cs, ^{131m}Te, ^{131}Te, ^{131}I, ^{131m}Xe, ^{132}Te, ^{132}I and ^{132}Xe. Some of this data has been recorded in ENDF/B4 format but no single isotope is complete due to complexities within the format demands.	Difficult to estimate when a <u>complete</u> FP data file will be available. The file will be built up in sensible stages. The aim is for the first stage to be available by June 1978.
3	Activation products of structural materials decay schemes.	Further evaluations are underway. The nuclides include:- ^{59}Ni, ^{63}Ni, ^{66}Cu, ^{65}Zn, $^{82,82m}Br$, ^{88}Y, $^{94,94m}Nb$, $^{93,93m}Mo$, $^{121,121m}Sn$, $^{122,122m}Sb$, $^{124,124m_1,124m_2}Sb$, ^{126}I, ^{128}I, ^{136}Cs, $^{133,133m}Ba$, ^{145}Pm, $^{152,152m_1,152m_2}Eu$, ^{154}Eu, ^{157}Tb, ^{175}Hf, ^{181}Hf, $^{182,182m}Ta$, ^{181}W, $^{185,185m}W$, ^{187}W, $^{197,197m}Hg$, ^{206}Hg, ^{206}Tl, $^{207,207m}Tl$, ^{208}Tl, ^{209}Tl, ^{209}Pb, ^{239}Np.	Preliminary data in ENDF/B format for ^{3}H, ^{10}Be, ^{14}C, ^{15}C, ^{16}N, ^{19}O, ^{22}Na, $^{24,24m}Na$, ^{27}Mg, ^{35}S, ^{36}Cl, $^{38,38m}Cl$, ^{39}Ar, ^{40}K, ^{41}Ar, ^{41}Ca, ^{42}K, ^{45}Ca, $^{46,46m}Sc$, ^{47}Sc, ^{48}Sc, ^{51}Cr, ^{54}Mn, ^{55}Fe, ^{56}Mn, ^{57}Co, $^{58,58m}Co$, $^{60,60m}Co$, ^{59}Fe, ^{64}Cu, $^{110,110m}Ag$, $^{115,115m}In$, $^{116,116m_1,116m_2}In$, $^{134,134m}Cs$, $^{198,198m}Au$, and ^{203}Hg.
4	Actinide decay schemes		
5	Decay schemes of other nuclides	Little effort available until items 2,3 and 4 are completed satisfactorily.	
6	Fission yields	Crouch's second round of evaluations completed.	Data on file in ENDF/B format. They are adjusted independent yields and adjusted mass yields
7	Delayed neutrons	Tomlinson data still recommended for use. New evaluation by Crouch underway (Dec '76)	
8	Spontaneous fission data	May be covered by evaluator (Glover) who, it is hoped, will maintain Rogers 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	

Fission Product Yields: consistent set (E.A.C. Crouch (AERE))

It has proved possible to improve the adjustment of chain yields and independent yields beyond the stage mentioned in UKNDC(76)P80 and AERE R.8152. The results of the assessments described above have been adjusted to be consistent with the following relations by the method of least squares.

$$\sum_A Y(A) = 2.0$$

$$\sum_A A.Y(A) = A_F + 1 - \bar{\nu}_r = \bar{A}$$

$$\sum_A Y(A).\bar{Z}(A) = Z_f \text{ when } \bar{Z}(A) = \sum_{Z(A)} Z.FIY(A,Z)$$

$$\sum_{Z(A)} FIY(A,Z) = 1.0$$

where Y(A) is the adjusted chain yield for fissile isotopes, mass number A, FIY (A,Z) is the adjusted fractional independent yield for mass number A, and atomic number Z, and $\bar{\nu}_r$ is the number of neutrons emitted in the fission reactions.

The fitting procedure produc s four simultaneous equations with undetermined multipliers λ_1, λ_2, λ_3, λ_4, whence

$$V(A) = -\sigma^2(A)\ (\lambda_2 + \lambda_3.A + \lambda_4 \cdot \sum_{Z(A)} Z.\ fiy\ (A,Z)\ )$$

and $$V(A,Z) = -\ fiy\ (A,Z)\ (\lambda_1 + \lambda_4 \cdot (y(A).Z))$$

where V(A) is the adjustment to y(A) the experimental chain yield (σ(A) is the experimental yield experimental error), giving Y(A) the adjusted chain yield. V(A,Z) is the adjustment to fiy (A,Z), the empirically deduced fractional independent yield, to give FIY (A,Z) the adjusted fractional independent yields. The assessed yields and the adjusted consistent sets have been submitted to Atomic Data and Nuclear Data Tables for publication. The consistent sets have been recorded on magnetic tape in ENDF/B4 format, for inclusion in the UKCNDC Nuclear Data File.

Survey of the present status of fission yield data (J.G. Cuninghame (AERE))

The successful 1973 Bologna meeting[(1)] on Fission Product Nuclear Data is to be followed by a second one in late 1977. J.G. Cuninghame has been asked to review all fission yield data under the following headings:

(i) current evaluations and best values of yields,
(ii) the effect of change of neutron energy,
(iii) independent yields,
(iv) ternary fission

The review paper will be produced for the meeting in September and will also be issued as an AERE report.

(1) Fission Product Nuclear Data, Proceedings of a Panel at Bologna (1973) IAEA-169

3. Related compilation studies

CASCADE - Computerised analysis of evaluated decay schemes (G. Evangelides (Imperial College, D.G. Vallis (AWRE))

The aim is to expand and improve CASCADE, a computer program which interprets evaluated decay schemes in terms of radiation data sets, and to produce a data base for input into CASCADE.

The major sources of information include

(i) the CASCADE code[1]

(ii) the internal conversion coefficient data of Hager and Seltzer[2], which will be extended using the data of Trusov[3],

(iii) the calculated $(E/E_o)_\beta$ of Widman[4] and the calculated EC/β^+ ratios of Zweifel[5]; a subroutine by Tobias[6] will also be included as an option to calculate the average β energies.

(iv) the decay scheme data base is being produced from the Nuclear Structure Data File (ENSDF) compilations of the Nuclear Data Project, Oak Ridge.

The CASCADE code has been set up at AERE Harwell, and some corrections and modifications have been made. The array dimensioning has been changed to use variable sets. Thus the maximum number of energy levels that the code can handle is only limited by the core limitation of the computer system available. The results compared very well with the original version. There are still a few minor snags within the code which will have to be eliminated before its capabilities can be extended e.g. to handle particle emissions.

A code is being developed which will extract the relevant data from the NSDF compilation into CASCADE input data format. It is hoped that eventually this will be in standard ENDF/B format and the code will be modified to handle ENDF/B data input and output.

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(1) D.G. Vallis, AWRE Report 045/74 (1974)

(2) R.S. Hager, E.C. Seltzer, Nucl. Data A4 (1968) No. 1-2

(3) V.F. Trusov, Nucl. Data 10 (1972) 477

(4) J.C. Widman, J. Mantel, N.H. Horwitz, E.R. Powsner, Int. J. Appl. Rad. and Isotopes 19 (1968) 1

(5) P.W. Zweifel, Phys. Rev. 107 (1957) 329

(6) A. Tobias, CEGB Report RD/B/N3740 (1976)

Publications

A. Tobias, A Brief Description of ENDF/B IV Format Data for Inventory and Decay Heating Calculations, CEGB Report RD/B/M3733 (1976)

A. Tobias, The Average Energy of Beta Spectra, CEGB Report RD/B/N3740 (1976)

BERKELEY NUCLEAR LABORATORIES, C.E.G.B

(Section Head: Dr. B.M. Wheatley)

TRANSLAT - A computer programme for tanslating and creating a subset of fission product ENDF/B-IV data (S. Nair, (CEGB-BNL))

A computer program has been developed which reads fission product yield and decay data in ENDF/B-IV data format. The program can be used to cross-correlate the yield and decay data files such that they refer to the same base set of 824 isotopes and to create a user-specified subset by truncating the decay chains at the low Z end. The resulting calculations assume that the half-lives of the isotopes to be discarded by the user are small compared to the time period of any calculation to be performed using the subset as source term. Fission yield contributions from radioactive decay and delayed neutron emission of the discarded isotopes are taken into account. The programme can also be used to extract from the ENDF/B-IV file the chemical symbols and average β and γ energies and to calculate the disintegration constants and an 18 group γ spectrum for the isotopes in the user-specified subset.

Compilation of Average β-energies for Heavy Isotope Decays (G.A. Harte)

A compilation of average β-energy per decay has been made for inclusion in the data library of the heavy isotope inventory code HYACINTH[(1)]. The β-energies were computed from data contained in a compilation of Nuclear Data Sheets made by the Nuclear Data Group at Oak Ridge[(2)] using a computer program of Tobias[(3)] which is currently being used in the production of ENDF/BIV data. Calculations have been made for each of the 74 isotopes considered in HYACINTH (isotopes of mass ranging from 208 to 253, and having half-lives greater than one hour) and for their shorter-lived daughters. In the HYACINTH library itself the mean β-energies of these daughters are added to the decay energies of their nearest included precursors.

The tabulations of Erdtmann and Soyka[(4)] have been used to compile a 15 group gamma-ray and X-ray spectrum for the same data library.

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(1) Harte, G.A., CEGB Report RD/B/N3564

(2) Nuclear Data Group (ORNL), 1973, Nuclear Level Schemes A-45 through A = 257 from Nuclear Data Sheets, Pub. Academic Press.

(3) Tobias, A., 1976, CEGB Report RD/B/N3740.

(4) Erdtmann, G. and Soyka, W., 1975, Journal of Radioanalytical Chemistry, Vol.26, pp. 375-495, and Vol. 27, pp. 137-286.

BIRMINGHAM RADIATION CENTRE, UNIVERSITY OF BIRMINGHAM

(Director: Professor J. Walker)

Neutronics Studies for CTR Blankets (T.D. Beynon, R.H. Curtis, C. Lambert, A. Oastler and N.P. Taylor)

1. Neutron Interactions with ^{7}Li [Relevant to request numbers: 1240-6]

R-Matrix theory has been applied to the neutron interactions with ^{7}Li in the range 0 to 14 MeV in order to calculate the elastic and all partial reaction cross sections.

Recent requests[1] for more data on the tritium production cross section ^{7}Li(n,n'α)t have emphasised the importance of theoretically interpreting this reaction. Earlier studies[2] show that the reaction proceeds mainly via two step decays of ^{5}He(g.s.) and ^{7}Li*(4.6 MeV). The theoretical energy dependence of these two cross sections arising from a compound nucleus mechanism has been calculated to be consistent with the few existing partial measurements. Direct mechanisms producing these reactions although important at higher energies are largely out-weighed by compound or possibly pre-equilibrium emission processes over most of the energy range studied.

The model requires parameterization of the ^{8}Li compound nucleus in terms of level positions and particle decay widths and recent shell-model calculations provide guide lines for this purpose. The 1972 cross section evaluation by Conlon[3] has been used as data for theoretical curve fitting whilst the more sensitive parameters have been derived from fitting to relatively scarce sources of differential cross section and polarization data. However, all fitting attempts require several broad states of both parities and indicate a loosely bound cluster-like model for ^{8}Li.

2. Analysis of CTR integral benchmarks and conceptual breeder structure

Analysis of most of the reported lithium bearing integral experiments has been performed using Monte Carlo and discrete ordinates codes[4]. Comparison of fluxes and tritium breeding rates has shown good agreement between experiment and theory, except at the 14 MeV source energy, which is thought to be due to inadequate source representation.

The method of matching the sensitivity profile of an integral lithium assembly to that of a conceptual fusion reactor blanket in order to maximise the usefulness of such integral experiments, has been investigated[4].

Initial analysis of the 1m dia. spherical lithium fluoride integral assembly at Birmingham has been carried out, and sensitivity analyses are underway to highlight the most important regions for future measurements.

Investigations of the heating rates in conceptual fusion reactor blankets have revealed significant differences in the amount of gamma ray heating in structural materials predicted by different workers. This is attributed to updating of the gamma ray production files in ENDFB, and indicates that a heating 'benchmark' calculation for fusion reactors (similar to the Steiner/Blow tritium breeding benchmark[5]) would be a useful exercise.

3. Neutron and gamma ray heating studies in CTR blankets

A method is being formulated for the evaluation of neutron and gamma energy release factors for use in nuclear heating calculations. The method uses the energy balance approach(6), which requires a minimal amount of computing time compared with the normal methods used for calculating kerma factors (see for example (7)). The calculation is performed using cross-sections already in energy group format. This enables heating factors to be computed from any existing group-wise cross-section sets, and ensures compatibility of the heating factors with cross-sections with respect to group structure, energy weighting and any modelling used in the procedure of creating group-wise cross sections from point data. Additional data required includes reaction Q-values. In order to calculate the energy released in inelastic neutron scattering via the continuum of levels in the target nucleus, an evaporation model is used to determine the average energy of gamma rays released. Parameters for this model are evaluated by fitting to known energy levels in the target nucleus. In use, the energy release factors, (which are computed for each energy group), are simply multiplied by the scalar neutron or gamma flux (also in energy group form) produced by a transport code such as ANISN.

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(2) V. Valkovic et al, Nucl. Phys. 98 305 (1967)

(3) T. Conlon, UKAEA rep. no. AERE-7186 (1972)

(4) T.D. Beynon, R.H. Curtis and C. Lambert, NEA/IAEA Shielding Conference, Vienna, October 1976.

(5) D. Steiner, Oak Ridge Nat. Lab. Report no. ORNL 4177 (April 1973)

(6) T.D. Beynon and N.P. Taylor, J. Phys D, 9 L53 (1976)

(7) M.A. Abdou and C.W. Maynard, Nucl. Sci. Engng, 56 360 (1975)

Neutron spectrum measurements in a LiF sphere (M.C. Scott, I.R. Brearley, N. Evans, J. Jowett and J. Perkins)

Preliminary neutron spectrum measurements have now been completed using proton recoil proportional counters in the energy range from 60 keV to 2.45 MeV in a 1.25 metre diameter sphere of natural lithium fluoride. Typical results are presented in figures 1 and 2 for measurements at 27 and 37 cm from a central D-T source, where they are compared with calculations using ANISN with the ENDF/B111 data set. The experimental results are arbitrarily normalised to the calculation, since associated particle yield determination had not been implemented for these measurements. It can be seen that close to the source the shape agreement between measurements and calculation is extremely good, but that at the greater distance there appears to be some discrepancy below 200 keV.

In order to extend the measurements up to the source energy at 14 MeV, a miniature (∿ 1 cc) NE213 scintillation counter has been developed. Preliminary measurements of the response functions indicate very good gamma discrimination which, combined with the fact that the response shapes are relatively undistorted compared to larger counters, means that the detector should be well suited for in situ measurements. Related theoretical studies of photon transmission in the detector, using Monte Carlo techniques indicates that there is a significant variation in the photon detection efficiency throughout the volume of the counter. These effects are being incorporated in predictions of the neutron response functions.

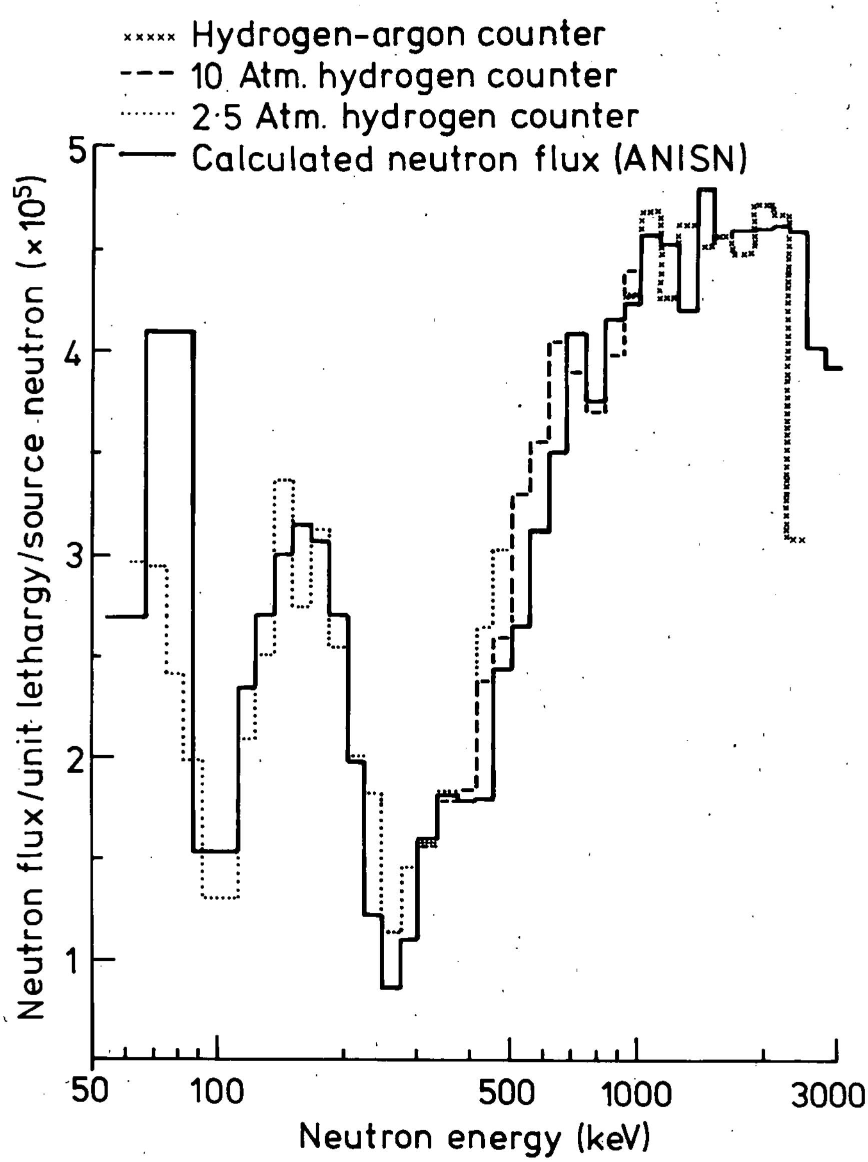

Fig. 1 Preliminary neutron spectrum measurements from a natural lithium fluoride sphere 27 cm from a central D-T source

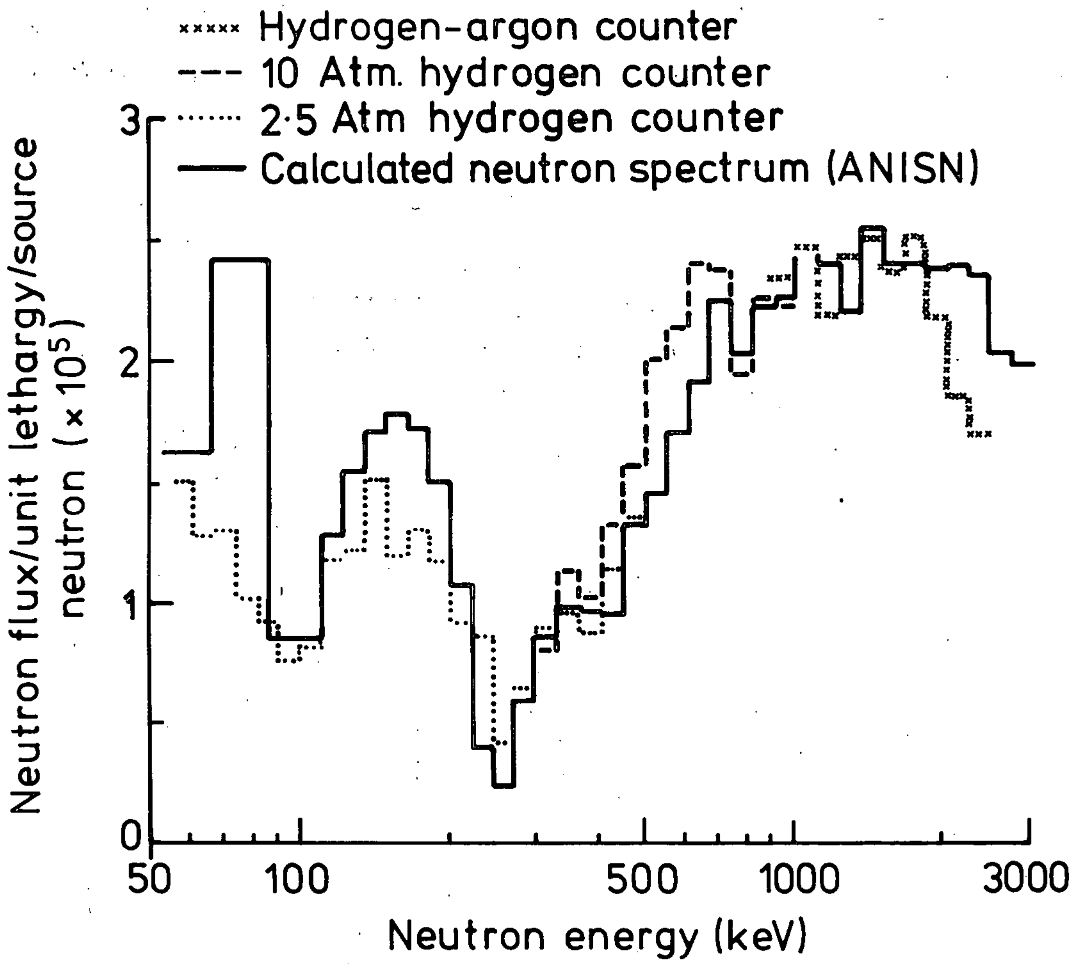

Fig. 2 Preliminary neutron spectrum measurements from a natural lithium fluoride sphere 37 cm from a central D-T source

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 request numbers: 169-172, 174, 559]

Measurements are continuing of the angular dependence of polarization and of the differential cross-section over the angular range 20° - 160° for the elastic scattering of 2.9 MeV and 16.1 MeV neutrons by medium and heavy nuclei. The 2.9 MeV measurements are made using $^{2}H(d,n)^{3}He$ neutrons in an associated particle time-of-flight system [(1)] and the 16.1 MeV measurements using $^{3}H(d,n)^{4}He$ neutrons from IBIS. In both cases the same multiple detector neutron polarimeter is employed, similar to that described previously [(2)]. Recent 16 MeV polarization measurements are illustrated in fig. 1. A large negative polarization at about 25° for the lighter nuclei (Fe, Cu) moves forward to 20° or less for the heavier nuclei, (W, Hg, Pb).

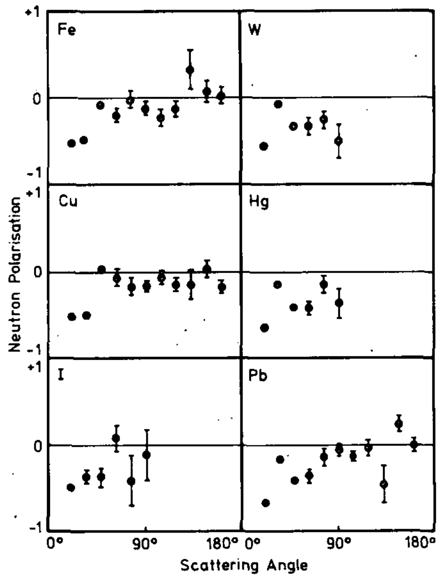

Fig. 1 Polarization of 16 MeV neutrons due to elastic scattering

The polarization of neutrons from the $^{2}H(d,n)^{3}He$ reaction for deuteron energies from 35 to 275 keV (A.M. Alsoraya and R. B. Galloway)

The dependence on deuteron energy of the polarization of the neutrons emitted at 45° from the $^{2}H(d,n)^{3}He$ reaction, in the range 35 to 275 keV, was determined from the asymmetry in the scattering of the neutrons by ^{4}He. There is no indication of the much discussed possible resonance at about 100 keV deuteron energy. Both Boersma [(3)] following a DWBA approach and Fick and Weiss [(4)] following an R-matrix approach deduced the same expressions relating the energy dependence of the neutron polarization to the energy dependence of the anisotropy of the differential cross-section. Within this theoretical framework a self consistent description of the energy dependence of the anisotropy coefficient and the polarization is possible. Of the previously proposed parameters those of Fick and Weiss [(4)] were found most satisfactory.

This work is to be published in Nuclear Physics.

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A gaseous scintillation detector for fission fragments with electric field enhancement of the light emission from the scintillator (D.E. Cumpstey and D.G. Vass)

A scintillation detector for fission fragments has been constructed consisting of a cell filled with purified gaseous xenon at 760 Torr viewed by a photomultiplier tube, EMI type 9791 QB. The application of a non-uniform electric field in the active region of the gas scintillator has been found to increase the light production following the detection of a fragment and to improve the resolution of the pulse height spectrum of the fragments. A typical spectrum due to the detection of the fragments emitted from a ^{252}Cf source at all angles between 0^{o} and 90^{o} (ie. emitted into a solid angle of 2π steradians) is shown in figure 2(a). The source has an active deposit of diameter 7 mm and a fission rate of about $10^{3}s^{-1}$.

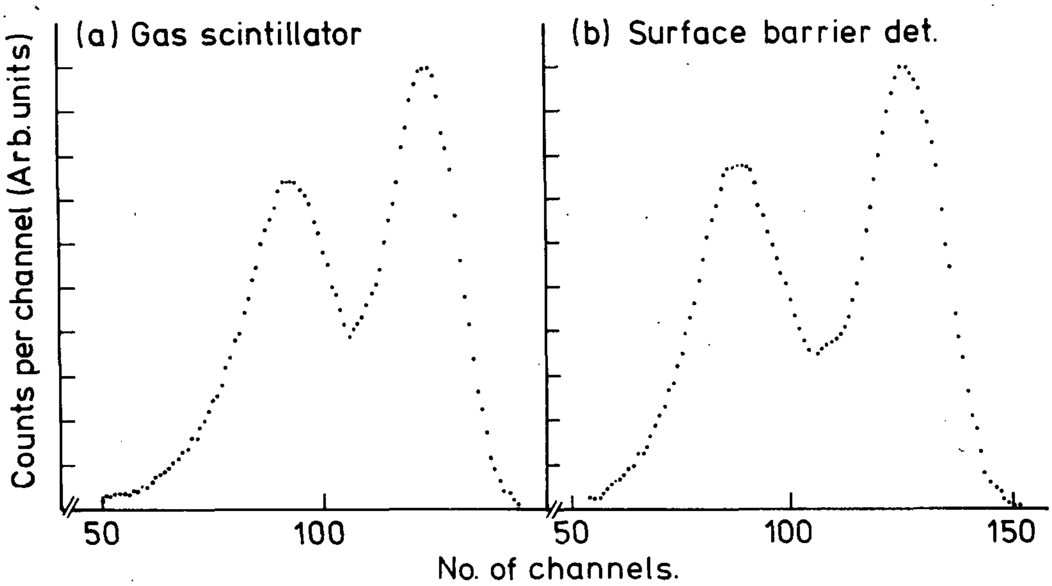

Fig. 2 ***Spectra from ^{252}Cf fission fragments in (a) A xenon gas scintillator with electric field enhancement of the light emission, and (b) A surface barrier detector***

For comparison a pulse height spectrum of the fragments from the same ^{252}Cf source recorded in vacuo using a surface barrier detector, Ortec type F60-300-60, mounted ∿7cm from the source is shown in figure 2(b); the solid angle subtended by the detector is about $2\pi \times 10^{-2}$ steradians. Within the accuracy of the measurements, the spectrum in figure 2(b) satisfies the criteria set out by Schmitt and Pleasonton[1)] for spectra obtained using semi-conductor detectors which exhibit good fragment energy resolution. Comparison of our spectra reveals that "low energy tailing" has occurred in the spectrum obtained using the gas detector; this we attribute mainly to the detection of fragments emitted from the source at grazing angles.

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(1) H.W. Schmitt and F. Pleasonton, Nucl. Inst. and Meths. 40 (1966) 204-208.

KELVIN LABORATORY, UNIVERSITY OF GLASGOW

(Director: Prof. J.M. Reid)

An analysis of the total neutron cross-section of ^{89}Y between 0.3 and 9.0 MeV
(G.I. Crawford, S.J. Hall and J.D. Kellie)

There are several reasons why a high resolution measurement of the neutron total cross section of ^{89}Y is of interest. ^{89}Y has a closed neutron shell with N = 50 so that it is reasonable to expect that the compound states in ^{90}Y can be formed via doorway resonances calculated from a two-particle and 3p-1h basis of the shell model. Since atomic mass 89 is situated at the peak of a p-wave optical model resonance the resulting enhancement of p-wave widths should also be observed in the total cross-section. In addition according to Elwyn et al.[1)] the parent state in ^{90}Y of the $T_>$ component of the E1 giant resonance in ^{90}Zr occurs at an excitation energy of ∿8 MeV and consequently the ^{89}Y total cross-section may be expected to exhibit a fairly large number of 1^- resonances near this energy. Furthermore, Divadeenam et al.[2)] mention that a structure of intermediate width is observed in ^{89}Y+n at about 600 keV which they claim is associated with the theoretically prediced $\frac{3}{2}^-$ doorway states occurring at the same energy in the isotones ^{89}Sr + n and ^{90}Zr + n.

The experimental cross-section between 0.3 and 9.0 MeV together with the optical model values calculated from the generalised potential of Wilmore and Hodgson[3)] have been shown in a previous report from the Kelvin Laboratory, University of Glasgow (1974/75).

An examination of the data reveals that between 0.9 and 1.4 MeV, the measured values are ∿15% larger than the optical model values. However since the present results agree very well with the results of Elwyn et al. between 0.8 and 1.4 MeV, and with the results of Glasgow and Foster[4)] above 3 MeV, the observed discrepancy is thought to be a genuine feature of the ^{89}Y total cross-section. Perhaps the enhancement in the cross-section is due to the presence of the parent states of the E1 giant resonance in ^{90}Zr previously referred to. It is also interesting to note that there is evidence of a broad resonance type structure at ∿610 keV with a width of ∿40 keV previously pointed out by Divadeenam et al.

A quantitative analysis of the total cross-section was attempted by firstly subtracting off the shape elastic cross-section calculated from the optical model in order to obtain the compound nucleus formation cross-section. From this latter cross-section were calculated, the unnormalised variance which was used to derive the nuclear level density in ^{90}Y as a function of excitation energy, and autocorrelation functions from which estimates of the average total neutron width were made.

The detailed procedures adopted in the analysis were the same as those described by Carlson and Barschall[5)] in their treatment of fluctuations in neutron total cross-sections.

The experimentally determined level densities are shown in table 1. Also shown are the values predicted from the Gilbert and Cameron[6)] formula and the back-shifted Fermi gas model of Dilg et al.[7)]. An examination of the ratio of the experimental to theoretical

TABLE 1

^{90}Y LEVEL DENSITY CALCULATIONS

	Gilbert and Cameron			Back-Shifted Fermi Gas		
Excitation Energy (MeV)	7.26	7.86	9.61	7.26	7.86	9.61
Density (MeV^{-1}) Experimental	9.15×10^3	8.4×10^3	1.05×10^4	7.8×10^3	7.6×10^3	9.9×10^3
Density (MeV^{-1}) Theoretical	1.8×10^4	3.2×10^4	1.55×10^5	3.9×10^3	6.1×10^3	2.4×10^4
Ratio $\frac{Exp}{Theo}$	0.51	0.26	0.068	2.0	1.24	0.41

densities reveals that the Gilbert and Cameron formula progressively overestimates the density (by a factor of 15 at 9.61 MeV excitation energy), while the back-shifted Fermi gas model underestimates the density at 7.26 MeV by a factor of 2, but overestimates it by a factor of 2 at 9.61 MeV. Since the errors in the experimentally determined level densities are ∿50%, the back-shifted Fermi gas model may be held to be in reasonable agreement with the experimental values.

However, from the experimental evidence, it is probably the case that over the range of energies being studied, the variation in level density with energy is not exactly exponential (as current theories assume) and that a more sophisticated energy dependence is required from the theoretical formulations.

Table 2 shows a comparison between the measured and theoretical values of $\langle\Gamma\rangle_{J^\pi}$, the average total neutron width of the compound nucleus resonances in ^{90}Y.

TABLE 2

^{90}Y COMPARISON OF MEASURED AND CALCULATED $\langle\Gamma\rangle_{J^\pi}$

Excitation Energy (MeV)	Γa (keV) from Autocorrelation	$\Gamma \ell$ (keV) Γa corrected	$\langle\Gamma th\rangle$ (keV) Theoretical	$\Gamma\ell/_{\langle D\rangle_{J^\pi}}$
7.26	0.8 ± 0.1	0.7 ± 0.2	0.41	0.2
7.86	2.8 ± 0.4	2.6 ± 1.0	0.69	0.6
9.61	6.8 ± 0.8	4.6 ± 2.0	1.74	1.4

In general the theoretical average total width is smaller by a factor of ∿2. It should be pointed out however that the theoretical average was taken for J = 0 and J = 1 resonances and that at the three energies considered the widths of the 0^+ resonances which are formed by incoming p-wave neutrons are equal to the experimental widths to within the errors present. In the far right column of table 2 the experimental ratio of $\Gamma\ell/_{\langle D\rangle_{J^\pi}}$ is shown where $\Gamma\ell$ is the experimental average total width and $\langle D\rangle_{J^\pi}$ is the average level spacing obtained from the experimentally determined total level density.

As expected, this ratio increases with excitation energy.

At present considerable theoretical interest in centered round the intermediate structure evident in the total cross-section of ^{90}Y. In a recent publication[8], Ramavataram et al. have managed to obtain an acceptable agreement between the general features of the experimental cross-section and an average of the cross-section obtained from R-matrix theory based on the shell model. As expected, the energies and widths of the resonances making up the details in structure in the cross-sections do not agree exactly. From the present results, it is hoped that an R-matrix fit to the data will provide resonance parameters which will put much greater restrictions on future shell model calculations of the cross-section.

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(2) M. Divadeenam et al., Ann. Phys. 69 (1972) 428
(3) D. Wilmore and P.E. Hodgson, Nucl. Phys. 55 (1964) 673
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(5) A.D. Garlson and H.H. Barschall, Phys. Rev. 158, (1967) 1142
(6) A. Gilbert and A.G.W. Cameron, Can. J. Phys. 43 (1965) 1446
(7) W. Dilg et al., Nucl. Phys. A217 (1973) 269
(8) S. Ramavataram et al., Ann. Phys. 97 (1976) 245

<u>Cross-sections for the reactions $^{235}U(n,f)$ and $^{238}U(n,f)$ up to a neutron energy of 9 MeV (G.I. Crawford, S.J. Hall, J.D. Kellie, W.W. Osterhage)</u> [Relevant to request numbers: 743; 833-4, 837-8, 841-2]

The fission cross-sections were measured using the continuous spectrum of neutrons between 0.3 and 9.0 MeV available from our neutron time of flight facility. The experiment was carried out using a 20m flight path and an electron beam pulse of 3.5 nsec F.W.H.M.

The fission cross-section was obtained by detecting the fission fragments from a foil inside a Xenon gas scintillation counter placed 20m from the neutron producing target. The gas scintillator is a 12.5cm x 12.5cm pressure chamber filled with Xenon at 2 atmospheres absolute pressure. The walls of the chamber are 15 thou" stainless steel and have a window viewing the foil, which is inclined at an angle of 45° to the incident neutron flux. The amount of fissile material on the foil was typically 1mg/cm^2 and the foil diameter 7cm. The scintillation pulse from Xenon has a decay time of 7.2 nsec, is in the ultraviolet region, and consequently necessitates using a quartz window and 58 UVP photomultiplier. The detector provides good separation between fission events and background α-particle activity.

Data taking was accomplished using an on-line PDP-7 computer operating in coincidence mode, in which the fission event timing pulse was stored as a function of pulse height. This made it possible to eliminate small amplitude pulses not related to fission, such as α-particles or noise associated with the γ-flash.

The incident flux was measured using a small plastic scintillator biased at $\frac{1}{5}$ ^{241}Am. At present the efficiency of this detector has been calculated using a Monte Carlo code and assuming a bias level of 255 keV neutron energy. Due to uncertainties in the relative light response of organic scintillators to electrons and protons at low energies, we do not consider the calculated efficiency to be sufficiently accurate. Consequently we will shortly set up the detector with the source bias level as was used in the experiment, and, by observing the spectrum of neutrons from a ^{252}Cf source, determine the efficiency of the detector as a function of energy. Since the spectrum of neutrons from ^{252}Cf is presently known to ∿3% down to a neutron energy of 300 keV[1], it is expected that an accurate efficiency curve will be obtained for the incident neutron detector, using this technique.

Although we shall eventually be able to present separate cross-sections for the ^{235}U(n,f) and ^{238}U(n,f) reactions, until the efficiency of the incident neutron detector has been determined accurately, the only information currently available is the ratio of the ^{238}U to ^{235}U cross-sections which of course is independent of the detector efficiency. The ratio is shown in Fig. 1. Also shown is the ratio calculated from the results of Leugers et al.[2]. It is obvious that in general the agreement between the two sets of results is good, apart from a region between 6 and 7 MeV where the results of Leugers et al. are significantly higher. Since this energy range is where second chance fission causes a sharp increase in both cross-sections, small differences in the energy calibration between the cross-sections for example, could cause large variations in the ratio.

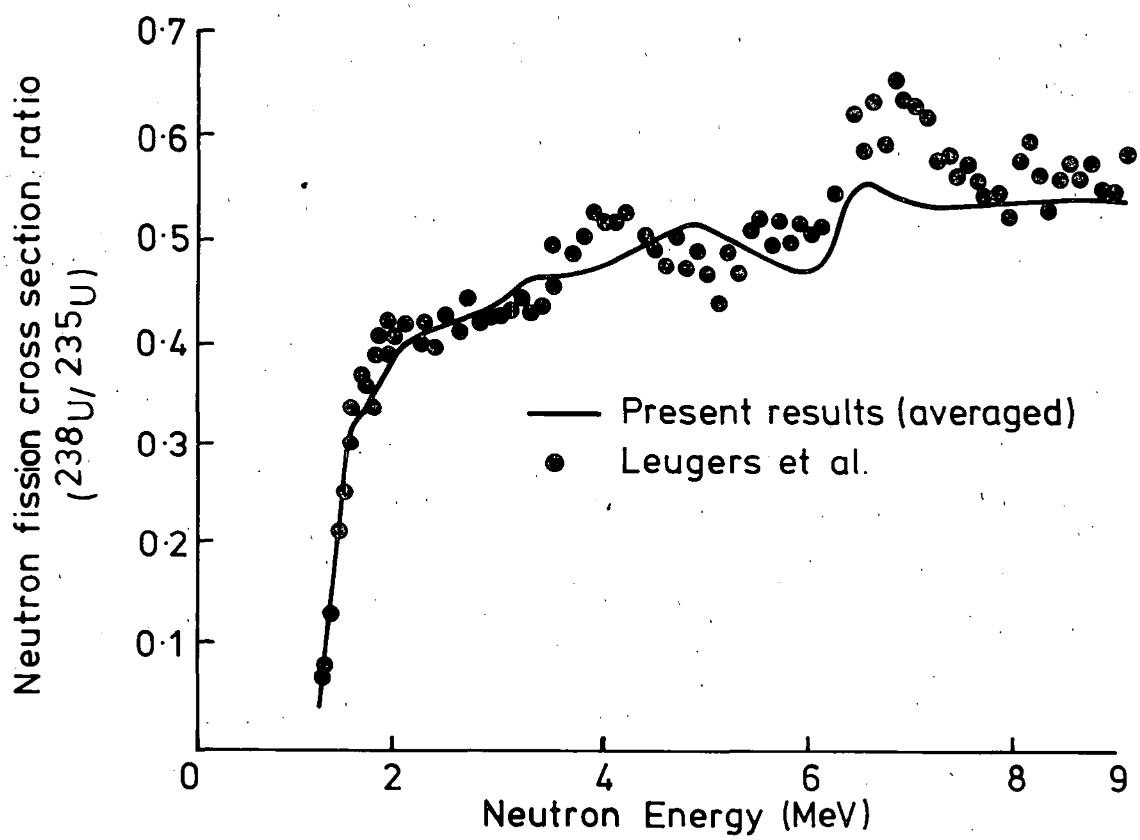

Fig. 1 The ratio of fission cross sections of ^{238}U and ^{235}U in the range 1.2 to 9 MeV. The averaged data of the present experiment (curve) are compared with the previous results of Leugers et al.

Currently, theoretical calculations of both fission cross-sections are in progress. The calculations follow the procedure outlined by Lynn[3] in his paper describing the systematics for neutron reactions in actinide nuclei. This is based on Hauser-Feshbach theory and incorporates the statistical model of level densities to calculate the total neutron transmission coefficient for elastic and inelastic scattering, and the giant dipole resonance model to estimate the total radiation width. A parameterisation of the double humped barrier is used to obtain the total fission transmission coefficients.

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(1) J.A. Grundl and C.M. Eisenhauer, Conf. on Nucl. Cross-sections and Technology, Washington D.C. (March 1975).

(2) B. Leugers et al., Karlsruhe. Private communication (1976).

(3) J.E. Lynn, AERE Report R7468 (1974)

Beta + Neutron + Gamma-Ray (BNG) decay mode of $^{93-96}Rb$ (G.I. Crawford, S.J. Hall, J.D. Kellie.)

In four separate experiments the isotopes of mass 93 to 96 of Rubidium were successively selected by the on-line mass separator Ostis (installed in a thermal neutron beam at the HFR at ILL) and collected on a plastic tape which was moved on intermittently to reduce the build-up of daughter activities. The separator uses a thermal ion source thus limiting the possible elements to Rubidium and Caesium: it then uses conventional mass spectroscopy to isolate the desired isotope with an estimated impurity level of about 10^{-3}.

Three detectors were used

(i) a thin plastic scintillator as beta detector, placed close to the tape

(ii) a liquid scintillator (12.7cm ∅ x 5.1cm) placed at 50cm from the tape

(iii) a NaI crystal (12.7cm ∅ x 12.7cm) placed with its front face 7.5cm from the tape.

A 'start' pulse taken from the beta-detector and a 'stop' from detector (ii) enabled neutron events to be separated from γ-ray events except that the very high instantaneous count rates in the two detectors led to a fairly high background of random delayed coincidences. These latter were largely eliminated by using the zero-cross PSD method to reject γ-ray events in the neutron detector. The γ-ray pulse height spectrum gated by a triple coincidence between beta, neutron and γ-ray was then recorded for each mass. Also recorded were (a) the total time of flight spectrum (with PSD) and (b) the time of flight spectrum (with PSD) gated by the triple coincidence requirement.

We also recorded the energy spectra from the γ-ray detector gated only by the beta detector (ie. β-γ coincidences instead of β-n-γ) for each isotope. Only the strong peakes seen in one of these spectra for a given mass would be expected to appear as background in the BNG spectrum of the same mass (where it can appear only by chance coincidence and imperfect PSD). However the true BNG peaks of mass A should appear as strong lines in the BG spectrum of mass A-1. Hence the BG spectra fulfil the dual role of confirming real BNG peaks and helping reject spurious ones. This is perhaps made more clear by reference to Fig. 2 which shows diagrammatic decay schemesof the two neighbouring isotopes of rubidium.

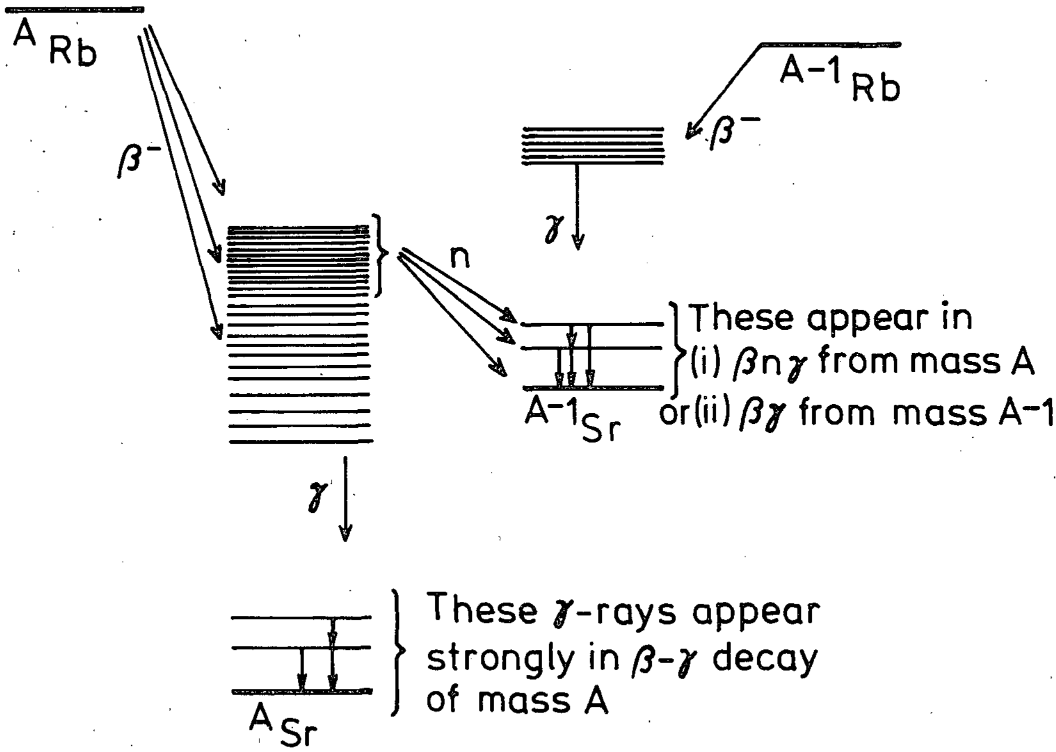

Fig. 2 Diagrammatic decay schemes for Rb isotopes, illustrating the origin of gamma transitions which appear as various coincidence events between observed beta, gamma and neutron emissions. Gamma rays due to transitions in ^{A}Sr appear strongly in the β-γ decay of ^{A}Rb. Gamma rays due to transitions in ^{A-1}Sr appear (a) in βnγ decays from mass A or (b) in βγ decays of mass A-1

Fig. 3 shows the BNG spectrum of ^{95}Rb together with the BG spectra of ^{94}Rb and ^{95}Rb. This shows clearly that the 845 keV state in ^{94}Sr is strongly populated by the BNG decay of ^{95}Rb. For each of the other isotopes studied similar evidence of BNG decay was found. The results are presented in Table 1 which presents our preliminary findings. In this table the quantity P_γ is defined by P_γ = Percentage of neutrons feeding a particular excited state. P_γ = No. of γ's of relevant energy in coincidence with a neutron event ÷ γ detector efficiency ÷ Number of neutron events. Note that the P_γ values have been corrected, where necessary and possible, to differentiate between γ-rays emitted following direct feeding of a particular level and those resulting from cascades from a higher state via the level in question.

In addition to these measurements we took neutron time of flight spectra for ^{94}Rb with an 80cm flight path and for ^{95}Rb with a 1m flight path. An unexpectedly large background of high energy γ-rays at the measuring position and an unexplained instability in the measuring chain which caused large changes in the zero of the time scale (it arose almost certainly in a multichannel analyser) restricted the amount and quality of the data which we recorded. However we have at least one spectrum for each of the two masses which seems to accord well with the most recent data taken with ^{3}He spectrometers. Our data has not yet been completely analysed but it would appear that we may be finding even more structure at low energy than did our collaborators with their ^{3}He detectors and also we suspect that they have a small error in their energy scale.

The potentially very interesting comparison of the total neutron energy spectrum with that of those neutrons which were *in* coincidence in the gamma-ray detector has not yet been made. Data has been taken for masses 93 to 96. Because of count rate restrictions a short neutron flight path was used and hence the spectra are of low resolution, but information about the envelope of the neutron energies in the two modes would still be valuable (and unique). A preliminary, necessarily qualitative, look at the data for only one isotope (^{95}Rb) suggests that the experiment may well have been successful.

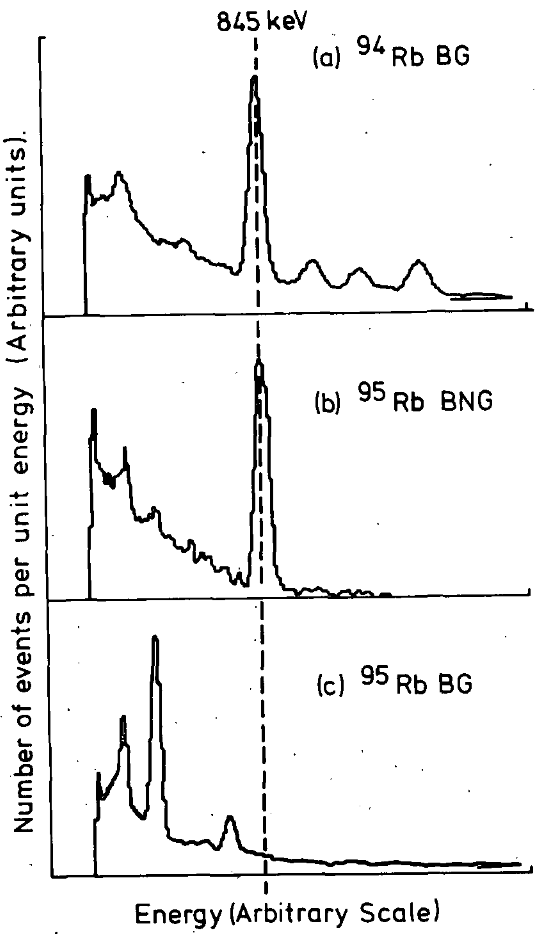

Fig. 3 Energy spectra from gamma ray detector in coincidence with (a) beta events from ^{94}Rb decay, (b) beta and neutron events from ^{95}Rb decay, (c) beta events from ^{95}Rb decay

TABLE 3

Precursor	γ-ray energy	P_γ	Comments
^{93}Rb	570	3.9%	2nd ES ⟶ 1st ES
	815	5.1%	1st ES ⟶ GS (ie. 1.2% direct feed + 3.9% cascade from 2nd ES).
	1385	1.9%	2nd ES ⟶ GS (∴ Cascade/direct = 2/1, as given in Nuclear Data Sheets)
			Hence total P_γ for ^{93}Rb = 7%
^{94}Rb	210	6.6%	Presumably includes predicted 213 and 219 keV
	450	6.2%	We do not yet have enough information to assign P_γ values to individual levels
	730	2.0%	
			Hence total P_γ for ^{94}Rb ≤ 14.8% (some cascades may have been counted twice)
^{95}Rb	845	36%	Total P_γ for ^{95}Rb = 36%
^{96}Rb	205	16%	Cascade from 2nd ES ⟶ 1st ES
	350	40%	Decay of 1st ES. 40% is direct feed, after correction for cascade
	670	8%	Decay of 3rd ES ⟶ GS Total P_γ for ^{96}Rb = 64%

DIVISION OF RADIATION SCIENCE, NATIONAL PHYSICAL LABORATORY

(Superintendent: Dr. W.A. Jennings)

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.

Neutrons in the 1-1000 eV energy range. (E.J. Axton and A.G. Bardell)

An experiment is in progress to determine the importance of the contribution of neutrons in this energy range to the total dose equivalent in a typical power station location. Measurements are being made with polythene spheres of 2", 3", 5", 8" and 10" diameter with gold foils at the centre.

The proton beam from the Van de Graaff accelerator has been transported successfully through three magnets to the target position and neutrons have been produced from the system. Not much progress is expected during the next year as the time will be taken up by conversion of the accelerator to pulsed operation.

Intermediate energy. (J.B. Hunt and R.A. Mercer)

The measurement of the long counter efficiency over the neutron energy range 500 keV to 1.2 MeV using the associated target activity method, employing the $^{57}Fe(p,n)^{57}Co$ reaction, is now completed. The induced ^{57}Co activity in seventeen different ^{57}Fe targets has been counted relative to a standard ^{57}Co source and preliminary results for the long counter efficiency have been obtained. These confirm previous determination of the efficiency, within the present experimental errors of $\pm$ 5%. The induced activity is at present being re-determined, using a different technique and it is hoped to improve the accuracy to about $\pm$ 3%.

Fast neutron energies (T.B. Ryves, K.J. Zieba and P. Kolkowski)

Activation measurements of the cross-sections for the $^{56}Fe(n,p)^{56}Mn$, $^{63}Cu(n,2n)\ ^{62}Cu$ and $^{65}Cu(n,2n)\ ^{64}Cu$ reactions have been completed for neutron energies between 14 and 19 MeV. Several small corrections to the measurements are being evaluated. Both the copper reaction cross-sections agree well with the ENDF/B-IV data file. In addition the $^{65}Cu(n,p)\ ^{65}Ni$ reaction cross-section has been measured, but the accuracy is likely to be poor due to the low level of induced activity.

Neutron Source Calibrations (E.J. Axton and A.G. Bardell)

In order to improve the accuracy and reduce the cost of calibration of low intensity neutron sources, the original AERE boron pile has been reconstructed and electronic instrumentation is in progress. The pile will be calibrated against a range of sources which have been standardized in the manganese sulphate bath. Manganese bath corrections for some unusual sources are being investigated by Monte-Carlo and diffusion calculations, and by measurement in two different bath sizes. Calculations for some of the sources, eg AmLi, AmB and AmF are affected by the lack of information on the low energy part of the spectrum. It is hoped that the two-bath technique will remove this problem.

Progress in the B.I.P.M. international intercomparison of neutron flux density

Since last year's report measurements have been made by I.M.M. (Russia) at 14 MeV neutron energy, using the iron foil technique only, by E.T.L. (Japan) using both methods at all energies and by B.I.P.M. at 2.5 MeV and 14 MeV neutron energies. A discussion of the results is scheduled for presentation by B.I.P.M. at the International Specialists Symposium on Neutron Standards and Applications, which will take place in Washington D.C. U.S.A. in March 1977.

Reference standard for fast neutron therapy dosimetry (E.J. Axton, V.E. Lewis, D. Thomas and D.J. Young)

Collimated beams of 14.7 MeV neutrons have been produced but the required dose-rates have not yet been achieved. Measurements of the total (neutron plus gamma) dose in tissue with a tissue equivalent cavity ionisation chamber and of the gamma dose with a C-CO_2 chamber have started. Other types of ionisation chamber are being constructed. A proton recoil telescope suitable for the direct measurement of kerma in hydrogen has been designed.

The gamma dose component is most accurately and conveniently measured with "neutron insensitive" GM counter. Three types have been used for the dosimetry facility and for a 14.7 MeV flux in a "low-scatter" environment. Consistent results were obtained. The 14.7 MeV neutron sensitivities of these counters were measured by an associated particle coincidence technique.

Thermoluminescent dosimetry for fast neutron therapy (M.J. Rossiter and J.W. Wood)

TLD is often used for the measurement of the gamma-dose component of neutron beams. The 14.7 MeV neutron sensitivities of four common Tl phosphors were measured using a flux produced in the low scatter area in which the gamma dose component had been measured with GM counters as $(1.10 \pm 0.20)\%$ of the total dose. The sensitivities to thermal neutrons were measured using the NPL thermal flux facility.

Nuclear decay scheme measurements (P. Christmas, M.J. Woods, R.A. Mercer, P. Cross and S. Brown)

Work is continuing on the measurement of the L & K internal conversion coefficients of ^{113}Xe, and on the γ branching ratio in ^{86}Rb. Half-life measurements have been made for ^{115m}In, ^{123}I and ^{47}Sc. An improved system for the measurement of half-lives by the differential ionization chamber technique is being developed.

W-value measurements (P. Christmas, M. Burke and I. Brearley (Birmingham University Physics)).

A research contract has been placed with Birmingham University for the determination of W-values for protons of energy 700 keV to 3 MeV in hydrogen, acetylene, ethylene and tissue equivalent gas. At Birmingham and at NPL measurements will be made of the number of ionizing events and the corresponding current produced in an ionization chamber. Protons will enter the NPL chamber through a polyester window; measurements have been made of the energy loss characteristics of this material for protons in the energy range of interest.

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