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U.K. Nuclear Data Progress Report

January – December 1987

Edited by M R Sené and J A Cookson

Nuclear Physics and Instrumentation Division
Harwell Laboratory, Oxfordshire
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PREFACE

This report, summarising nuclear data research in the United Kingdom during 1987, has been prepared at the request of the U.K. Nuclear Data Committee (UKNDC).

Apart from work coordinated by the Chemical Nuclear Data Committee of the UKNDC, which appears under the heading of Chemical Nuclear Data, progress reports are presented by laboratory. This year there have been contributions from the UKAEA establishments at Harwell and Winfrith, from the National Physical Laboratory and from the Universities of Birmingham, Oxford and Sussex. Included in these contributions, however, are reports of work carried out by collaborations extending involvement to the following Institutions: Queen Mary College and Imperial College of the University of London, Liverpool Polytechnic, Manchester University, Culham Laboratory, JET, CEGB Berkeley Nuclear Laboratory, Dounreay Nuclear Power Establishment, AWE Aldermaston, Daresbury Laboratory, Hammersmith Hospital, the Technical University of Vienna and the Laboratoire de Spectrometrie Nucléaire, CSNSM, Orsay.

Where work is clearly relevant to requests in WRENDA 87/88 (INDC(SEC)-095/URSF), the appropriate numbers are given after the title of the contribution. In addition, a CINDA-type index is included at the end of the report.

The editors would like to thank all those who contributed so promptly at the beginning of the year and to apologise for the delay in publication which was, inevitably, due to circumstances beyond our control.

M. R. Sené

J. A. Cookson

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1. NUCLEAR PHYSICS DIVISION, HARWELL LABORATORY

(Division Head: Dr. A. T. G. Ferguson)

1.1 Evaluation of cross-sections for the Joint Evaluated File (M. C. Moxon, M. G. Sowerby and B. H. Patrick)

1.1.1 Phase 1 review of proposed ENDF/B-VI standard cross-sections [WRENDA 16, 34, 92, 599, 677, 728, 749, 806]

The standard cross-sections for the ENDF/B-VI library have been evaluated using a simultaneous evaluation procedure[1]. As part of our contribution to the JEF library we have undertaken the Phase 1 review of the proposed evaluations. This involved investigating both the data base used for the evaluation and the evaluation method. Though we were unable to consider in detail the R-matrix analyses of the ^{6}Li and ^{10}B cross-sections we found that the data base of W. P. Poenitz used for the other cross-sections was complete and free from significant error. As far as we could tell the methods adopted in performing the evaluations were also correct. As a result of the review we came to the conclusion that the cross-sections recommended for the following reactions were correct and free from serious error: ^{3}He(n,p), ^{6}Li(n,t), ^{6}Li(n,n), ^{10}B(n,α_0), ^{10}B(n,α_1), ^{10}B(n,n), Au(n,γ), ^{235}U(n,f), ^{239}Pu(n,f) and ^{238}U(n,f). We did not consider the H(n,n) cross-section and found the ^{238}U(n,γ) cross-section to be in error. In principle the incorrect ^{238}U(n,γ) cross-section should influence the other cross-sections because the simultaneous evaluation method was employed. However, in practice the effect can be ignored because the sensitivity of the other cross-sections to changes in the ^{238}U(n,γ) data is sufficiently small.

1.1.2 ^{238}U cross-sections

The evaluation of the ^{238}U cross-sections described in the previous report (UKNDC(86)P114, p.1) has continued though progress has been inhibited by reductions in funding for the work. Most of our work has been in the resolved resonance range and currently 1558 resonances are included in the evaluation between 0 and 10 keV. These are arbitrarily divided into s- and p-wave

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(1) A. D. Carlson, W. P. Poenitz, G. M. Hale and R. W. Peelle, Proc. of International Conference on Nuclear Data for Basic and Applied Science, Santa Fé, Vol. 2, p.1429 (1986).

populations though of course some resonances have had their spins correctly identified. In the past year Harwell has worked to improve the parameters below 4 keV while the NEA Data Bank has worked at higher energies. The Harwell work has emphasised the energy range below 1 keV where there have been no recent shape analyses with the improved resolution functions which have been shown to be so necessary at higher energies. The main aims of this work have been to (a) get better data for the first few resonances that are important for thermal reactors, (b) improve knowledge on $\langle\Gamma_\gamma\rangle$ and (c) investigate the gas model of Doppler broadening, which is normally used in reactor calculations. Though final assessment of the analyses is incomplete it appears that

(1) the best $\langle\Gamma_\gamma\rangle$ is 23.0±0.1 meV which is slightly lower than the 23.5 meV usually assumed;

(2) good fits to the 6.6 eV resonance cannot be achieved (high χ^2 per degree of freedom) but similar sized resonances at higher energies are well fitted. This suggests, not unexpectedly, that solid state effects are important for the 6.6 eV resonance thus confirming the results of Meister et al[1] and Jackson and Lynn[2].

(3) the effective temperature which describes the Doppler broadening function is found to be ~305.7±0.6 K for uranium metal. The Debye temperature derived from this is 283±7 K which is inconsistent with the values obtained from specific heat data (180-200 K). The values are closer to the data recommended for UO_2 by Butland[3] which were verified experimentally by Haste and Sowerby[4] (T_{eff} = 303.6 K, Θ_D = 258.5 K for a thermodynamic temperature of 293 K).

A paper with the following abstract was presented to the IAEA Advisory Group Meeting on Nuclear Data for the Calculation of Thermal Reactor Reactivity Coefficients, Vienna, 7-11 December 1987:

Doppler Broadening Effects in Low Energy Resonances

M. C. Moxon and M. G. Sowerby

Abstract

The gas model of Doppler broadening is used both when resonance parameters are extracted from measurements of nuclear data and when these parameters

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(1) A. Meister, S. Mittag, W. Pilz, D. Seeliger and K. Seidel, Nuclear Data for Basic and Applied Sciences, Vol. 1, p.489, Gordon and Breach, New York (1986).
(2) H. E. Jackson and J. E. Lynn, Phys. Rev. 127, 461 (1962).
(3) A. T. D. Butland, Ann. Nuc. Sci. and Eng. 1, 575 (1974).
(4) T. J. Haste and M. G. Sowerby, J. Phys. D: App. Phys. 12, 1203 (1979).

are converted to the cross-sections needed for reactor calculations. A brief review is made of the available information on the adequacy of the gas model for low energy resonances ($\lesssim$10 eV), as these are particularly significant for thermal reactors. It is found that the gas model with an effective temperature is not always an adequate prescription.

The work being done above 4 keV is aimed at resolving problems observed when a given set of parameters has to fit both transmission and capture data. Occasionally it is found that consistency can only be achieved if either Γ_γ deviates considerably from a constant value or more than one resonance of the same spin are very close together. The evaluation is being performed assuming the latter conclusion is correct. An example of a typical problem, provided by Dr. Nakajima (NEA Data Bank) is shown in Fig. 1.1 where the capture yield and transmission calculated from a given set of parameters are compared to experimental data. It is difficult to get good fits to the resonances at ~5040 eV.

1.2 The fission reactor inventory code FISPIN (D. A. J. Endacott)

Work has continued in support of the inventory code FISPIN[1] on the Harwell main frame IBM 3084Q computer. Most of the effort has been expended in giving advice on the use of the code and in solving problems encountered by a variety of users throughout the nuclear industry. Some work has also been needed to maintain the code and its data libraries. Additional cross-section libraries AGRHYA20, AGRHYA26 and AGRHYA32 have been obtained which give burn-up dependent cross-sections for the Heysham/Hartlepool reactors for enrichments of 2.0, 2.6 and 3.2% respectively. In order to reduce running costs work has started to convert the current recommended version of the code (FISPIN-6) so that it will run on the CRAY-2 computer.

1.3 Iron capture cross-section measurements (D. B. Gayther, M. Bailey, J. E. Jolly and R. B. Thom (Tessella Support Services Ltd.))

Work has continued on the analysis of the iron capture yield data obtained on HELIOS in measurements which have been described in previous reports. The capture cross-section is derived by applying a pulse amplitude weighting

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(1) R. F. Burstall, ND-R-328 (1979).

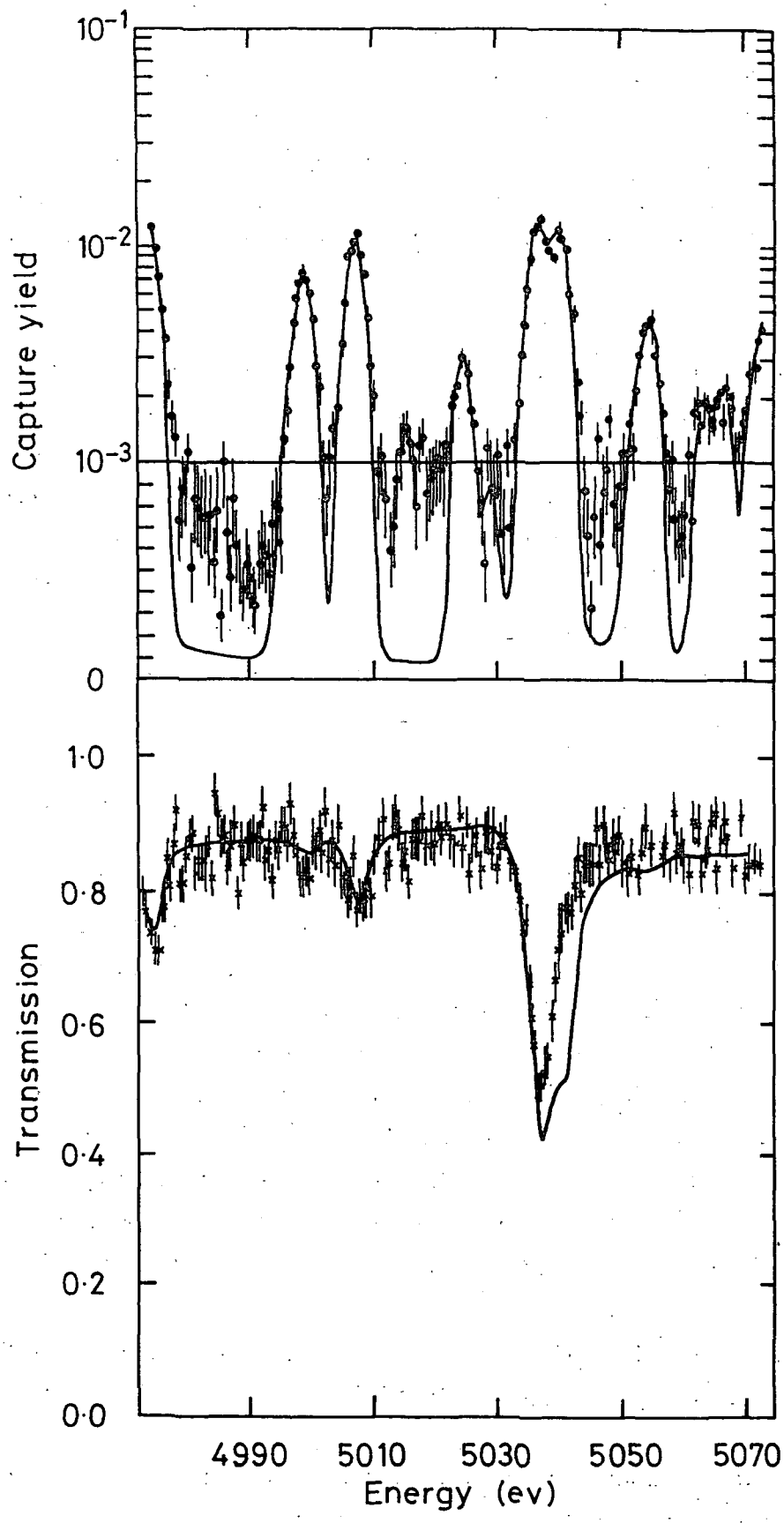

Figure 1.1 Comparison of measured and calculated ^{238}U capture and transmission data

function to the data (see UKNDC(86)P113, p.6). The generation of this function requires a knowledge of the response of the particular detector used in the measurements to monoenergetic gamma-rays with energies up to ~10 MeV. It is difficult experimentally to provide gamma-ray sources over the complete energy range and the response is therefore calculated with a suitable Monte Carlo code. Where experimental responses are available, it has been found in this and other laboratories that even quite sophisticated calculations fail to agree with observed responses for higher energy gamma-rays, although reasonable agreement is obtained for energies below ~2 MeV. For this reason it has not been possible to complete the analysis of the capture yield data.

In the Autumn of 1987 there was a breakthrough. Francis Perey of ORNL compared responses of C_6D_6 detectors, such as those used at Harwell, to monoenergetic gamma-rays produced with accelerator sources with responses calculated with the computer code EGS4. He showed that when all the materials in the accelerator target and nearby objects are taken into account properly, good agreement is obtained between calculation and experiment. The program EGS4 originates from the Stanford Linear Accelerator Centre and treats in a very comprehensive way the Monte Carlo simulation of electromagnetic cascade showers. Arbitrary geometry can be handled using the combinatorial geometry subprograms of the MORSE-CG code. The shape of the response function of the Harwell C_6D_6 detector to 6.13 MeV gamma-rays produced in the $^{19}F(p,\alpha\gamma)$ reaction on the IBIS Van de Graaff is predicted by EGS4 to better than 15% when all local materials are included in the calculation. Figure 1.2 shows the result of Perey's calculations. In the IBIS measurement 500 keV protons were used, resulting in some excitation of the 6.92 and 7.12 MeV levels in ^{16}O. The contribution to the observed spectrum from the decay of these levels was determined with a NaI detector capable of resolving the gamma-rays from the main 6.13 MeV line. The EGS4 code has now been implemented on the IBM at Harwell and the calculation shown in the figure has been confirmed.

In previous calculations using such codes as GAMOC and McBEND, the shape of the 6.13 MeV response curve differed by as much as a factor of two from experiment. Although the treatment of the physical processes leading to the production of light in C_6D_6 is probably adequate in these codes, it appears that insufficient account for the effect of local materials was made in calculating the response.

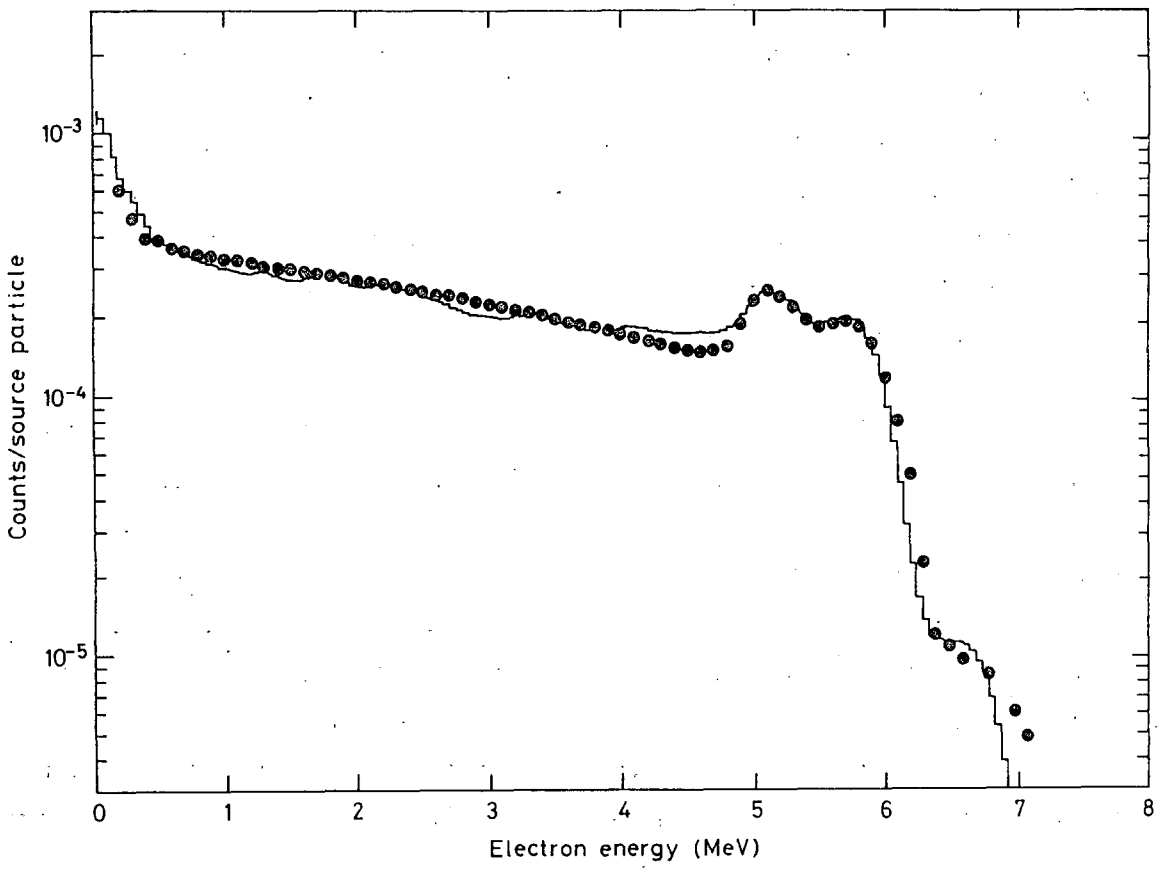

Figure 1.2 Comparison of the response of a C_6D_6 detector to the 6.13 MeV gamma-rays produced in the $^{19}F(p,\alpha\gamma)$ reaction as measured on IBIS (circles) and calculated with the EGS4 code (histogram, F. Perey (private communication)). An experimentally determined 7% contribution from gamma-rays at 6.92 and 7.12 MeV is included in the calculation.

An important result of Perey's calculations is to show that in generating a weighting function for capture measurements, it is necessary to take account of all materials in the vicinity of the capture sample itself, as well as in the vicinity of the gamma-ray detector. These considerations cast doubt on the validity of the results of many existing neutron capture cross-section measurements.

In the IBIS experiment, only the shape of the 6.13 MeV gamma-ray response was measured. It is considered necessary to establish that EGS4 is capable also

of calculating the absolute efficiency of the detector before applying it to the generation of the weighting function. A $^{19}F(p,\alpha\gamma)$ measurement has been planned for the 6 MeV Van de Graaff at Harwell, in which the efficiency of the C_6D_6 detector will be compared directly with that of a standard NaI detector of known efficiency. As in the IBIS measurement, a minimum amount of material will be placed near the target and the detector allowing the geometry to be accurately simulated in the Monte Carlo calculation.

1.4 Neutron resonance capture gamma-ray spectroscopy (S. Croft, L. C. Pratt (Queen Mary College) and B. H. Patrick)

Over the past year several aspects of data acquisition on the neutron capture gamma-ray facility (see UKNDC(85)P112, p.39) have been improved.

The energy resolution of the data acquisition has been improved by doubling the number of channels in both TOF and PHA. This will enable higher energy resonances to be studied than previously, in particular the first s-resonance in ^{52}Cr and the second in ^{54}Fe, at 50.19 keV and 52.67 keV respectively.

The code that handles the storage of the data on cartridge disk and the interactive graphics routine has been modified appropriately to deal with the additional channels.

The opportunity has been taken to modify the code to handle background subtraction of the PHA spectrum. The improvements include the use of a more stringent statistical test for accepting a calculated background, which removes an existing bias towards too high a background, and also the addition of a facility based on a moments method to find the centroid position of a peak, which aids the energy calibration process.

A series of calibration measurements to investigate the effect of melding the thermal capture data (extended source geometry) with the standard gamma source (point source geometry) data have been made using ^{7}Be disk sources of different diameters. These show that there is a significant effect at about the 5% level, which must be corrected for when performing the efficiency calibration.

The transmission data used to determine the n-value of the ^{10}B sample used in neutron flux measurements is in the process of being reanalysed.

A ^{10}B ion-chamber intended to go into the beam line has been designed and built to give an on-line measurement of the neutron beam spectrum. This will remove the need for the ^{10}B sample capture runs, giving more efficient use of beam time.

1.5 Fission chambers for the intercomparison of fast neutron flux density measurements (D. B. Gayther)

Comparison of the measurements made so far with the two fission chambers show no large discrepancies. The quantity which is studied in the intercomparison is the neutron detection sensitivity of each chamber, which is defined as the quotient (fission events)/(incident neutron fluence). Twenty-five determinations of this quantity have now been made by the six laboratories who have participated. The results are in reasonable agreement with the calculated sensitivities based on the ENDF/B-VI fission cross-section and the accurately determined fissile content of each chamber. The latter quantity is not known by the participants. A progress report on the work will be presented at the 8th Meeting of Section III (neutron measurements) of the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) to be held at the Bureau International des Poids et Mesures. It is hoped to make measurements on HELIOS in early Summer 1988. Table 1.1 summarises the present state of the programme.

1.6 The measurement of accurate total cross-sections for lead and carbon in the energy range below 100 keV (J. Schmiedmayer (Institute of Nuclear Physics, Technical University, Vienna) and M. C. Moxon)

The neutron transmissions through lead and carbon samples have been accurately measured in the neutron energy range below 100 keV using both the 150 m flight path on the Fast Neutron Target and the 8/15 m flight path of the Condensed Matter Target of HELIOS. These measurements were undertaken in order to obtain accurate values of the energy dependence of the neutron total cross-section for lead and carbon from which it is hoped to determine values of the electric polarizability of the neutron and the neutron electron scattering length. In the accurate determination of the background for these measurements

Table 1.1

Current status of the fission chamber intercomparison measurements

LABORATORY	DATES	ENERGIES (MeV)	ACCELERATOR	FLUENCE MONITOR	COMMENTS
NBS+	Jan.-July 1983	0.53	Linac, Pulsed Van de Graaff	Black detector	Only ^{235}U chamber used. Excellent agreement between Linac and Van de Graaff measurements. Final report written.
BIPM+	Feb.-May 1984	14.65	Unpulsed D-T generator	Associated particle	Both chambers used. Preliminary report written.
PTB+	Oct. 1984 - March 1985	2.5,5.0, 14.65	Pulsed Van de Graaff	Proton recoil telescope	Both chambers used. Final report written.
CBNM+	April 1985 - February 1986	All	Linac, Pulsed Van de Graaff	Proton recoil telescope and proportional counter	Van de Graaff measurements completed with both chambers at 0.565, 2.5, 5.0, 14.8 MeV and final report written. Linac not yet used.
ETL+	Spring 1986	0.144, 0.565, 5.0,14.6	Cockcroft-Walton Pelletron		Both chambers used. Final report written.
NPL+	Spring 1987	0.565, 14.7	Pulsed Van de Graaff, Sames generator	Long Counter, Associated particle and foil activation	14.7 MeV measurement completed with both chambers and report written.
HAR+		All	Linac, Pulsed Van de Graaff?		Last measurement.

+NBS: National Bureau of Standards (USA), BIPM: Bureau International des Poids et Mesures (France), PTB: Physikalische Technische Bundesanstalt (FRG), CBNM: Central Bureau for Nuclear Measurements (EEC, Belgium), ETL: Electrotechnical Laboratory (Japan), NPL: National Physical Laboratory (UK), HAR: Harwell Laboratory (UK).

values of some of the resonance parameters for cobalt and manganese, used as background filters, have been obtained.

1.6.1 Measurements

The measurements were carried out in two energy regions:

(i) ~0.1 eV to ~100 eV using the transmission spectrometer on the Condensed Matter Target of HELIOS. This uses two thin lithium glass scintillators as neutron detectors at distances of 8.7 and 14.7 m from the neutron source. The neutron detector at the 18.4 m position was a ^{10}B loaded liquid scintillator.

(ii) The energy range ~10 eV to ~100 keV was measured using the 150 m flight path on the Fast Neutron Target of HELIOS and the same ^{10}B loaded liquid scintillator mentioned above.

Both sets of measurements used the same electronics system which is capable of recording simultaneously, with a dead time of 10 ns, both time-of-flight and amplitude information from up to three separate detectors.

The carbon samples were manufactured from reactor grade 'A' graphite. The measured density of 1.623 Kg/ℓ is low but within the limits of 1.5 to 2.2 Kg/ℓ quoted by the manufacturer. X-ray radiographs revealed no variation in the density of the samples to within the limits of the measurements, which was equivalent to a variation in thickness of ~±0.2 mm (i.e. ±2% for the thinnest sample).

The lead samples were made from sheets of 99.98% pure material. The nominal impurity content supplied by the manufacturer is shown in Table 1.2. (A neutron capture measurement on a smaller diameter sample made from the same material only indicated the presence of silver at the 1 to 2 ppm level.)

The dimensions and thicknesses of the samples are given in Table 1.3.

Table 1.2

An impurity analysis for the lead samples

Element	Abundance %
Pb	99.98
Cu	0.003
Sb	0.002
Bi	0.005
Fe	0.003
Ni + Co	0.001
Ag	0.002
Zn	0.002

Table 1.3

Sample No.	Diameter (mm)	Thickness (mm)	Weight (grams)	Density Kg/ℓ
Lead				
1	149.71	7.01	1387.28	11.242
2	150.05	7.07	1408.46	11.266
3	150.08	7.03	1402.97	11.281
4	149.99	7.04	1406.04	11.303
5	149.98	6.98	1395.59	11.317
6	149.85	7.03	1406.40	11.343
7	149.94	7.09	1410.34	11.266
8	149.87	7.07	1412.48	11.325
9	149.93	6.96	1388.06	11.296
10	150.06	7.00	1402.26	11.327
11	149.84	7.01	1400.43	11.329
12	149.88	7.02	1402.49	11.324
13	149.93	6.99	1398.72	11.334
14	149.66	7.10	1411.81	11.304
15	149.88	7.02	1404.28	11.338
16	149.94	7.05	1409.23	11.321
17	149.51	7.01	1389.11	11.287
Carbon				
1	150.00	12.55	359.41	1.6206
2	150.00	25.04	717.82	1.6222
3	150.00	50.06	1435.89	1.6231

Uncertainties on the dimensions are ±0.02 mm and uncertainties on the weight are ±0.1 gm

1.6.2 Results

(a) Carbon

The measurements on the carbon samples were initially used to check both the data acquisition equipment and the data analysis programs. Figure 1.3 shows that the observed average transmission for the energy region 1 to 10 eV of the graphite samples as a function of thickness follows the expected exponential form.

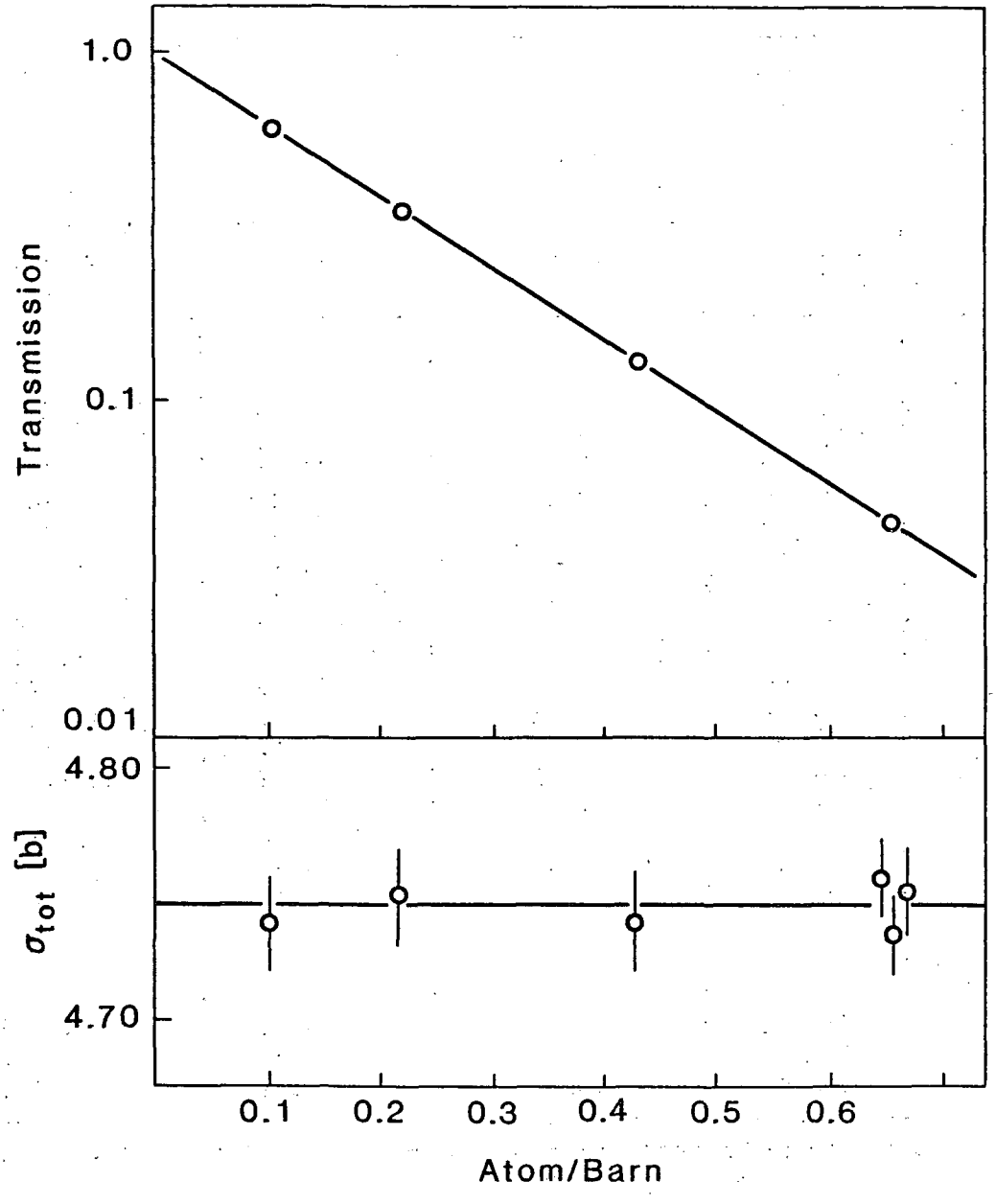

Figure 1.3 The average transmission and the deduced total cross-section values for the carbon samples as a function of sample thickness.

A least squares fit to all the transmission data over the neutron energy range 50 eV to 60 keV gives the total cross-section $\sigma_T(E)$ as a function of neutron energy E in MeV as the following polynomial.

$$\sigma_T(E) = 4.7435 \pm 0.026 + (3.41 \pm 0.24)E \qquad (1)$$

The uncertainties quoted include statistical errors, errors in the determination of the background and in the dimensions and composition of the samples.

In the energy range below 100 keV there is a surprising lack of accurate measurements of the neutron energy dependence of the carbon total cross-section.

The measurements of Uttley and Diment[1] are the only other data that cover completely this energy range. The present data are in good agreement. Uttley and Diment fitted a fourth order polynomial to their data over the energy range 70 eV to 1.5 MeV.

$$4.744 - 3.707E + 2.389E^2 - 1.114E^3 + 0.244E^4 \qquad (2)$$

They quote a statistical error of ~±½% and an estimated systematic error of ~±½%. The energy dependence of the carbon cross-section calculated from the polynomial fit to the present data is shown in Table 1.4. It is systematically higher by ~0.2% than the values given in the IAEA Nuclear Data Standards Report[2] but within the quoted errors.

Table 1.4

Carbon cross-section calculated from fits to the data and compared with evaluated values

Energy (eV)	Cross-section* (b)	Standard Value (b)	Difference %
0	4.7435±0.026	4.7390±0.022	+0.095
10^3	4.7401±0.026	4.7350±0.022	+0.108
5×10^3	4.7265±0.026	4.7160±0.022	+0.223
10^4	4.7094±0.026	4.6990±0.022	+0.221
2×10^4	4.6753±0.026	4.6650±0.022	+0.221
5×10^4	4.5730±0.029	4.5660±0.021	+0.153

*carbon cross-section calculated from least squares fit to all the transmission data. $\sigma_T(E) = 4.7435 \pm 0.026 + (3.41 \pm 0.24)E$ where E is in MeV.

(1) C. A. Uttley and K. M. Diment, Proc. Conf. on Neutron Standards and Flux Normalisation, Argonne (1970) Series 23, p.201.

(2) A. B. Smith, Nuclear Data Standards for Nuclear Measurements, Tec. Report 227 (1983) p.25.

(b) Lead

The measured transmission of the thicker lead sample carried out on the 150 m flight path is shown in Figs. 1.4 and 1.5. The curve is a least squares fit to the data. The parameters determined in this fit included some of the resolution parameters, an effective nuclear radius, the resonance energies and the neutron width of the resonance in ^{207}Pb at 41 keV (E_R = 41.196±0.009 keV, Γ_n 1.080±0.012 keV). The uncertainty in the neutron width is about a factor of three less than that given in the data published by Mughabghab et al in reference 1. The neutron widths of the other resonances are unchanged from the values given in reference 1. The measured total cross-section averaged in convenient energy intervals over the neutron energy range 5 eV to 50 keV is shown in Fig. 1.6.

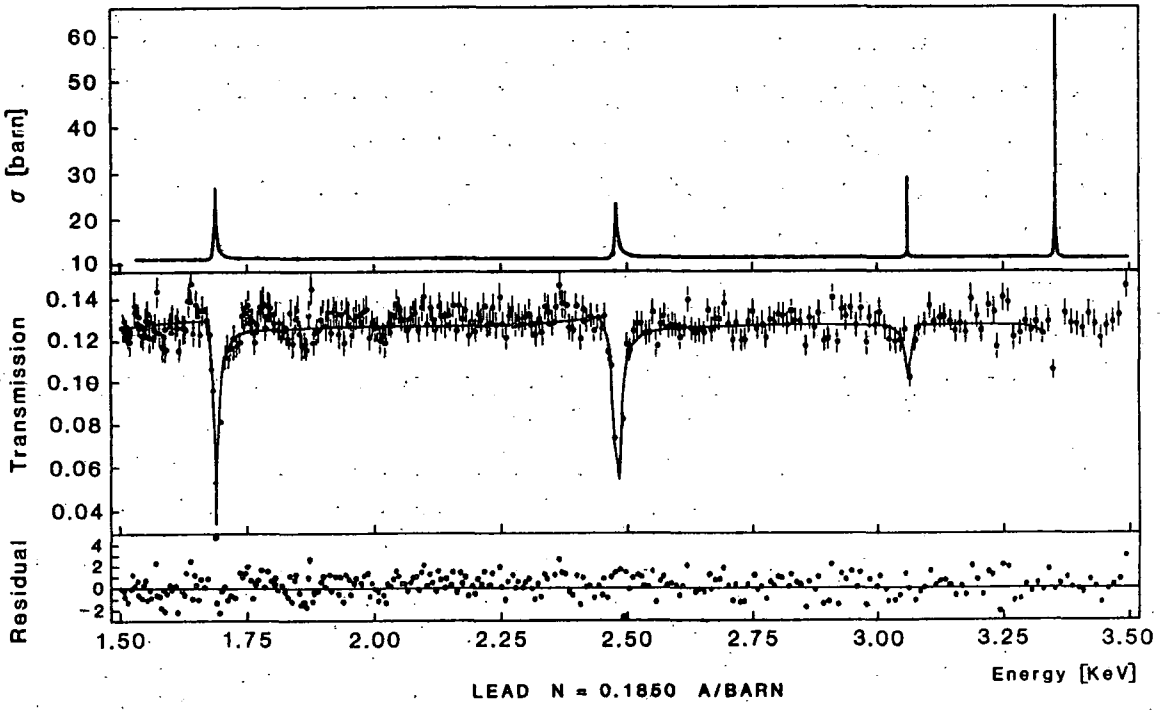

Figure 1.4 The transmission of the thickest lead sample in the energy range 1.5 to 3.5 keV, together with the cross-section from a fit to the data using REFIT.

(1) S. F. Mughabghab, M. Divadeedam and N. E. Holden, Neutron Resonance Parameters and Thermal Cross-sections, Vol. 1 (1981).

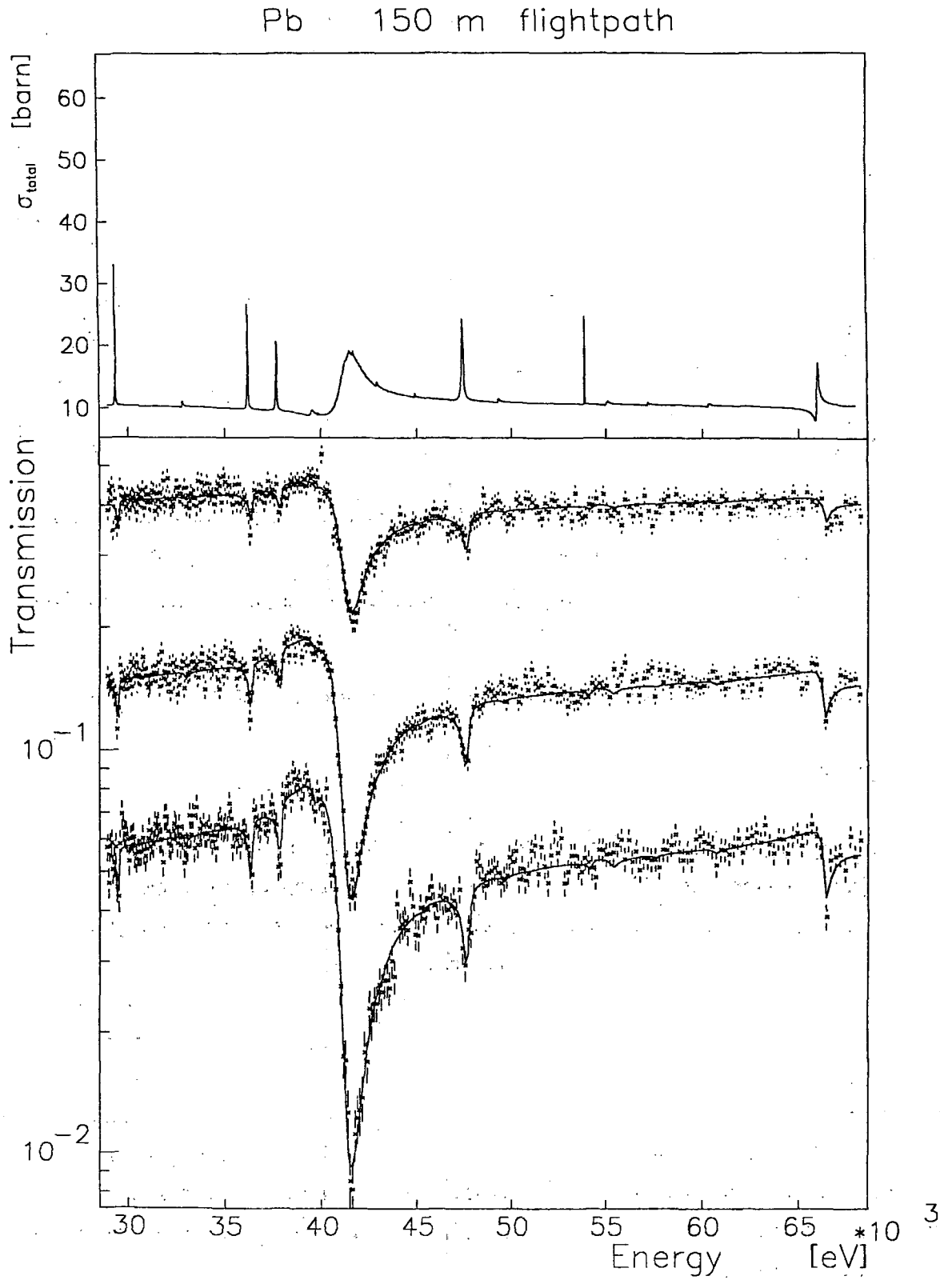

Figure 1.5 The transmission of the thicker lead samples in the energy range 28 to 68 keV, together with the cross-section from a fit to the data using REFIT.

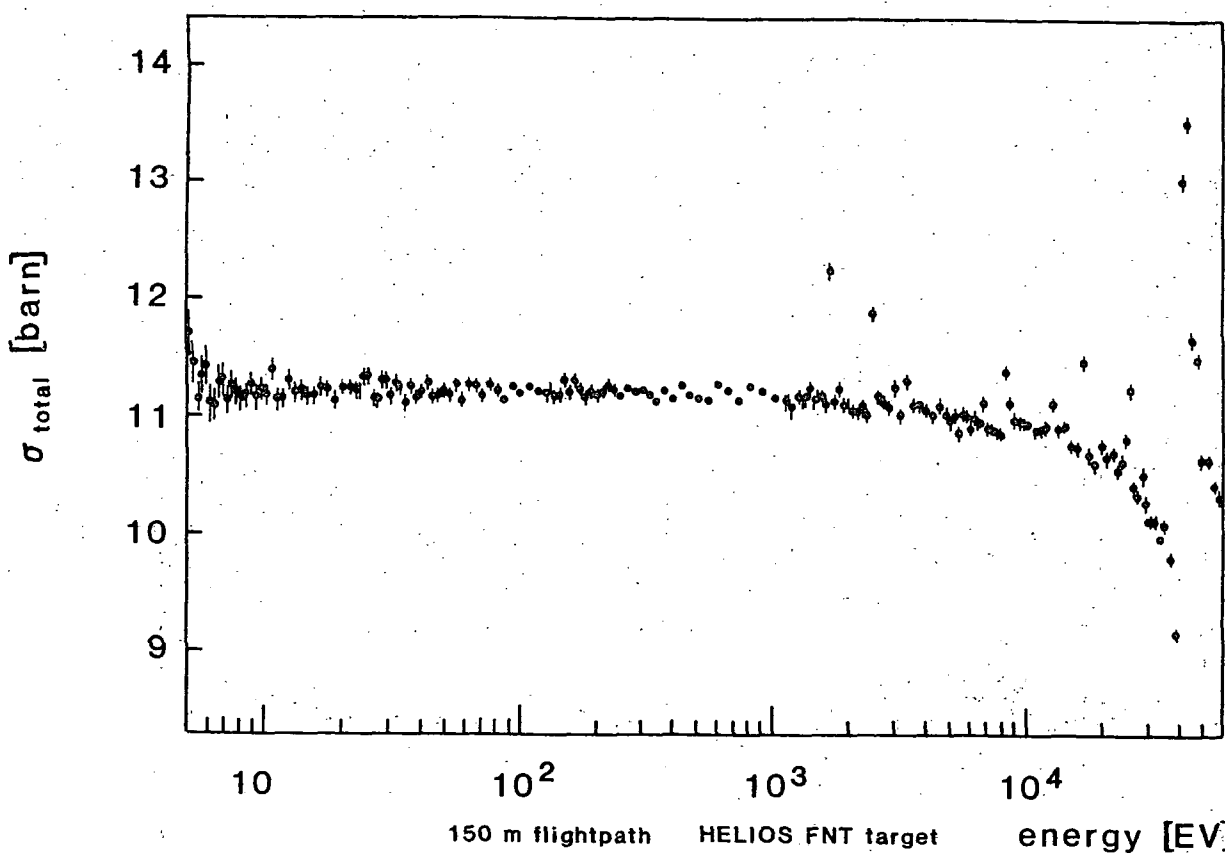

Figure 1.6 The total cross-section of lead in the energy range ~5 eV to ~60 keV

1.6.3 Resonance parameters

The determination of the background for the measurements on lead and carbon used the 'black' resonance filter technique in which samples of elements thick enough that the transmission in the regions around the resonance energies is zero are placed in the neutron beam. The observed count rates in these transmissions are then used to deduce the amplitude and time dependence of the background. To approach zero transmission in the tens of kilovolt energy region very thick filters are needed. Such filters greatly attenuate the background itself and straightforward extrapolation to zero filter thickness is inaccurate. In order to combat this effect a resonance shape fitting program such as REFIT[1] can be used to deduce the magnitude and shape of the background from thinner samples provided the transmission in the region of the resonances is small. In carrying out these fits it was found necessary to adjust the resonance energies and neutron widths. Figure 1.7 shows a fit in the energy

(1) M. C. Moxon, Proc. Conf. on Neutron Data of Structural Materials for Fast Reactors, EUR 6108, p.644 (1979).

region from 14 to 24 keV for the cobalt filters. The values obtained from these data for cobalt, shown in Table 1.5, are as accurate as published values[1] while for manganese they are more accurate than the data published in reference 1.

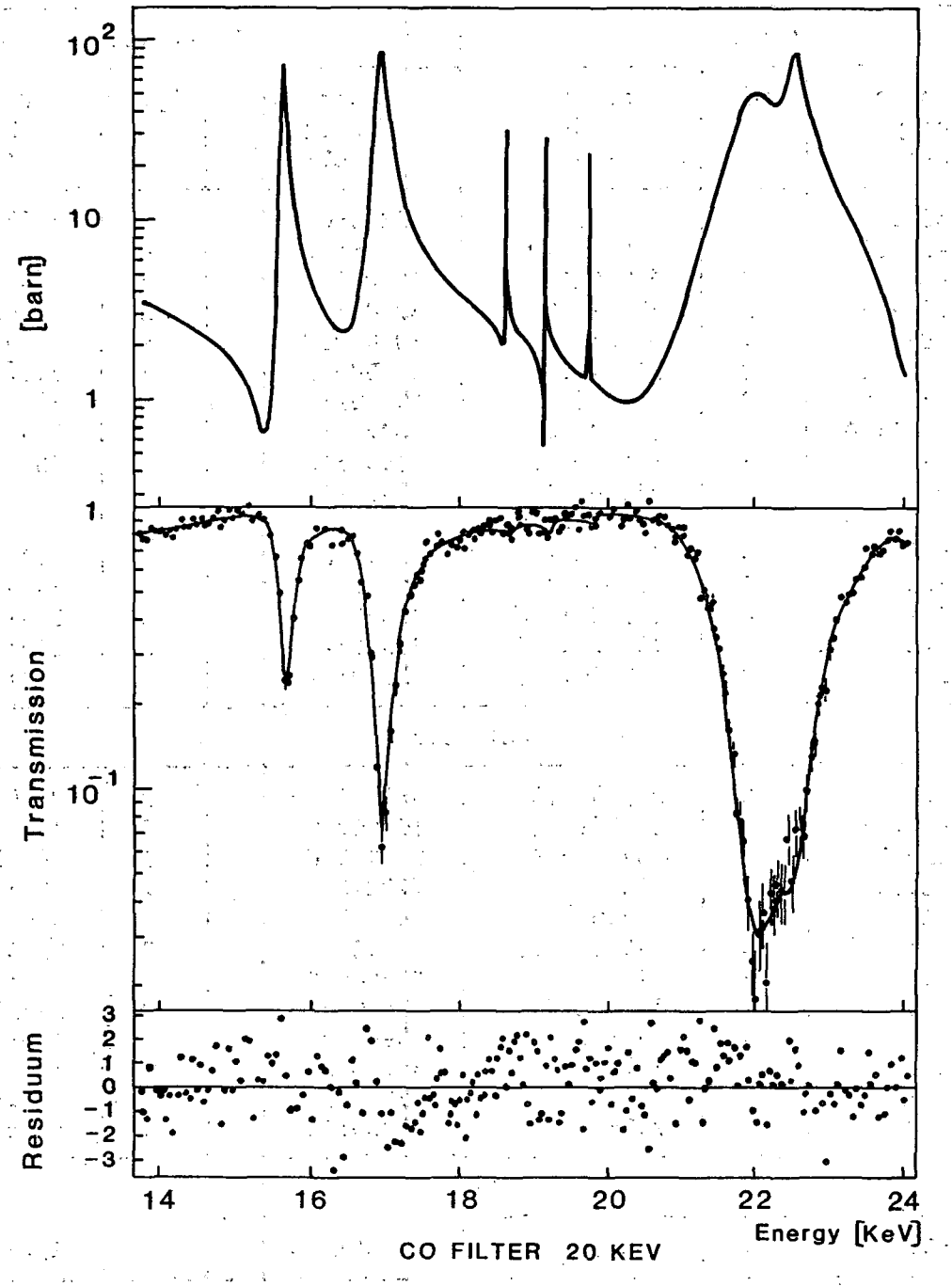

Figure 1.7 A least squares fit to the measurement on the cobalt filter in the energy region ~14 to 24 keV.

(1) S. F. Mughabghab, M. Divadeedam and N. E. Holden, Neutron Resonance Parameters and Thermal Cross-sections, Vol. 1 (1981).

Table 1.5

Resonance parameters determined from fits to the data for ^{57}Co, ^{58}Mn and ^{207}Pb

Cobalt					
Measured			Reference 1		
Resonance Energy (eV)	Spin	Neutron Width (eV)	Resonance Energy (eV)	Spin	Neutron Width (eV)
131.565±0.22	4	5.08±0.02	132.0±0.5	4	5.15±0.035
4338.4±11.0	4	116.0±6.0	4320±4.0	4	111.1±6.2
5009.46±11.6	3	679.9±11.0	5000±4	3	674.3±23.0
8051.75±2.4	3	37.4±1.9	8050±7	2	36.6±1.7
10706.0±6.0	4	65.6±2.7	10700±9	4	64.9±5.5
13280.5±5.0	3	21.6±1.8	13280±11	3	21.7±2.3
15643.5±8.2	3	72.2±5.6	15640±13	3	74.1±6.9
16931.0±11.0	4	169.3±10.0	16920±14	4	164.4±13.3
21976±17	3	825.0±32.0	21950±18	3	765.7±68.6
22542±29	4	225.0±23.0	22520±18	4	249±27
24449±14	3	372.0±23.0			
25160±17	4	179.0±17.0	25150±21	4	184±18
25971±24	4	30.0±6.7	25940±22	4	25±5
30105±14	4	323.0±13.0	30090±25	4	329±18
31405±22	3	164.0±13.0	31375±26	3	149±17
32762±18	3	159.0±14.0	32800±27	3	143±14
Manganese					
339.3±0.10	2	23.25±0.05	336.0±1.0	2	22.0±0.5
1098.9±0.44	3	14.97±0.17	1098±2.0	3	15.4±0.7
2382.6±1.25	3	404.1±0.8	2370±3.0	3	394.3±21.0
7172.0±3.5	2	414.0±1.5	7102±6.0	2	398±10.
8850.2±0.87	3	352.0±4.0	8815±7.0	3	370±10.
20895.0±11.0	3	845.0±11.0	20852±17	3	934±51
23685±12.0	2	321.0±11.0	23658±20	3	288±17
26492±13.0	3	142.0±17.0	26460±22	2	132±12
26992±16	3	299±17	26983±22	3	420±34
34991±32	3	1775±75	35300±29	3	1371±34
35717±117	2	438±78	35500±30	2	1320±120
41027±22	3	253±18	40920±34	3	454±43
^{207}Pb					
41196±9.0	1	1080±12	41260±100	1	1220±30

(1) S. F. Mughabghab, M. Divadeedam and N. E. Holden, Neutron Resonance Parameters and Thermal Cross-sections, Vol. 1 (1981).

1.7 The $^{93}Nb(n,n')^{93m}Nb$ reaction (D. B. Gayther and C. A. Uttley (Harwell Laboratory), M. F. Murphy (AEE, Winfrith) and K. Randle (University of Birmingham)) [WRENDA 40, 407, 409-415]

The measured ^{93m}Nb production cross-section given in Harwell Report AERE-R 12612 (The $^{93}Nb(n,n')^{93m}Nb$ cross-section, D. B. Gayther, M. F. Murphy, K. Randle, W. H. Taylor, C. A. Uttley) is based on the ENDF/B-V evaluation of the $^{235}U(n,f)$ cross-section. The isomer cross-section has now been re-calculated using the ENDF/B-VI version of the fission cross-section and a few minor changes have been made to the analysis of the niobium activation measurements. The resultant cross-sections are on average 1.8% lower than the values given in the Harwell report AERE-R 12612 but at all energies the new values differ from the old by less than the original uncertainties. The new values will be released when the final uncertainties in the ENDF/B-V ^{235}U fission cross-section become available.

1.8 Measurements of 14 MeV cross-sections on materials of interest to fusion (B. H. Patrick, M. G. Sowerby, R. A. Forrest (Harwell Laboratory) and P. M. Denning (Culham Laboratory and Liverpool Polytechnic)) [WRENDA 184, 187, 188, 563, 576, 584-588]

In order to minimise the effects of activation in the structural materials of fusion reactors (particularly in the first wall and blanket), a project to develop low activation materials has been initiated by the UK Fusion Programme. Part of that programme is devoted to the production of a new nuclear data library (see separate report), to be used in assessing possible materials. Tungsten and tantalum have been identified as potential components of such structural materials but their use may be limited by the production of an isomeric state in ^{178}Hf, with a half-life of 31 years. Although this state is not expected to be formed in any great quantity by primary reactions, as it is believed to have $J^{\pi} = 16^{+}$ or 17^{+} and the cross-sections are likely to be very small, it was noted that there is an isomeric state in ^{179}Hf with $J^{\pi} = 25/2^{-}$. This state might be produced in an (n,2n) reaction from the ground state of ^{180}Hf ($J^{\pi} = 0^{+}$), and once produced, it would live long enough for a second (n,2n) reaction to take place, leading to the ^{178}Hf isomer, as the angular momentum change is then modest.

A search of the literature showed that there are no measurements of the cross-sections leading to the states in ^{178}Hf and ^{179}Hf of relevance to fusion.

It was felt that theoretical models were not sufficiently developed to calculate the cross-sections with any degree of reliability and it was therefore decided that a new measurement should be undertaken. The neutron fluxes available for a measurement would not be expected to be large enough to produce significant quantities of the two-step reaction in Hf noted above and any 31-year activity observed would be the result of single-step reactions. However, it was felt that a measurement of the production of the ^{179}Hf isomer and even an upper limit on the cross-sections for formation of the ^{178}Hf isomer would be useful information.

The Lawrence Livermore National Laboratory very generously agreed to irradiate a package of foils on the intense 14 MeV neutron generator, RTNS-11. The package contained Hf, W, Ta, Ti, along with a sample of stainless steel and fluence monitor foils of Ni, Cu, Mn, Au and Co. The foils were subjected to a fluence of 10^{18} n/cm^2 and following the irradiation were returned to the UK for gamma spectroscopy.

Measurements of the gamma-ray spectrum emitted by the decay of each foil have been made with a Ge(Li) detector at intervals and will continue for some time in order to determine the long-lived components. Early results from the Hf foil have shown that the decay of the ^{179}Hf isomeric state is seen quite strongly but as yet there is no sign of the 31-year state. This is not surprising as the activity is dominated at present by the 25-day state and it is expected that any 31-year activity will not be visible until the 25-day state has largely decayed away.

1.9 Fusion reactor activation calculations (R. A. Forrest, M. G. Sowerby, B. H. Patrick and D. A. J. Endacott)

There is a continuing programme of work concerning the arising of various nuclides due to activation in fusion reactor neutron fluxes. This includes experimental measurements, nuclear data evaluations and calculations.

Calculations of the activation of material in fusion reactors require both data libraries and an inventory code. The library UKACT1 contains neutron induced reaction cross-sections and UKDECAY1 contains decay data for all the nuclides considered as targets or daughters of reactions in UKACT1. The inventory code FISPACT has been developed from the existing code FISPIN. It is

able to read the data libraries and produces output relevant to fusion rather than fission applications.

UKACT1[1] is an essentially complete library containing activation cross-section data for neutron induced reactions with thresholds up to 14.9 MeV. Most of the work on this library has been to ensure completeness rather than in trying to significantly improve the accuracy of the individual reactions. It contains cross-section data in 100-group GAM-II format for reactions in 625 target nuclides. These are shown in Table 1.6 and include all stable isotopes and radionuclides with half-lives greater than one day. In addition, some nuclides with shorter half-lives have been included (indicated by * in Table 1.6) where a product formed by a single reaction is a long-lived nuclide. These reactions are especially important in some cases, e.g. ^{45}Ti(n,2n)^{44}Ti where there is no other route for the production of ^{44}Ti.

The target nuclides include 49 first isomers (m) and 4 second isomers (n). It is extremely important that all relevant isomers for all elements are included because in some cases such as ^{178}Hf and ^{192}Ir the second isomers are very long lived (31 and 241 years respectively). In addition to the 625 target nuclides a further 689 are required as products of reactions or as decay daughters.

UKACT1 is developed from the REAC library. Some of the important changes are described below. THRES-G generated cross-sections have been added for 162 reactions. These are normalised using the systematics given by Forrest[2]. THRES-G is a modified version of THRES-F with new systematics, graphic output and automatic generation of isomeric cross-sections in the 100-group format.

Many more isomeric states have been considered in the present library and these include both 1st and 2nd isomers. The data on capture reactions have been improved using processed data from the JEF-1 and ACTL libraries. However, it is appreciated that this still remains a weakness and a future library will try and improve capture data.

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(1) Forrest, R. A., 'The activation cross-section library UKCT1 and the inventory code FISPACT', IAEA Specialists Meeting on The International Nuclear Data Library for Fusion Reactor Technology, Vienna, November 1987.

(2) Forrest, R. A., 'Systematics of neutron-induced threshold reactions with charged products at about 14.5 MeV', AERE-R 12419 (1986).

Table 1.6 Isotopes considered as targets in UKACT1

Element	Atomic Mass	Number
H	1,2,3	3
He	3	1
Li	6,7	2
Be	9,10	2
B	10,11	2
C	12,13,14	3
N	14,15	2
O	16,17,18	3
F	19	1
Ne	20,21,22	3
Na	22,23	2
Mg	24,25,26	3
Al	26,27	2
Si	28,29,30,31*,32	5
P	31,32,33	3
S	32,33,34,35,36	5
Cl	35,36,37	3
Ar	36,37,38,39,40,41*,42	7
K	39,40,41,42*	4
Ca	40,41,42,43,44,45,46,47,48	9
Sc	44m,45,46,47,48	5
Ti	44,45*,46,47,48,49,50	7
V	48,49,50,51	4
Cr	50,51,52,53,54	5
Mn	52,53,54,55	4
Fe	54,55,56,57,58,59,60	7
Co	56,57,58,59,60	5
Ni	56,57,58,59,60,61,62,63,64,66	10
Cu	63,64*,65,67	4
Zn	64,65,66,67,68,70,72	7
Ga	67,69,71	3
Ge	68,69,70,71,72,73,74,76	8
As	71,72,73,74,75,76,77	7
Se	72,73*,74,75,76,77,78,79,80,82	10
Br	77,79,81,82	4
Kr	78,79,80,81,82,83,84,85,86	9
Rb	83,84,85,86,87	5
Sr	82,83,84,85,86,87,88,89,90	9
Y	87,88,89,90,91	5
Zr	88,89,90,91,92,93,94,95,96	9
Nb	91,91m,92,92m,93,93m,94,95,95m	9
Mo	92,93,94,95,96,97,98,99,100	9
Tc	95,95m,96,97,97m,98,99	7
Ru	96,97,98,99,100,101,102,103,104,105,106	11
Rh	99,101,101m,102,102m,103,105	7
Pd	100,101*,102,103,104,105,106,107,108,109*,110	11
Ag	105,106m,107,108m,109,110m,111	7
Cd	106,108,109,110,111,112,113,113m,114,115,115m,116	12
In	111,113,114m,115	4
Sn	112,113,114,115,116,117,117m,118,119,119m,120,121,121m, 122,123,124,125,126	18
Sb	119,120m,121,122,123,124,125,126,127	9
Te	118,119,119m,120,121,121m,122,123,123m,124,125,125m,126, 127*,127m,128,129*,129m,130,131m,132	21
I	124,125,126,127,128*,129,130*,131	8
Xe	124,125*,126,127,128,129,129m,130,131,131m,132,133,133m, 134,136	15
Cs	129,131,132,133,134,135,136,137	8
Ba	128,129*,130,131,132,133,133m,134,135,135m,136,137,138, 139*,140	15
La	137,138,139,140,141*	5
Ce	136,137m,138,139,140,141,142,143,144	9
Pr	141,142*,143	3
Nd	140,141*,142,143,144,145,146,147,148,149*,150	11
Pm	143,144,145,146,147,148,148m,149,150*,151	10
Sm	144,145,146,147,148,149,150,151,152,153,154	11
Eu	145,146,147,148,149,150,150m,151,152,152m,153,154,155, 156	14
Gd	146,147,148,149,150,151,152,153,154,155,156,157,158,159*, 160	15
Tb	153,154*,155,156,156n,157,158,159,160,161	10
Dy	154,155*,156,157*,158,159,160,161,162,163,164,165*, 166	13
Ho	163,165,166,166m	4
Er	162,164,165*,166,167,168,169,170,171*,172	10
Tm	165,166*,167,168,169,170,171,172	8
Yb	166,168,169,170,171,172,173,174,175,176	10
Lu	169,170,171,172,173,174,174m,175,176,177,177m	11
Hf	174,175,176,177,178,178n,179,179n,180,180m,181,182	12
Ta	177,179,180,180m,181,182,183	7
W	178,180,181,182,183,184,185,186,187,188	10
Re	181*,182,183,184,184m,185,186,186m,187,188*,189	11
Os	184,185,186,187,188,189,190,191,192,193,194	11
Ir	188,189,190,191,192,192n,193,193m,194,194m	10
Pt	190,191,192,193,193m,194,195,195m,196,197*,198	11
Au	194,195,196,197,198,198m,199	7
Hg	194,195*,195m,196,197,198,199,200,201,202,203,204	12
Tl	200,201,202,203,204,205	6
Pb	202,203,204,205,206,207,208,209*,210	9
Bi	205,206,207,208,209,210,210m	7
Po	206,207*,208,209,210	5
	Sum of target isotopes	625

With a library of such a large size (70161 card records) it is most important to have some systematic check that all possible reactions are included in the library. To provide this a checking program called CHECK has been written. This reads the index of target nuclides (essentially Table 1.6) and for each target checks that all of the standard twelve reactions shown in Figure 1.8 are present in the library. It is reasonably sophisticated in that the 'boxes' generated for each reaction are split into two or three parts if product isomers exist. The 3 x 3 character symbols indicate whether the cross-section in the library is zero (0) or if there are 1, 2 or 3 routes. Multiple routes mean for example, that (n,np) and (n,d) cross-sections are given separately even though the same product nuclide is formed. An asterisk indicates that the reaction is missing.

This checking program enabled many missing reactions to be included, and it is now believed that UKACT1 is complete within the following constraints. The energy range covered is thermal to 14.9 MeV, only nuclides with $Z<84$ and half-lives greater than 1 day are included as targets (although a few additional short-lived targets are included) and cross-sections must be greater than 10^{-7} barns.

In addition to the cross-section data for the target nuclides the inventory code aso requires radioactive decay data for the target and short-lived product nuclides formed either by reactions or by decay. FISPACT reads the decay data in ENDF/B-V format and it is therefore possible to use existing JEF-1 evaluations for most of the nuclides. In all 1314 nuclides require data, although for the 266 stable isotopes only identifying information is needed. Where data are not available in the JEF-1 library, data were extracted by hand from standard handbooks.

In total 435 nuclides had ENDF/B-V files constructed and the complete library is termed UKDECAY1.

1.10 The measurement of eta for ^{235}U in the energy region below 1 eV (M. C. Moxon, J. B. Brisland and D. S. Bond) [WRENDA 689-691]

The analysis has continued of the measurements made to determine eta for ^{235}U that were reported in UKNDC(86)P114, p.8. Effort has concentrated on the corrections which have to be made to the observed counts because of sample

NUCLIDE : PT195

MAT NUMBER : 1207

M / G PT193	PT194	M / G PT195	PT196
000 / 000 0 0 / 0 0 000 / 000	1 1 1	1 / ##### 1 / ##### 1 / ##### #####	1 1 1
TRI / TRI	STABLE	TRI / STB #####	STABLE
(N,3N)	(N,2N)	(N,N')	(N,G)

N / M / G IR192	M / G IR193	M / G IR194	M / G IR195
* * / 000 / 000 * / 0 0 / 0 0 * * / 000 / 000	222 / 222 2 / 2 222 / 222	222 / 222 2 / 2 222 / 222	1 / 1 1 / 1 1 / 1
JEF / JEF / JEF	TRI / STB	TRI / TRI	TRI / TRI
(N,NT)	(N,T)	(N,D)	(N,P)

M / G OS191	M / G OS192	M / G OS193	OS194
1 / 1 1 / 1 1 / 1	1 / 1 1 / 1 1 / 1	* * / 000 * / 0 0 * * / 000	000 0 0 000
TRI / TRI	TRI / STB	TRI / TRI	JEF
(N,NA)	(N,A)	(N,H)	(N,2P)

KEY TO BOXES

* REACTION MISSING
0 REACTION HAS ZERO CROSS SECTION
1 REACTION HAS ONE ROUTE
2 REACTION HAS TWO ROUTES
3 REACTION HAS THREE ROUTES

~~~ DECAY DATA MISSING
JEF DECAY DATA FROM JEF LIBRARY
TIR DECAY DATA FROM TABLE OF RADIOACTIVE ISOTOPES
STB STABLE NUCLIDE

G M N REFER TO ISOMERS
TARGET NUCLIDE

Figure 1.8 The output of CHECK for ^{195}Pt; a similar output is produced for each of the other 624 targets.

thickness effects. Thick samples of both ^{235}U (for the neutron yield measurements) and ^{10}B (for the incident neutron spectrum determination) were used. The fission neutrons produced in the ^{235}U sample have a significant chance of further interactions before they leave the sample, and the 480 keV gamma-rays produced following neutron absorption in ^{10}B have a significant chance of being absorbed. The magnitude of the necessary corrections depends on
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the detector position relative to the sample as well as the relevant nuclear properties of the samples themselves. A Monte Carlo treatment is essential.

The detector for both the spectrum and eta measurement was a NE213 liquid scintillator 10 mm thick and 100 mm diameter mounted on a photomultiplier using a pulse shape discrimination unit to separate the output into fast neutrons and gamma-rays. The layout of the detector and sample are shown in Figure 1.9.

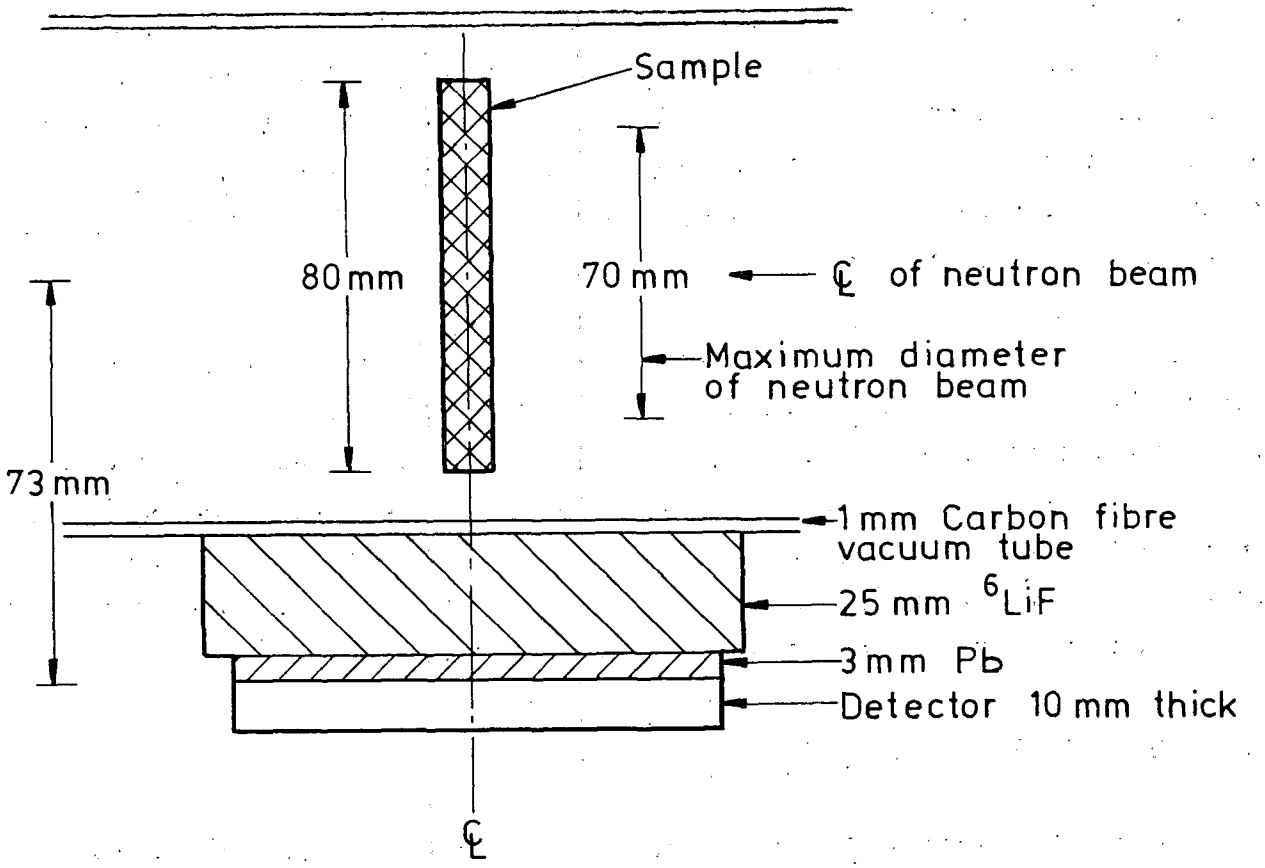

Figure 1.9 Layout of detector and sample position used in the eta measurement.

The neutron spectrum was measured using the 480 keV gamma-rays emitted from the $^{10}B(n,\alpha\gamma)^{7}Li$ reaction. A 5 mm thick sample of $^{10}B_2O_3$ canned in a 0.005" walled aluminium vessel was used in these measurements. A simple Monte Carlo program was written to calculate the fraction of 480 keV gamma-rays that reached the detector as a function of the incident neutron mean free path. It was assumed that if a gamma-ray interacted in the sample or any other material between the sample and detector it was not detected. In the calculation the intensity of the incident neutron beam could be varied radially across the

sample. Figure 1.10 shows the results of the calculation of the relative detection efficiency as a function of thickness to the incident neutron flux. The relative efficiency varies from 0.707 at 1 eV, 0.7165 at 0.1 eV to 0.721 at 0.01 eV, i.e. a variation of 3% over the range of these measurements.

The ^{235}U sample was 5 mm thick and 80 mm diameter. The calculation of the effect of the finite sample size on the emitted fast neutron flux could not be treated in the same way as the gamma-rays due to the fact that the fast neutrons can be elastically or inelastically scattered or cause further fission events as well as being captured. Using the program MCNP, M. Swinhoe (Harwell Laboratory) has calculated the probability of detecting a fission neutron from a uniform thin plane of fission events taking place in the ^{235}U sample at a given position along the neutron beam axis of the sample. Each point in the curve shown in figure 1.11 required at least 30 hours computing time on a Vax 11/750 computer to reach the required accuracy.

The variation of the relative detection efficiencies of fast neutrons versus the product of the thickness of the sample and the incident neutron cross-section is shown in figure 1.12 and is obtained by folding the data in figure 1.11 with an exponential attenuation of the flux through the sample. The relative efficiency varies from 0.9622 at 1 eV to 0.9658 at 0.01 eV, i.e. a maximum variation of 0.4% over the range of these measurements. The effects of a non-uniform neutron beam have still to be investigated.

1.11 Nuclear materials assay

Good measurement of nuclear material quantity is essential throughout the nuclear fuel cycle for reasons of accountancy, criticality control, plant performance monitoring, fuel performance, safeguards and non proliferation and nuclear waste management. In the Neutron Systems Group of the Nuclear Physics Division there are current programmes of research on non-destructive assay of fissile materials by different methods of pulsed neutron interrogation and also by passive observation of spontaneously emitted neutrons and gammas radiation. Progress on these is described below.

1.11.1 Study of benchmark matrix effects in the neutron die-away assay of fissile material in 200ℓ drums (B. H. Armitage and M. J. Cogbill)

The neutron die-away technique allows the fissile material content of

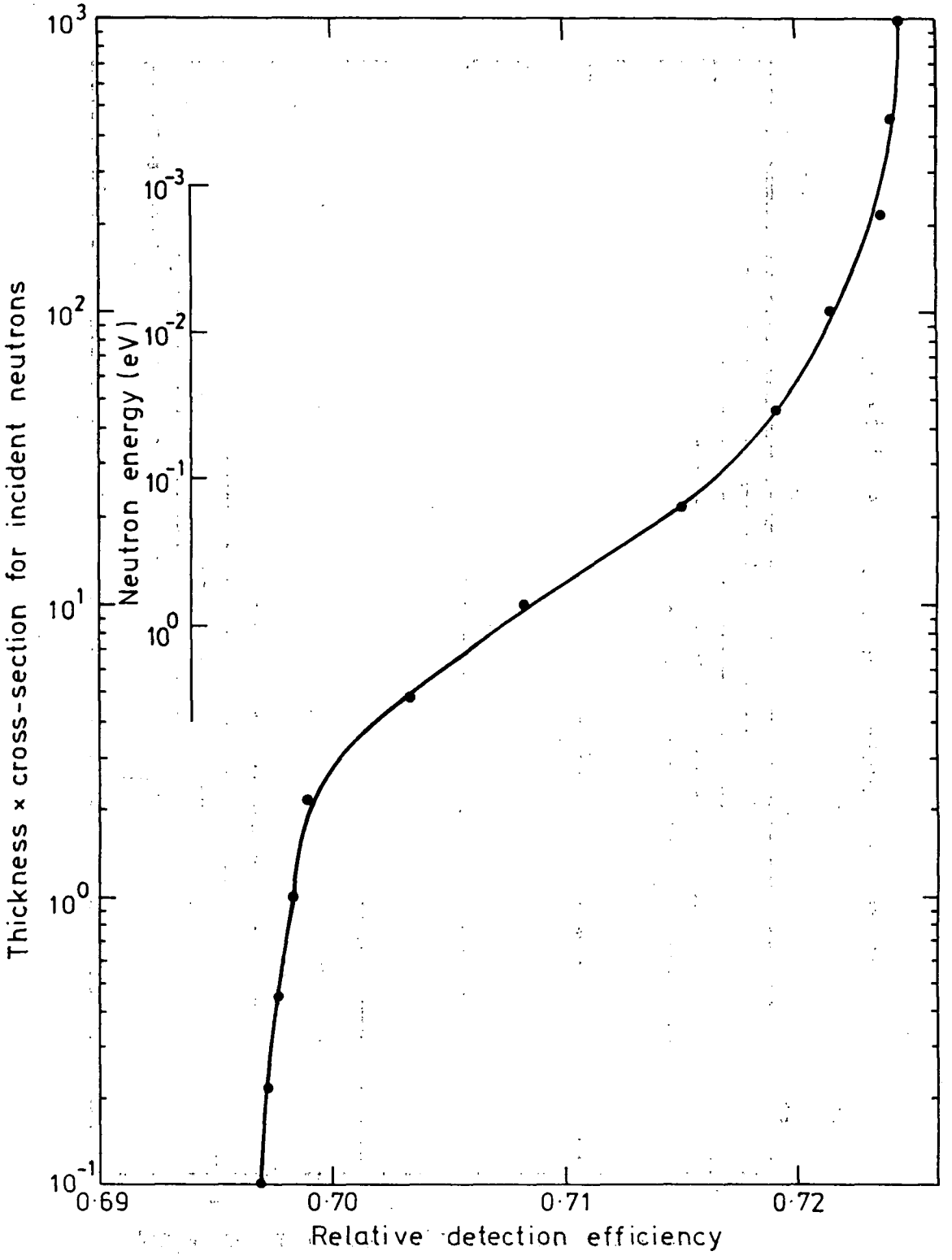

Figure 1.10 The relative efficiency for detecting the 480 keV gamma-ray from the $^{10}B(n,\alpha)^{7}Li$ reaction as a function of the product of thickness and incident neutron cross-section.

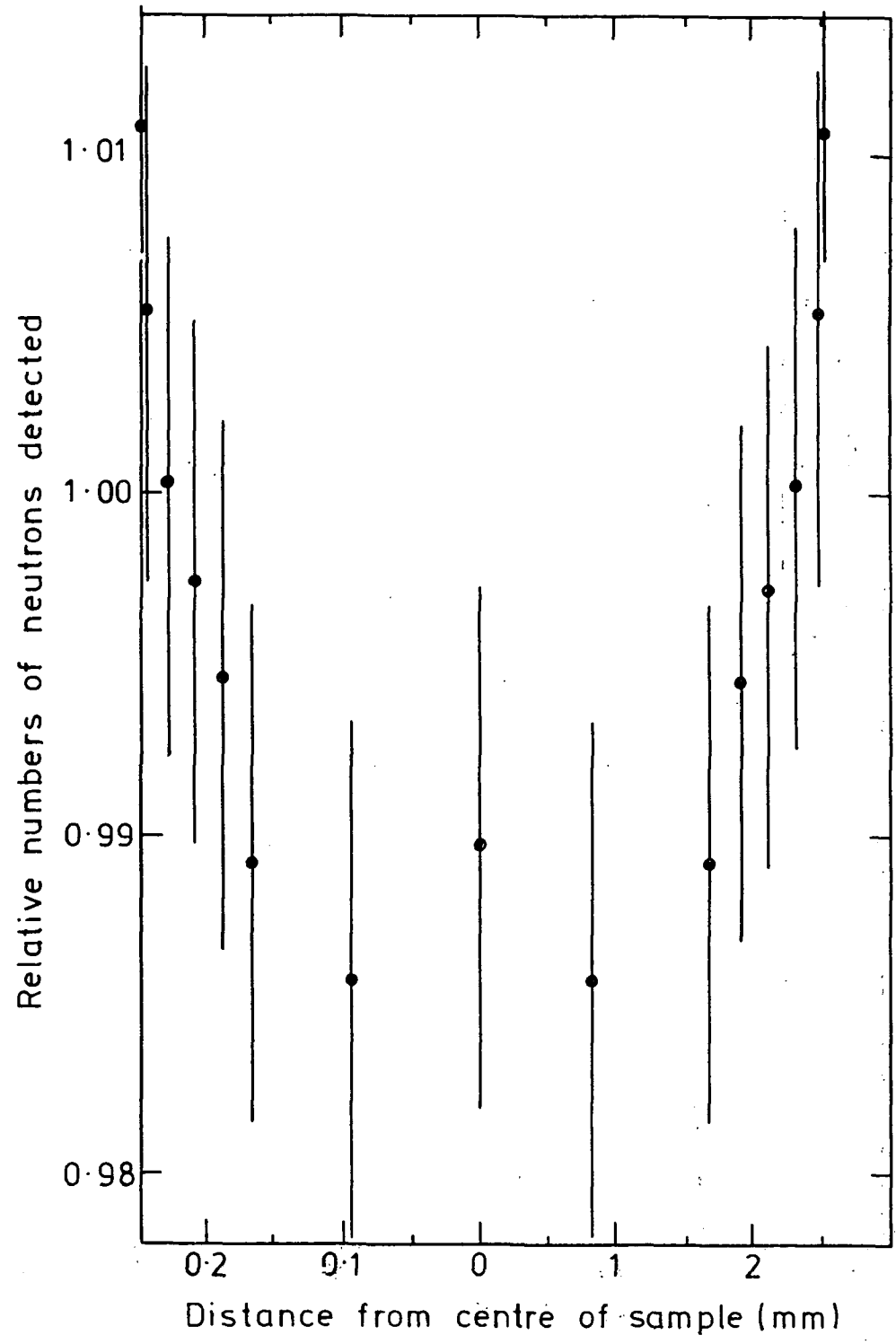

Figure 1.11 The relative detection efficiency for fast neutrons produced in a thin uniform plane as a function of position along the axis of the sample.

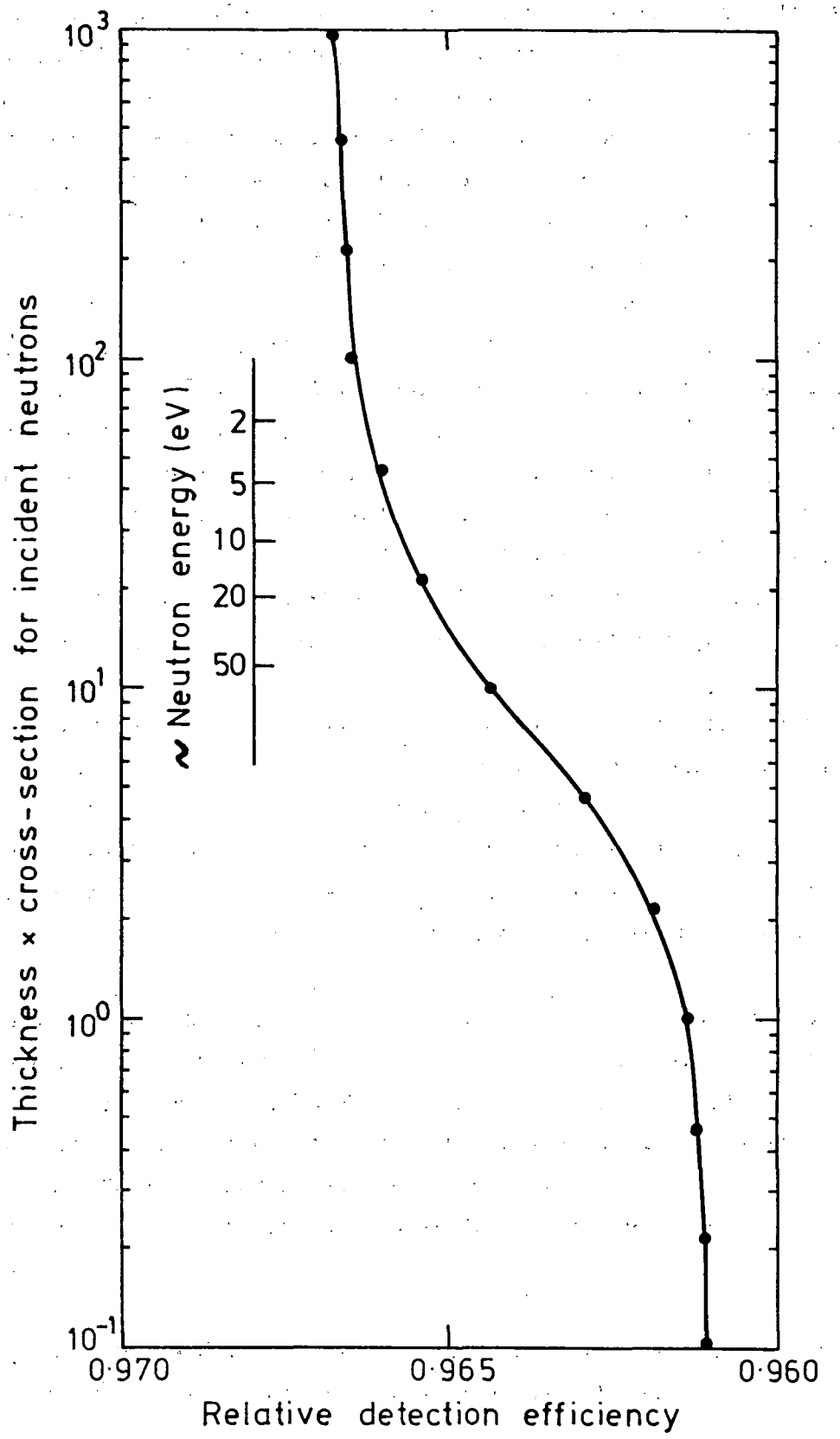

Figure 1.12 The relative efficiency for detecting fast neutrons from the thick ^{235}U sample as a function of the product of thickness and the incident neutron cross-section.

waste to be measured with mg sensitivity. The method utilises a pulsed 14 MeV source situated inside an interrogation chamber with graphite and polyethylene walls. A full description of the assay system can be found in reference (1) which gives details of the original system and reference (2) which describes subsequent modifications. An experimental study of the effects of eighteen different matrices on the accuracy of fissile material assay in 200ℓ drums was described in last year's report (UKNDC(86)P.114, p.17). The result of this work was that a procedure has been defined whereby it is possible (within specified limits) to assay fissile material in 200ℓ drums by the neutron die-away technique without a prior knowledge of the matrix. In essence the method provides compensation for matrix effects with a resultant minimisation of assay errors. The work reported here results from a request to discover if certain matrices typical of BNFL waste arisings are susceptible to assay using procedures identical to those used in the eighteen matrix study. Of the three benchmark matrices A and B are non-combustible and differ only in that their bulk densities are 0.5 g cm^{-3} and 1.0 g cm^{-3} respectively, while matrix C is capable of being shredded and has a bulk density of 0.2 g cm^{-3}.

The nominal compositions of these matrices are shown in Table 1.7. Although there are differences between the nominal and actual compositions of these matrices they are not significant as far as fissile material assay is concerned. This is because there is little difference between the most significant parameters of the matrices, i.e. the hydrogen content, and also the thermal neutron macroscopic absorption cross-sections.

The measurement procedure adopted was similar to that described in last year's report. The interrogating thermal flux was measured with a bare BF_3 detector located on one of the inner walls of the chamber (M). Another bare BF_3 monitor was placed in direct contact with the underside of the drum. This detector is referred to as the external matrix monitor (EMM) because a Cd shield placed below the detector made it sensitive only to the neutrons emerging from the matrix.

The fissile material response was measured with a 1.02 g sample of ^{235}U (20% enriched) at six different locations in the drum. As before

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(1) T. E. Sampson, B. H. Armitage and T. L. Morgan, 7th ESARDA Symposium on Safeguards and Nuclear Material Management, Liege, 21-23 May 1985.

(2) B. H. Armitage and A. C. Sherwood, 9th ESARDA Symposium on Safeguards and Nuclear Material Management, London, 12-14 May 1987.

Table 1.7

Nominal constituents of matrices

Matrices A and B are identical except that their densities are 0.5 and 1.0 g cm^{-3} respectively

Matrix		Matrix	
A	Small plant items and tools (23.8 kg s.steel, 23.8 kg m.steel) Cans (15.9 kg aluminium, 15.9 kg m.steel) Fuel pins/cans (4.1 kg steel) Gas filters (5.2 kg fibre-glass) Process solids (4.1 kg calcium fluoride) Glass (7.2 kg boro-silicate glass)	C	PVC (20.8 kg) Rubber (8 kg) Polyethylene (4.4 kg) Cellulose (2 kg) Polypropylene (2 kg) Cans (1.4 kg aluminium, 1.4 kg m.steel) Gas filters (0.5 kg fibre-glass) Glass (0.6 kg boro-silicate glass)

(UKNDC(86)P114, p.17) the results were expressed as $\bar{R}(0.4\text{-}5)$ which corresponds to the volume material response from each drum integrated over the time interval 0.4 to 5.0 ms after each pulse from the 14 MeV pulsed neutron source. The values obtained for the three matrices together with those from a matrix-free drum are shown in column 5 of Table 1.8 and cover a range from 0.53 to 1.0 with a standard deviation of 32%.

Table 1.8

Values of analysis function in eighteen matrix study and in present work

The symbol $\bar{x}$ in the second column refers to mean values of $\bar{R}(0\text{-}5)E^{-0.2}$ obtained in the earlier work for each of the four matrix categories.

Results of eighteen matrix study			Present work				
Category	x	Sigma	Matrix	R(0.4-5)	R(0-5)	$R(0\text{-}5)E^{-0.2}$	Sigma
1	1.08	10%	1	1.00	1.00	1.10	9%
2	1.06	10%	A B	0.70 0.55	1.17 0.98	1.16 0.97	25%
3	1.09	26%					
4	1.16	28%	C	0.53	1.05	1.10	21%

In last year's report (UKNDC(86)P114, p.17) an account was given of how values of $\bar{R}(0\text{-}5)$ were obtained from $\bar{R}(0.4\text{-}5)$ by the use of the EMM. Again, in the present work it was found that the corresponding values of $\bar{R}(0\text{-}5)$ had a range (0.98 to 1.17) and a standard deviation (22%) which was significantly less than that of $\bar{R}(0.4\text{-}5)$.

Another factor taken into account in the earlier work is the inferred value of the detection efficiency E for fission neutrons emitted from fissile material at the centre of the drum. By measuring the yield at the detector for a Cf spontaneous fission source placed under the drum and from the use of appropriate calibration data a value of E can be found for an unknown drum. An empirical approach to the problem of the inclusion of a term depending on E in the eighteen matrix study resulted in the response being given as $\bar{R}(0\text{-}5)E^{-0\cdot2}$. As a result of the inclusion of this term the standard deviation was reduced to 21%.

On the basis of measured values of thermal neutron lifetime in the M and EMM detectors, matrices in the eighteen matrix study were placed in categories of high/low absorption and high/low moderation. The standard deviations obtained for each matrix in the eighteen matrix study are shown in Table 1.8 together with the equivalent results for the present matrices. The explanation for the larger assay error (25%) obtained for the non-combustible matrices in the present study is that the thermal neutron macroscopic absorption cross-sections are considerably greater than any of the Category 2 matrices in the more comprehensive work.

The conclusion is that the procedure whereby it is possible to assay fissile material without a prior knowledge of the matrix applies to the BNFL specified matrices.

1.11.2 Technique to assay lumps of fissile material in drummed metallic waste (M. J. Cogbill and B. H. Armitage)

When the time comes to decommission active facilities such as glove boxes there will be a need to dismantle machinery such as lathes and milling machines. Such tools tend to accumulate fissile material in cavities and crevices. In this respect ^{235}U presents a problem as its radiations are hard to detect.

It is difficult to measure fissile content of waste by any means other than neutron interrogation. In active neutron interrogation a burst of fast neutrons from a 14 MeV pulsed neutron source interrogates the waste drum in a chamber viewed by suitable detectors. Fast fission neutrons are released by the U and Pu present. These are counted soon after the burst by the neutron die-away method or after some considerable time (delayed neutron counting). Such measurements are required to determine the alpha-activity content of waste presented for disposal. However, it is not yet known if accumulations and lumps of fissile material can be assayed in a quantitative manner. The differential die-away technique is suitable for assaying fissile material in dispersed form, but accumulated lumps are subject to severe underestimation. This underestimation is due to the inability of a thermal neutron flux to fully penetrate lumps of fissile material.

As the origin of this problem stems from the magnitude of thermal neutron cross-sections in ^{235}U and ^{239}Pu, any attempt at alleviation will necessitate the use of an interrogating neutron flux containing an appreciable non-thermal component. Delayed neutron interrogation contains such a component, and Monte-Carlo calculations have shown that a marked reduction in self-shielding should be achievable in comparison with neutron die-away interrogation. The practicability of undertaking simultaneous differential die-away and delayed neutron measurements has been demonstrated in an earlier progress report (UKNDC(84)P111, p.69).

In order to make an initial attempt to minimise self-shielding in lumps of fissile material a series of well characterised samples was prepared. This has been achieved by obtaining U metal foils enriched to 93% in ^{235}U, and varying in thickness from 0.025 to 5.5 mm. As these foils contain only 7% ^{238}U it was assumed (and confirmed by Monte-Carlo calculations) that the contribution to the delayed neutron response from fission in ^{238}U is small.

Progress on this work has been hampered by the low yield currently available from the pulsed neutron source ($2\text{-}4.10^7$ neutrons per second). However, with the samples at the centre of the drum, the pulsed neutron source was used to undertake both delayed neutron interrogation and neutron die-away interrogation. The measurements obtained so far are unsatisfactory insofar as they are subject to large statistical errors. They indicate, however, that for the thicker samples there is less self-shielding observed in delayed neutron interrogation than is the case with neutron die-away interrogation. The

conclusion is that the experiments generally agree with the calculations, but the statistical precision needs to be improved and measurements are required with a more intense neutron source so that the benefits of this technique can be properly evaluated.

1.11.3 Tailoring of a 14 MeV neutron source (B. H. Armitage and M. J. Cogbill)

This work has been undertaken to support the development of the technique to assay lumps of fissile material in drummed waste. Here we are primarily concerned with delayed neutron interrogation in which the interrogating neutron flux contains a significant non-thermal component. This should result in less underestimation of fissile material in the form of lumps and aggregates than would be the case with an entirely thermal flux.

We have made a Monte Carlo study using the MCNP computer code aimed at modifying the energy spectrum of an initially 14 MeV neutron source. If the spectrum is too hard the relative contribution from fast fission of ^{238}U in comparison with that from the thermal fission of ^{235}U could be large. If, however, the spectrum is too soft self-shielding will be a problem. Another consideration is that (n,2n) reactions in the material used to tailor the neutron source can have the beneficial result of producing a modest increase in the available neutron flux.

Calculations have been made with a pulsed neutron source with a configuration similar to that of the GEC Avionics neutron tube. For the purpose of the calculation the 14 MeV neutrons are considered to arise from a point source on the axis of a cylindrical canister of diameter 7.6 cm. The material used to tailor the neutron source is in the form of a 15 cm long cylindrical collar surrounding the neutron canister on a common axis.

Calculations were first made of the effect of (n,2n) reactions on increasing the emerging neutron flux from a range of collar materials (Be, W, Ni, Pt, Fe and Cu) and thicknesses. The results for 4 cm collars are given in the table below.

Material	Be	W	Ni	Pb	Pt	Fe	Cu
Multiplication	1.28	1.34	1.04	1.23	1.36	1.11	1.15

Although they give good multiplication Be, W and Pt are not as practicable for the present application as Ni, Pb, Fe and Cu.

Calculations were also made of the energy dependence of neutrons emerging from the collar and it was found that Cu produced a higher neutron flux below 1 MeV than Pb or any of the other low cost materials.

Further calculations were made with a variety of collar configurations including one with a block of material 10 cm in thickness between the source and the drum. These calculations incorporated a model interrogation chamber and a 500ℓ drum containing natural U. They showed that with an empty drum the use of a Cu collar could result in a 70% increase in delayed neutron response from the ^{235}U present, while at the same time depressing the relative contribution from ^{238}U by about 2.5. In addition it was found that such source tailoring was advantageous in differential die-away interrogation. Here a 70% increase in response to ^{235}U was found to be achievable in future experimental programmes.

1.11.4 Pulsed neutron sources for neutron interrogation (J. W. Leake and B. H. Armitage)

A long-lived pulsed neutron source of good reliability is required before active neutron interrogation can be brought into routine use in UK nuclear plants. The recently concluded development programme with GEC Avionics has resulted in some improvement in the tube lifetime but not its variability. The improvements can be attributed to:

1. Change of target material to one of lower specific energy loss which means that the incident deuterium beam can penetrate deeper into the target with a resultant increase in neutron output from the (d,t) reaction.
2. Reduction in excess target thickness so as to match the penetration of the incident deuterons. This has had the effect of lowering the tritium energy so that tubes no longer fail due to gas build up.
3. Introduction of Mo backstop so as to reduce sputter.
4. Introduction of a suppressor electrode.

The improvements in the characteristics of the tube have resulted in an increase in useful life but have not led to improved reliability. In fact the conclusion is that the modified K tube does not represent an adequately reliable source of neutrons for routine plant operation.

Attention was drawn in last year's progress report (UKNDC(87)P114, p.22) to premature failure of transformers, and to the intention to introduce a larger more heavy duty transformer. At the beginning of the contract GEC had no evidence that their high voltage transformers were a source of weakness. Despite numerous attempts to construct a satisfactory transformer this problem remains unsolved.

In the light of the current situation Harwell have independently decided to obtain a pulsed neutron source from SODERN in France. This source which has a guaranteed life of 1000 hours is expected to be delivered in July 1988.

1.11.5 Methods of monitoring the ^{235}U enrichment of UF_6 gas in centrifuge enrichment plants operating at low pressure (T. W. Packer)

Work has continued on the development of an non destructive analysis (NDA) instrument that will rapidly confirm that UF_6 gas in the pipework of a uranium centrifuge enrichment plant is in the LEU range (i.e. <20%). As described in previous reports the instrument that has been developed in conjunction with the Los Alamos National Laboratory is based on two types of measurement:

(1) Energy-dispersive, i.e. X-ray fluorescence, analysis to determine the mass (pressure) of UF_6 gas in the pipe

(2) A passive gamma-ray spectrometry procedure which determines the total mass of ^{235}U in the pipe by measuring the number of emitted 185.7 keV gamma-rays. The present instrument, which has been on loan to the IAEA Seibersdorf Laboratory since October 1986, incorporates a choice of two methods of separating the UF_6 gas and deposited uranium signals known as the 'Deposit Correction' and 'Two Geometry' techniques, which enables complete measurement procedures on product pipes at Capenhurst with high (up to 15:1) uranium deposit to UF_6 gas mass ratios to be carried out in approximately 30 to 45 minutes.

A simpler technique has recently been developed that enables the enrichment of low enriched UF_6 gas in pipes with relatively low (<3:1) uranium deposit to UF_6 gas mass ratios to be confirmed as being in the LEU range (<20%) in less than 10 minutes. The existing measurement procedure is being modified to

incorporate this new technique and is shortly to be demonstrated in appropriate pipes in a centrifuge enrichment plant at Capenhurst to the IAEA and EURATOM Inspectorate.

1.11.6 Development of a californium shuffler for delayed neutron interrogation (J. P. Argyle, G. B. Huxtable, T. W. Packer and M. T. Swinhoe)

The pneumatic shuffler system which has provided the experimental data previously reported has been replaced. The new system uses the existing 200ℓ die-away chamber, in which the original shuffler BF_3 detectors are located. The detection efficiency of the new system has been measured and is similar to the previous detector arrangement. The new source storage position is in a steel tank 1.5 metres high and 1 metre diameter, located above the die-away chamber. The actual storage location is surrounded by 5 cm of lead to reduce the gamma-ray dose. The transfer tube is curved from the storage location to the point of exit from the drum (to prevent neutron streaming) and then runs vertically down an inside corner of the chamber. The source store is filled with a boron loaded soft wax which is heated and pumped in, and is sufficiently fluid to fill the tank completely. The source movement mechanism is based on a Compumotor stepping motor and driver which is interfaced to an IBM-PC. The motor drives a teleflex cable through a twin wheel gearbox. A limited amount of testing has been carried out of the movement mechanism and this shows satisfactory performance at modest speeds.

The multiscaler front end for the Harwell 6000 series histogramming memory module 6191 has been tested together with some rudimentary software running on an IBM-PC. The intention is to run both the control and data acquisition simultaneously on one PC.

1.11.7 Investigation of neutron coincidence counter measurements (M. T. Swinhoe)

A safeguards report[1] has been issued which describes how neutron coincidence counter measurements can be made with multiplication corrections on plutonium nitrate solutions and on plutonium oxide samples with known moisture content.

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(1) M. T. Swinhoe, SRDP-138 (1987).

Some analysis has been carried out of measurements made in a neutron coincidence counter with and without a lead liner designed to reflect neutrons. The results indicate that the original simple model is inadequate to explain the results and further work is in progress.

A method of determining the deadtime of HLNCC-type electronics has been developed. This is done by recording the distribution of time intervals between pulses and allows the deadtime to be determined at relatively low count-rates. The method is very sensitive to malfunctions of the amplifiers (e.g. double pulsing) and can be used as a check on the correct operation of the equipment.

1.12 Work for JET - nuclear techniques applied to fusion plasma diagnostics

Most of the major neutron diagnostic instruments have been upgraded and are now operational with improved instrumentation, data handling and presentation. The JET operational programme has included only three short periods of shots with significant neutron yield and these have been used mainly to recommission the new instruments and confirm the extended methods of data analysis now available. In addition during 1987, analysis of the data taken at the end of 1986 has been extended.

1.12.1 JET neutron activation system (KN2) (G. B. Huxtable, J. P. Argyle and collaborators at JET)

The KN2 activation system (see UKNDC(85)P112, p.57) has been extended to include the four upper irradiation positions, and the capsule transit and data acquisition can now be run under manual or computer control. At present these aspects are in the final stages of commissioning. The future programme will contain a survey of yields and burn-ups over a larger series of shots with a more systematic variation of plasma parameters than was hitherto available.

The KN2 neutron activation system was used at the end of 1986 to measure the triton burn-up ratio ζ over a wide range of JET operational conditions in collaboration with JET staff and the Frascati group. The few ohmic shots measured gave $\zeta = (0.81 \pm 0.08)\%$ while calculations (Frascati) using a classical model for the particle slowing down and confinement gave $\zeta = (1.0\% \pm 0.2)\%$.

1.12.2 Time resolved measurement of 14 MeV neutron production (JET diagnostic KN7) (G. B. Huxtable, S. Conroy**, O. N. Jarvis* and G. Sadler*)

Observation of the 14 MeV neutron flux using a silicon diode with good time resolution, in collaboration with JET staff, has allowed derivation of the triton slowing down time by comparing the timescales for 2.5 MeV and 14 MeV neutron emission. The measured slowing down times of around 1 sec have been compared with code predictions. Though the agreement is good there is an indication that the measured energy loss rate is higher than predicted by a factor of 1.2 ± 0.2.

1.12.3 Neutron emission profiles from JET (J. M. Adams, N. Watkins, O. N. Jarvis*, G. Sadler* and O. Van Belle*)

The KN3 neutron emission profile diagnostic (see UKNDC(87)P114, p.31) has been reinstalled with improved instrumentation and the JET shots in the period with substantial neutron yields have been used mainly for commissioning. The data analysis techniques have been much extended so that the neutron emission profiles can be displayed and analysed as a function of time together with statistical parameters describing the shape of the profiles such as mean position, variance, skewness, etc. The profiles can also be displayed in terms of intensity contours versus position and time through the JET shot, a necessary step to meaningful tomography. The use of these techniques in studying sawtooth phenomena is illustrated in the figure.

Figure 1.13 shows the vertical neutron emission rate profiles in JET (as seen by the horizontal camera) for twenty 10 ms bins. The peaked distribution in the first picture becomes flattened in the sawtooth crash and then builds up again slowly with time until the next crash. The peaked neutron emission ($\sim n^2T^4$) reflects the build-up of the central ion temperature between sawteeth. It is interesting that the neutron emission from the outer regions peaks just as the central sawtooth crashes, i.e. sawteeth reversals are observed in the outer regions. Such pictures have been seen before from the X-ray emission diagnostics but these are the first successful neutron emission equivalent, with the advantage of direct information on the thermonuclear reactions of interest.

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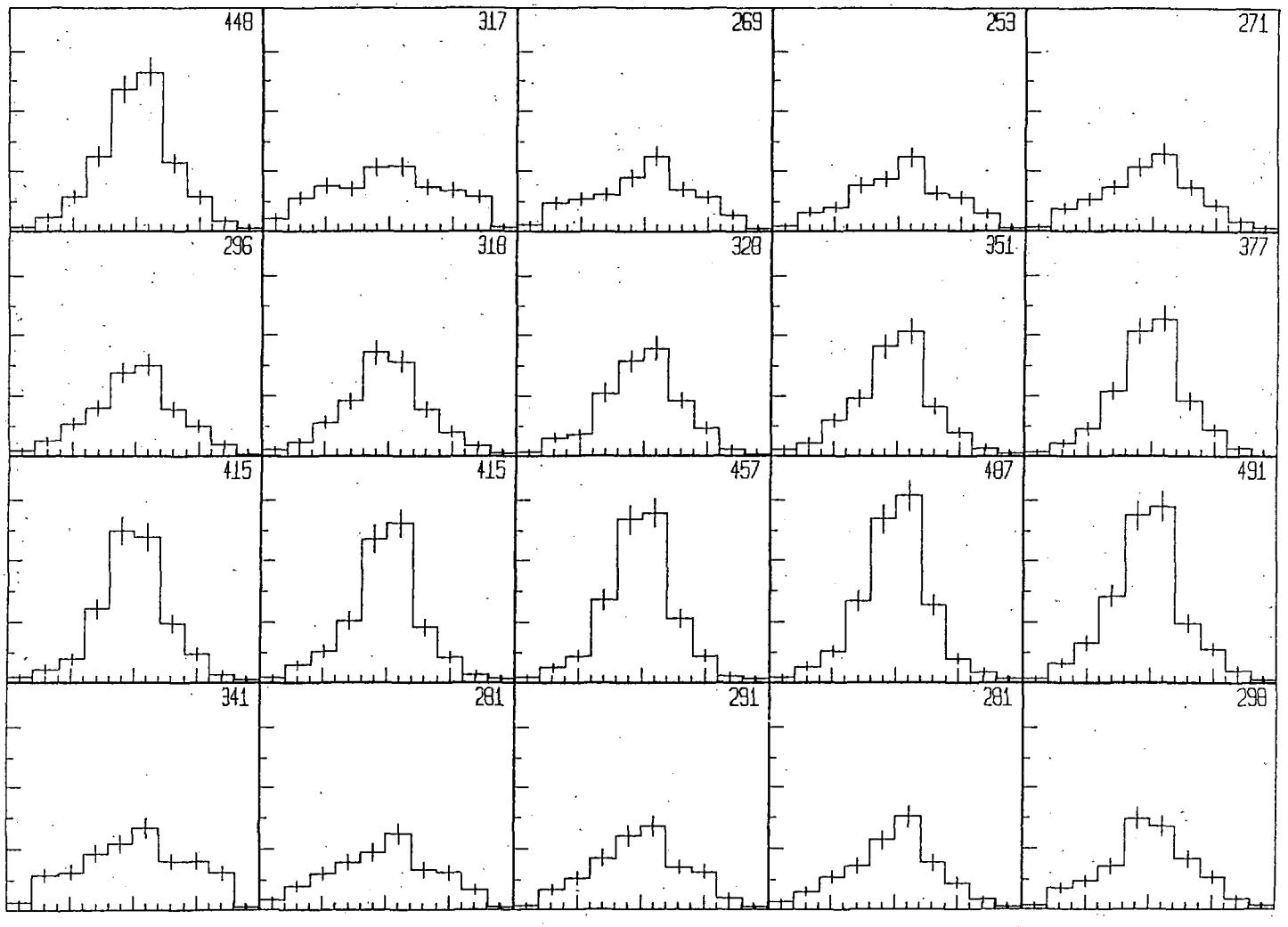

Figure 1.13 Vertical neutron emission rate profiles in JET as seen by the horizontal camera for twenty 10 ms bins. Each small histogram shows the number of counts during the time bin for each of the ten different lines of sight in the horizontal camera. The total number of counts in each time bin appears in the top right hand corner of each plot.

A major new phenomenon became apparent during high ICRF shots involving D_2 plasmas with a ^3He minority in that the gamma-ray yield increased by more than an order of magnitude. Whereas the normal gamma-ray background due to neutron capture in the vessel walls results in an essentially isotropic gamma-ray emission profile, this increase was due to gamma-ray production in the plasma itself. Clear evidence for this was the observation of gamma-ray sawteeth in the central channels and associated sawteeth reversals in some of the outer channels. These gamma-rays are due to nuclear reactions by the main plasma species (ICRF accelerated) with plasma contaminants such as carbon and oxygen, e.g. (d,p), (^{3}He,p), etc. These reactions are an important sink of fusion power in some conditions and their cross-sections are not well known in general.

Preliminary analysis of the neutron emission profiles indicates a much more strongly peaked emission profile than would be expected from an assumption that the ion temperature profile, T_i, is the same as the electron temperature profile, T_e. However, the ion temperature profile might be modified by the presence of the plasma contaminants. A considerable amount of detailed analysis is still required.

1.12.4 2.5 MeV neutron spectrometers (N. P. Hawkes, M. J. Loughlin, D. B. Syme, G. Sadler* and O. N. Jarvis*)

The neutron spectrometry system currently producing data at JET comprises the KM1 shielded enclosure (into which various different detectors may be placed) inside the Torus Hall, plus two ^{3}He ion chambers in the Roof Laboratory.

The main emphasis in KM1 work over the period of this report has been on the installation of detectors and auxiliary equipment additional to the ^{3}He ion chamber already in place, namely two NE213 scintillators of different sizes (both with Pulse Shape Discrimination electronics to separate neutron events from gammas), a chiller unit to maintain a steady temperature inside the cavity, three temperature sensors, a set of magnetic field sensing coils, and (as a temporary experiment) a NaI detector on the floor of the cavity to monitor the energy spectrum of the gamma-rays which penetrate the KM1 shield. In addition

*JET

JET has installed adjustable collimators in the KM1 and Roof Lab lines of sight to increase the count rate range of the instruments.

There have been two principal topics in the analysis of neutron spectrum data. Firstly, spectra unfolded from ^{3}He data from Neutral Beam Injection shots in the way described in UKNDC(86)P.114, p.35, have been compared with theoretical calculations. Agreement is very encouraging as can be seen in Figures 1.14 (a-d) which show a comparison of calculated and measured neutron spectra for a sum of Neutral Beam Injection (NBI) shots. Figure 1.14(a) shows the shape of the Beam-Plasma contribution calculated by the Monte Carlo code FPS[1] for the Roof Lab line of sight for a typical NBI shot. The x-axis in this figure is labelled in terms of the offset from 2.45 MeV. The Plasma-Plasma contribution, assumed to be a gaussian with width determined by the ion temperature (as measured by nickel X-ray doppler broadening[2]), is shown in Figure 1.14(b). The sum of the two contributions added together in the proportion predicted by the code PENCIL[3] is shown in Figure 1.14(c) and is compared with the spectrum unfolded from the Roof Labs ^{3}He data in Figure 1.14(d).

Secondly, ion temperatures derived from ^{3}He data from ohmic and RF-heated shots and (in collaboration with the Swedish KM3 group) have been compared with ion temperatures derived from time-of-flight techniques. The comparison extends over the temperature range 2 to 6 keV and shows agreement within the combined errors (10-15%).

Work is currently in hand to investigate whether the count rate range of the ^{3}He chambers can be increased by correcting for the pulse pile-up which becomes a problem at high rates, and (in the longer term) to what extent a combination of NE213 and ^{3}He data can separate out from the total neutron flux the individual contributions from the various neutron production mechanisms which operate in JET.

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(1) P. van Belle and G. Sadler, 13th European Conference on Controlled Fusion and Plasma Heating, Schlierese, Volume 1.

(2) R. Criannella, F. Bombarda, E. Källne, L. Panaccione and G. Tallents, Bull. Am. Phys. Soc. 31 (1986) 1590.

(3) P. M. Stubberfield and M. L. Watkins, "Multiple Pencil Beams", JET internal report DPA(06)/87.

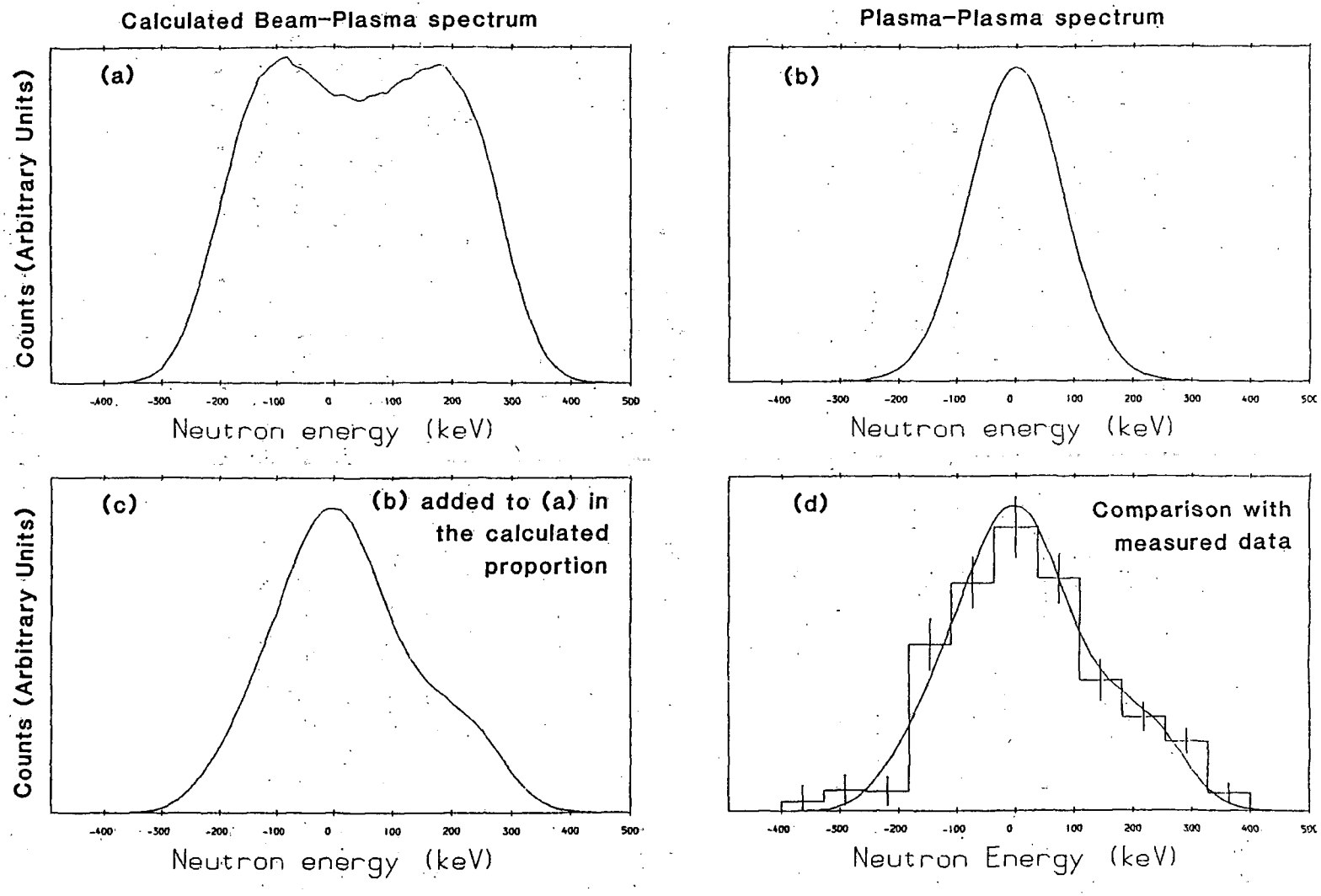

Figure 1.14 Comparison of calculated and measured neutron spectra for a sum of NBI shots (pulses 10789, 10793 and 10794, time intervals 51.0 - 56.0 seconds). See text for details.

2. CHEMICAL NUCLEAR DATA

2.1 Introduction

During 1987 the UK Chemical Nuclear Data Committee (UKCNDC) held only one meeting (Chairman A. L. Nichols (AEEW) and Secretary F. G. Eltham (AEEW)); the normal December meeting had to be postponed for one month and moved into 1988. The Data Library Sub-committee (Chairman A. Tobias (CEGB) and Secretary M. F. James (AEEW)) met twice during the year. Efforts have focussed on assessing the need and UK capabilities for measuring specific fission product yields and decay data for radionuclides of immediate importance in reactor design and fuel management. Recent laboratory developments have involved the preparation of facilities to measure fission yield data for tritium, ^{99}Tc, ^{129}I and other important fission products in the fast reactor and reprocessing programmes.

Evaluation efforts continue to be linked to the development of the European Joint Evaluated File (JEF). However, unforeseen reductions in effort occurred during the year, and progress has been much slower than anticipated. This is viewed as a temporary problem that should be resolved in 1988.

Support for chemical nuclear data stands at between 1½ and 2½ scientist-years in the UK, shared over a number of people within AWE, CEGB, UKAEA, NPL and specific universities. Significant items of work continue to be identified with modest Extra Mural Research (EMR) contracts between the nuclear industry and universities; this method of funding continues to grow slowly and needs to be encouraged in the current climate so that requests for the measurement and evaluation of fission yields, neutron emissions, half-lives and decay data can be satisfied.

2.2 Measurements

2.2.1 The measurement of tritium fission yields (J. W. McMillan and I. G. Jones*)

A limited programme of work on the measurement of the fast neutron

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*Harwell Laboratory

fission yield of tritium for actinide radionuclides was commenced in May 1987. The objective of the programme is to measure the tritium produced in specimens of ^{235}U and ^{239}Pu irradiated in ZEBRA several years ago.

The initial phase of the studies was the design, building and commissioning of a glove box system for the separation of tritium from the encapsulated specimens. The separation equipment consists of a furnace for the high temperature release of tritium under a stream of helium containing 1% hydrogen as a carrier, a second furnace containing copper oxide to convert tritium and hydrogen to tritiated water, and silver to remove halogens, as well as cryogenic water-collection traps. The commissioning of this equipment has proved to be unexpectedly difficult and protracted.

Early recovery experiments were completely vitiated by the presence of very high tritium blanks. Discovery of the source of the extraneous tritium and its elimination has been protracted and continues. Initially the blanks were ~100 times higher than the amount of tritium expected in the irradiated actinide specimens. Replacement of apparatus components, and purging the equipment with a 1% hydrogen in helium mixture humidified with low tritium content water has produced blanks ~2-3 times the expected tritium content of the samples. Replacement of the 1% hydrogen in helium gas mixture by pure helium produced a further improvement suggesting that the former was the probable source of contamination. Certainly operations involving the transfer of separated tritiated water to counting vials has been shown to contribute a negligible blank component. An alternative source of hydrogen is now being sought, and hydrogen may have to be produced from ultra-low tritium content water by electrolysis. The objective is to reduce blanks to 1/10th of the amount in the irradiated actinides. As soon as this is achieved, tritium recovery experiments will be recommenced, followed by measurement of the tritium present in the empty aluminium irradiation containers, and examination of the ^{235}U and ^{239}Pu specimens.

2.2.2 Absolute fission yields of selected fission products (T. W. Kyffin*)

The aim is to measure the fission yields of Nd nuclides, ^{95}Nb, ^{95}Zr, ^{106}Ru, ^{137}Cs and ^{144}Ce in high burn-up samples of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu. The sub-assembly containing the fission yield pins has been transferred

*Dounreay Nuclear Power Development Establishment (DNPDE)

to the breakdown cave in the reprocessing plant, and the pins removed. All pieces have been recovered and will shortly be transferred to the post irradiation examination (PIE) facilities. When the items arrive in the PIE caves they will be examined in detail to see if the pinlets containing the various uranium and plutonium isotopes are still intact. If they can be recovered undamaged, they will be moved to DNPDE analytical facilities for storage until a final decision on funding can be made.

A proposal has been formulated in the hope of obtaining support from the UKAEA underlying research budget. It may also prove necessary to seek funding from outside the UKAEA, but more concrete information about the integrity of the pinlets and a formal decision from the underlying research controller will determine future plans.

2.2.3 Measurements of alpha in PFR (A. Tyrrell and P. Thompson*)

This work is part of a collaborative effort between AWE, DNPDE and AERE to measure alpha at various positions in the PFR core. Samples of ^{239}Pu (two), ^{240}Pu (two), ^{241}Pu (one) and ^{242}Pu (one) irradiated in PFR Dounreay have now been analysed at AWE. The quantities of specific nuclides have been measured (Table 2.1) and total atoms calculated for zero cooling time (some earlier data were incorrectly reported as atoms per gramme of solution rather than total atoms in the irradiated sample (UKNDC(86)P114, p.45)). These data are listed in Table 2.2, and are final data except for ^{241}Am and ^{243}Am where alpha spectrometry studies will be attempted to improve on the quoted gamma results. Data from one more sample (RST 28/42) may also become available.

2.2.4 Measurements of radionuclide decay data (M. F. Banham, A. J. Fudge, G. Raw and R. McCrohon**)

Efforts continue to improve the current measurement facilities. Details of work completed or in progress are listed below.

(a) A method for the assay of the fast neutron dosimeter ^{93m}Nb using liquid scintillation counting of the conversion electrons has been developed. This method has been found satisfactory for a range of samples provided that the production of β-emitting nuclides by thermal

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Table 2.1 Nuclides Studied

Nuclide	Method of Measurement	Half life	Energy (keV)	Gamma Emission Probability (%)	Corrections Applied*
^{239}Pu	mass spectrometry	24120y	-	-	
^{240}Pu	mass spectrometry	6570y	-	-	
^{241}Pu	mass spectrometry	14.4y	-	-	
^{242}Pu	mass spectrometry	376300y	-	-	
^{60}Co	gamma spectroscopy	5.17y	1332	0.9998	
^{125}Sb	gamma spectroscopy	2.77y	428	0.3010	
^{134}Cs	gamma spectroscopy	2.062y	795	0.8544	
^{137}Cs	gamma spectroscopy	30.12y	661	0.8505	
^{144}Ce	gamma spectroscopy	284.5d	133	0.1112	
^{154}Eu	gamma spectroscopy	8.55y	1004	0.1736	
^{155}Eu	gamma spectroscopy	4.96y	105	0.2320	
^{241}Am	gamma spectroscopy	433y	60	0.3570	Corrected for ingrowth from ^{241}Pu
^{243}Am	gamma spectroscopy	7370y	75	0.6630	
^{243}Cm	gamma spectroscopy	28.50y	278	0.140	Corrected for presence of ^{239}Np, daughter of ^{243}Am

*No blank or detector background corrections have been made to the gamma spectroscopy data.

Table 2.2 PFR Plutonium Results

Sample	^{239}Pu		^{239}Pu		^{240}Pu		^{240}Pu	
Dounreay	C2/JWW	88/19	A2/JWW	47/29	A2/JWW	25/10	RST	39/40
AWE	519	39	529	39	510	40	540	40
Zero time	1-3-78		1-3-78		1-3-78		18-8-79	
Nuclide	Atoms	% rsd	Atoms	% rsd	Atoms	% rsd	Atoms	% rsd
^{239}Pu	5.109×10^{15}	0.713	3.227×10^{15}	0.486	8.118×10^{12}	0.559	1.282×10^{13}	0.556
^{240}Pu	1.175×10^{14}	0.893	7.412×10^{13}	0.618	4.203×10^{15}	0.255	6.721×10^{15}	0.524
^{241}Pu	1.351×10^{12}	0.968	8.441×10^{11}	2.727	8.753×10^{13}	1.616	2.109×10^{14}	0.646
^{242}Pu	4.087×10^{10}	10.22	3.227×10^{10}	8.179	7.597×10^{12}	1.651	1.429×10^{13}	1.430
^{60}Co	1.504×10^{10}	5.166	4.468×10^{9}	6.972	8.202×10^{9}	2.864	1.892×10^{10}	2.974
^{125}Sb	5.174×10^{11}	0.807	3.087×10^{11}	0.637	7.234×10^{10}	7.194	2.125×10^{11}	1.682
^{134}Cs	2.757×10^{11}	0.849	1.625×10^{11}	1.253	4.874×10^{10}	0.844	2.234×10^{11}	1.671
^{137}Cs	3.118×10^{13}	0.694	1.847×10^{13}	0.121	5.708×10^{12}	0.305	1.709×10^{13}	1.489
^{144}Ce	1.209×10^{13}	8.324	6.462×10^{12}	2.067	2.248×10^{12}	0.527	3.984×10^{12}	1.322
^{154}Eu	8.911×10^{10}	3.439	4.722×10^{10}	4.859	1.983×10^{10}	9.389	8.622×10^{10}	0.661
^{155}Eu	7.186×10^{11}	0.183	3.925×10^{11}	0.499	1.530×10^{11}	1.263	4.232×10^{11}	1.387
^{241}Am	6.571×10^{11}	21.658	5.163×10^{11}	10.933	7.857×10^{12}	4.005	1.916×10^{13}	1.509
^{243}Am	ND	-	ND	-	ND	-	1.737×10^{12}	23.967
^{243}Cm	ND	-	ND	-	ND	-	2.540×10^{10}	63.299

ND, not detected

All values reported are atoms in total sample, corrected to quoted zero-time.

% rsd are agreement between replicate counts for gamma spectroscopy, and combined tracer and replicate agreement errors for mass spectrometry.

Table 2.2 PFR Plutonium Results (continued)

Sample	^{241}Pu		^{242}Pu		Blank		GeLi detector background	
Dounreay	A2/JWW	56/31	A2/JWW	74/22	JWW	75/02		
AWE	531	41	522	42	505	00		
Zero time	1-3-78		1-3-78		1-3-78		1-3-79	
Nuclide	Atoms	% rsd	Atoms	% rsd	Atoms	% rsd	Atoms	% rsd
^{239}Pu	4.145×10^{13}	2.509	2.588×10^{13}	0.507	ND	-	-	-
^{240}Pu	2.264×10^{14}	2.014	3.767×10^{13}	0.952	ND	-	-	-
^{241}Pu	1.714×10^{15}	1.299	7.838×10^{12}	0.943	ND	-	-	-
^{242}Pu	5.440×10^{13}	2.139	2.372×10^{15}	0.269	ND	-	-	-
^{60}Co	2.629×10^{10}	2.238	1.311×10^{10}	3.144	2.064×10^{10}	3.259	2.747×10^{8}	47.012
^{125}Sb	1.133×10^{11}	0.273	2.489×10^{10}	19.079	2.498×10^{10}	23.254	ND	-
^{134}Cs	1.150×10^{11}	2.748	2.317×10^{10}	2.493	2.208×10^{9}	29.397	ND	-
^{137}Cs	1.399×10^{13}	0.918	2.419×10^{12}	0.923	ND	-	5.318×10^{8}	53.150
^{144}Ce	6.014×10^{12}	4.714	1.304×10^{12}	1.454	ND	-	ND	-
^{154}Eu	5.531×10^{10}	0.578	1.502×10^{10}	23.807	4.713×10^{9}	23.877	ND	-
^{155}Eu	7.092×10^{11}	0.134	1.984×10^{11}	2.312	5.351×10^{8}	8.770	ND	-
^{241}Am	6.737×10^{14}	0.944	7.975×10^{12}	0.508	ND	-	ND	-
^{243}Am	1.297×10^{12}	40.698	3.816×10^{13}	1.307	2.941×10^{10}	*59.668	ND	-
^{243}Cm	3.884×10^{11}	2.378	2.806×10^{10}	8.917	ND	-	ND	-

*Found on one count only, and probably statistical variation to background

ND, not detected

All values reported are atoms in total sample, corrected to quoted zero-time.

% rsd are agreement between replicate counts for gamma spectroscopy, and combined tracer and replicate agreement errors for mass spectrometry.

neutron capture is not high. The greater sensitivity of the method allows the measurement of lower activity samples to be measured than the long established method of X-ray counting. A report will be published in 1988.

(b) Work is continuing on the development and assembly of liquid scintillation equipment for α-spectrometry and neutron counting.

(c) Two experimental fuel pellets of ^{241}Am and ^{242}Cm oxides irradiated in PFR have been dissolved and the solutions analysed by α-, γ- and mass spectrometry. Dissolution and analysis of a third irradiated oxide pellet consisting of americium, curium and four selected lanthanides in known initial proportions will take place in early 1988. A report of this work will be published in 1988. This work should provide improved reaction rate data for fission and capture for these nuclides in PFR core-centre neutron spectra.

(d) Work on the measurement of ^{129}I fast fission-yield from ^{239}Pu has started. An investigation into the quantitative extraction of fission product iodine from milligram quantities of fast reactor irradiated ^{239}Pu sealed in silica has been carried out. A method of extraction has been proposed and approved on safety grounds. Two samples will be processed in early 1988 and the ^{129}I in the iodine extracted will be counted on a low background liquid scintillation counter. It is intended that results of this work will be published late in 1988.

(e) A new gamma scanner has been commissioned and been used to demonstrate the feasibility of using γ-emission tomographic data to provide cross-pin flux gradients and fission product profiles within intact CAGR fuel pins. This work is still in its early development stage but results so far are very promising.

(f) The feasibility of using the γ-spectrometry code GAMANAL for the analysis of α-spectra is being studied. Analysis of the spectra of transactinium nuclides finds direct application in isotopic analysis and decay scheme studies. By careful adjustment of peak shape parameters good fits have been obtained on two spectra of ^{238}Pu and ^{240}Pu.

(g) Preparations are in hand to participate in an international exercise to measure P_γ for ^{75}Se. The need for this measurement was recognised as a direct result of the successful CRP on transactinides set up by the IAEA, when the nuclear data of some of the nuclides used for detector calibration were found to be inadequate.

2.2.5 Measurements and evaluations of half-lives and gamma-ray emission probabilities (M. U. Rajput, I. M. Lowles and T. D. MacMahon*)

(a) Measurements of P_γ in ^{65}Ni, ^{125}Sb and $^{239}U/^{239}Np$ have continued or started in 1987. None of these studies is yet complete.

(b) An evaluation of ^{137}Cs half-life data has been carried out and published as an Ascot Reactor Centre Report (ICRC/87/1) and as a UKCNDC paper (CNDC(87)P18). The recommended half-life is 30.13±0.09 years.

(c) The gamma-ray emission probability data for 29 transitions in Sb have been evaluated. Problems arise when attempting to construct a consistent decay scheme, and so a new measurement of P_γ values has been started.

2.3 CNDC data library sub-committee

Current membership: A. Tobias (Chairman, CEGB/BNL), M. F. James (Secretary, AEEW), A. J. Fudge (Harwell), A. L. Nichols (AEEW), P. Robb (AEEW), D. R. Weaver (University of Birmingham) and A. Whittaker (British Nuclear Fuels plc).

2.3.1 Data library development

The current status of the UKCNDC Data Libraries is summarised in Table 2.3. Reduced evaluation efforts during the last year have limited the progress towards revisions of the UK decay data files. However, the recently released JEF-1 data files, which include a sizeable UK contribution, have been recommended for use.

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* Imperial College, Silwood Park

Table 2.3

UK Chemical Nuclear Data Libraries: Status Table, December 1987

Data	Present Status	File Development
1. Fission Product Data	Exists as UKFPDD-2 (ENDF/B-IV format) - replaces UKFPDD-1 Total no. of nuclides = 855 Radioactive nuclides = 736 Ground state = 175 1st excited state = 133 2nd excited state = 5 Nuclides with spectra = 390 Total no. of γ lines = 11,978 Total no. of β^- lines = 3,592 Total no. of β^+ lines = 91	Robb (AEEW) evaluating ^{125}Sb, ^{129}Sb, ^{134}Cs, ^{151}Sm, ^{152}Eu, and ^{155}Eu. Adoption of delayed neutron emission probabilities and consideration of inclusion of delayed neutron spectra.
2. Activation Product Decay Data	Available in ENDF/B-IV and V format for 91 nuclides as UKPADD-1. Now includes detailed K X-ray spectra.	60 nuclides have been evaluated for UKPADD-2, 56 are in ENDF/B-V format. ^{51}Cr, ^{65}Zn, ^{75}Se and ^{198}Au have been re-evaluated as part of an IAEA-CRP programme, and are available in ENDF/B-V format.
3. Heavy Element and Actinide Decay Data	Completion of UKHEDD-1, including spontaneous fission data in June 1982. Data in ENDF/B-V format. Total no. of nuclides = 125 Ground state = 111 1st metastable state = 13 2nd metastable state = 1 Total no. of α lines = 767 Total no. of β^- lines = 527 Total no. of β^+ lines = 39 Total no. of γ lines = 3,475 Total no. of discrete electrons = 6,755 Total no. of x-rays = 381	^{228}Th, ^{224}Ra, ^{220}Rn and ^{216}Po completed. Evaluation of ^{239}Np/^{243}Am is underway. Preparation of evaluations for ^{236}Np (g and m) and ^{212}Pb underway. ^{231}Pa, ^{234}U and ^{239}U decay data and ^{242m}Am half life have been evaluated.

(Table continued overleaf)

Table 2.3 (continued)

UK Chemical Nuclear Data Libraries: Status Table, December 1987

Data	Present Status	File Development
4. Fission Yields	Available in ENDF/B-V format based on Banai/James revision. Whole library called UKFY1; UKIFYU1 - unadjusted independent yields UKIFYA1 - adjusted independent yields UKCFYA1 - adjusted cumulative yields	Report on evaluation being prepared. Initially work for next evaluation will concentrate on production of new database and revised fractional independent yields.

Notes:

(i) Spectral data from the decay data files may be accessed via the retrieval system described by Tobias (RD/B/5170N81, 1981).

(ii) Much of the decay data and the fission yields from these files have been incorporated in JEF-1 data library.

(a) Heavy elements (A. L. Nichols**)

There have been no evaluations made specifically for the UKCNDC data files during this period. Efforts have been directed towards evaluation problems identified with the 4n decay chain of ^{232}U, and the aim is to complete this work by mid-1988.

(b) Fission products (A. Tobias* and P. Robb**)

The recent influx of new effort in this area has resulted in preparations to evaluate the decay data for a selected number of fission-product radionuclides specified by British Nuclear Fuels plc.

(c) Activation products (A. L. Nichols and P. Robb**)

Decay data for ^{51}Cr, ^{65}Zn and ^{198}Au have been re-evaluated on the basis of critical discussions at a Rome meeting of the IAEA-CRP on X- and Gamma-ray

* CEGB, Berkeley Nuclear Laboratories (BNL)
**Atomic Energy Establishment Winfrith (AEEW)

Standards for Detector Calibration, 11-13 June 1987 (INDC(NDS)-196/GE). Further efforts are required to re-evaluate the gamma-ray emission probability data for ^{75}Se and $^{243}Am/^{239}Np$ to assist in this exercise.

(d) Fission yields (M. F. James** and D. R. Weaver+)

The fission yield library UKFY1 is now available in ENDF/B-V format. It consists of three separate files: UK1FYU1, containing independent yields that are the result of a thorough evaluation but which have not been adjusted to fit physical constraints; UKIFYA1, containing independent yields obtained by adjusting the data in the former library by least-squares to fit several physical constraints; and UKCFYA1, containing cumulative yields corresponding to UKIFYA1. These have been compared with USA, French and Chinese libraries in a paper presented at the Specialists' Meeting on Data for Decay Heat Predictions at Studsvik in September 1987.

A further revision of the UK library is now underway. This will concentrate on bringing the database up-to-date, and re-evaluating fractional independent yields. The former task will be made much easier by the agreement at Studsvik that the international data format EXFOR should be the internationally used format for data bases of measured fission yields. EXFOR is already fairly complete from 1981 onwards, and V. McLane at Brookhaven National Laboratory is converting the database of B. F. Rider to this format. The resultant database is being examined and checked by a Chinese physicist (Wang Dao) working at the University of Birmingham on an IAEA fellowship. It is planned that Wang Dao and his colleague, Zhang Dongming, will extract fractional independent yields from the completed EXFOR file and help to develop evaluation methods for these data.

2.3.2 Joint Evaluated File (JEF)

An assessment of the uncertainties in JEF-1 integral decay heat predictions has been made from comparisons with a least squares fit to available measurements of total decay heat. The results were given in a paper presented to the Specialists' Meeting on Data for Decay Heat Predictions (Tobias - Studsvik, 1987). A summary of the paper is given below.

+ University of Birmingham
**AEEW

Systematic and random uncertainties in JEF-1 decay heat predictions for both ^{235}U and ^{239}Pu have been quantified from comparisons with benchmarks derived from least squares fits to measured data. The lack of reliable decay data for short lived nuclides results in systematic errors in JEF-1 (and other summation) predictions of typically up to 8.5% at short cooling times. This decreases with cooling time and becomes negligible at times exceeding 10^4 s. Corresponding random uncertainties derived from the least squares fits were increased to reflect outstanding and unresolved discrepancies in measured data. Uncertainties in capture contributions were also examined briefly in order to estimate the uncertainty in JEF-1 integral decay heat predictions for most practical applications. Best estimate decay heat predictions may be derived from corresponding JEF-1 values via the systematic factors determined in the present work while upper bound values, required for certain applications, may be obtained by applying a factor equal to the sum of the systematic error plus two standard deviations (Table 2.4).

It is concluded that further decay heat measurements, for ^{239}Pu in particular, are required in order to resolve outstanding discrepancies between different sets of measurements. Extension of measurements to longer cooling times for both ^{235}U and ^{239}Pu is desirable in order to establish improved confidence in decay heat evaluations for practical applications.

Table 2.4

Adjustment Factors and Uncertainties for JEF-1 Decay Heat Predictions

Cooling Time (s)	Adjustment Factors and Uncertainties			Upper Bound
	^{235}U	^{239}Pu	General	
1.0	1.085 ± 0.021	1.074 ± 0.036	1.085 ± 0.036	1.157
10	1.078 ± 0.021	1.074 ± 0.035	1.078 ± 0.035	1.148
10^2	1.064 ± 0.021	1.073 ± 0.035	1.073 ± 0.035	1.143
10^3	1.046 ± 0.023	1.048 ± 0.037	1.048 ± 0.037	1.122
10^4	1.020 ± 0.030	1.000 ± 0.043	1.020 ± 0.043	1.106
10^5	1.000 ± 0.040	1.000 ± 0.050	1.000 ± 0.050	1.100
10^6	1.000 ± 0.040	1.000 ± 0.050	1.000 ± 0.050	1.100
10^7	1.000 ± 0.045	1.000 ± 0.050	1.000 ± 0.050	1.100
10^8	1.000 ± 0.045	1.000 ± 0.050	1.000 ± 0.050	1.100

2.4 On-line chemical separation and studies of short-lived nuclides in fission and other nuclear reactions (H. E. Sims*, A. Szymanski**, G. W. A. Newton** and V. J. Robinson**)

The decay properties of a number of rhenium and tungsten radionuclides have been studied over a number of years using the Harwell Variable Energy Cyclotron (VEC), a helium jet transport system and Ge(Li) spectroscopy. The absolute gamma-ray emission probabilities of mass numbers 171, 172, 173, 174 an 175 have been measured following production via the reactions:

^{165}Ho(^{16}O, 10n)^{171}Re and ^{165}Ho(^{14}N, 8n)^{171}W
^{165}Ho(^{16}O, 9n)^{172}Re and ^{165}Ho(^{14}N, 7n)^{172}W
^{165}Ho(^{16}O, 8n)^{173}Re and ^{165}Ho(^{14}N, 6n)^{173}W
^{165}Ho(^{16}O, 7n)^{174}Re and ^{165}Ho(^{14}N, 5n)^{174}W
^{165}Ho(^{16}O, 6n)^{175}Re and ^{165}Ho(^{14}N, 4n)^{175}W

These studies also included measurements of the gamma-ray emission probabilities for ^{173}Ta from ^{165}Ho(^{14}N,p5n)^{173}Ta. Details and results of this work can be found in the following publications:

A. Szymanski, G. W. A. Newton, V. J. Robinson, S. M. A. Hoffmann and H. E. Sims, Absolute Gamma-ray Abundances of Re and W Isotopes, Part I, A = 175, Radiochimica Acta, 37 (1984) 121.

A. Szymanski, G. W. A. Newton, V. J. Robinson and H. E. Sims, Absolute Gamma-ray Abundances of Re and W Isotopes, Part II, A = 174, Radiochimica Acta, 38 (1985) 113.

A. Szymanski, G. W. A. Newton, V. J. Robinson and H. E. Sims, Absolute Gamma-ray Abundances of Rhenium and Tungsten Isotopes, Part III, A = 173, Radiochimica Acta, 40 (1986) 61.

A. Szymanski, G. W. A. Newton, V. J. Robinson and H. E. Sims, Absolute Gamma-ray Abundances of Re and W Isotopes, Part IV, A = 172, Radiochimica Acta, 40 (1986) 67.

A. Szymanski, G. W. A. Newton, V. J. Robinson and H. E. Sims, Gamma-ray Abundances of Re and W Isotopes, Part V, A = 171, Radiochimica Acta, 41 (1987) 5.

Experimental data associated with the heavy ion transfer reactions of ^{197}Au and the formation of ^{198}Au are being prepared for publication.

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* Harwell Laboratory
**University of Manchester

3. REACTOR PHYSICS DIVISION, AEE WINFRITH

3.1 Resonance parameter evaluations [WRENDA 758]

a) ^{238}U: The provisional spin and width assignments of ^{238}U resonances up to 14 keV derived at Harwell[1] from measurements made at ORNL are being analysed using the programs DEEBAR (for resonance spacing analysis) and LJPROB (for width distribution analysis).

b) Hf isotopes: A new evaluation of the resonance parameters of isotopes of hafnium for inclusion in JEF-2 is in progress.

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(1) See section 1.1.2 of this report

4. DIVISION OF RADIATION SCIENCE AND ACOUSTICS
NATIONAL PHYSICAL LABORATORY

Superintendent: Dr. A. T. Cox
(Radioactivity and Neutron Measurements Branch)
(Branch Head: Dr. P. Christmas)

4.1 International intercomparisons (under the auspices of the International Bureau of Weights and Measures, BIPM)

4.1.1 Radioactivity measurements (D. Smith and M. J. Woods)

The final report on the full-scale intercomparison of measurements of the activity of ^{109}Cd, involving 18 laboratories world-wide, gave an overall spread of 2.6%, with the NPL result being within 0.2% of the weighted mean value of all the results. A summary report is being prepared for publication.

4.1.2 Neutron measurements (J. B. Hunt, V. E. Lewis and T. B. Ryves)

Measurements of all participating groups (including NPL) involved in the neutron dosimetry intercomparison organised by BIPM are now complete, and the results are being analysed by BIPM.

Measurements have been made at a neutron energy of 14.7 MeV using the ^{235}U and ^{238}U fission chambers constructed by Harwell Laboratory, as part of an intercomparison of fluence measurements. The SAMES accelerator was used and the d+T neutron field was standardised using associated alpha particle monitoring and iron foil activation techniques. The responses of both fission chambers were measured over a range of about 50 cm to 175 cm distance from target. The data were fitted, with and without subtraction of the scattered component as measured employing the shadow cone, using polynomial functions of the distance. A report has been prepared for submission to the coordinator, Harwell Laboratory (see section 1.5 of this report).

Measurements for the intercomparison using the NPL dual moderating sphere system have been postponed again due to delays elsewhere.

4.2 Neutron cross-sections (V. E. Lewis and T. B. Ryves)

The results of the previously measured 14 MeV neutron cross-sections for ^{107}Ag and ^{109}Ag have been analysed and a paper accepted for publication. Measurements have been completed on the 14 MeV ^{59}Co(n,p), (n,α), (n,2n), and ^{165}Ho(n,p) cross-sections. These are important in helping to establish the systematics of neutron induced threshold reactions for the fusion reactor programme. In addition, a very precise value for the ^{59}Co(n,α) cross-section was determined as data input for an evaluation.

A simultaneous evaluation of twelve cross-sections, including those for the standard reactions ^{1}H(n,n), ^{27}Al(n,α), ^{235}U(n,f) and ^{238}U(n,f), has been made at an energy of 14.7 MeV. A generalised least-squares method employing full covariances was used. Uncertainties (at one standard deviation level) from 0.5%, for reactions such as ^{27}Al(n,α) and ^{56}Fe(n,p), to 1.5% were achieved, with a χ^2 per degree of freedom of 1.34 for 204 measurements taken from the literature. Most of this work was done by a NPL staff member during two three-month periods of detached duty at Central Bureau for Nuclear Measurements, Geel. A specimen graphical fit (Fig. 4.1) is shown for the ^{197}Au(n,2n)$^{196m+g}$Au reaction for which a result of (2127±26) mb was obtained.

4.3 Decay data (P. Christmas, D. Smith, M. J. Woods, S. A. Woods, W. Gelletly* and S. L. Waters**)

^{65}Ni Measurements of the half-life and gamma-ray emission probabilities have been published(1).

^{47}Ca Measurements of the end-point energies of the beta-ray branches have been published(2).

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* Schuster Laboratory, University of Manchester
**NRC Cyclotron Unit, Hammersmith Hospital, London

(1) S. M. Judge, C. Grant, S. E. M. Lucas, R. A. Mercer, A. Munster, A. M. Privitera and M. J. Woods, Appl. Radiat. Isot., 38 (1987) 907.
(2) S. M. Judge, P. Christmas, P. Cross, D. Smith and W. D. Hamilton, Appl. Radiat. Isot., 38 (1987) 839.

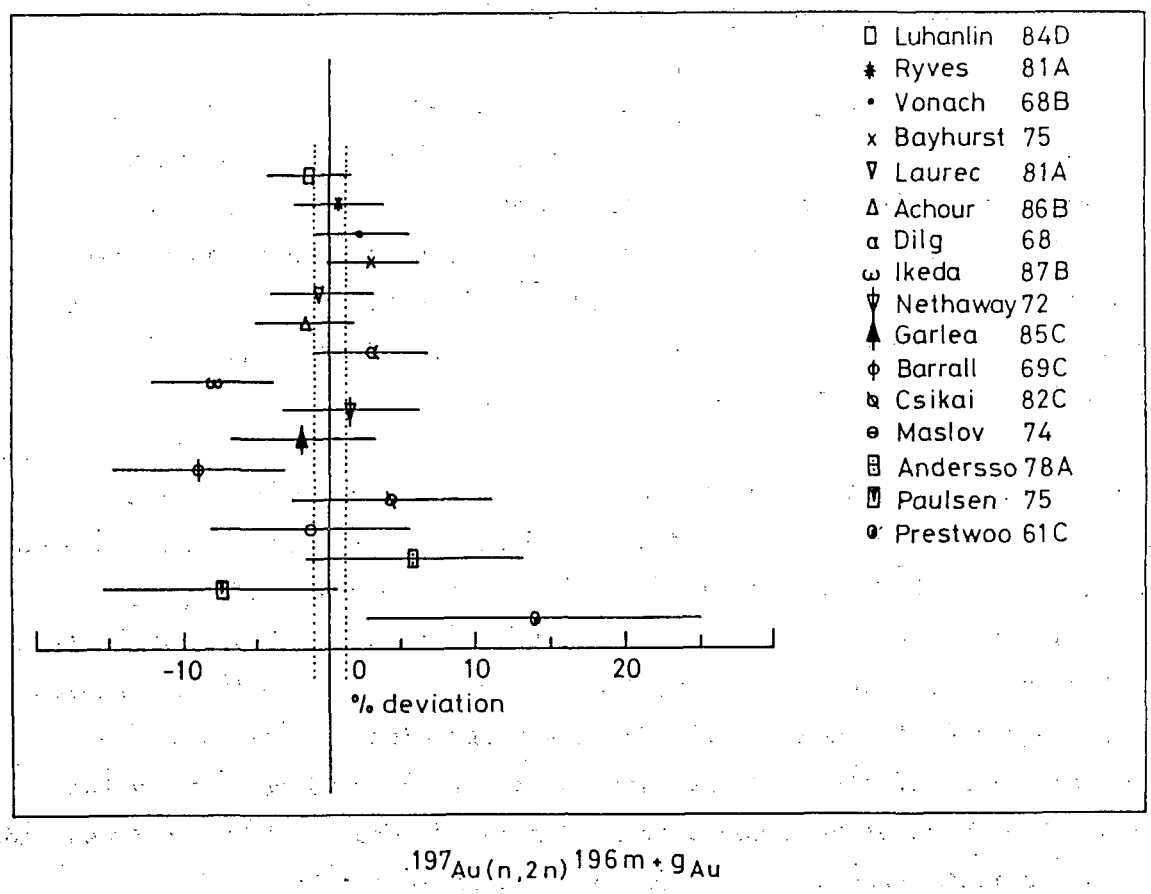

Figure 4.1 Deviation of individual data from the evaluated mean of the cross-section of the $^{197}Au(n,2n)^{196m+g}Au$ reaction at 14.7 MeV

^{82}Rb Decay scheme parameters measured, and values published[1,2] for P_γ, P_{β^+}, P_{ec} and half-life.

^{201}Tl As part of an international comparison to resolve a discrepancy in activity measurements, the gamma-ray emission probabilities and half-life have been determined. The results will be submitted for publication.

^{124}I In collaboration with Manchester University, measurements have started to determine the gamma-ray and positron emission probabilities and the half-life. Recent improvements in production techniques mean that ^{124}I can be used for positron emission tomography.

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(1) S. M. Judge, M. J. Woods, S. L. Waters and K. R. Butler, Appl. Radiat. Isot., 38 (1987) 185.
(2) M. J. Woods, S. M. Judge, S. E. M. Lucas, Appl. Radiat. Isot., 38 (1987) 191.

$^{237}Np/^{233}Pa$ The low energy spectrum (<20 keV) has been scanned with the β-ray spectrometer using an array of channel electron multiplier detectors. The work previously reported has been accepted for publication[1].

^{241}Am The SERC-supported collaboration with Manchester University has continued. Further analysis of the internal conversion coefficients for this nucleus, with an improved efficiency correction for the 16-element proportional counter assembly used on the β-ray spectrometer, is progressing.

^{180m}Hf No further work on this nucleus has been possible through the lack of a suitable source.

^{244}Cm In collaboration with Manchester University and Harwell Laboratory, the decay scheme of this nucleus is being determined through alpha, gamma and conversion electron measurements.

^{170}Tm Preliminary measurements on the β-decay of this nucleus are to commence using the electron-gamma coincidence system on the β-ray spectrometer. These studies may reveal the existence of the proposed heavy neutrino.

4.4 Evaluations (P. Christmas and M. J. Woods)

The evaluation of half-life data for 33 radionuclides has now been completed. This work was carried out jointly by NPL and Physicalisch Technische Bundesanstalt (PTB) within the framework of the IAEA Coordinated Research Programme. NPL is now continuing this exercise for a large number of other radionuclides.

(1) S. A. Woods, P. Christmas, P. Cross, S. M. Judge and W. Gelletly, to be published in Nucl. Instr. and Meth. in Phys. Res. A.

5. DEPARTMENT OF PHYSICS, UNIVERSITY OF BIRMINGHAM

5.1 Delayed neutron yields and spectra (D. R. Weaver, J. Walker, J. G. Owen, M. Cogbill and P. O. F. Garze)

Experiments on the yields of delayed neutrons from natural uranium when bombarded with fast neutrons from a Be(d,n) source have been undertaken. The sample consisted of a disc of natural uranium which was shuttled automatically between the irradiation position and the counting position where the delayed neutron emission was counted during the beam-off period by a precision long ^{3}He counter. The fission rate was calibrated absolutely with a ^{238}U fission chamber mounted very close to the sample and having a fission foil identical in diameter to the delayed neutron sample; this was done in order to minimise the corrections required to account for small differences in the geometry of the sample and the fission chamber. Experiments are continuing and will include runs with monoenergetic neutrons from (p,n) and (d,n) sources.

A second piece of work relates to the analysis of earlier measurements of delayed neutron spectra. The Birmingham group has pioneered the calculation of full covariance error matrices for the delayed neutron spectra. As reported earlier[1] the technique requires the provision of the equivalent covariance matrices for the response function parameters used in the spectrum unfolding program. Until now it had been possible to calculate only portions of the covariance matrix of the response function because of the way the corresponding parameters had been evaluated. By employing the Davidon minimisation technique[2], it has been possible to make a calculation of all of the response function parameters simultaneously, and hence to derive the overall covariance matrix for the response function uncertainties. The results obtained for the parameters are little different from those obtained earlier, giving confidence that the earlier method was not likely to be seriously in error and that the Davidon method is appropriate for this type of problem. The implications of the new results on the covariance matrices for the final delayed neutron spectra have yet to be assessed.

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(1) J. G. Owen, D. R. Weaver and J. Walker, Nucl. Instr. Meth. 188 (1981) 579.
(2) Davidon method: in B. R. Martin "Statistics for Physicists", Academic Press (1971).

5.2 Yields of fission products from the fission of ^{238}U induced by monoenergetic neutrons (H. A. Garideh and K. Randle*)

Absolute yields have been determined for 45 binary fission products, representing 35 mass chains created during the fission of ^{238}U with monoenergetic neutrons.

The neutrons were produced via either the $t(p,n)^3He$ or $d(d,n)^3He$ reactions, using the 3 MV Dynamitron accelerator in the Physics Radiation Centre, University of Birmingham. Fission was investigated at five neutron energies, ranging from 1.75 MeV to 5.8 MeV. At least two irradiation periods were used at each neutron energy, one of a few tens of minutes and the other of several hours. This allowed an investigation of fission products with half-lives varying from a few minutes to several months.

Neutron fluences were determined using a calibrated fission chamber as the primary monitor and metal foils as secondary flux monitors. The experimental arrangement consisted of a pack of metal foils mounted in a recess of the fission chamber. They were immediately in front of a Pt foil coated with a deposit of ^{238}U of accurately known weight and a diameter identical to the foils in the pack. The latter contained a ^{238}U foil, Al guard foils and In flux monitor foils.

At the end of the irradiation, fission product activities were measured with a large, hyperpure Ge detector by direct counting of the ^{238}U foil and the Al guard foils. In most cases fission yields were determined from gamma-ray spectra taken at several, different cooling times. A least-squares computer program was written for the analysis of multicomponent decay curves in cases where different fission-product photopeaks were unresolved. Analysis of the fission-product spectra and gamma-ray peak areas was by the use of the SAMPO80 computer code.

The results include several mass chains for which no prior yield data exist. In most of the other cases only one other experimental determination has been reported. There is some agreement between the results presented here and those previously determined.

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*Department of Chemistry, University of Birmingham

It is important to find the relation between the yield, Y, of a particular isotope and neutron energy. The best fit to the data was determined by the use of an exponential function (using the weighted least-squares technique) of the form

$$Y = Y_0 \exp(b\, E_0) \qquad (1)$$

where Y_0 and b are constants.

By determining the value of these constants in equation (1), it is then possible to predict the fission yields for any given neutron spectrum. The fast fission yields (FFY) can be determined from

$$FFY = \sum_{i=0}^{N} Y(E_i)\, \sigma_f(E_i)\phi(E_i) \Big/ \sum_{i=0}^{N} \sigma_f(E_i)\phi(E_i)$$

where N is the number of data points starting from the fission threshold energy to maximum neutron energy; $\sigma_f(E)$ is the fission cross-section at neutron energy E_n, and $\phi(E)$ is the neutron spectrum.

The values of the fission cross-sections were taken from the JEF file. The predicted value of fission product yields for neutrons having a Watt spectrum is shown in Table 5.1. Table 5.1 also includes the experimentally determined values of FFY by Chien Chung and Ming-Yung Woo[1] and the published, evaluated[2] data for fast neutron-induced fission of ^{238}U.

5.3 An investigation of alpha particle and triton emission in the spontaneous fission of ^{252}Cf and neutron-induced fission of ^{238}U (H. A. Garideh, K. Randle* and S. A. Durrani)

The energy spectrum of α particles emitted in the spontaneous ternary fission of ^{252}Cf was determined using two independent methods. In the first method, in which the energy distribution of tritons was also determined, the light fission fragments were identified with a particle detector telescope. This consisted of two surface barrier detectors, shielded from heavy fission fragments by a 12 μm foil of Al, mounted in front of a ^{252}Cf source in a vacuum chamber. The total fission events were monitored with a separate surface barrier detector. Using suitable electronics a mass v energy spectrum was

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(1) Chien Chung and Ming-Yung Woo, J. Radioanl. and Nucl. Chem. 109 (1987) 117.
(2) E. A. C. Crouch, Atomic Data and Nucl. Data Tables 19 (1977) 417.
*Department of Chemistry, University of Birmingham

Table 5.1 Comparison of fission yields predicted from this work for neutrons with a Watt spectrum and those for fast neutron-induced fission of ^{238}U as measured by Chien Chung and Ming-Yung Woo and evaluated by Crouch.

Nuclide	Yield		
	This work	Chien Chung	Crouch
^{85m}Kr	.958	.74	.74
^{87}Kr	1.34	-	1.59
^{88}Kr	1.75	-	2.37
^{89}Rb	3.07	3.01	3.06
^{91}Sr	3.70	4.41	4.13
^{92}Sr	4.27	-	4.57
^{93}Y	4.78	4.86	5.18
^{94}Y	4.36	4.88	5.03
^{95}Zr	5.43	5.28	5.25
^{97}Zr	5.47	5.55	5.67
^{101}Tc	7.15	-	-
^{103}Ru	6.31	6.38	6.34
^{104}Tc	4.58	-	-
^{105}Ru	4.24	3.48	3.95
^{107}Rh	.85	-	-
^{129}Sb	.64	-	.54
^{131}I	3.63	3.19	3.28
^{132}I	5.04	5.11	5.26
^{133}I	6.81	6.47	6.60
^{134}Te	6.40	7.19	7.38
^{135}I	6.89	6.47	7.19
$^{138}Cs(Xe)$	5.77	5.94	6.13
^{140}Ba	5.75	6.07	6.0
^{141}Ba	4.94	-	5.55
^{142}La	4.71	4.86	4.62
^{143}Ce	4.50	4.68	4.67
^{146}Ce	3.63	-	3.51
^{147}Nd	2.73	-	2.61
^{149}Nd	1.69	-	1.67

obtained of the light fragments (128 x 64 channels matrix). The alpha particles and tritons were well-resolved allowing the energy distributions for both particles to be determined. Figure 5.1 illustrates the three-dimensional plot of particle mass versus total particle energy. As can be seen from this figure, the alpha-particles are well separated from the tritons. The ratio of t to α was found to be $7.6 \pm 0.4 \times 10^{-2}$.

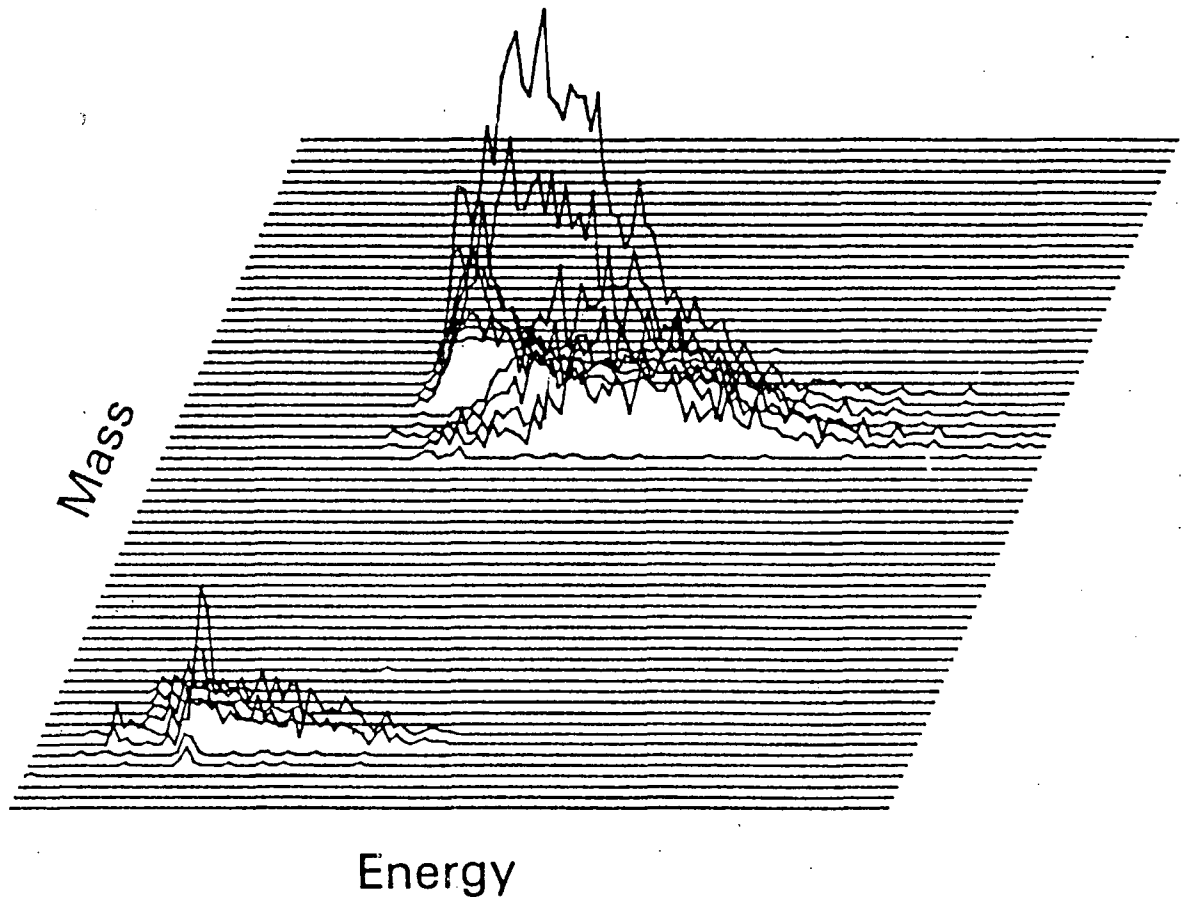

Figure 5.1 Three-dimensional plot of particle mass versus particle energy for spontaneous fission of ^{252}Cf obtained with surface barrier detector telescope

The second method was used primarily to investigate the low-energy tail of the α-particle distribution. It involved the use of LR115, cellulose nitrate plastic detectors with Al degrader foils to measure the energy distribution of the α particles. This allowed measurements down to a cut-off energy of 2 MeV, much lower than the detector telescope method. The energy spectrum of

LRA-particles emitted in the spontaneous fission of ^{252}Cf using the LR115 detector is shown in Figure 5.2. A Gaussian fit to the data of Figure 5.2 shows no significant deviation of data from the curve in the low energy tail. This result is in contrast to that obtained by Loveland[1], who found such a deviation.

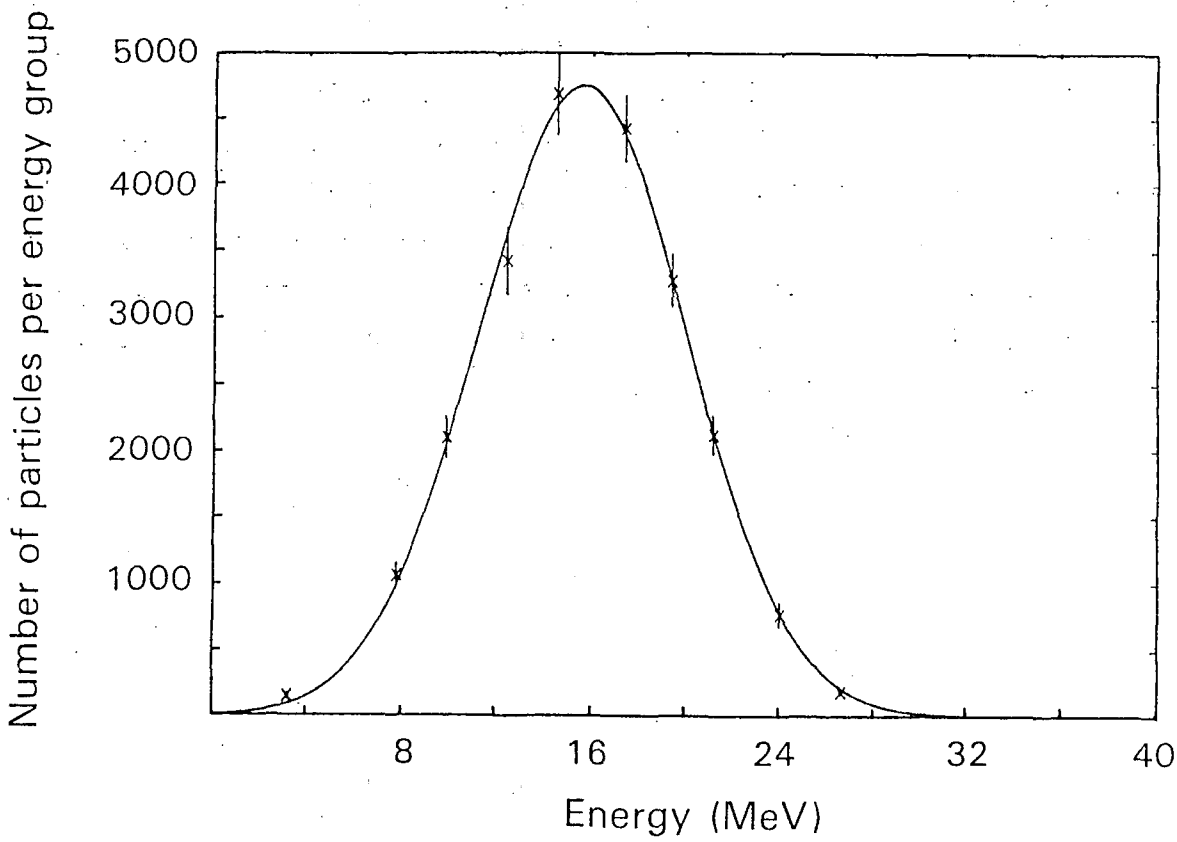

Figure 5.2 The energy spectrum of LRA-particles from ^{252}Cf spontaneous fission measured using the LR115 detector. The line is a Gaussian fit to the data.

In the monoenergetic-neutron-induced fission of ^{238}U the detector telescope technique was again used. The experimental set-up was similar to that used for ^{252}Cf except that the ^{252}Cf source was replaced by a neutron-producing target and a thin deposit of ^{238}U on a gold-coated polymide foil. Measurements were carried out at neutron energies of 3.6 and 4.12 MeV. Monoenergetic neutrons were produced from the $d(d,n)^3He$ reaction using the Physics Radiation Centre's 3 MV Dynamitron accelerator. The detector telescope and fission detector were on two arms at 30° to the ^{238}U source. Irradiations were carried out for a

(1) W. Loveland, Phys. Rev. C9 (1974) 395.

total of 24 hours with an average neutron flux at the ^{238}U source of 2.0×10^8 $n/cm^2/sec$. Again a mass versus energy spectrum was produced but with poorer resolution than obtained with ^{252}Cf due to the neutron degradation of the detectors. The spectrum, however, allowed an accurate determination of the ratio of the alpha particle to triton yield at both energies. This experiment produced a rather unexpected result for tritons in that the yield of tritons to α-particles was found to be 16-18%. If this is confirmed, it indicates that tritium production is not as high as reported by Buzzelli[1] for the reactor-neutron-induced-fission of ^{238}U but is three times higher than its production in the thermal-neutron-induced-fission of ^{235}U. This high yield of tritons will require serious consideration for the development of fast breeder reactors in which natural uranium is used as the fuel. A further consequence of high tritium yield from these reactors would be an increased environmental hazard as compared with thermal ones.

(1) G. S. Buzzelli, C. C. Langer, C. Jones and B. Gainey, Trans. Am. Nucl. Soc. 24 (1976) 458.

6. NUCLEAR PHYSICS LABORATORY, UNIVERSITY OF OXFORD

6.1 Neutron elastic scattering (P. E. Hodgson)

A review paper on this topic with the title "The Neutron Optical Potential" was presented to the IAEA Advisory Group Meeting on "Nuclear Theory for Fast Neutron Data Evaluation" at the Institute of Atomic Energy, Beijing, China (October 1987). The paper had the following abstract:

> The present status of optical model calculations of neutron scattering and interactions is reviewed, with special emphasis on more recent developments and the more promising lines of research. The use of dispersion relations to provide an extra constraint on the potential is discussed, together with their application to studies of the Fermi surface anomaly. The application of potential inversion techniques to determine the form of the potential is also considered.

6.2 Neutron inelastic scattering (A. M. Street)

Neutron inelastic scattering cross-sections are an important part of the input data for reactor calculations for reactors of the breeder type. These cross-sections are often difficult to measure accurately and so there is a need for reliable predictions over a wide range of energies. We have developed a fast and reasonably accurate method for calculations of this type using a normalised 'compound plus direct' interaction approach. We find that the optical potentials input to these calculations, derived from phenomenological fitting, typically have errors of the order of 20% of the partial cross-section. In order to reduce the errors in form and magnitude of these optical potentials we use microscopic theory which allows us to better control the fitting procedures and obtain more accurate forms for the optical potential. By improving the microscopic theory to include 3-body terms we further enhance this process. The overall effect is to produce more accurate and reliable reaction cross-sections.

This work formed the subject of a D.Phil. thesis submitted in 1987 (University of Oxford).

6.3 Neutron reaction cross-section calculations

6.3.1 Weisskopf-Ewing calculations of neutron-induced reactions (S. Ait-Tahar and P. E. Hodgson)

This work, described last year (UKNDC(86)P114, p.60), has now been published in J. Phys. G13 (1987) 945.

6.3.2 Neutron scattering and reactions on ^{93}Nb from 1 to 20 MeV (D. Wilmore and P. E. Hodgson)

A paper on this work with the following abstract has been accepted for publication in Journal of Physics G.

The cross-sections of all the more important reactions of neutrons on ^{93}Nb are calculated and the results compared with the experimental data. The optical model is used to obtain the differential elastic scattering cross-section and the Weisskopf-Ewing, Hauser-Feshbach and Feshbach-Kerman-Koonin theories are used for the compound and statistical multistep compound contributions to the neutron and proton emission cross-sections. Several other reaction channels, in particular the (n,2n), (n,p) and (n,α), are also studied using one or more of these theories.

6.3.3 Statistical theory calculations (M. Chadwick)

The Weisskopf-Ewing statistical theory of nuclear reactions has been used to investigate the energy dependence of neutron induced reactions on medium atomic mass nuclei. In particular the (n,α) reaction was studied, and it was found that if individual final nuclear states were taken into account using the Hauser-Feshbach formalism, good agreement with data was obtained.

The Statistical Multistep compound theory of Feshbach, Kerman and Koonin has been used to calculate n and p emission cross-sections for the n + ^{59}Co reaction. At a neutron incident energy of 14 MeV, where the multistep-direct contribution is small, good agreement with experiment was found. Alpha emission will be incorporated into the multistep compound code to determine the importance of pre-equilibrium emission of alpha particles.

6.3.4 Multistep analysis of neutron reactions (R. Bonetti, P. E. Hodgson, G. M. Field and M. Chadwick)

The quantum mechanical statistical multistep compound emission (SMCE) theory of Feshbach, Kerman and Koonin is being applied to the reactions of 14 MeV neutrons on ^{59}Co, ^{93}Nb and ^{209}Bi. Calculations carried out in the framework of the SMCE model formalism were found to give a fair account of both the neutron and proton emission data above the (n,2n) and (n,np) thresholds. The SMCE theory was then improved by a reformulation of the original model. The revised model was confined explicitly to a description of particle-hole bound states and included the finite depth of the potential well. Subsequent calculations improved the pre-equilibrium emission predictions compared with the earlier model. Contributions from the multiparticle emission processes were evaluated with the Weisskopf-Ewing theory, using the SMCE results as input for the second stage calculations. Considered together with the results of a statistical multistep direct emission (SMDE) calculation of the (n,n') reaction on ^{59}Co at 14 MeV, the multistep theory was seen to provide a good fit to the emission data at both the forward and backward angles. The revised model was then used to predict the variation of SMCE with excitation energy and compound-state mass number. The energy dependence was seen to reflect the changing proportions of compound nucleus and pre-equilibrium processes. From a consideration of the model formalism the mass dependence of pre-equilibrium SMCE was derived. Values for the effective interaction strength deduced from these calculations were found to be rather constant over the entire energy and mass ranges.

Some of this work has been published as the D.Phil. thesis (Oxford, 1987) of G. M. Field.

6.3.5 Neutron reaction theory reviews (P. E. Hodgson)

Two papers reviewing theories for direct, pre-equilibrium and compound nucleus reactions have been published.

A review article was published in Rep. Prog. Phys. 50 (1987) 1171 with the following abstract:

The theories of compound nucleus reactions to discrete and continuum states are reviewed and compared with experimental data. In particular, the Weisskopf-Ewing, Hauser-Feshbach and Feshbach-Kerman-Koonin theories are described and their range of validity investigated. Recent work on the width fluctuation correction and the elastic enhancement factor is included in the review.

An invited paper entitled "Multistep Compound Processes in Nuclear Reactions" was presented at the IAEA Advisory Group Meeting on "Nuclear Theory for Fast Neutron Nuclear Data Evaluation" at the Institute of Atomic Energy, Beijing, China (October 1987). It had the following abstract:

The quantum-mechanical theory of multistep compound reactions due to Feshbach, Kerman and Koonin is reviewed and applied to the analysis of reactions of neutrons with ^{59}Co, ^{93}Nb and ^{209}Bi. A detailed study is made of reactions at 14 MeV, and in addition the total cross-sections in several reaction channels are presented in the range 10-20 MeV. Conclusions are drawn concerning the energy variations of the contributions of direct, pre-equilibrium and compound nucleus reactions.

6.3.6 The systematics of (n,p) cross-sections for 14 MeV neutrons (S. Ait-Tahar)

A paper on this topic with the following abstract has been published in J. Phys. G13 (1987) L121:

A new global formula for the (n,p) cross-section around 14 MeV is obtained. This formula uses two parameters and gives the cross-section in terms of the parameter (N-Z+1)/A instead of the more generally used parameter (N-Z)/A. The predictions of this formula are compared with those of previous formulae and with the experimental data over a wide range of nuclei. This formula is found to give a better fit to the data than previous comparable formulae.

6.4 An intercomparison of nuclear model computer codes (P. E. Hodgson)

An invited paper on this topic with the following abstract was presented to the IAEA Advisory Group Meeting on "Nuclear Theory for Fast Neutron Nuclear Data Evaluation" at the Institute of Atomic Energy, Beijing, China, 12-16 October 1987:

"The present state of the programme of intercomparison of nuclear model computer codes, organised under the auspices of the Nuclear Data Bank in Paris, is reviewed. The different types of intercomparison are described, and the general principles underlying the intercomparisons are critically discussed."

7. PHYSICS DIVISION, UNIVERSITY OF SUSSEX

7.1 Octupole deformation of ^{223}Ra (S. E. Eid, Ch. Briançon*, W. D. Hamilton, C. F. Liang*, R. J. Walen* and V. Green**)

A thorough examination of the level structure of ^{223}Ra has been carried out providing evidence that leads to an extensive re-evaluation of spin assignments and hence band structure. Altogether six bands, corresponding to three coupled pairs, have been identified and the interpretation of the data strongly indicates that this N=135 nucleus possesses a stable but soft octupole deformation.

Results from α-γ, γ-γ directional correlation and γ-ray direction distribution measurements were combined and together with ICC data give unique spin-parity assignments to most levels. A continuously purified source was used to make unambiguous γ-ray identification. Level half-lives were obtained from recoil distance and Doppler methods.

The results show that the ground state is $3/2^+$ with a $3/2^-$ coupled band-head at 50.1 keV. Other band-head pairs were identified as $1/2^+$ (286.1 keV) with $1/2^-$ (350.5 keV) and $5/2^+$ (234.8 keV) with $5/2^-$ (369.3 keV). The multipole mixing ratios of many of the stronger γ-ray transitions have been determined and also the amplitudes and relative phases of the angular momentum components carried by the α-decays.

Figure 7.1 shows the level structure determined in this work.

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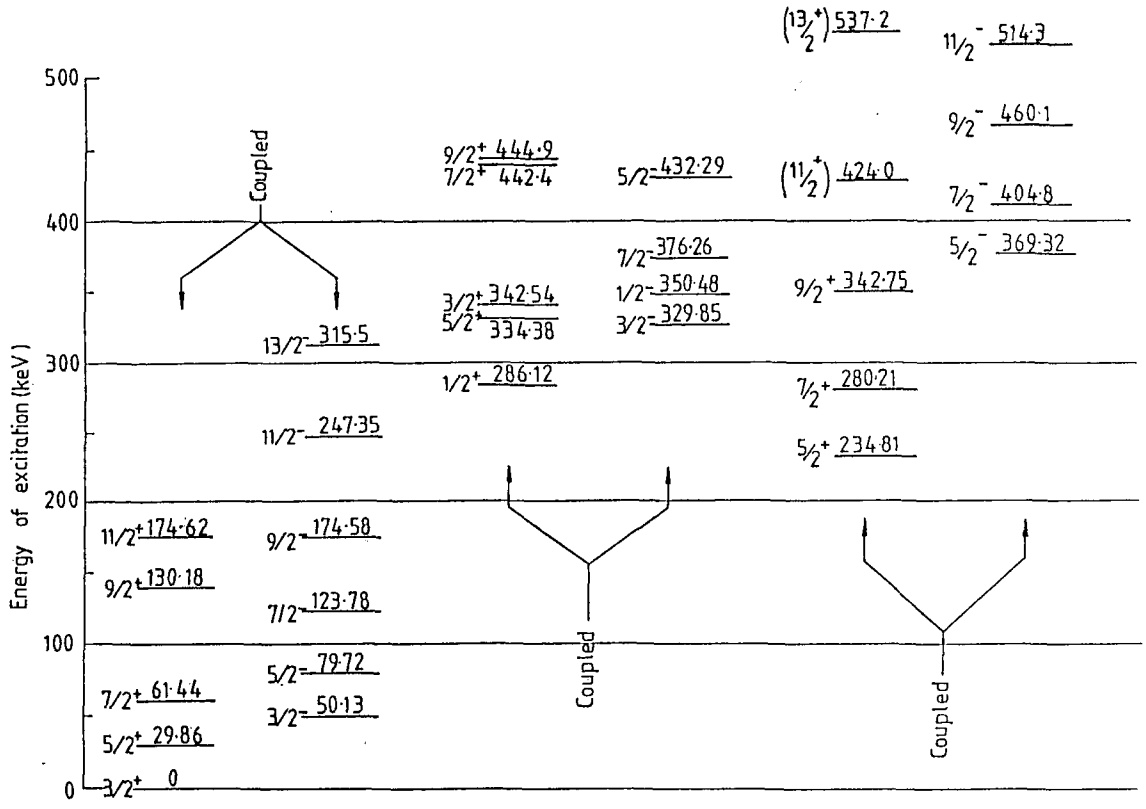

Fig. 7.1 Level structure of ^{223}Ra as determined in this work

CINDA INDEX

Element	Isotope	Quantity	Lab	Type	Energy Min	Energy Max	Page	Ref. Date	Author and comments
Ne	3	NP	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
Li	6	NT	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
Li	6	SEL	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
B	10	NAO	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
B	10	NA1	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
C	NAT	TOT	HAR	EXP	1.0-1	1.0+5	8	UKNDC DEC 87	SCHMIEDMAYER+ measurement of σ_T to $\pm\leq$½%
Mn	55	RES	HAR	EXP	3.4+2	4.1+4	8	UKNDC DEC 87	SCHMIEDMAYER+
Fe	NAT	NG	HAR	EXP	1.0+0	1.0+5	3	UKNDC DEC 87	GAYTHER+
Co	59	RES	HAR	EXP	1.3+2	3.2+4	8	UKNDC DEC 87	SCHMIEDMAYER+
Co	59	NP	NPL	EXP		1.4+7	59	UKNDC DEC 87	LEWIS + RYVES analysis in progress
Co	59	NP	NPL	EXP		1.4+7	59	UKNDC DEC 87	LEWIS + RYVES analysis in progress
Co	59	N2N	NPL	EXP		1.4+7	59	UKNDC DEC 87	LEWIS + RYVES analysis in progress
Co	59	Many	OXF	CAL			71	UKNDC DEC 87	BONETTI+ comparison of multistep compound emission with experiment
Nb	93	SIN	HAR	EXP			19	UKNDC DEC 87	GAYTHER+ renormalisation of data in AERE-R 12612
Nb	93	Many	OXF	CAL			71	UKNDC DEC 87	BONETTI+ comparison of multistep compound emission with experiment
Nb	93	Many	OXF	CAL			70	UKNDC DEC 87	WILMORE + HODGSON comparison of theory and experiment for many reactions
Ag	107	ACT	NPL	EXP		1.4+7	59	UKNDC DEC 87	LEWIS + RYVES TBP
Ag	109	ACT	NPL	EXP		1.4+7	59	UKNDC DEC 87	LEWIS + RYVES TBP
Cd	109	ACT	NPL	EXP			58	UKNDC DEC 87	SMITH + WOODS report on international comparison
Au	197	NG	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
Hf	178	SIN	HAR	EXP		1.4+7	19	UKNDC DEC 87	PATRICK+ production of 31 year isomer of Hf-178
Pb	NAT	TOT	HAR	EXP	1.0-1	1.0+5	8	UKNDC DEC 87	SCHMIEDMAYER+ measurement of σ_T to $\pm\leq$½%
Pb	207	RES	HAR	EXP			8	UKNDC DEC 87	SCHMIEDMAYER+ E_R = 41196±9 eV Γ_n = 1080±12 eV
Bi	209	Many	OXF	CAL			71	UKNDC DEC 87	BONETTI+ comparison of multistep compound emission with experiment
U	NAT	NF	BIR	EXP		FAST	62	UKNDC DEC 87	WEAVER+ measurement of delayed neutron spectra and yield

CINDA INDEX
(continued)

Element	Isotope	Quantity	Lab	Type	Energy Min	Energy Max	Page	Ref. Date	Author and comments
U	235	NF	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
U	235	ETA	HAR	EXP	3.0-3	4.0-1	23	UKNDC DEC 87	MOXON+ accurate ±½ from ~0.01 to 0.2 eV
U	235	NFY	HAR	EXP		FAST	44	UKNDC DEC 87	McMILLAN + JONES tritium yield from ZEBRA core
U	235	NFY	HAR	EXP		FAST	45	UKNDC DEC 87	KYFFIN absolute fission yields
U	238	RES	HAR	EVAL	0.0	1.04	1	UKNDC DEC 87	MOXON+ review of standard cross-sections
U	238	NF	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
U	238	NFY	HAR	EXP		FAST	45	UKNDC DEC 87	KYFFIN absolute fission yields
U	238	NFY	BIR	EXP	1.7+6	5.8+6	63	UKNDC DEC 87	GARIDEH + RANDLE
U	238	NFY	BIR	EXP			64	UKNDC DEC 87	GARIDEH+ measurement of alpha and tritium yield in ternary fission
Pu	239	NF	HAR	EVAL			1	UKNDC DEC 87	MOXON+ review of standard cross-sections
Pu	239	NFY	HAR	EXP		FAST	45	UKNDC DEC 87	KYFFIN absolute fission yields
Pu	239	ALP	HAR	EXP		FAST	46	UKNDC DEC 87	TYRRELL + THOMPSON
Pu	239	NFY	HAR	EXP		FAST	44	UKNDC DEC 87	McMILLAN + JONES tritium yield from ZEBRA core
Pu	240	NFY	HAR	EXP		FAST	45	UKNDC DEC 87	KYFFIN absolute fission yields
Pu	240	ALP	HAR	EXP		FAST	46	UKNDC DEC 87	TYRRELL + THOMPSON
Pu	241	NFY	HAR	EXP		FAST	45	UKNDC DEC 87	KYFFIN absolute fission yields
Pu	241	ALP	HAR	EXP		FAST	46	UKNDC DEC 87	TYRRELL + THOMPSON
Pu	242	ALP	HAR	EXP		FAST	46	UKNDC DEC 87	TYRRELL + THOMPSON
Am	241	ALP	HAR	EXP		FAST	46	UKNDC DEC 87	TYRRELL + THOMPSON
Am	243	ALP	HAR	EXP		FAST	46	UKNDC DEC 87	TYRRELL + THOMPSON
Many	-	ACT	HAR	EVAL		FUSION	20	UKNDC DEC 87	FORREST activation cross-section for fusion spectra
Cf	252	NFY	BIR	EXP			64	UKNDC DEC 87	GARIDEH+ measurement of alpha and tritium yield in ternary fission
Many	-	ACT	NPL	EVAL			59	UKNDC DEC 87	LEWIS + RYVES simultaneous evaluation
Many		HALF LIFE	HAR	EXP			51	UKNDC DEC 87	RAJPUT+ gamma decays and half lives for many isotopes
Many	-	HALF LIFE	NPL	EVAL			61	UKNDC DEC 87	CHRISTMAS + WOODS