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United Kingdom Atomic Energy Authority

HARWELL

UK Nuclear Data Progress Report for the Period January-December 1980

Editor: E.W. Lees
Nuclear Physics Division
AERE Harwell, Oxfordshire
June 1981

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U.K. NUCLEAR DATA PROGRESS REPORT FOR THE PERIOD

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*For a key, see the Introduction to Chapter 1 on page 20.

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PREFACE

This report is prepared at the request of the United Kingdom Nuclear Data Committee and covers the period from January to December, 1980.

Nuclear data are presented by laboratory. There are contributions this year from the Harwell and Winfrith laboratories of the UKAEA, the National Physical Laboratory, the National Radiological Protection Board, the Birmingham Radiation Centre, the University of Birmingham and the University of Edinburgh.

This report includes work from various collaborations between laboratories of Harwell, Dounreay, Winfrith, Windscale, MOD Aldermaston, Imperial College and Manchester University. Contributions on "Chemical Nuclear Data" are gathered by the Chemical Nuclear Data Committee and grouped under that heading.

Contributions to the report on nuclear data topics are welcome from all sources and we extend an invitation to researchers in other laboratories of industry, government, the universities and polytechnics to use this channel of communication.

Where the work is clearly relevant to requests in WRENDA 79/80 (INDC(SEC)-73/URSF) request numbers are given after the title of the contribution.

CHANGES IN UKND SUB-COMMITTEES

Nuclear Incineration (Chairman: M.G. Sowerby)

This has been disbanded since there are no immediate plans for using nuclear incineration as a technical option for waste disposal.

Bio-medical (Chairman: J.A. Dennis)

Current data needs have been identified and this committee is temporarily in abeyance.

Chemical (Chairman: J.G. Cunninghame)

See section 2 of this report.

Fusion (Chairman: C.A. Uttley)

The fusion sub-committee met once during the period covered by this report. The main topics discussed concerned the latest measurements of the tritium breeding reaction $^{7}Li(n,n'\alpha t)$, the Birmingham fusion programme and the addition to the fusion section of the U.K. data request list of measurements of the secondary neutron spectrum from lead for primary neutron energies up to 14 MeV.

NUCLEAR DATA FORUM LECTURES

The fourteenth Nuclear Data Forum was held on December 8th at the Birmingham Radiation Centre, University of Birmingham. The themes this year were nuclear data requirements for neutron energies up to 40 MeV in the diverse fields of fusion and medical applications. The meeting was well supported, there being 70 registrations and 15 contributed papers. The invited talks were given by Dr. T.D. Beynon (fusion requirements) and by Professor J.H. Fremlin (medical requirements); both talks are reproduced below. Ten of the contributed talks gave direct support to the main speakers, while the others covered aspects of (n,p) measurements, delayed neutron energy spectra, the multiplicities of neutrons emitted in fusion, and the neutron output from a mixed oxide fuel pin.

FUSION SYSTEMS DESIGN AND DATA REQUIREMENTS

T.D. Beynon

Department of Physics, University of Birmingham

Lecture given at the Nuclear Data Forum, Birmingham

1. Introduction

The nuclear design and analysis of fusion systems has now become an important factor in an overall fusion development programme. Present studies of reactor systems are based on the thermonuclear reaction of a deuterium/tritium plasma operating at a temperature of about 10 keV. This reaction produces 14 MeV neutrons, with a contribution of 2.5 MeV neutrons from the D-D reaction. The major nuclear data requirements for a D-T fusion reactor, whether the system be magnetically or inertially confined, are defined by the following system components:

(1) Breeding

Neutron transmutation of lithium in the blanket is the only known practical method of breeding tritium for the fuel. Neutron multiplication via (n,2n) reactions may be necessary to achieve good neutron economy in the blanket. Additionally, the 14 MeV neutrons may also serve to breed ^{239}Pu or ^{233}U in hybrid and symbiotic reactor systems.

(2) Heat production

The primary energy source in a fusion system is the 14 MeV kinetic energy of the neutron, together with a few MeV available from exothermal reactions. Thus elastic, inelastic and γ-production cross sections are needed. For the hybrid fission-fusion system, the capture, scattering and fission cross sections for the fertile and fissile isotopes are an added requirement.

(3) Shielding

As with fission reactors, there is a well-defined personnel shielding requirement, with an additional requirement of shielding of the cryogenic magnet system for magnetically-confined reactors.

(4) Materials damage and activation

With 14 MeV neutrons incident on the first wall of a fusion system, materials damage and activation, particularly shut-down activity, become major considerations, with a resultant requirement for appropriate cross section data.

2. Fusion R and D programmes

Present fusion R and D programmes encompass four major activities, each of which

has its own data requirements.

(i) Near-term experimental hardware for plasma and scaling experiments

These devices include the Tokamak Fusion Test Reactor (TFTR) at Princeton, the Joint European Torus (JET) at Culham, and the Mirror Fusion Test Facility (MFTF) at Livermore. Major neutronics data requirements for these devices are largely for biological shielding and for the shielding and detection associated with the neutron diagnostics.

(ii) Design of next-generation fusion experiments

These will differ significantly from the hardware in (i), in that they will have significant fusion power, and shielding of sensitive elements will become a key issue. The important systems in this category include the Fusion Materials Irradiation Test Facility (FMIT) at Richland, and the Engineering Test Facility (EFT), a Tokamak pulsed-burn non-breeder ignited by neutral beams and run at a wall loading of about 2.3 MW/m^2. The most ambitious design study in this category is the International Tokamak Reactor, INTOR, which is aimed at demonstrating both fusion and reactor technology for a DEMO system, including facilities for blanket tritium production and extraction, electricity production, materials activation and plasma heating.

(iii) Conceptual reactor designs

These are conceptual design studies of complete commercial fusion power systems, where the entire range of nuclear data requirements becomes important.

(iv) Integral experiments

These are simple-geometry experiments (spheres, cylinders, slabs) to investigate data library uncertainties associated with tritium breeding in lithium and lithium compounds, and with neutron multipliers, like ^{9}Be(n,2n), Pb(n,2n) etc.

3. Data requirements

As systems studies have become more refined it has become possible to list the plausible breeder-coolant combinations for a commercial fusion reactor. These are listed in Table 1 where the key issues associated with each choice are also shown. Attention is drawn to some of the latest entries to this list, the Li/Pb eutectics and oxides, which may need the addition of neutron multipliers for viable tritium breeding ratios.

To identify the cross section needs in any detail it is necessary to identify the materials in the various components of the reactor system.

Table 1

Plausible Breeder-Coolant Combination

Material	Combination Breeder	Coolant	Key Issues
A. Liquid Breeders			
1. Li	Li	Li	MHD
	Li	He	Chemical reactivity (Air/Water)
2. Li_{17} Pb_{83}	Li_{17} Pb_{83}	L_{17} Pb_{83}	Peak operating temperature
	Li_{17} Pb_{83}	He, H_2O	Corrosion. Mass transfer
B. Solid Alloys and Intermetallics			
1. Solid Alloys			
Li_7 Pb_2, Li_3 Bi, Li Al	Li_7 Pb_2	He	Temperature range, tritium recovery, blanket engineering.
2. Li_{62} Pb_{38} (Eutectic) mp 737K	Li_{62} Pb_{38}	He	Chemical reactivity with water. Radiation effects.
C. Oxides			
1. Li_2O	Li_2O	He, H_2O	Chemical reactivity with water.
	Li_2O	Li_2O	Tritium recovery
2. Ternary Oxides			
α-Li AlO_2			Radiation effects
γ-Li AlO_2			Blanket engineering
Li_2 SiO_3	-	He, H_2O	Phase stability
Li_4 SiO_4			Corrosion
Li_2 TiO_3			Neutron multipliers

(a) Coolant

H, He, ^{6}Li, ^{7}Li, Be, N, O, F, Na, K, Pb.

(b) Shielding

H, ^{10}B, ^{11}B, C, O, Si, Ca, Cr, Fe, Ni, W, Pb. Most of the data requirements here are met by the current fission reactor disometry files.

(c) Reflector, moderator

H, D, T, Be, ^{10}B, ^{11}B, C, O, Fe. The D and T data are required to evaluate neutron spectrum moderation in ICF pellets.

(d) Magnetic conducting materials

Be, Al, Ti, V, Cu, Ga, Nb, Sn.

(e) Structural materials

C, Al, Si, Ti, V, Cr, Mn, Fe, Ni, Zr, Nb, Mo.

(f) Breeder materials

^{6}Li, ^{7}Li, ^{232}Th, ^{238}U.

(g) Neutron multipliers

Be, Pb, ^{232}Th, ^{238}U.

(h) First Wall Protectors

Be, C, O, Al, Si, Mo, W.

It is obvious that many of the needs for energies $E_n \lesssim 15$ MeV are currently being met by the various fission reactor programmes. Nevertheless, a number of important nuclides are not included in this programme, notable amongst these being Pb, Li, V, Ga and Sn. To identify the reactions requiring detailed evaluation in this energy range we must resort to sensitivity and uncertainty analysis. In broad terms one can divide the nuclides of interest into two regions with mass number A > 120 and A < 120.

(a) A > 120

The elastic and the inelastic cross sections can be calculated with reasonable confidence for $E_n \lesssim 12 - 14$ MeV. For $E_n \gtrsim 14$ MeV, (for the D-Li driven FMIT device) better calculations and more experiments are required. For the reactions (n,2n) (n,3n), (n,p) (n,α), (n,n',α) etc., there is a weak data base particularly for energy-angle correlations of secondaries. The implementation of multistep Hauser-Feshbach codes and more measurements are required.

(b) A < 120

The data base is often poor here, when optical and statistical codes are suspect and there is a paucity of good or recent measurements for many nuclides. Outstanding in importance in this region is the tritium production cross section for both ^{6}Li and ^{7}Li, where both reaction cross sections and energy-angular correlations (for ^{7}Li) are important. The target accuracy for all ^{6}Li and ^{7}Li reactions is 2-5%, which has not yet been achieved.

More specific data requirements can be identified with the following areas.

Fissile breeding

For breeding in U and Th, the $^{238}U(n,\gamma)$ and $^{232}Th(n,\gamma)$ cross sections are poorly known in the 5-10 MeV energy range, although target accuracies of about 5% have been identified here.

Dosimetry and reference neutron spectra

These data requirements are essentially the same as for the fission reactor programme.

Displacement damage

Primary knock-on atom (PKA) spectra require (n,n) and (n,n') data, and there is also a need for (n,2n) and charged particle emission cross sections. Existing data files contain insufficient data for constructing the PKA spectra but the required accuracies are not yet fully assessed.

Gas production

A 15-20% accuracy has been deemed necessary for the reliable prediction of gas production rates. Whilst the (n,p) and (n,α) cross sections generally meet this requirement, the data for (n,n'α), (n,n'p), etc. are poor, and more integral and differential measurements are necessary.

Nuclear heating

The generation of KERMA factors for neutron and photon heating in the blanket, reflector and shield assemblies require a very wide range of isotopic reaction cross sections, partial cross sections, energy and angular distributions and Q-values, together with γ-production cross sections, and γ-energy distributions as a function of E_n and relevant charged particle-emission cross sections. Minimum accuracy requirements for these data are estimated at $\pm$ 10%, a particularly stringent requirement. It should be noted that there is no equivalent data requirement for heating KERMA factors in the fission programme and this requirement must therefore be met separately. This is an area where well designed integral experiments would be valuable.

Activation

Activation estimates, particularly in the first wall and other demountable components, are at present estimated from multistep Hauser-Feshbach theory, with occasional spot measurements at 14 MeV. This data requirement represents a major problem, but nevertheless accuracies of about $\pm$ 25% are required. There is only a partial overlap with fission reactor data requirements here, the significant difference in the two types of reactor being the considerably harder neutron spectrum associated with the fusion reactor.

4. Conclusion

In conclusion, there is a considerable amount of work ahead, both experimental and

theoretical, to meet the nuclear data demands of a commercial fusion power reactor. Certainly a significant fraction of these needs can be achieved in parallel with the various ongoing fission data programmes, but an equally significant fraction cannot and this must be included on the budget of a fusion reactor research programme.

NUCLEAR DATA FOR MEDICAL APPLICATIONS

J.H. Fremlin

Department of Physics, University of Birmingham

Lecture given at the Nuclear Data Forum, Birmingham

I must begin by admitting that I cannot think of any new nuclear data for which there is an important medical need. There may be a few radioisotopes of convenient half-life which emit gamma rays with an energy apparently identical with that of the absorption edge for the K or L X-rays of some element that may become of medical interest. It would then be useful to have an extra decimal point. We could then tell whether the radioisotopes could or could not be used as a source for X-ray-fluorescence analysis in vitro or in living patients. We recently found such a case; we are developing a fluorescence method of measuring skeletal lead in vivo and could not tell from the literature whether or not ^{109}Cd could be used to excite the K X-rays of lead.

Even this cannot be said to be of much importance; if one is equipped at all for such measurements it does not take more than an hour or so to irradiate a block of the element of interest with a small borrowed source and find out. We were lucky; ^{109}Cd does excite the K X-rays of lead.

If we redefine nuclear data to include any of the topics dealt with in a good book on nuclear physics, however, (for example that by Professor Burcham of this Department) there are several fields in which more information is badly needed. This is true both for applied medicine and for pure research in both medical and biological fields.

Applied medicine can be divided into prevention, diagnosis and cure. Much the most important is prevention - even in the fields of cancer and mutation with which I shall be mostly concerned.

In Fig. 1 is shown the variation of age-corrected cancer rates in the white population of USA with the average background radiation levels in each of the States of the Union.

Each of the points represents some tens of thousands of deaths so that purely statistical errors are negligible. There is quite clearly a negative correlation. I do not want to claim that radiation protects you from cancer, though this cannot quite be ruled out. It is just possible that our immune systems, which have far less challenge

under modern American conditions than they did during our earlier evolution, are given a bit of extra exercise in youth by a little extra radiation which improves their ability to cope in after life.

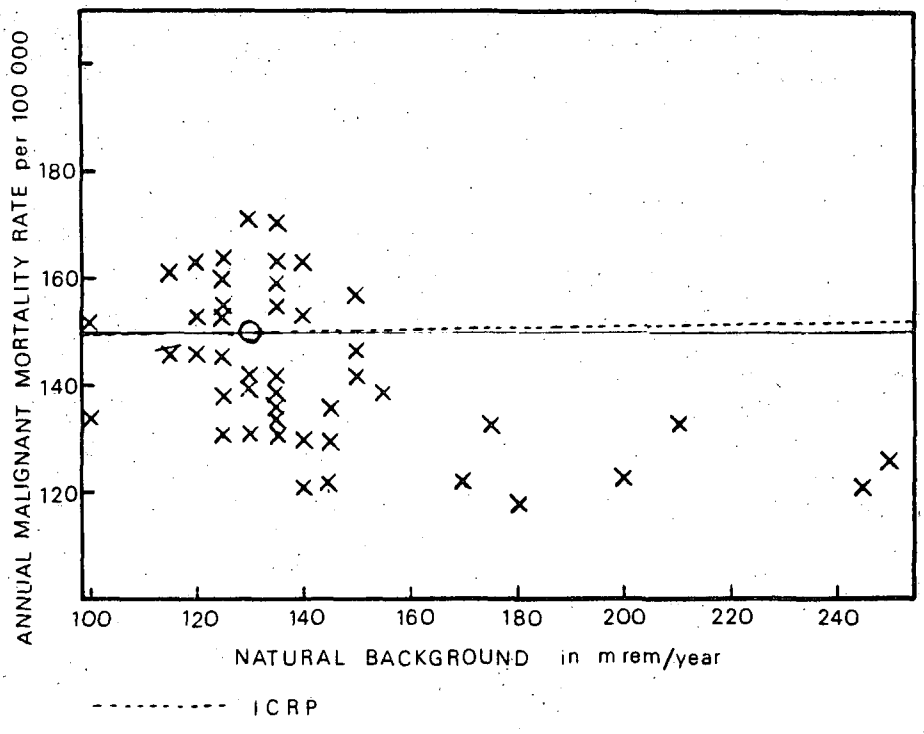

Fig. 1

It is far more probable, however, that the effects of background radiation in USA are negligible - ICRP estimates would suggest at most an additional one per thousand over the radiation range and in the seventeen years covered by the graph - and that the differences are due to other environmental factors. The negative correlation shown in the figure then represents merely the fact that the industrial Eastern States are more heavily polluted with carcinogens (and of course mutagens) than are the Western mountain States with more uranium and thorium in their underlying rocks.

In order to study effectively the man-made chemical pollutants which must almost certainly be responsible for the industrial excess of cancers, we shall want to use radioactive tracers; many of them in special chemical forms and some of them of unusual elements. For some of these, special techniques may need to be developed for producing suitable radioisotopes on an adequate scale. Meanwhile there is a lot of detailed information which is needed for cancer therapy using neutrons. The high LET (linear energy transfer) knock-on protons produced by fast neutrons, and the α particles from

reactions with carbon and oxygen, are more effective in destroying the oxygen-deficient interior cells in malignant tumours than are X-rays or γ-rays, but fast neutron beams will be much more seriously scattered by the overlying tissues. There is never any difficulty in killing a tumour; the problem is not to do lethal damage to the patient in doing so. Much very necessary work on fast-neutron interactions will be needed before we can reliably predict the conditions in which the increased tumour-killing capacity of neutrons can be used successfully without a proportional increase in destruction of healthy tissue. Other papers in this forum are dealing with aspects of this, so I shall say no more here but will go on to my final theme, which is concerned with improving our understanding of the first stage in the initiation of cancers by radiation.

The primary event is almost certainly damage to the DNA in the nucleus of a single cell. The damage must be of a highly improbable kind. The ICRP estimate suggests that on the average one cancer will result from ten thousand man-rems. One rem represents two fast electrons with low LET passing through the average cell nucleus, each producing 4-5 ionisations. Each person contains about 10^{13} cells so that in 10,000 man-rems 2×10^{17} electrons have passed through nuclei, leaving 10^{18} ionisations. These will initiate one cancer. The DNA in a human being consists of only about 10^{13} atoms so that no single ionisation of any atom at any specific point in the DNA can be effective. For many other reasons than this simple numerical one it is evident that at least two rather specific types of damage must be needed to initiate a single cancer.

Alpha particles have high LET and do a great deal more damage. Indeed, in all but a very small percentage of cases passage of an alpha particle through the nucleus will make cell division, and hence cancer development, impossible. In spite of this, alpha particles are quite effective in producing cancers and it is of great interest to understand better the form of the damage that they do.

An alpha particle of a few MeV will produce an average of one ion pair for every atom it traverses; the electron of the pair will be ejected at high velocity, leaving in 10^{-13} seconds or so a positive charge along the core of its track with an initial electric field of the order of 10^{10} volts per metre at a nanometre radius. This leads to an ion 'spike' or explosion which in crystals or solid polymers can be shown to disrupt the atomic structure over a diameter of some 10 or 20 atom diameters. The effect does not occur in metals, where the number of free electrons is so great as to be able to neutralise the positive core before the ions have time to move appreciably. It seems likely that this type of damage is more important in cell nuclei than the primary

ionisation, but we have no experimental data on what happens in an ionically conducting and highly polar liquid such as water. Data on this are badly needed and I would like to conclude by asking for suggestions as to how they can best be obtained.

CINDA LISTINGS

Element S	Element A	Quantity	Type	Energy Min.	Energy Max.	Documentation Ref.	Vol	Page	Date	Lab	Comments
B	10	Absorption Xsec	Expt-Prog	Fast		UKNDC	P100	65	3/81	HAR	Crouch + check cross section data for CFR spectra TBC
Fe	56	Res. Parm.	"	1.1 3	8.3 4	"	"	22	"	"	Moxon + Analysis of geel capture data TBL.
Nb	93	Isomer prod.	"	Fast		"	"	69	"	WIN	Taylor dosimetry intercomparison experiment.
Nb	93	n,n'	"	1.4 7		"	"	74	"	NPL	RYVES + (n,n') xsec = (36.5 ± 3.0) mb
Nb	93	n 2n	"	1.4 7		"	"	74	"	NPL	RYVES + (n,2n) xsec = (453 ± 11) mb
Nb	93	n,alpha	"	1.4 7		"	"	74	"	NPL	RYVES + (n,α) xsec = (5.56 ± 0.18) mb
Ta	181	n 2n	"	1.4 7		"	"	74	"	NPL	RYVES + (n,2n) xsec = (1307 ± 40) mb
Au	197	n,gamma	"	1.4 7		"	"	74	"	NPL	RYVES + (n,γ) xsec = (1.09 ± 0.10) mb
Au	197	n 2n	"	1.4 7		"	"	74	"	NPL	RYVES + (n,2n) xsec = (2170 ± 67) mb
Th	230	Fission	"	7.2 5		"	"	32	"	HAR	James + Measurement of fission fragment angular distribution
Th	230	Half life	"			"	"	66	"	HAR	Glover + planned
U	235	Absorption x sec	"	Fast		"	"	65	"	HAR	Crouch + check cross section data for CFR spectra TBC
U	235	Fission prod data	"	Fast		"	"	70	"	WIN	Taylor Beta decay power
U	238	Total xsec	"	1.0 3	1.0 5	"	"	28	"	HAR	BEE Analysis of transmission data on U and UO_2
U	238	Absorption xsec	"	Fast		"	"	65	"	HAR	Crouch + check cross section data for CFR spectra TBC
U	238	Fission yield	"	Fast		"	"	59	"	"	Cunninghame + effects of changes in reactor spectrum TBC
U	238	n 2n	"	1.4 7		"	"	74	"	NPL	RYVES (n,2n) xsec = (778 + 23) mb provisional

CINDA LISTINGS

Element S A	Quantity	Type	Energy Min.	Energy Max.	Documentation Ref.	Vol	Page	Date	Lab	Comments
Np 237	Half life	Expt-Prog			UKNDC	P100	65	3/81	HAR	Brown + planned 1981
Pu 239	Fission yield	"	Fast		"	"	59	"	HAR	Cunninghame Q effects of changes in reactor spectrum TBC
Pu 239	Fission prod beta	"	Fast		"	"	70	"	WIN	Taylor Beta decay power
Pu 239	Neutron spectra	"	5.0 5	2.0 6	"	"	81	"	BIR	Owen + spectrum of delay neutrons
Pu 239	Half life	"			"	"	65	"	HAR	Brown + Value given 24,088 ± 51 years
Pu 240	Absorption xsec	"	Fast		"	"	65	"	HAR	Crouch + check cross section data for CFR spectrum TBC
Pu 241	" "	"	Fast		"	"	65	"		" " "
Pu 242	" "	"	Fast		"	"	65	"		" " "
Am 241	n,gamma	"	Fast		"	"	63	"	HAR	Glover + production of ^{242}Cm
Am 241	Absorption xsec	"	Fast		"	"	65	"	HAR	Crouch + check cross section data for CFR spectrum TBC
Am 243	n,gamma	"	Fast		"	"	63	"	HAR	Glover + production of ^{242}Cm
Am 243	Absorption xsec	"	Fast		"	"	65	"	HAR	Crouch + check cross section data for CFR spectra TBC
Am 243	Diff xsec	Eval Prog	1.0 5	1.5 7	"	"	34	"	"	Cunninghame + effects
Cm 242	Half life	Expt-Prog			"	"	65	"	HAR	Wiltshire + Alpha half life TBC
Cm 242	Half life	"			"	"	65	"	HAR	Wiltshire fission half life planned '81
Many	Elastic diff.	"	2.9 6		"	"	84	"	EDG	Annand + polarisation due to differential elastic cross sect.
Many	Evaluation	Eval Prog	1.4 7		"	"	75	"	NPL	Ryves evaluation of important standard x sec at ∿14 MeV

1. NUCLEAR PHYSICS DIVISION, AERE, HARWELL

(Division head: Dr. J.E. Lynn)

Introduction

Nuclear data measurements in Nuclear Physics Division are diverse and are performed on a variety of sources. Individual research items are labelled with a single letter indicating on which accelerator the experiments were performed. These labels are as follows:

Cockcroft-Walton Generator	A
3 MV pulsed Van de Graaff Generator IBIS	B
6 MV Van de Graaff Generator	C
14 MeV Tandem Generator	D
Electron Linac	E
Variable Energy Cyclotron	G
Synchrocyclotron (now defunct)	H

In the contents pages there is a cross reference to the accelerator where a measurement was made (when this applies).

The material for this contribution is taken from the chapter on Nuclear Data and Technology for Nuclear Power in the 1980 Nuclear Physics Division Progress Report AERE PR/NP28. Additionally, one item from Environmental and Medical Sciences Division is included.

1. NUCLEAR DATA AND TECHNOLOGY FOR NUCLEAR POWER

1.1E The new machine for the electron linac laboratory (J.E. Lynn, M.S. Coates, P.P. Thomas*, B.P. Clear, J. Down, P.W. Swinden and L. Wilkinson)

Completion of the commissioning test programme (PR/NP 27, p.9) by the linac manufacturers has been seriously delayed, chiefly as the result of an unexpected technical difficulty associated with the harmonic output of the klystrons. The basic problem is one of impedance mismatch. Although the main power output from a klystron at the fundamental frequency of 1300 MHz is matched to the impedance of the complicated feed waveguide and accelerator section system, the much lower power content in the harmonic frequencies is not. This mismatch results in the build-up of standing waves in the waveguide sections, following reflections and feedback to a klystron, which in unfavourable circumstances causes an unacceptable R.F. breakdown. The degree of mismatch is not constant since the effective impedance changes as one alters the settings of phase shifter elements in the waveguides. (A phase shifter is a device for adjusting the relative phase of the R.F. wave in the 2 accelerator sections fed by a single klystron). The practical consequence is that only a limited range of phase shifter settings can be used for machine operation, although it was found that the pattern of acceptable phase shifter positions could be altered by introducing short spacer sections into the waveguides. Fortunately it proved possible to continue the commissioning tests using the available range of phase shifter positions optimised by spacers. This makeshift solution is not satisfactory for operation on a permanent basis and at present the linac manufacturers and the klystron suppliers are looking for ways of making the harmonic effects insignificant. The commissioning tests have now been completed apart from a small number of items. The short pulse performance at the highest repetition frequencies is not achievable and the manufacturers will modify the machine during 1981 so that the specification can be met. However Harwell will provisionally accept the linac for use before this work is carried out and experiments are now expected to resume before summer 1981.

1.2E Modifications to equipment for measuring neutron capture cross sections (M.C. Moxon)

Improvements and extensions have been made to the experimental assemblies which

---

*Deceased

will be used in the measurement of neutron capture cross sections on the new linac installation. The existing 32 m flight path of the Neutron Booster Cell has been provided with a larger detector station which will also serve a 42 m flight path of the Fast Neutron Cell. Changes have been made to reduce the sensitivity of the detector system on the 32 m path to the effects of scattered neutrons. The linear dimensions of the detector shield have been doubled, and the cylindrical aluminium sample holder and other surrounds have been replaced with components made from carbon fibre*. This material has the advantages that its overall capture cross-section is about 2 orders of magnitude lower than that of aluminium and that its scattering cross-section does not have the resonance structure which is present in aluminium over the important neutron energy region up to 1 MeV. As another improvement, the detector photomultipliers have been replaced by quartz-faced tubes. The original tube faces were made from a boro-silicate glass and neutron capture in the contained boron was significant. All of these modifications to the detector and its surroundings will reduce the efficiency of the detector to events induced by scattered neutrons by at least a factor of 10. This value will now be a factor 10^5 lower than the efficiency of the detector to the desired capture events.

1.3E Analysis of neutron capture data (M.C. Moxon)
(Relevant to request number 521)

Experimental samples of some elements and separated isotopes for neutron capture cross section measurements are only available as compounds. The use of such samples adds to the complexity of the data analysis. The analysis program REFIT, which is used to determine resonance parameters from neutron transmission and capture data, originally used an effective mass to compute the neutron energy after a scattering event in the capture samples. The effective mass M was given by

$$M = \Sigma_E \Sigma_I M_{IE} \sigma_{SIE} / \Sigma_E \Sigma_I \sigma_{SIE}$$

where M_{IE} is the nuclear mass of isotope I in element E and $_{SIE}$ is its scattering cross section. This assumption reduces the computing time required for the calculation and is adequate for most elemental samples. However, for some important compounds, for example oxides, only poor fits to the data could be determined, and erroneous resonance parameters were deduced. To overcome this problem the program has been modified so

*Manufactured by Mr. T. Thorpe of Materials Development Division

that different nuclear masses present in a sample are treated separately. Neutron resonance parameters determined with the modified program from capture data taken with thick oxide samples of depleted uranium oxide on the 45 MeV linac are in very good agreement with the latest results from Geel[1] Oak Ridge[2]. In addition REFIT has been used to determine the neutron energy dependence of the ^{238}U capture cross section below 5 eV from the observed depleted uranium oxide data. The program calculated the corrections for self screening, multiple scattering, the presence of small amounts of ^{235}U and ^{234}U, as well as the effects of the presence of the oxygen. Although the observed capture cross section of 2.74 $\pm$ 0.33 b at 0.0253 eV agrees with the presently accepted value of 2.70 $\pm$ 0.02 b the error on our experimental value is large, due chiefly to a high background count rate, and a remeasurement under better experimental conditions is planned on the new linac. In the energy region 1 to 5 eV the observed cross section is $\sim$40% higher than that calculated from the known resonance parameters. This apparent discrepancy can be resolved by increasing the time dependent background by only $\sim$1.5 standard deviations. Such an increase in the time dependent component of the background would reduce the thermal cross-section value by 0.07 b.

The modified version of REFIT has been used also to determine resonance parameters for ^{56}Fe from neutron capture measurements carried out at Geel by F. Corvi, A. Brusegan and G. Rohr on an oxide sample of separated ^{56}Fe canned in aluminium. Preliminary analysis was carried out up to a neutron energy of 85 keV. The parameters listed in Table 1.1 are in reasonable agreement with the Harwell data. In the analysis it proved necessary to vary both resonance parameters and background values to obtain an acceptable fit to the data. The adjustments to the background were typically within 10% of the measured values.

The moderation mean free path could be determined from fits to some of the resonances, giving an average value of (5.383 $\pm$ 0.025) x 10^{-3} m which is in good agreement with the calculated value of 5.33 x 10^{-3} m. The effective temperature used to allow for Doppler broadening effects was determined from the 1.15 keV resonance to be (0.02887 $\pm$ 0.00034) eV. This value was used for all the calculations although it is higher than the value derived from the Debye temperature for elemental iron by $\sim$2.5%.

Fig. 1.1 shows the fit in the energy region around the resonance at 1.15 keV. This illustrates the effects on the multiple scattering of the two different masses present in the sample. The increase in the yield at $\sim$1500 eV is due to neutrons initially scattered from oxygen nuclei and the further increase at $\sim$1230 eV is due to neutrons

Table 1.1

Preliminary resonance parameters determined from a least squares fit to capture cross section measurements carried out at Geel on an oxide sample of separated ^{56}Fe. The parameters in square brackets have been assumed to be correct. The errors given are from the fit only

Assumed values J	L	E_R (eV)	Γ_n (eV)	Γ_γ (eV)	Alteration to background (x 10^{-5})	χ^2_{pdf}	$g\frac{\Gamma_n \Gamma_\gamma}{\Gamma_n+\Gamma_\gamma}$
1/2	1	1148.812±0.010	(56.64±0.13)x10^{-3}*	0.5678±0.0070	-5.22±0.95	1.78	0.0515
3/2	1	2348.97±0.27	(0.202±0.014)x10^{-3}	[0.55]	-8.88±7.14	1.46	0.0004
1/2	1	17742.61±0.40	(15.40±0.31)x10^{-3}	[0.55]	-5.8 ±27.5	1.81	0.015
3/2	1	20163.7±1.60	(4.0±0.25)x10^{-3}	[0.55]	-6.1 ±2.1	1.18	0.008
1/2	1	22790.61±0.086	0.2062±0.0011	[0.55]	-7.2 ±1.3	1.88	0.150
5/2	1	27252.9±6.0	(1.64±0.45)x10^{-3}	[0.55]	-7.49±0.48	1.96	0.0048
1/2	0	27719.3±11.9	1361±31	0.9986±0.015			0.999
3/2	1	34236.5±0.23	0.485±0.013	[0.58]	-5.88±1.42	1.07	0.528
5/2	2	36633.97±0.45	0.0913±0.0019	[0.4169]	-3.90±2.03	0.93	0.225
3/2	1	38321.41±0.14	0.226±0.007	[0.55]	-2.76±1.75	0.84	0.320
1/2	1	45942.5±0.40	[8.0639]	0.4238±0.0036	-2.31±1.66	1.35	0.403
3/2	1	52004.3±2.21	[15.649]	0.3214±0.0097	-1.07±1.60	0.85	0.630
1/2	1	53444.6±1.01	[1.0]	0.419±0.022	-1.91±1.63	1.16	0.295
5/2	2	53570.3±2.51	0.0114±0.0017	[0.55]			0.033
3/2	1	59098.4±1.3	[4.4735]	0.493±0.021	-2.90±1.09	2.30	0.888
3/2	1	63317.8±1.2	[1.025]	0.319±0.012	-3.65±0.77	1.97	0.486
1/2	1	72826.8±0.56	[3.0]	0.674 ±0.011	-2.30±0.22	0.96	0.551
1/2	0	73864.9±12.9	[645.2]	0.665±0.013			0.664
1/2	1	76905.9±5.9	[13.0]	0.272±0.015	-0.22±1.26	1.00	0.266
5/2	2	80387.3±6.4	(8.33±2.50)x10	[0.55]	-1.5 ±1.3	1.2	0.025
5/2	2	80660.0±3.2	[7.0]	0.588±0.051			1.628
1/2	0	83442.3±24.5	[1105.3]	0.554±0.042	-1.81±0.60	1.35	0.554

* t_{eff} = (28.87±0.34) x 10^{-3} eV

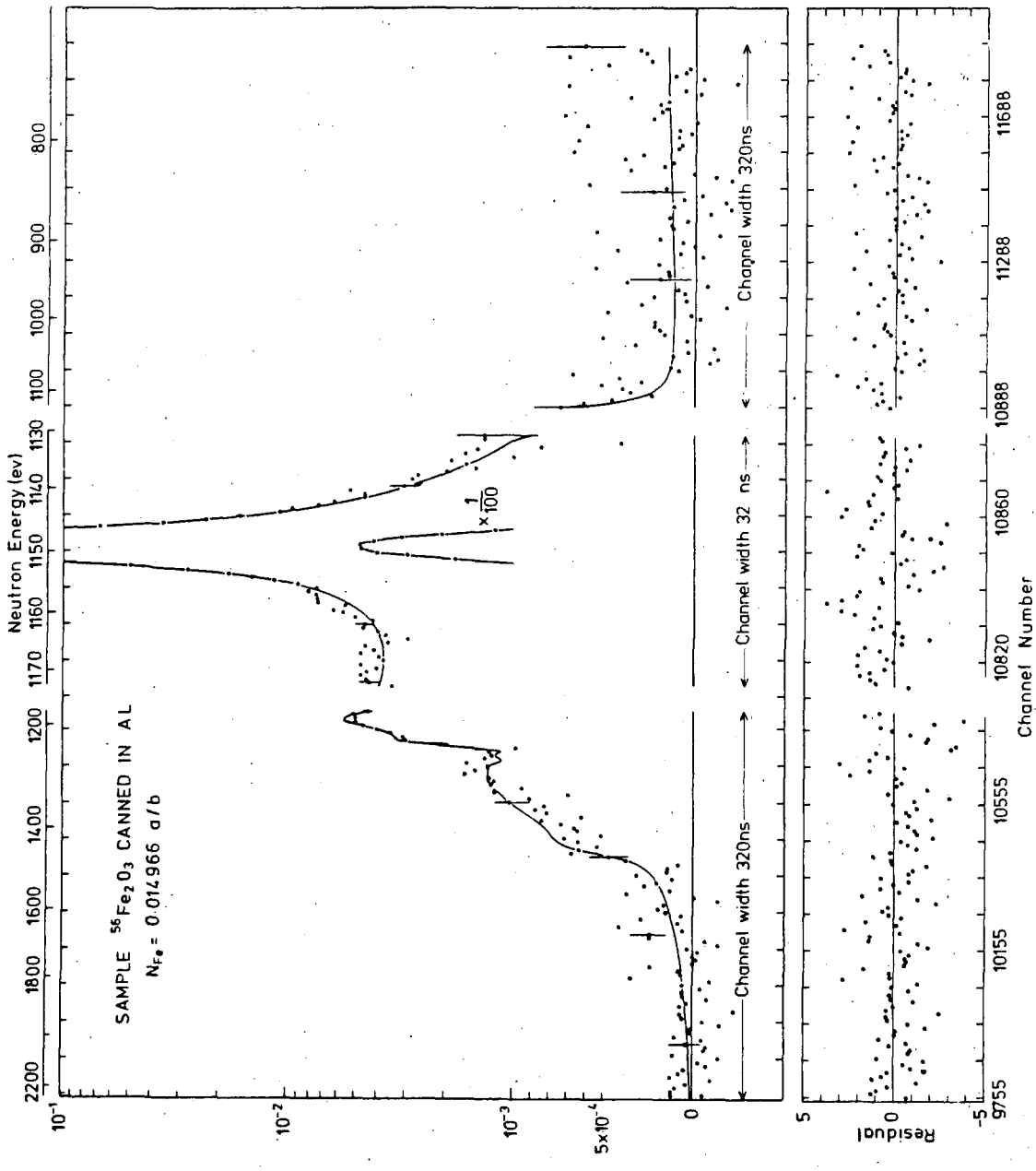

Fig.1.1 Least squares fit to the neutron capture yield in the energy region of the 1.15 keV resonance of ^{56}Fe. The derived parameters are:

E_R 1148.812±0.010 eV

Γ_n (56.64±0.13)x10^{-3} eV

Γ_γ (0.5678±0.0070) eV

Background adjustment -(5.22±0.95)x10^{-5}

Effective temperature (28.87±0.34)x10^{-3} eV

where the errors quoted are obtained only from the fit to the data.

initially scattered from iron nuclei. Such scattered neutrons have lost energy and are subsequently captured by iron nuclei in the energy region of the 1.15 keV resonance. The time between the neutron arriving at the sample and its capture after scattering is small and in the program is assumed to be zero. This assumption together with the assumption of isotropic scattering may account for the difference between the calculated and measured values in the energy region between 1150 and 1500 eV.

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(2) D.K. Olsen, G. De Saussure, R.B. Perez, E.G. Silver, E.C. Difilippo, R.W. Ingle and H. Weaver, Nuc. Sci. Eng. 62 (1977) 479.

1.4E Total energy capture detector (R.B. Thom (Imperial College), D.B. Gayther and T.M. Horscroft)

The capture detector based on a 0.4 l cell of C_6D_6 liquid scintilator (PR/NP27, p.10) has been developed further during the past year.

Gamma detection efficiency

A weighting function similar to the one shown in PR/NP27, p.10, Fig. 1.1 was tested by observing the pulse amplitude spectrum from gamma-rays emitted following thermal neutron capture in samples exposed to a beam extracted from the reactor DIDO.

The observed counting rate summed over all amplitude channels can be expressed in the following way:-

$$\sum_i C_i = \phi\, Y\, \varepsilon$$

where ϕ is the incident neutron flux (n's/cm^2/s)

Y, the expected primary capture yield from the sample = $(1-e^{-n\sigma_T})\frac{\sigma_\gamma}{\sigma_T}$

σ_T is the total cross section

n is the sample thickness (atoms/barn)

σ_γ is the capture cross section

ε is the detector efficiency

For the purpose of measuring capture cross sections it is convenient to apply a weighting function which forces the response of the detector to be proportional to the neutron separation energy of the residual nucleus

$$\text{i.e. } \sum_i W_i C_i = \phi\, Y\, (k\, E_b)$$

where E_b is the binding energy.

If the weighting function has been calculated correctly, the quantity

$$k\phi = (\sum_i W_i C_i)/(Y\ E_b)$$

should be a constant for each sample. Table 1.2 shows this quantity for several samples covering a wide range of binding energies. Samples were chosen which covered a wide range of binding energies, which have substantial capture cross sections (to minimise background effects) and which are mono-isotopic or have one isotope which dominates the cross section at thermal energies. Two thicknesses of gold were included as a consistency check on the correction due to self absorption of gamma-rays in the sample. Although the low and high values of $k\phi$ for ^{10}B and ^{113}Cd respectively are at the extremes of the binding energy range these values are thought to arise from experimental effects. The error in the ^{10}B values stems mainly from the uncertainty in estimating the significant fraction (10%) of the weighted amplitude spectrum below the detector bias. The error in the ^{113}Cd result is mainly a consequence of the large count loss correction (67%) which was necessary due to the high count rate from that sample.

Table 1.2

The product $k\phi$ as a function of sample binding energy (see text for further details)

Sample	Binding Energy (MeV)	Capture cross section at 60 MeV	$k\phi$
^{10}B	*0.481	+2477	2.95±0.17
Ta	6.06	13.6	3.12±0.08
Au (thin)	6.50	64	3.12±0.06
Au (thick)			3.18±0.10
Rh	7.00	97	3.21±0.08
Co	7.49	24	3.16±0.04
^{113}Cd	9.04	12852	3.39±0.24

*gamma-ray energy following alpha emission

+$(n,\alpha\gamma)$ cross section

Neutron sensitivity

To minimise unwanted background signals resulting from neutron capture in detector materials close to the capture sample several improvements have been made to the original design.

Firstly, the aluminium scintillator container has been replaced by a thin-walled beryllium equivalent, beryllium being chosen for its particularly low neutron capture cross section. Secondly, the boro-silicate glass window of the cell has been replaced by fused silica, ^{10}B being an important capturing component of the original glass. Thirdly, a quartz window photo-tube was preferred to the boro-silicate equivalent for the same reason.

Two detectors of this type have been built and tested and are ready for use in capture cross section measurements.

1.5E Experimental studies of Doppler broadening in uranium dioxide (N.J. Bee (Imperial College) and M.G. Sowerby)

Work has begun to refurbish the 42 m flight path of the booster target to extend the transmission measurements described in AERE-R.8961, to include neutron capture and self-indication measurements on ^{238}U as a function of temperature. Before starting these experiments, some transmission measurements will be repeated using new UO_2 fuel pellets which are expected to have fewer defects than the samples used previously.

1.6E Analysis of ^{238}U time-of-flight data (N.J. Bee (Imperial College))

To facilitate comparisons of experimental time-of-flight data with theory a computer program has been written to view the data interactively. The data are first transferred from tape to magnetic disk, and can then be plotted against channel number, time-of-flight, energy, the square root of energy or the log of energy. The scale of the plotting is selected interactively. To reduce statistical errors, clarify the graphs and reduce plotting time, a bin width can be specified interactively in any of the above variables. The data are then averaged in these bins, and the error bars reduced appropriately. Some output from this program is shown in Fig. 1.2 using data described in ref. (8).

The structure of the transmission of ^{238}U in the resolved energy region up to 4 keV is well understood[1], as is its temperature dependence (see for example PR/NP25,p.17). The unresolved region above 4 keV is not well understood and is known to exhibit fluctuations on a much larger scale than the resonance widths. These fluctuations, which can be seen in Fig. 1.2 appear in transmission[2,3,8], capture[4] and self-indication[3] measurements. They are due to local variations in average resonance parameters such as the neutron strength function. Fig. 1.3 shows the variations in the ^{238}U s-wave strength function observed in the resolved region when averages are taken over 150 eV intervals. (The curve was obtained using the strength function definition in reference 6 and was produced from the known resonance parameters.)

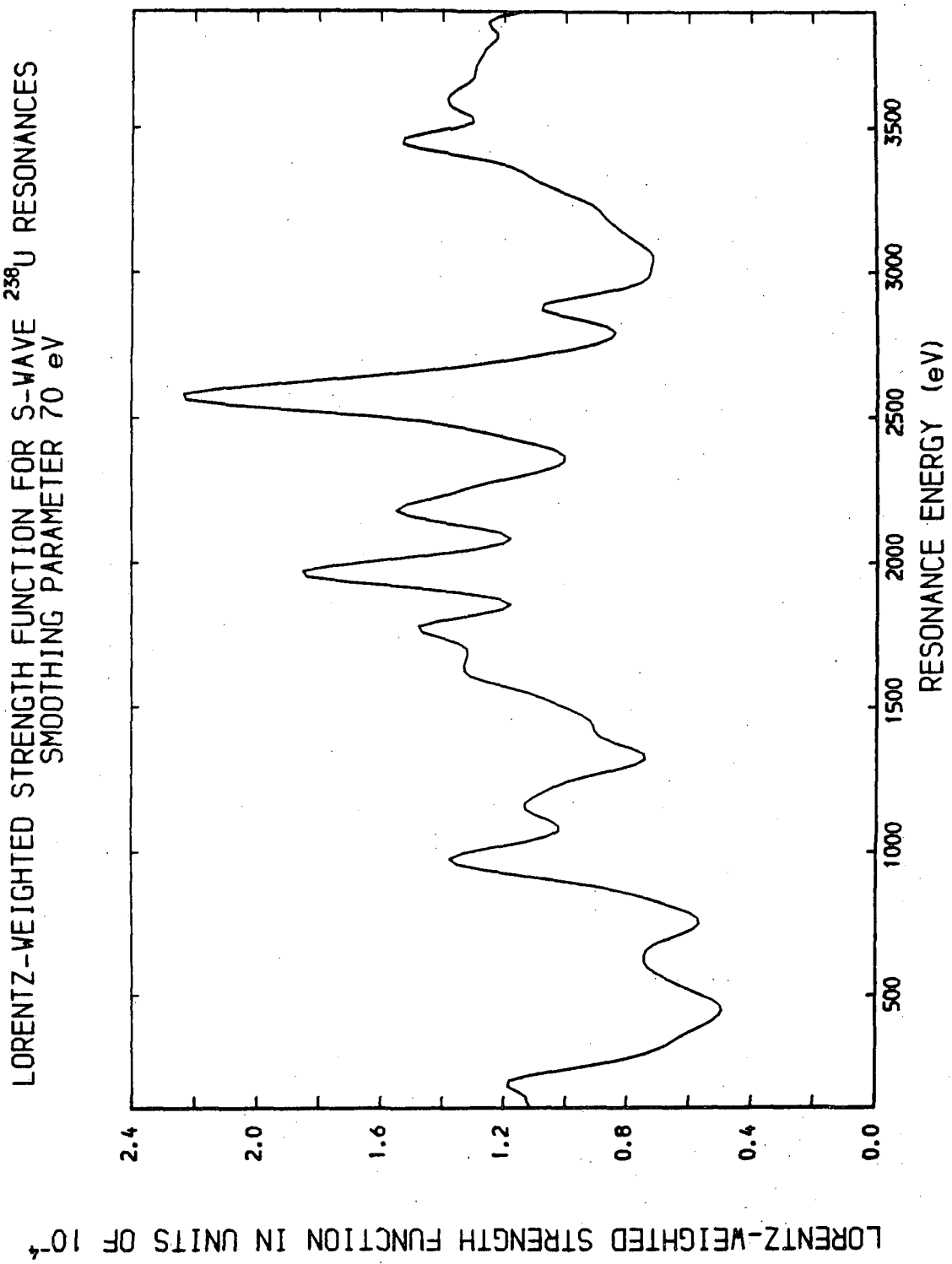

Fig. 1.2 Lorentz-weighted strength function for s-wave ^{238}U resonances, with the half-width of the convolving Lorentzian being 70 eV

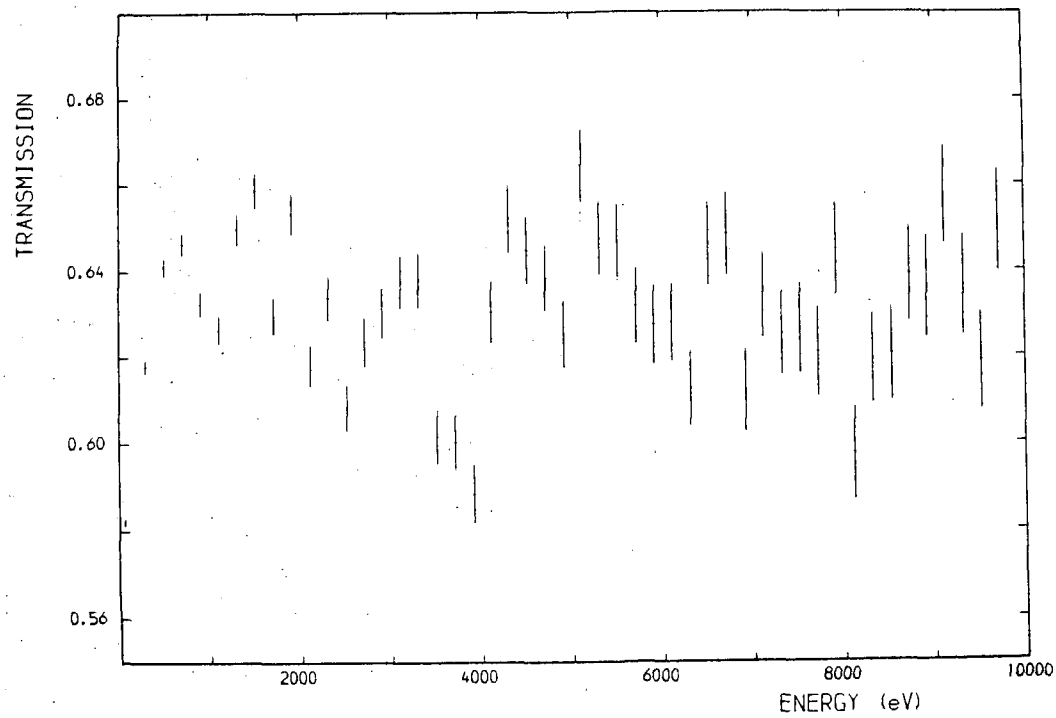

Fig. 1.3 Transmission through 1 cm of depleted UO_2 at room temperature

Information about these local variations in the unresolved energy region is needed to make improved safety calculations of the effects of reactor overheating in reactivity transients, and it is planned to analyse the available experimental data as follows. First, using the techniques of reference (5), the transmission data will be analysed to give values of the local neutron strength functions similar to those in Fig. 1.3. Then using these values and assuming that the spacing of resonances is constant and that the neutron widths have a Porter Thomas distribution, the variation of average transmission with neutron energy, sample thickness and temperature will be predicted. This will be done by averaging the transmission area function, whose properties are well known[7], over a number of resonances. If these predicted values agree with experiment then the average resonance parameters can be further checked against other measurements such as average capture cross sections and average self-indication ratios. If the predicted values disagree with experiment then more complex assumptions will have to be made about the distribution of resonance parameters and the prediction repeated until agreement is reached.

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(2) D. Kopsch, S. Cierjacks and G.D. Kirouac, Proc. Second International Atomic energy Conference on Nuclear Data for Reactors, Helsinki, 1970 (IAEA, Vienna, 1971) Vol. II, p.39.

(3) T.Y. Byoun, R.C. Block and T. Semler, U.S. National Aeronautics and Space Administration Centre, Cleveland Report N-M73-30715 (1972).

(4) R.B. Perez, G. de Saussure, R.L. Macklin and J. Halperin, Phys. Rev. C 20 (1979) 528.

(5) J.E. Lynn, Proc. Phys. Soc. 82 (1963) 903.

(6) W.M. MacDonald, Phys. Rev. C 20 (1979) 426.

(7) J.E. Lynn, Nuclear Physics 7 (1958) 599.

(8) T.J. Haste and M.G. Sowerby, UKAEA Report AERE-R 8961 (1978).

1.7H Neutron transmission data on structural materials (G.D. James)
(Relevant to request numbers: 326, 442, 450, 451, 474, 519, 522, 535, 551)

To speed up the processing of neutron transmission data, a new processing program (TOF 80) has been introduced. Written with the aim of producing a readable, well-structured program, it presents considerable improvements in core and CPU utilisation over the version which it replaces such that TOF 80 can process twenty transmission runs per class B job compared with one run per class D job. These considerations will have an important bearing on the rate at which useful information can be derived from the large body of transmission data available from the Harwell synchrocyclotron.

1.8H Background evaluation for a neutron time-of-flight spectrometer based on a compact pulsed source (D.B. Syme and A.D. Gadd)

Much microscopic nuclear data is obtained by the time-of-flight technique in which the backgrounds are determined by the well-known notch filter method. We have shown that this technique can produce erroneous results if simply applied to spectrometers with a compact source geometry (PR/NP27, p.19). To derive true backgrounds in such a case the source and background spectra must first be calculated and the effect of the filters predicted and compared with experiment. Initial results from a Monte Carlo simulation of the Harwell synchrocyclotron source were given in PR/NP27, p.20.

It has since been confirmed that over the energy range of interest (0.1 - 500 keV), the time spectrum at each energy for prompt neutrons leaving the water moderator (having come directly from the tungsten source) is the characteristic moderation function:

$$\phi(x) \sim \tfrac{1}{2} x^2 e^{-x}; \quad x = t/\Sigma v$$

Here t is the moderator time delay, Σ is the macroscopic scattering cross section and v

is the neutron velocity. The backgrounds arise from neutrons leaving the tungsten source and scattering in either nearby magnet pole before entering the moderator. The corresponding time spectrum at any energy is well represented by the sum of two functions of type $\phi(x)$ but of different delay and intensity. These two components arise from neutrons which have or have not suffered inelastic scattering in their history of scatterings in the iron magnet pole. (The iron acts as an intermediate moderator delaying and reducing in energy the incident neutron pulse from the source and re-emitting it towards the moderator). The energy dependences of the coefficients defining the time spectra are smooth and are well fitted by simple functions of energy. It is then straightforward to calculate time and energy spectra for prompt and background neutrons at any flight path and to predict the effect of resonance filters. This work is now in progress.

1.9B Fission fragment angular distribution measurements for the reaction ^{230}Th(n,f) near 715 keV (G.D. James, J. Grainger (Queen Mary College), D.B. Syme and M.A Wilkins)

Ten years after the start of detailed measurements[1,2], measurements of the fission cross section and fission fragment angular anisotropy of ^{230}Th near the spectacular intermediate structure resonance at 715 keV continue to arouse considerable interest. It is now thought likely that this resonance occurs in a third, rather than in the second, fission potential barrier minimum. Revealed by the calculations of Möller and Nix[3], a third minimum occurs, at a certain nuclear deformation, as a split in the direction of reflection (or mass) asymmetry. In consequence, the resonance would be composed of two rotational band structures, of opposite parity, characterised by decoupling parameters of closely equal magnitude but of opposite sign[4]. At present, this hypothesis cannot be tested because of discrepancies between the data on fragment anisotropy available from several laboratories. These data have been presented for discussion at Julich[5] and reviewed by Bjørnholm and Lynn[6].

A series of fragment anisotropy measurements have been planned at Harwell and the results for incident proton energy resolution of 16 keV and 8 keV, measured at the threshold of the ^{6}Li(p,n) reaction, are shown in Fig. 1.4. The figure also shows, for comparison, the most recently available data of comparable energy resolution, measured by Boldeman et al[7]. It will be seen that, with the exception of one datum, the data are in good agreement. A comparison with theoretical predictions based on the triple-hump barrier will be made when measurements with improved energy resolution are complete.

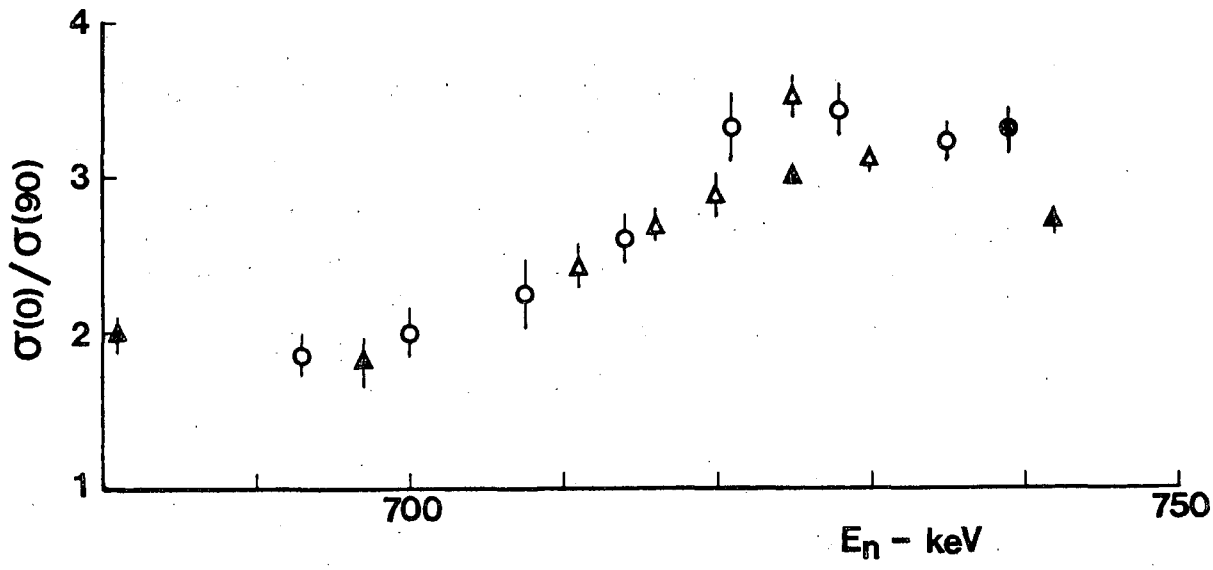

Fig. 1.4 Fission fragment anisotropy for the reaction ^{230}Th(n,f) near the resonance at 715 keV. Circles represent data from the present experiment at an energy resolution of 8 keV (open circles) and 16 keV (closed circles.) Triangles represent the data of Boldeman et al[5] at an energy resolution of 8 keV (open triangles) and 16 keV (closed triangles)

In the present measurement, the fission fragments were detected by a cylindrical arrangement of 10 μm thick Makrofol KG. The cylinder, of radius 100 mm and 100 mm high, was set with its axis along the incident proton beam direction. This arrangement was adopted in order to change as much as possible the arrangement used previously at Harwell[1] and in use at Bordeaux[7]. The change, however, entailed detailed investigations of the etching and sparking conditions required to ensure that all fragments, emerging from the ^{230}Th foil at angles between 0° and 75° and entering the Makrofol at angles between 0° and 45°, are detected with known efficiency. Measurements at angles of emergence greater than 75° were not made and the 0°/90° ratio is obtained by extrapolation. The etching and sparking conditions adopted are as follows. Using a 6N solution of NaOH at 60°C, the exposed Makrofol is etched to a thickness of 8 μm. Then, using a succession of 0.05 mm aluminium sheet electrodes, the Makrofol is sparked once at 1200 V and four times at 600 V. The fragment angular distribution is derived from the last of these aluminium electrodes. The Makrofol is then etched to a thickness of 7 μm and sparked once at 800 V and four times at 600 V. The last of these electrodes is also counted. The exact voltage used is varied slightly depending on the thickness reached after etching. This is determined by weighing. The

etchant temperature and concentration are closely controlled. The etching time required, however, is also a function of how much use the etchant has had and has been observed to double from the 30 min per μm thickness reduction established for freshly prepared etchant.

The energy resolution function for the energy range of neutrons reaching the ^{230}Th has been calculated using convolution routines written by James Cummings. For the geometry adopted, the resolution function is approximately triangular with a peak at an energy below the maximum neutron energy at 0° by an amount equal to the full width at half height. The convolution routines allow pointwise, cubic spline or functional representation of the input functions. They are of general application and will be made available through the subroutine library.

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(1) G.D. James, J.E. Lynn, and L.G. Earwaker, Nucl. Phys. A189 (1972) 225.

(2) G. Yuen, G.T. Rizzio, A.N. Behkami and J.R. Huizenga, Nucl. Phys. A171 (1971) 614.

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(4) J. Blons, C. Mazur, D. Paya, M. Ribrag and H. Weigmann, XVIII International Winter Meeting on Nuclear Physics, Bormio (1980).

(5) J.W. Boldeman, Physics and Chemistry of Fission 1979 (IAEA, Vienna, 1980) I, 219.

(6) S. Bjørnholm and J.E. Lynn, Rev. Mod. Phys. 52 (1980) 725.

(7) A. Sicre, F. Caitucoli, G. Barreau, T.P. Doan, T. Benfoughal, B. Leroux, Physics and Chemistry of Fission 1979 (IAEA, Vienna, 1980) I, 187.

1.10 Evaluation of differential nuclear data for ^{243}Am (J.E. Lynn, B.H. Patrick, M.G. Sowerby and E.M. Bowey)

The evaluation of differential nuclear data for ^{243}Am has been completed and a file, DFN 1010, covering the energy range 10^{-5} eV to 15 MeV, produced for inclusion in the U.K. Nuclear Data Library. Work on a report giving details of the evaluation has begun.

1.11 Neutron interrogation facilities (B.W. Hooton, B.H. Armitage, E. Wood, W. Crane and A.R. Talbot

Neutron interrogation facilities for use in research programmes concerned with Safeguards, the determination of plutonium in waste and the measurement of fissile material in a reprocessing plant are being installed.

A. A ^{252}Cf shuttle

The system shown in Fig. 1.5 has been constructed for use with a ^{252}Cf source

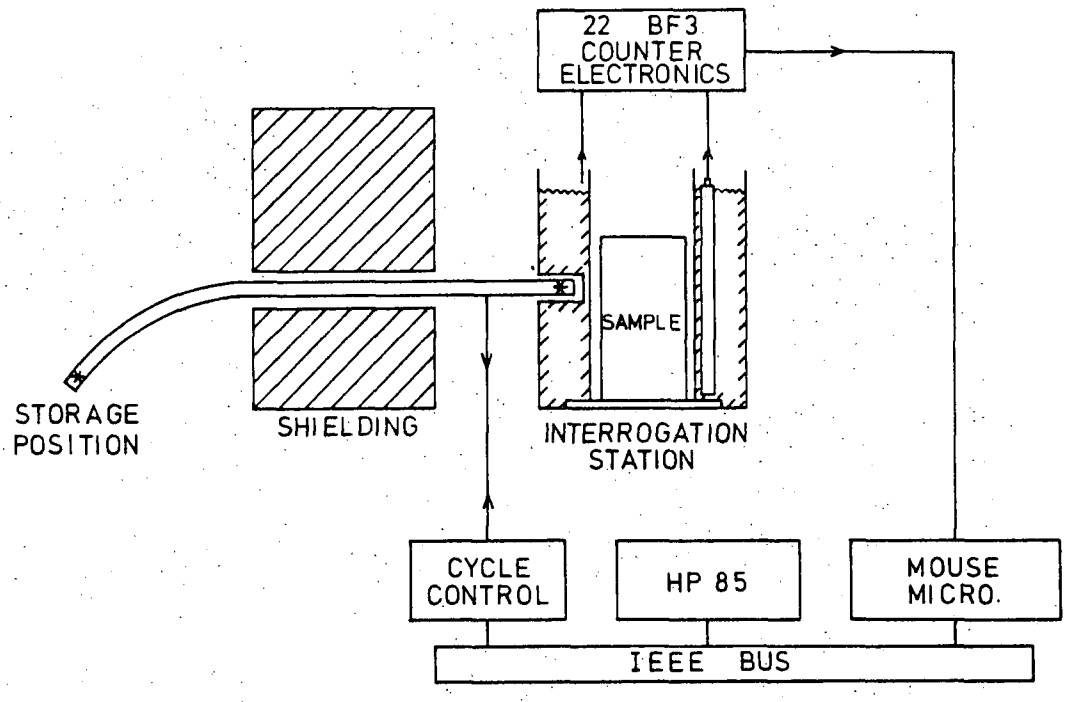

Fig. 1.5 Neutron interrogation system

of 5 x 10^8 n/sec intensity.

The system uses a commercially available magnetic latch to retain the source capsule at each end of a 7 m long seamless stainless steel tube. A pressure of 20 psi is maintained behind the source which moves as soon as the electromagnetic latch is switched off. Handshake signals to confirm and measure the source movement are provided by photodiode timing devices at both ends of the tube. The system has been assembled and tested with a 7 m transfer time of about 0.3 s. Counting and control will be carried out using a MOUSE microprocessor to collect data from six banks of four BF3 counters. A Hewlett Packard 85 computer will program the cycle control, the data acquisition and display. In addition to measuring the gross delayed neutron counts the system will measure in time bins of 1 sec (say).

B. A 500 keV Van de Graaff

The increasing use of neutron interrogation in commercial plant is in some instances limited by the cost and reliability of intense neutron sources. The current cost of a 5 x 10^9 n/sec ^{252}Cf source ($T_{\frac{1}{2}}$ = 2.65 y) is about £40,000 and such a source is a continuous radiation hazard. A 500 keV electrostatic accelerator of length 1.75 m can be used to produce an intense source of neutrons and one aspect of this installation

will be to assess its reliability over a number of years. It will be operated as a machine dedicated to deuteron beams in a DC or terminal pulsed mode. The pulsed mode will be particularly useful for carrying out measurements on the differential die away method[1] for measuring fissile material at levels of about 1 mg. The machine is expected to be operational by mid-1981 with beam currents of 100 μa.

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(1) LASL Report LA-UR-80-1289

1.12 Safeguards research

1.12.1 Analysis of variable dead time counters (VDC) (B.W. Hooton and E.W. Lees)

Our research program into the behaviour of these instruments has finished this year with the publication of two reports[1,2]. We report on two aspects covered in more detail in these reports and elsewhere[3].

(a) Variation of VDC response with random rate

The VDC parameter X is defined by

$$X = b - \frac{c}{1 - cd} \qquad (1)$$

where b is the count rate in a detector of zero dead time and c is the rate in a counter with dead time d. The value of X can be calculated using probability theory and shown to depend on the random rate[1]. This variation has been confirmed using the NETMOC simulator and the results are shown in Fig. 1.6.

Since X varies with randoms and also varies non-linearly with plutonium mass its usefulness as a parameter for measuring plutonium is severely restricted. The method should only be applied to masses below 50 g ^{240}Pu and in situations where the random component is small.

(b) Sensitivity of ^{240}Pu mass to uncertainties in the dead time

From equation 1 it is easy to show that the sensitivity of the VDC response X to the non-extending (slow scaler) dead time is given by

$$\frac{\delta X}{X} = - \frac{c^2 d}{(1 - cd)^2} \frac{1}{X} \frac{\delta d}{d} = k \frac{\delta d}{d}$$

where δX is the uncertainty in X resulting from an uncertainty δd in the slow scaler dead time.

However, the ^{240}Pu mass is related to X by a polynomial of order 3 for large samples, e.g. NMACT have deduced for the Euratom VDC

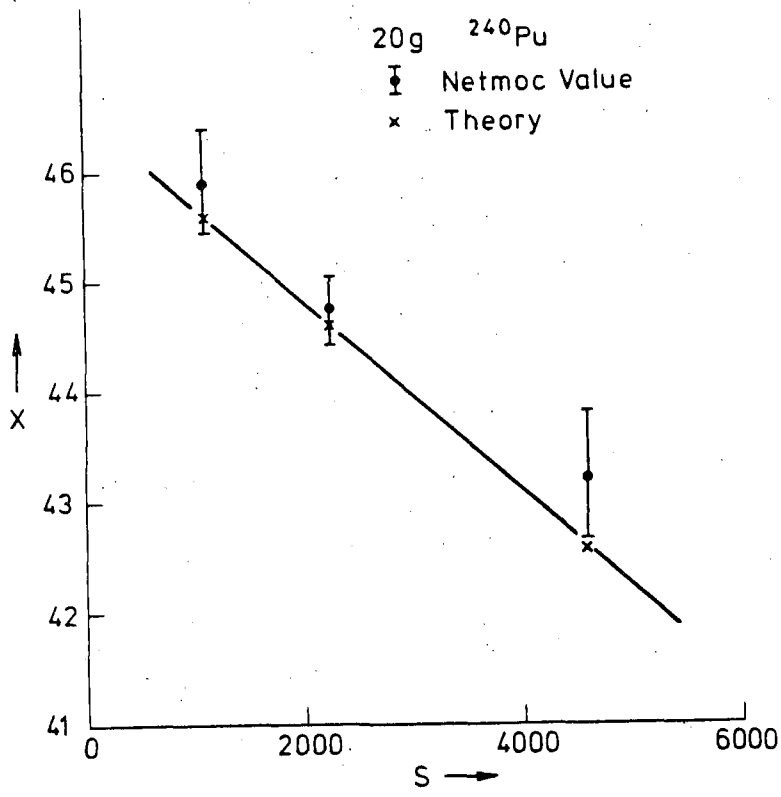

Fig. 1.6

The variation of X with the singles rate S is shown for a ^{240}Pu mass of 20 g. The theoretical values were calculated using the method given in ref. 1.

$$M_{240} = -5.64 + 0.778X - 1.99 \times 10^{-3} X^2 + 2.7 \times 10^{-6} X^3$$

Thus

$$\frac{\delta M}{M} = k^1 \frac{\delta X}{X} = k^1 k \frac{\delta d}{d}$$

where k^1 denotes the sensitivity of mass with respect to X. Typical values of the sensitivity coefficients k and k^1 are given in Table 1.3 for large samples measured with the Euratom VDC; also given is the overall mass sensitivity (kk^1) with respect to scaler dead time. Clearly, the overall sensitivity coefficient is very large and increases rapidly with increasing count rate/larger mass samples. This is to be expected since X is the difference of two large numbers and small changes in one of the numbers have a disproportionate effect in X. Even for PuO_2 samples under a total mass of 1 kg, to reduce the systematic uncertainty in X to less than 1%, the dead time must be known to better than .03%; no account of electronic drift of the gate width or its temperature variation has been considered and these will just make the situation worse.

Table 1.3

Values of the sensitivity coefficients, k and k^1, as a function of ^{240}Pu mass for the 32 μs dead time scaler of the Euratom VDC (^{240}Pu content ∿20%)

Mass ^{240}Pu (g)	k	k^1	kk^1
167	27	1.1	29
391	73	6.8	496
574	116	11.9	1380

1.12.2 Experimental measurements of the properties of neutron coincidence counters (NCC) (E.W. Lees)

It is important to understand fully the response of any instrument used in Safeguards work in order to assess its limitation and also to have confidence regarding its deployment in the 'field'. Consequently, we have been calculating the theoretical response of NCC at Harwell (see section 1.12.3). However, it is necessary to have accurate knowledge of certain physical properties of the instrument in order to proceed with the theoretical calculations and we have continued our measurement programme with the revised NMACT PNCC and the IAP NCC.

(a) Revised NMACT PNCC

Two major changes have been made to improve the efficiency and the portability of the instrument. Firstly, the open-hexagon structure of the moderating slabs has been closed up so that all slabs are now touching; the ^3He detectors are consequently much closer to the sample resulting in an increase in solid angle ∿50% compared to the previous geometry. Secondly, the stainless steel plates which performed the dual role of γ-ray shield and neutron spectrum shifter have been removed.

The revised efficiency as measured with calibrated ^{241}Am (α,n) sources is shown in Table 1.4; also shown are the efficiencies of the original PNCC (PR/NP26, p.54) and the ratio of the efficiency for the two forms of PNCC. The ratio is a marked function of neutron energy because for the revised PNCC the highest energy neutrons no longer undergo inelastic scattering in the steel plates. Thus for the revised form, the detection efficiency has been increased but at the expense of an even greater variation and non-linearity as a function of neutron energy.

Table 1.4

NMACT PNCC efficiency as a function of neutron energy

Source	Average neutron Energy (MeV)	Efficiency (%)		Ratio
		Original form	Revised form	
Am/Li	0.45	8.32 ± 0.04	13.23 ± 0.08	1.59
Am/F	1.25	6.73 ± 0.03	10.18 ± 0.07	1.51
Am/B	2.7	5.19 ± 0.05	7.35 ± 0.04	1.42
Am/Be	4.2	4.87 ± 0.05	6.53 ± 0.13	1.34

We reported last year (PR/NP27, p.38) on the problems encountered when pulses from the NMACT PNCC were processed using SR circuits with two separate gates to measure the 'real + accidental' (R + A) and 'accidental' (A) coincidences. For electronic reasons, the widths of the gates were not identical and a factor f was introduced to multiply the R + A count rate so that the effective widths of the two gates were identical. The factor f is determined from

$$f \times (R + A) - A = 0$$

which must be true for a random (α,n) source. It was found that f differed from unity by ∿5% and was count-rate dependent.

The revised NMACT PNCC contains SR processing circuits of the type which interrogate the same, single gate on a prompt and delayed basis. With the new circuitry, f was determined using an Am/F source to be 0.9954 ± 0.0070 and is consistent with unity.

(b) IAP NCC

The design of this instrument is similar to that employed by LASL[8]. It consists of 2 cylindrical shells of polythene, the inner contains 18 ^{3}He tubes and has a removable Cd liner interposed between it and the outer cylinder. The Cd shortens the mean lifetime of a neutron in the detector but at the expense of detection efficiency; consequently the Cd liner is used for high count rate situations to minimise the random coincidences.

The detection efficiency and the neutron capture probability distribution as a function of time have been measured as described in PR/NP26, p.54) for the IAP instrument both with and without the intermediate Cd liner in place. The results for the efficiency are shown in Table 1.5; the accuracy of the measurements is ∿1%

in all cases. Removal of the Cd liner increases detection efficiency by ∿20%.

Table 1.5

Detection efficiency for the IAP NCC

Source	Average neutron Energy (MeV)	Efficiency :	
		With Cd liner	Without Cd
Am/Li	0.45	23.21	27.65
Am/F	1.25	18.50	22.67
Am/B	2.7	13.70	17.18
Am/Be	4.2	12.34	15.30

With the Cd liner in place, the capture probability curve (Fig. 1.7) is well described between 10 and 110 μs by an exponential curve with die-away time = 38.7 μs. Without the Cd, the die-away time is ∿49 μs.

Finally, the effective dead time of the detector was measured to be 0.52 μs which is an improvement over the NMACT PNCC which has a value 0.80 μs (PR/NP26, p.55).

This information proved invaluable in determining the ratio of (α,n) to spontaneous fission neutrons in an unirradiated fuel pin (see section 1.16).

1.12.3 Shift register response and neutron multiplication (E.W. Lees and B.W. Hooton)

A clear derivation of the shift register (SR) response to spontaneous fission events occurring in a neutron coincidence counter (NCC) is given by Lambert[4]. If the neutron probability of capture in the detector as a function of time is denoted by f(t) and the efficiency of the detector by ε, then the response in R is

$$R = F\,\varepsilon^2\,\frac{\langle\nu_{SF}\,(\nu_{SF}-1)\rangle}{2}\int_{T_1}^{T_1+\Delta T} f(t)dt \qquad (2)$$

where F is the spontaneous fission rate, T_1 is the pre-delay[4] and ΔT is the width of the SR. The quantity $\langle\nu(\nu-1)\rangle/2$ represents the average number of pairs emitted in SF and depends on the neutron multiplicity distribution.

Equation 2 is valid only in the absence of neutron multiplication. It can be rewritten as

$$R_{zM} = F\,Q\,(\varepsilon,\ \bar{\nu}_{SF})$$

Following the procedure and approximations of reference (5), when neutron multiplication

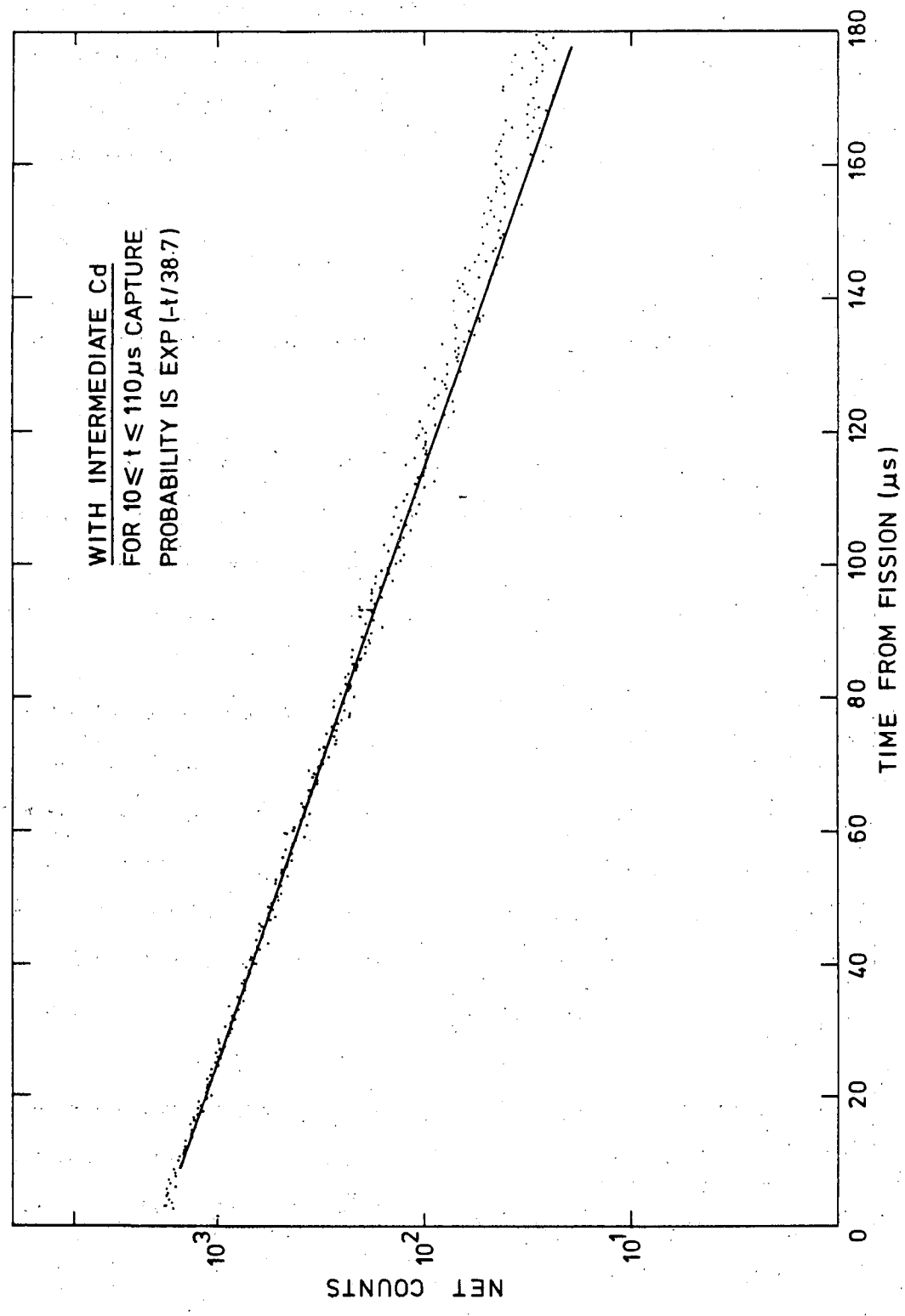

Fig. 1.7 The neutron capture probability distribution as a function of time after the fission event. The net counts are plotted on a logarithmic scale

occurs within the sample, then

$$\bar{\nu}_{eff} = \bar{\nu}_{SF} + \bar{\nu}_{FF} - 1$$

where $\bar{\nu}_{eff}$ is the effective average number of neutrons seen by the NCC. For multiplication processes induced by (α,n) neutrons, then the effective $\bar{\nu}$ seen by the NCC is $\bar{\nu}_{FF}$ ($\bar{\nu}$ for fast fission). In both cases, it is the distribution of neutron multiplications around $\bar{\nu}$ which is important and these were calculated from the information contained in reference (5). For spontaneous fission of ^{240}Pu, then measured values[6] of the multiplicity distribution were used:

$$\langle\nu(\nu - 1)\rangle = \sum_{\nu=2} \nu(\nu - 1)P(\nu)$$

where $P(\nu)$ is the probability of emitting ν neutrons. Hence, with approximations similar to those discussed in reference (5),

$$R = (F - F_{FF})Q(\varepsilon, \bar{\nu}_{SF}) + F_{FF}\, Q(\varepsilon, \bar{\nu}_{eff}) + F_{\alpha n}\, Q(\varepsilon, \bar{\nu}_{FF}) \qquad (3)$$

where F_{FF} is the number of fast fissions per second induced by the SF neutrons and $F_{\alpha n}$ is the number of fissions per second induced by neutrons from (α,n) reactions. The quantities F_{FF} and $F_{\alpha n}$ were calculated using the Monte Carlo code MONK as described previously[5].

Well defined samples of PuO_2 powder were measured in the revised NMACT PNCC (see section 1.12.2). The capture probability integral and efficiency were known and F could be calculated from the deduced sample composition. A comparison of the theoretical and experimental results is given in Fig. 1.8; the agreement is encouraging. It should be noted that the SR used in the measurement is a 'one gate' version and overcomes the problems previously encountered with the two separate gates (PR/NP27, p.38).

However, the response of the SR is not entirely understood at high count rates as was demonstrated by the following experiment. Four small ^{252}Cf sources of strengths 5.88×10^5, 2.05×10^5, 1.38×10^5 and 4.88×10^4 n/s were measured in the revised NMACT PNCC. Since they were physically small sources, neutron multiplication is negligible. The gross counting rate after correction for background, N is given by

$$N = \bar{\nu}_{SF}\, \varepsilon\, F \qquad (4)$$

and hence

$$N/R = \frac{2\bar{\nu}_{SF}}{\langle\nu_{SF}(\nu_{SF} - 1)\rangle} \frac{1}{\varepsilon} \left[\int f(t)dt\right]^{-1} \qquad (5)$$

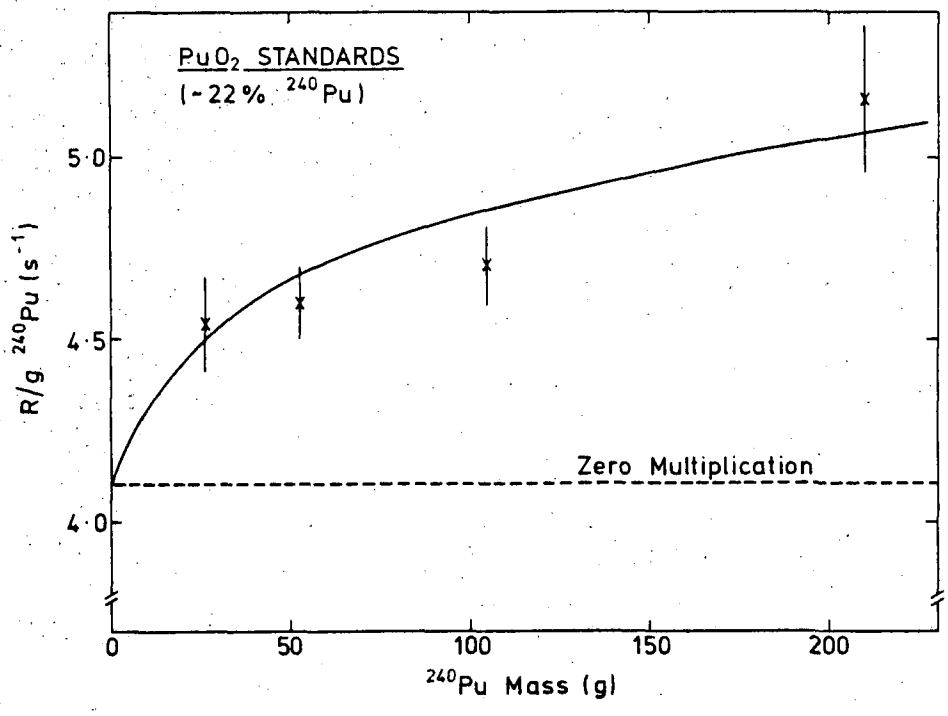

Fig. 1.8 Comparison of the experimental data obtained with a SR analysis on the NMACT PNCC for the PuO_2 standards with the present calculations. The response per gram of ^{240}Pu has been plotted to accentuate the effects of neutron multiplication

Clearly this should be a constant for all 4 samples; this is not the case as evidence by Fig. 1.9. The theoretical estimate of equation (5) agrees well only for the weakest sample.

This deviation is presumably analogous to the behaviour reported[7] when a ^{252}Cf source was counted in the presence of various random (α,n) neutron strengths; as the random count rate (and hence the total neutron rate) increased, the value of R fell exponentially. This problem can be overcome by a correction of the form $Re^{\delta N}$, where δ is defined as the coincidence dead time. The exact physical significance of this dead time is currently under investigation.

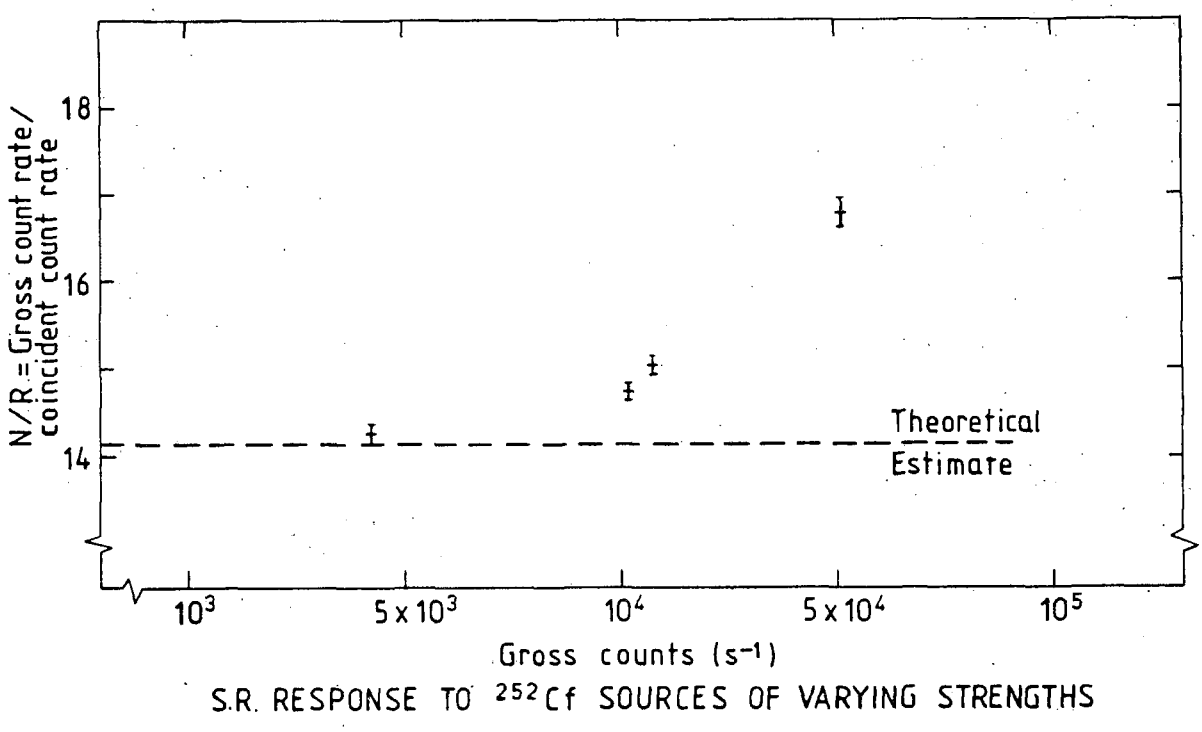

Fig. 1.9 Variation of the ratio of the gross and coincidence count rates as a function of the gross count rate for the four ^{252}Cf sources described in the text. The dashed curve is the theoretical estimate of this ratio from equation (5)

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(1) B.W. Hooton and E.W. Lees, Report AERE-R 9367.

(2) E.W. Lees and B.W. Hooton, Report AERE-R 9701.

(3) E.W. Lees, B.W. Hooton and F.J.G. Rogers, Proceedings of the 2nd Annual ESARDA Symposium, Edinburgh, 1980, p.364.

(4) K.P. Lambert, Report AERE-R 8303 revised (1977).

(5) E.W. Lees and B.W. Hooton, Report AERE-R 9168 (1978).

(6) J.W. Boldeman, 2nd All Union Conf. Neutron Physics, Kiev, (1974), Vol. 4, p.83.

(7) J.E. Swansen, P.R. Collinsworth and M.S. Krick, LA-8319-MS (1980).

(8) N. Ensslin et al, Nucl. Mat. Management 7 (1978) 43.

1.13A (n,α) cross sections (J.A. Cookson and M.A. Langton)*
(Relevant to request numbers 502-9, 576-84, 424-30)

This work, which has been mentioned in previous reports, has continued. Development of the counter telescope used for the measurements and its electronic system has concentrated on improving the reliability of the resulting data.

Considerable efforts have been made to understand the various sources of background in the alpha particle spectra. There has been a change of proportional counter gas from hydrogen with a small amount of methane to an argon-methane mixture. Together with the use of some modern electronic units this has permitted a reduction in the coincidence resolving time of the counter telescope and has made an appreciable reduction in the random component of background.

Trouble was experienced with short life of the titanium tritide targets used to make 14 MeV neutrons on the Cockcroft-Walton accelerator. A combination of improved target cooling and a liquid nitrogen trap to prevent carbon deposition has now given much enhanced target life.

1.14D Neutron yields from (α,n) reactions in the light elements (D. West and A.C. Sherwood)
(Relevant to request numbers 16, 17, 113, 118, 119, 160, 195-199, 258, 259, 275 and 286)

Final corrections have now been made to all the thick target neutron yields measured prior to February 1980 when the Tandem Generator was shut down for modifications. The corrections are:

Calibration source neutron leakage	- 1.0%
Calibration source neutron self absorption	- 0.2%
Neutron absorption in the beam pipe and target Faraday Cup	between + 2.4% and + 5.4%

The beam pipe absorption is measured directly for the four sources AmBe, AmB, AmF and AmLi and a relation derived between absorption and r.m.s. spread in radius for the thermal neutron distribution. For any measured yield the r.m.s. spread in radius of the neutrons then enables the relevant neutron absorption correction to be obtained. The estimated net error on all these corrections is ± 0.7%, and the overall error on the thick target yields is expected to be between 1 and 2% in most cases.

The measurements taken on each target are listed in Table 1.6. The energies were monitored by Rutherford Scattering and when evaluated were not round numbers. Cubic spline interpolation at regular intervals of 100 keV has been carried out.

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Table 1.6

Target	Measured Energy Range (MeV)	Number of Measurements
Al	3.7 - 9.9	24
Mg	3.7 - 9.9	24
C	3.7 - 9.9	24
Si	3.7 - 9.9	23
Fe	4.7 - 9.9	16
M316 Stainless Steel	4.7 - 9.9	11
UO_2	3.8 - 9.9	19
UC	3.8 - 9.9	17
Zirconium	5.0 - 9.9	7
Be	4.1 - 9.9	20
BeO	4.1 - 9.9	20
BN	4.1 - 6.7	11

The most recently reported measurements of (α,n) yields from thick targets are those of Bair and Gomez del Campo[1] using a graphite sphere which has appreciable leakage for neutrons above 1 MeV in energy. Table 1.7 shows a comparison between these measurements and ours.

Table 1.7

Target	(Bair & Gomez) - (West & Sherwood) / (West & Sherwood)	Energy region of comparison (MeV)
Al	-8.1%	5-9
Mg	-9.5%	5-9
Si	-9.1%	5-9
Be	-9.6%	5-9

A consistent difference of 9% exists between the two sets of data.

Bair and Gomez state that the estimated correction for leakage (which was not applied to their results) would be

for Al + 4 ± 3%

Mg + 5 ± 3%

Si + 5 ± 3%

Be between 6.9 ± 2% and 10 ± 4%

This therefore would reduce the differences between the two sets of data. Bair and Gomez claim an accuracy of ± 5% exclusive of the leakage correction.

When the Tandem resumes operation on He ions early next year we hope to resume measurements. Targets to be measured include B, oxides, fluorides and nitrides and Li, Na and Ca. Great difficulty is being experienced in obtaining thick targets of pure elemental boron.

The data on UO_2 have been used in comparing calculations and measurements of neutron production in a fuel pin described in section 1.16.

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(1) J.K. Bair and J. Gomez del campo, Nuc. Science and Eng., 71 (1979) 18.

1.15 Reactive target handling for (α,n) measurements (A.C. Sherwood)

Thick targets of the reactive elements lithium, sodium and calcium present special problems. In addition to the problem of target preparation, there is the problem of maintaining the integrity of the target surface purity during beam energy changes, alignments and energy measurements.

When not in use the targets will be stored under vacuum and will be placed in and removed from the beam line in an argon atmosphere contained in a collapsible welded PVC glove box fitted to the end of the beam line. The glove box has been made collapsible so that it can be nearly exhausted using a rotary vacuum pump and then filled quickly with argon several times in succession to eliminate the time factor necessary when purging.

Attempts to produce a thick lithium target by melting have so far been unsuccessful largely due to evaporation problems, however an etching technique may be used on dry lithium sheet to produce an acceptable metallic surface. The dry lithium sheet can be etched in methanol, rinsed in benzene and then cooled in liquid nitrogen or argon. The target is then allowed to warm up under vacuum where after the evaporation of the thin benzene layer the lustrous surface can be maintained.

The sodium target can be made from available dry material without further

treatment. The calcium target has not yet been obtained.

1.16 Comparison of the measured and calculated neutron output from a mixed oxide fuel pin (E.W. Lees and D. West)

The aim of this work was to experimentally measure the neutron yield to a few % accuracy from an unirradiated fuel pin and to compare this value with that calculated from basic nuclear data properties and from inventory codes such as FISPIN[1].

The fuel pin (M120) was a conventional mixed oxide (U - 32.25% Pu)$O_{1.975}$ pin with fuel dia. 5.0 mm and length 103 mm. Information on the isotopic composition and chemical history of the fuel were obtained from the PFR data bank.

The neutron output from the pin was first measured in the BF_3 detector assembly which was designed for photofission and photoneutron studies[2]. This is a high efficiency detector (44.37 ± 0.72%). After small corrections, for dead time, background and reflected neutron multiplication (calculated using the Monte-Carlo code MONK[3]) the resulting neutron output was 1668 ± 28 n/s.

The neutron output was next measured in the large detector constructed to measure (α,n) yields from thick targets bombarded by α-particles[4]. This detector has an intrinsically low efficiency (∿0.1%) and measures the neutron density at various radii in a large polythene cylinder; numerical integration of the density is then performed to obtain the neutron strength. After corrections for background, neutron leakage and reflected neutrons, the pin yield was estimated to be 1656 ± 18 n/s in excellent agreement with the above measurement.

The weighted mean of these results must be corrected for fast neutron multiplication occurring within the pin; this was estimated to be a 0.84 ± 0.22% using MONK. Thus the 'base' yield for M120 is 1646 ± 16 n/s on 6 June 1980, and is the value to be compared with nuclear data calculations.

The calculated neutron strengths were obtained as follows:

(1) The information currently available in Nuclear Data Sheets (NDS) was used to calculate the neutrons arising from spontaneous fission (SF). To this was added the (α,n) contribution obtained by scaling from the measurements in UO_2 by D. West[4]. The calculated total neutron yield was ∿9% lower than the experimental value (see Table 1.8).

(2) If the value of the ^{240}Pu S.F. half life [(1.15 ± 0.03) x 10^{11} y] as measured recently by Budtz-Jorgen et al[5] is used then this increases the SF neutrons from ^{240}Pu by 14.9%. With all other nuclear data as above, calculation and experiment

are then in agreement to better than 1% (Table 1.8); the accuracy of the calculation is ∿3%.

Table 1.8

Calculated neutron o/p of M120

Isotope	Mass June 1980 (g)	Neutrons/s		
		SF	(α,n)	SF
^{235}U	8.2×10^{-2}	-	-	-
^{238}U	12.77	0.2	-	0.2
^{238}Pu	6.69×10^{-3}	18	97	18
^{239}Pu	3.713	0.1	148	0.1
^{240}Pu	1.077	962	159	1105
^{241}Pu	0.164	-	0.2	-
^{242}Pu	3.71×10^{-2}	63	0.1	63
^{241}Am	2.35×10^{-2}	-	65	-
Total n/s		1043 → 1513 ←	470 → 1656 ←	1186
		From NDS	From West's measurements	From NDS but using Budtz-Jorgen et al ^{240}Pu $t_{\frac{1}{2}}$ (SF)

(3) The total neutron yield calculated by the inventory code FISPIN is only 3.3% below the experimental value. However, the agreement is fortuitous; FISPIN has the same SF information as NDS but predicts ∿20% more yield from (α,n) reactions compared to the measurements of West[4].

By defining a ratio

$$\alpha = \frac{(\alpha,n)}{SF} \frac{n/s}{n/s}$$

then there is a marked difference between the predictions of α from FISPIN (0.529) and that from using the revised ^{240}Pu $t_{\frac{1}{2}}$ (SF) and West's experimental measurements (0.396).

A third measurement was made on the fuel pin using a Safeguards instrument whose principal function is to determine ^{240}Pu mass by coincidence or correlation counting. The instrument used was the I&AP neutron coincidence counter with the shift register form of analysis; the physical properties of this instrument had recently been determined (see section 1.12.2). By rearranging the expressions used to describe the

shift register response, an expression is obtained for α which is independent of SF rate and which involves only measured quantities or physical parameters of the detector. The measurement gave $\alpha = 0.367 \pm 0.038$, in disagreement with the FISPIN prediction and in good agreement with the value obtained using the new ^{240}Pu $t_{\frac{1}{2}}$ (SF) and (α,n) data from ref. (4).

In conclusion, the revised ^{240}Pu $t_{\frac{1}{2}}$ (SF) as measured by Budtz-Jorgen et al and the (α,n) yields in UO_2 as measured by West have been validated by this work. Also the code FISPIN is wrong; both the (α,n) and SF data libraries need to be updated.

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(1) R.F. Bustall, UKAEA ND-R-328(R) (1979).

(2) E.W. Lees, B.H. Patrick and E.M. Bowey, Nucl. Instr. and Meth. 171 (1980) 29.

(3) V.S.W. Sherriffs (1978) SRD R86.

(4) D. West and A.C. Sherwood, AERE-R 9195 (1978).

(5) Budtz-Jorgen et al, BNL 50991 (1979) 239.

1.17 A fission chamber for the intercomparison of fast neutron flux density measurements (D.B. Gayther)

The main components of the multi-plate chamber which was described in PR/NP26, p.35 have been constructed and a dummy fission foil assembly mounted satisfactorily. Enough components have been made to assemble three chambers (standard ^{235}U chamber, standard ^{238}U chamber, and one chamber containing thinner ^{235}U deposits for cross section measurements).

All the fission foils for the three chambers have now been made and satisfactory uniformity of deposit has been demonstrated for each foil. One additional foil has also been made for each set which will be mass-assayed to destruction by weighing, low geometry alpha-counting, controlled potential coulometry, and isotope dilution and mass spectrometry. These measurements will serve as a check on the techniques of determining the fissile mass deposited on the permanent foils (weighing and alpha-counting).

The low geometry alpha-counter used in the above measurements was designed in collaboration with Mrs. K.M. Glover's group of the Chemistry Division, AERE. Tests with standard sources indicate that this counter is capable of determining the fissile mass deposits with an uncertainty of $\sim$0.2%.

All the foils are currently being assayed with the low geometry alpha-counter and final assembly of the chambers awaits the completion of this task.

1.18 A Monte Carlo program for calculating the response of deuterated scintillators to monoenergetic neutrons (N.P. Hawkes, C.O. Blyth*, S.D. Hoath* and G. Rai*)

The deuterated scintillator NE230 is used at Birmingham as a neutron detector, and is being considered for use as a target in n+d elastic scattering experiments. In the former case, one requires the lineshape (pulse height distribution produced by monoenergetic neutrons) in order to unfold the incident neutron spectrum; in the latter, one wishes to know the effects of processes such as multiple scattering and neutron production from deuteron breakup.

A Monte Carlo-type simulation can provide the necessary information in both cases. The program described here was developed from an existing program[1] for calculating neutron detection efficiencies in ordinary liquid scintillators. The chief modifications required were in the interpolated cross section tables, the logic of the tracking routine (to cope with deuteron breakup), and in the analysis routines at the end of the calculation.

The ENDF/B IV cross section data compilation was used both to replace the existing interpolated tables (which are now outdated) and to provide the data for the two new processes introduced by the presence of deuterium (deuteron breakup and d(n,n)d elastic scattering). The interpolation subroutines, which originally generated the tables each time the program was run, were significantly slowed and enlarged by the addition of the data for the new processes. The routines were therefore re-written as a completely separate program, needing to be run only once, which writes the tables to disk, ready for immediate use by the Monte Carlo code. Currently the tables cover neutron energies up to 15 MeV, in 0.1 MeV steps.

In a deuterated scintillator, there is a possibility that an impinging neutron will cause a deuteron to break up. This produces an extra neutron within the scintillator, and the Monte Carlo program must track both. Furthermore, either of the neutrons from a breakup event may themselves cause a breakup, and so on. Fortunately, the Q-value for the process is negative, so there is a strict limit on the number of neutrons which can arise from a single incident neutron. The logic used to deal with breakup is shown in the simplified flowchart, Fig. 1.10. The breakup kinematics routine uses the formulae of Ohlsen[2] to produce the required energies and directions.

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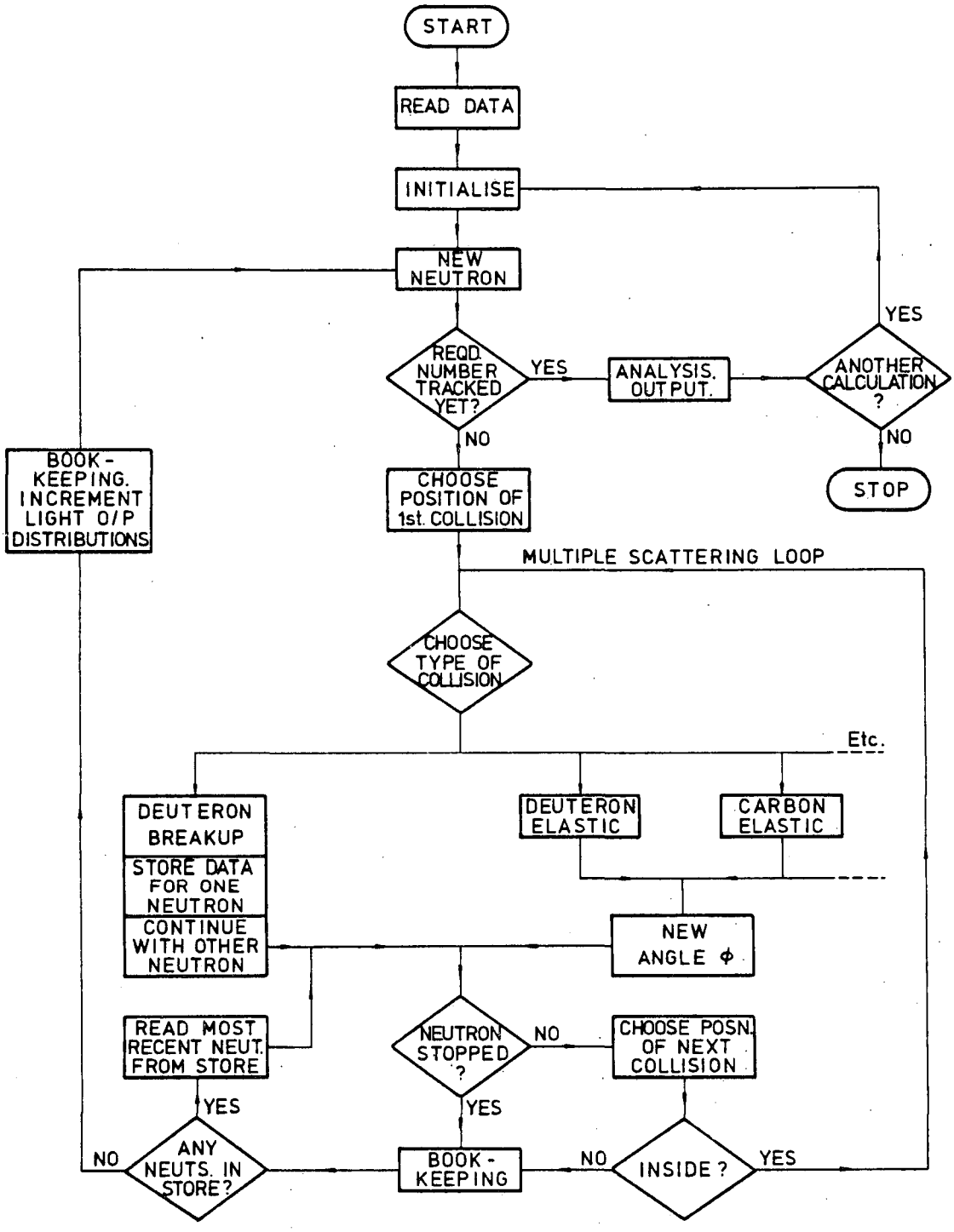

Fig. 1.10 Simplified flowchart of Monte Carlo program

At present, the light output from recoiling charged particles (protons, alpha-particles, deuterons or carbon nuclei) is calculated using data for NE213, with the assumption that the light output from a deuteron of energy E is twice that of a proton with energy E/2. It is intended to incorporate experimental measurements on NE230[3] in the near future.

When the required number of neutrons has been tracked, the results are printed out, and some analysis is performed on the light output pulse height distribution built up during tracking.

One routine calculates the efficiency of the scintillator. This is done by firstly smearing the pulse height distribution to simulate the detector resolution and then finding the percentage of the incident neutrons which gave rise to a pulse height greater than the experimental bias. The smearing is carried out by re-distributing the contents of each channel in the distribution amongst the neighbouring channels according to a Gaussian function. The width of the Gaussian is derived from the resolution function[4]

$$\left(\frac{\Delta E}{E}\right)^2 = A + B/E$$

where A and B are experimentally-determined constants.

Another routine compares the calculated distribution with an experimentally-measured one provided by the user. The two distributions (the calculated one smeared as before) are plotted out together on the lineprinter, and a statistical test of similarity is also carried out.

It is intended to extend the energy range of the program from the current maximum of 15 MeV to a new maximum of 20 MeV, and further carbon inelastic processes are being added to the program with this end in view.

A detailed description of the program is currently in preparation.

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(1) P. Saunders and G.G. Shute, UMP Report, (1969) unpublished.

(2) G.G. Ohlsen, Nucl. Instr. and Meth. 37 (1965) 240.

(3) D.L. Smith, R.G. Polk and T.G. Miller, Nucl. Instr. and Meth. 64 (1968) 157.

(4) J.B. Birks, 'The Theory and Practice of Scintillation Counting', Pergamon Press, 1964.

1.19 ^{239}U β^- Decay (S.P. Holloway, B.W. Hooton, T.D. MacMahon*)

An experiment is in progress to determine the major branching intensities in the β^- decay of ^{239}U by studying the levels of ^{239}Np populated by the reaction $^{238}U(n,\gamma)^{239}U$ and by the α decay of ^{243}Am. An accurate β^- decay study is important for decay heat calculations at the beginning of irradiated fuel handling and storage.

The measured intensity of a particular γ ray in the decay scheme (Fig. 1.11) is

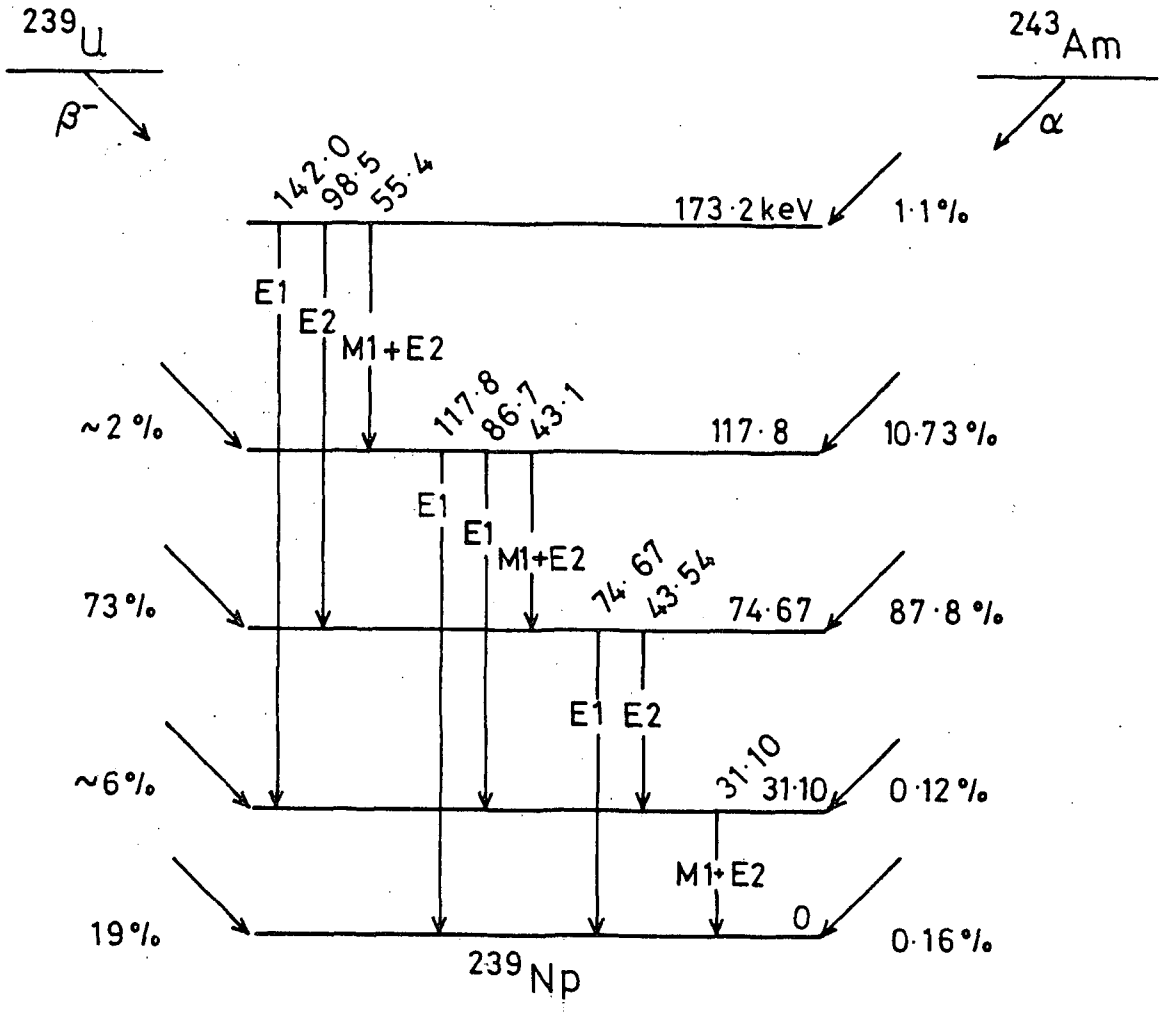

Fig. 1.11 Low energy ^{239}Np transitions populated by the (β^- decay of ^{239}U and the α decay of ^{243}Am.

given by

$$I_\gamma = S\beta E_\gamma F_\gamma$$

where S is the absolute β decay source strength, β is the unknown β^- branching, E_γ is the absolute γ ray detector efficiency and F_γ is the fraction of level decays which produce this particular γ ray. In general F_γ is unknown because of internal conversion

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and γ branching but since the mode of decay is independent of the mode of formation a similar experiment using ^{243}Am α decay would give

$$I_\gamma = A\alpha E_\gamma F_\gamma$$

where A is the absolute intensity of the α source and α is the well-known α branching ratio. If these two measurements are combined then β can be obtained and an independent measurement of $E_\gamma F_\gamma$ is not required. Correction for the population of levels by decay of higher excited states will be required.

The method necessitates making measurements of the absolute activities of the ^{239}U and ^{243}Am sources; a $4\pi\beta$-γ coincidence system is available at the University of London Reactor Centre to determine the absolute activity of a thin disc source of ^{239}U and a low geometry Si surface-barrier α detection system has been constructed to determine the absolute activity of the ^{243}Am disc source. ^{239}U sources suitable for the $4\pi\beta$-γ system are prepared by freeze drying a soluton of irradiated uranium nitrate (uranium content = 99.999% ^{238}U) onto a thin VNYS disc.

A preliminary experiment has been carried out to identify transitions in ^{239}Np from the reaction ^{238}U(n,γ)^{239}U; a few mg of uranium oxide (uranium content = 99.995% ^{238}U) were irradiated at the University of London 100 kW research reactor and then transferred rapidly to the counting position of an intrinsic Ge detector. It was essential to count for only a short period of time to reduce interference from the 2.3d β^- emitting ^{239}Np daughter. Fig. 1.12 shows the low energy γ spectrum from the ^{239}U decay.

^{243}Am α-γ coincidences have been studied using a 50 mm^2 Si surface-barrier α detector and 1500 mm^2 x 10 mm deep planar intrinsic Ge γ detector in a fast-slow coincidence system. The coincidence technique removes the 99.5 keV Pu Kα_2 and 117.2 keV Pu Kβ_1 X-rays from the spectrum making it possible to determine the absolute γ intensities of the 98.5 and 117.8 keV transitions respectively. The 142.2 keV transition indicated in Fig. 1.11 can also be seen in the coincidence γ spectrum, although there is no evidence of the reported 55.4 keV transition(1).

The 43.10 keV transition is not seen in either the singles γ spectrum from ^{239}U or the α-γ coincidence spectrum from ^{243}Am. The 31.10 keV transition has a high internal conversion coefficient ($\alpha \sim 170$) but it has been observed in both ^{239}U β^- decay and ^{243}Am α decay using an intrinsic Ge detector and will be used to estimate the β^- branch to the 31.10 keV level. It is planned to provide additional data on these low energy transitions from experiments investigating coincidences between

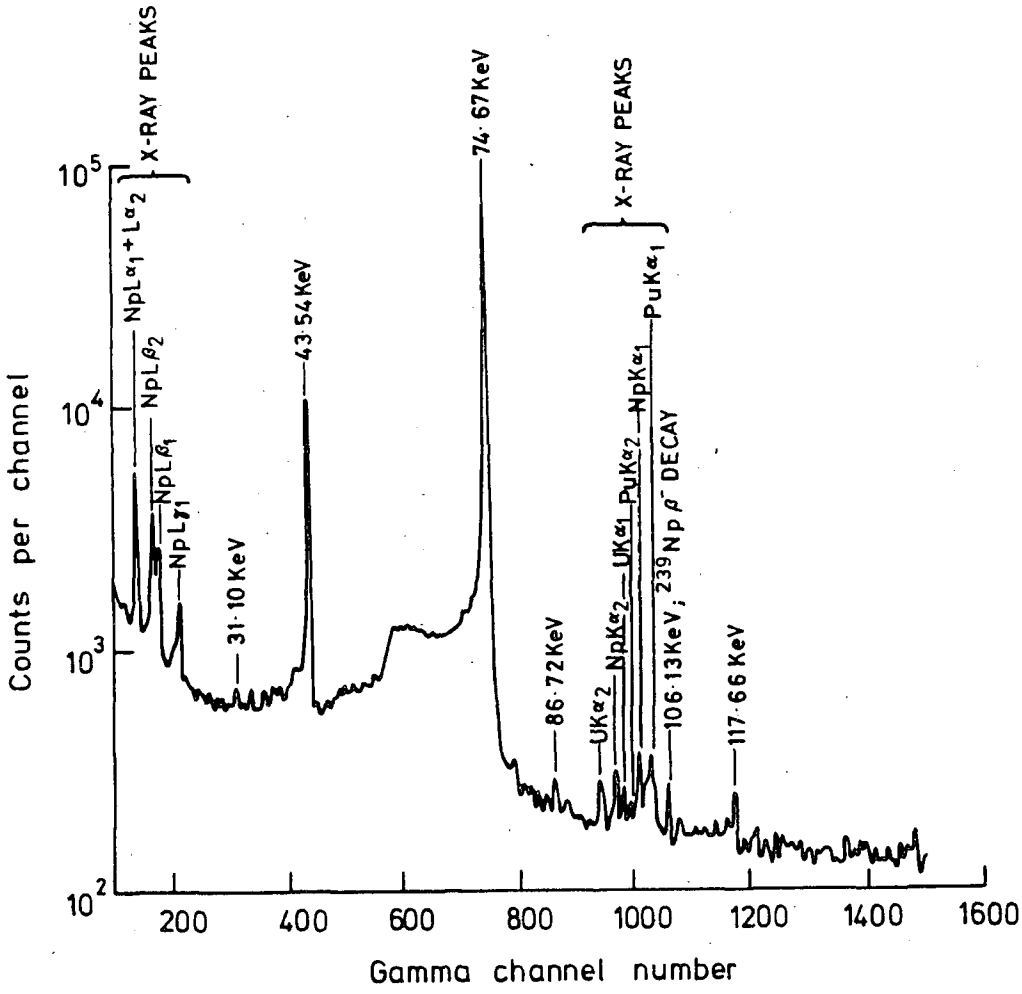

Fig. 1.12 ^{239}U low energy γ-ray spectrum

selected α groups and conversion electrons.

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(1) J.R. Van Hise and D. Engelkemeir, Phys. Rev. 171 (1968) 1325.

1.20 Nuclear data files (E.M. Bowey)

During the past year improvements have been made to computer programs employed for accessing data in the various Nuclear Data Libraries, through the use of the IBM TSO system. Further codes, particularly relevant to ENDF/B Libraries, have been obtained and are being implemented on the Harwell computer system.

1.21 The status of FISPIN on the Harwell Computer (D.A.J. Endacott)

A version of the code FISPIN[1] and its associated data libraries is maintained

on the Harwell computer for use by internal and external organisations. During the year the FISPIN 5 version of the code has been obtained from Risley and implemented on the Harwell computer. A series of test and production calculations have been performed with this and it has been found that the Risley and Harwell versions of the code give essentially identical results. Improvements to the data libraries used with the code have been implemented as they are received from Risley.

Though the code is well documented it has been necessary to provide help for users who are experiencing difficulties in using the code. Some users also require additional features in the code and these have been provided when necessary.

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

1.22 Aspects of Bonner Sphere neutron spectrometry (P.M. Thomas and K.G. Harrison EMSc Division, AERE Harwell)

Work has begun on developing a Bonner Sphere system at Harwell for measuring neutron spectra, primarily for radiological protection applications.

The system consists of eight polyethylene moderating spheres of radii 3.80 to 12.7 cm each of which may be placed over a 1.6 cm radius spherical ^{3}He counter (Centronic Type SP9).

A computer program has been developed for unfolding neutron spectra from a set of Bonner sphere counting rates. Harwell subroutine VA05A[1] is used for non-linear least squares minimisation and the following 5 parameter function is used to represent the spectrum:

$$\phi(E) = \phi_s E^{-\gamma} + \phi_p E^{\beta} \frac{2}{\sqrt{\pi}} \left(\frac{1.5}{\alpha}\right)^{1.5} \exp\left(-\frac{2E}{3\alpha}\right)$$

Initial investigations have shown this function to be an adequate representation of most shielding spectra likely to be encountered. Random perturbations are introduced to input counting rates for error analysis.

The sphere response functions have been calculated using the Monte Carlo neutronics codes MONK 5.3[2] and MORSE-CG[3] (University of Birmingham version[4] using UKCTRI multigroup data[5]). Good agreement between response functions calculated by these two codes was observed. Initial experimental calibrations are to be carried out using the Harwell IBIS accelerator.

The thermal neutron decay constants have been measured for each of the sphere

assemblies using (D,T) neutrons produced from the University of Birmingham Dynamitron accelerator operating in a pulsed mode (p.r.f. ∿ 170 Hz). Good agreement with diffusion calculations[6] and also time-dependent MORSE Monte Carlo calculations was obtained.

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(1) M.J.D. Powell, Computer J. 7 (1965) 303.

(2) V.S.W. Sherriffs, SRD-R-86 (1977).

(3) MORSE - A Multigroup Neutron and Gamma-ray Monte Carlo Transport Code. RSIC, Oak Ridge National Laboratory (1978) CCC-203/MORSE-CG.

(4) MORSE-B A revised version of the Monte Carlo Code MORSE, N.P. Taylor, University of Birmingham, Dept. of Physics. Paper No. 80-05.

(5) The UKCTRI Data Library - 46 group neutron cross sections for fusion reactor calculations, T.D. Beynon, and N.P. Taylor, University of Birmingham, Dept. of Physics. Paper 79-02.

(6) N.G. Sjostrand, J. Mednis and T. Nilsson, Arkiv fur Fysik 15 (1959) 471.

2. CHEMICAL NUCLEAR DATA

2.1 Introduction

Both the Main Committee and the Data Library Sub-Committee have met twice during the year.

The following pages give detailed reports on individual items of work carried out in the area of Chemical Nuclear Data but four items may be mentioned as of general interest and importance.

(a) A new evaluation of the Heavy Element and Actinide Data File has now been completed and installed in the current version of the complete Data File.

(b) cascade is now available at Harwell and Daresbury. Prospective users should contact Dr. H.E. Sims (Harwell) or Dr. G. Evangelides (Daresbury). The User Guide and the Manual are in the course of publication as AERE reports.

(c) The new Chemical Nuclear Data Request List has been discussed at the DIDWG and the amended version is awaiting publication along with the Physics Request List by AEE Winfrith.

(d) A completely new programme of measurement of fission product decay scheme data has been started at Harwell to satisfy demands in the current Request List.

2.2 Fission measurements

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

A series of 4 irradiations in ZEBRA core BZD/1, each of samples of ^{235}U, ^{238}U and ^{239}Pu have been carried out in both core and breeder island. The resulting fission product activities have been measured by γ-analysis which completes the experimental part of this study, while analysis of the data is now proceeding.

2.2.2 Fission yield measurements at Dounreay (W. Davies and V.M. Sinclair (DNPDE))

Irradiation of the capsules of the PFR fission yield experiment commenced in June 1978 and should be completed early in 1981.

The work for this experiment was outlined on pages 43-44 of UKNDC(75)P71.

2.2.3 Development of a helium jet recoil transport system for VEC studies of short-lived nuclides (R. Bett, J.G. Cuninghame, H.E. Sims (AERE), W. Gelletly (Physics Department, Manchester University) and V.J. Robinson (Chemistry Department, Manchester University))

Using helium as carrier gas and di-ethyl sulphide as cluster impurity, we have established a range of working conditions for a helium jet on Beam Line 3 of the Harwell VEC by transporting the products of the following reactions:

$$^{107,109}Ag + {}^{4}He\ (84\ MeV) \rightarrow \text{In isotopes}$$
$$^{107,109}Ag + {}^{16}O(100\ MeV) \rightarrow \text{Cs isotopes}$$

The reaction products were transported through a ∿10 m long polythene capillary of 1.2 mm i.d. to a tape transport system and hence to Ge(Li) detectors. Several unidentified In isotopes were seen from the first reaction and $^{120,\ 121,\ 122}Cs$ from the second.

2.2.4 Decay scheme studies on short-lived fission products (R. Bett, J.G. Cuninghame, H.E. Sims, H.H. Willis (AERE))

The UK Chemical Nuclear Data Request List asks for detailed decay scheme data for a variety of short-lived fission products from Zr to Ag with masses ranging from 102 to 111. We have chosen the Ru isotopes of mass 107 to 111 (with half-lives ranging from 4.5 m to 1.5 s) for the first series of measurements. Fission products will be generated by the reaction $^{209}Bi(\alpha,f)$ using α particles from the VEC. The products will be rapidly transferred by Helium Jet Transport system to separation and counting equipment. In addition Ru fission products will be used from an intense ^{252}Cf source for some measurements.

So far the helium jet equipment has been successfuly tested by transporting mixed fission products a distance of ∿10m using di-ethyl disulphide as the cluster impurity. The Cf source chamber has been designed and is now under construction.

2.2.5 Software for pulse height analysis on a PDP11 (J.G. Cuningham, H.E. Sims (AERE) and G. Hayton, E. Adlington (F. International))

We are developing associated codes which will permit on-line data acquisition from various types of detectors and off-line data processing. All the codes will run on a PDP11/34 or PDP11/05 computer under RT11 Version 4.

The codes are as follows:-

(a) Independent data acquisition from 4 ADC's, each having 4096 channels.

(b) 4-parameter event-by-event data acquisition.

(c) Rapid repeated acquisition of a 4096 channel spectrum from a fast decaying source and superposition of similar data from as many additional sources as is required.

(d) Peak search and analysis of all spectra.

(e) Reformatting Darmstadt γ-ray catalogue (40,000 γ-rays) to fit into the PDP11 so as to identify γ-ray peaks found by search routines.

(f) Use of PDP11 as an "intelligent terminal" to run the γ-analysis code (GAMANAL) on the Harwell Central Computer with spectra acquired by the above programs and to

return the results to our own terminal.

(g) Linking of PDP11 to a MOUSE microprocessor via an IEEE interface to control experimental equipment used in our decay data work.

2.2.6 Isomer ratios of fission fragments at high excitation (J.G. Cuninghame, J.A.B. Goodall (AERE), J.E. Freeman, G.W.A. Newton, V.J. Robinson, Chemistry Department, Manchester University), J.L. Durell, G.S. Foote, I.S. Grant, M. Rathle (Physics Department, Manchester University))

We have measured isomer ratios in antimony and bromine fission fragments in the $^{12}C + ^{209}Bi$), ($\alpha + ^{204}Pb$) and ($^{12}C + ^{196}Pt$) reactions. The values for the isomer ratios and their variation with energy are in accordance with the fragment angular momenta predicted by the Fermi gas model for the fissioning nucleus. Fig. 2.1 shows a comparison of the radiochemically measured isomer ratios with calculated values.

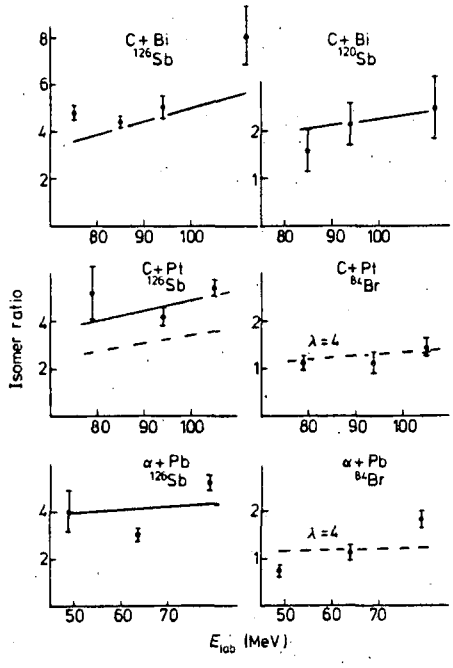

Fig. 2.1 Comparison of experimental isomer ratios with calculated values (full curves). The broken curve in the (α + Pb) figure for ^{126}Sb assumes saddle-point excitations. The broken curves on the bromine data are the calculated isomer ratios assuming a trapping efficiency parameter $\lambda = 4$.

This work has now been published in J. Phys. G: 6 (1980) 127.

2.2.7 The role of angular momentum in nuclear reactions (H.E. Sims (AERE), and E.M. Shaw, G.W.A. Newton, V.J. Robinson of Manchester University, Chemistry Department

Excitation functions and isomer yield ratios have been measured for the reactions $^{103}Rh(\alpha,xn)^{107-x}Ag$ for x = 1 to 5 at energies between 16 and 81 MeV using the Manchester HILAC and the Harwell Variable Energy Cyclotron.

The excitation functions are in good agreement with the 'ALICE' code theoretical calculations, indicating a compound nucleus reaction followed by evaporation of neutrons; allowances were made for pre-equilibrium reactions on the high energy tail of

the excitation function. Isomer ratios however are lower than predicted and can be explained on the basis of a by-pass fraction, due to the high-spin state being unfavoured in the de-excitation process, and the low spin state being populated in preference. This by-pass fraction has been calculated for $^{103}Rh(\alpha,n)^{106}Ag$, $^{103}Rh(\alpha,3n)^{104}Ag$ and $^{103}Rh(\alpha,5n)^{102}Ag$ and found to be approximately 30%, 16% and 18% respectively.

2.2.8 Fission-spallation competition in the A = 200 mass region (H.E. Sims (AERE) and S.M.A. Hoffmann, A. Szymanski, G.W.A. Newton, V.J. Robinson (Chemistry Department, Manchester University))

The effect of angular momentum on fission/spallation competition is being studied using two systems. In the first, $^{181}Ta + ^{16}O \rightarrow ^{197}Tl^*$, the long-lived isomer states of Tl isotopes give information on the role of angular momentum. Unfortunately absolute γ-abundances for some of the isomer pairs are uncertain but this has been remedied by measuring the absolute γ-intensities of both states of ^{190}Tl, and ^{192}Tl, using parent-daughter growth and decay relationships.

The second system studied is $^{16}O + ^{165}Ho \rightarrow ^{181}Re^*$ and we are evaluating measurements made on absolute γ-intensities of some of the isomer pairs, whose yields were also measured.

2.2.9 Competition between fission, spallation and deep inelastic scattering in heavy ion induced reactions (H.E. Sims (AERE) and R.J. Smith, G.W.A. Newton, V.J. Robinson (Chemistry Department, Manchester University))

Excitation functions have been determined, for several niobium (target) based products in oxygen (projectile) induced nuclear reactions.

Irradiations were performed, using the Manchester HILAC and the Harwell V.E.C., at ^{16}O projectile energies between 117 and 184 MeV.

The independent individual yields of a number of Y, Zr, Nb, Mo and Tc products are inconsistent with a compound nucleus evaporation reaction mechanism. It is suggested that the form of the excitation functions is the result of the superposition of a number of deep inelastic transfer reaction channels. The experimental technique used cannot distinguish between these channels.

In addition to absolute product yields, target foil escape fractions, for a number of products, have been evaluated at projectile energies of 183.6, 162.0 and 145.6 MeV. These provide information on the momentum transfer in forming the various products observed, offering a means of distinguishing between compound nucleus and deep inelastic transfer reaction products.

2.2.10 A study of some neutron deficient isotopes of Po (R. Bett, J.G. Cuninghame, H.E. Sims (AERE) and I.S. Grant, P. Misaelides of Physics Department, Manchester University)

We have made preliminary measurements of excitation functions for the formation of ^{200}Po, ^{201}Po, ^{202}Po, ^{203}Po and ^{204}Po in the $^{196}Pt(^{12}C,xn)$ reaction.

2.2.11 Studies of the reaction $^{238}U(\alpha,p)^{241}Np$ R. Bett, J.G. Cuninghame, H.E. Sims and B.W. Hooton (AERE) and S. Holloway (Imperial College)

The purpose of this experiment is to investigate the levels of ^{241}Np by on-line measurements while also examining its decay by off-line measurements. For the first part a thin depleted uranium target is bombarded with α-particles from the VEC to give the reaction

$$^{238}U + {}^{4}He \rightarrow {}^{241}Np + {}^{1}H$$

The use of an intrinsic Ge detector with a proton detector enables on-line γ-spectrum to be viewed in coincidence with the emitted protons.

For off-line measurements a catcher foil is used to collect the recoiling ^{241}Np nuclei which are counted on a normal Ge(Li) detector after a suitable time.

Preliminary experiments have revealed problems with the on-line proton detector which are being resolved. In off-line measurements a number of 25 m half-life γ-lines were detected which have yet to be identified. Catcher foils (are being prepared) which are only just thick enough to stop ^{241}Np recoils in order to reduce collection of fission fragments.

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

The samples of ^{235}U and ^{239}Pu in dilute nitric acid solution, which have been irradiated in the thermal reactor GLEEP, are awaiting chemical separation and counting.

Samples of pure metallic ^{235}U and ^{239}Pu were irradiated in the zero energy fast reactor ZEBRA during a special long irradiation in March/April 1980. These will be processed when the thermal work is completed.

Samples of ^{240}Pu and ^{241}Pu, 1 gram of each, have been obtained for use in further work.

2.3 Cross section measurements

2.3.1 Integral experiments to measure the partial capture cross section for the production of ^{242}Cm and ^{244}Cm (K.M. Glover, B. Whittaker, R.A.P. Wiltshire, M. King, D. Anstey and T. Brooks)
(Relevant to request numbers 1604, 1607 and 1672)

Eleven ampoules containing ^{241}Am and four ampoules containing ^{243}Am were

subjected to an extended irradiation, from March 10th until April 22nd 1980, in typical fast reactor core and breeder region spectra in the Zebra reactor at Winfrith, to measure the cross sections leading to the production of ^{242m}Am and ^{242}Cm (from ^{241}Am) and ^{244}Cm (from ^{243}Am).

The ^{242}Cm and ^{244}Cm produced in the irradiation are separated from ^{241}Am and ^{243}Am respectively by radiochemical techniques using ion exchange.(1)

Six ^{241}Am ampoules have now been processed, ampoules 1 and 2 from block 2 element location 50, 38; ampoules 3 and 4 from block 3 element location 54, 34 and ampoules 7 and 8 from block 4 element location 50, 45.

Provisional values for these cross sections are shown in Table 2.1.

Table 2.1

^{242}Cm production cross sections in ZEBRA reactor

Ampoule No.	Core Position	Production Cross Section
1	50, 38	2.05 barns
2	"	2.05 barns
3	54, 34	1.14 barns
4	"	1.14 barns
7	50, 45	3.97 barns
8	"	4.00 barns

Dissolution of further ampoules is complete.

The column for the ^{243}Am separations has been calibrated and an archive sample processed to measure accurately the ingrowth of ^{242}Cm from the ^{242m}Am present in the ^{243}Am prior to irradiation. Measurement of the production cross section of ^{244}Cm is more complex than for ^{242}Cm because of corrections which have to be applied. These are for ^{242}Cm ingrowth from ^{242m}Am present in the ^{243}Am, for ^{243}Cm present in ^{242}Cm, and because the ^{244}Cm peak lies in the low energy tail of the alpha peak from the ^{242}Cm spike. Optimisation of the quantity of spike to be added is important if an accurate result is to be achieved. Dissolution of ampoule No. 21 from block 2 is complete and this sample will be processed, when the ancillary data measurements are complete.

(1) Radiochemical techniques used to measure the cross sections leading to the

production of ^{242}Cm and ^{244}Cm in ^{241}Am and ^{243}Am samples irradiated in the Zebra reactor at Winfrith. R.A.P. Wiltshire Symposium on Modern Radiochemical Practice, York 1980.

2.3.2 Measurement of neutron cross sections in PFR (E.A.C. Crouch, I.C. McKean, J.G. Cuninghame and H.H. Willis (AERE), W. Davies, D.J. Lord and V.M. Sinclair (DNPDE), N.R. Daly (AWRE))

Details of this programme, which will check cross section data in neutron spectra similar to CFR, were given in UKNDC(75)P71, page 53. Irradiation of most of the capsules, which contain ^{10}B, ^{235}U, ^{238}U, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am and ^{243}Am is now complete, and dispatch of the irradiated capsules to the analytical laboratories at DNPDE, AWRE and AERE is imminent.

2.4 Half-life Measurements

2.4.1 ^{242}Cm alpha half-life (R.A.P. Wiltshire, A.J. Eccles and T. Brooks)

The ^{242}Cm half-life has been measured by direct decay and data has been collected over several half-lives. The experimental work is complete and evaluation of the data is in progress.

2.4.2 ^{242}Cm spontaneous fission half-life (R.A.P. Wiltshire)

It is planned to start this measurement, which is a priority 1 data requirement, in 1981.

2.4.3 ^{239}Pu half-life measurement (D. Brown, K.M. Glover, M. King, G. Phillips, F.J.G. Rogers and R.A.P. Wiltshire)

The half-life of ^{239}Pu has been determined(1) by specific activity measurements on solutions prepared from the stoichiometric compound Cs_2PuCl_6 using plutonium 99.04% enriched in ^{239}Pu. The value obtained is 24,088 years with a standard error of ± 12 years. A realistic uncertainty, including systematic error component, of $\pm$ 51 years is ascribed to this measurement.

2.4.4 ^{239}Pu half-life evaluation (K.M. Glover and A.L. Nicholls (AEE Winfrith)

A comprehensive evaluation of all ^{239}Pu half-life measurements published in the open literature is in progress. Some data associated with relatively large ill defined systematic errors has been rejected and an interactive computer program is being used to calculate the weighted mean value from the remaining data.

2.4.5 ^{237}Np half-life and I_α (D. Brown, K.M. Glover, M. King, G. Phillips and R.A.P. Wiltshire)
(Relevant to request number 1323)

It is anticipated that the half-life of ^{237}Np will be redetermined by specific activity measurements during 1981. Two stoichiometric compounds are under consideration,

$Cs_2NpO_2Cl_4$ and $NaNp(CH_3COO)_3$. Sodium neptunyl acetate has the advantage that the source thickness for a given mass of ^{237}Np will be less than for $Cs_2NpO_2Cl_4$. To achieve high accuracy it is important that source thickness be minimised and for this reason it is planned to measure the alpha disintegration rate in the new medium geometry counter rather than in the low geometry counter used to measure the half-life of ^{239}Pu. As a related study, I_α (relative branching intensities for α-decay) for ^{237}Np will be investigated. These measurements have a high priority in the IAEA actinide data request list.

2.4.6 ^{230}Th half-life (K.M. Glover, R.A.P. Wiltshire and B. Whittaker)

There is a need to redetermine the half-life of ^{230}Th since the IAEA NDC recommended half-life of $7.7 \pm 0.3 \times 10^4$ is questioned by oceanographers using U/Th dating. Their results indicate that a half-life value of 7.5×10^4 y is more correct. It is proposed to remeasure the half-life of ^{230}Th by specific activity measurements using electromagnetically enriched material.

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(1) A redetermination of the half-life of ^{239}Pu by specific activity measurements. D. Brown et al Symposium on Modern Radiochemical Practice, York, 1980.

2.5 Fission product decay data

2.5.1 Data Library Sub-Committee

Data Library Sub-Committee Members: B.S.J. Davies (Chairman, CEGB), K.M. Glover (AERE), M.F. James (AEEW), A.L. Nichols (AEEW), B. Aldred (BNFL), A. Tobias (Secretary, CEGB), D.G. Vallis (AWRE), H.E. Simms (AERE).

The sub-committee is responsible for the development and maintenance of the data files which together constitute the UK Chemical Nuclear Data Library, the current status of which is shown in Table 2.2.

A file (UKHEDD-1) has been set up which contains decay data for 125 nuclides in the heavy element region extending from mercury-206 to einsteinium-253. These data, which are in ENDF/BV format, are complete except for spontaneous fission decay data which will be added later.

Extensive revisions to the fission product decay data file UKFPDD-1 have been completed[1], the revised file being called UKFPDD-2. The data have been tested both by comparison on an item-by-item basis with the US-ENDF/BV file and by using them as input for the inventory code FISP, the results being compared both with calculations

Table 2.2

UK Chemical Nuclear Data File

status table, October 1980

Data	Present Status	File Development
1. Fission Product Decay Data	Exists as UKFPDD-2 (ENDF/B-IV format) - Total no. of nuclides = 855 Radioactive nuclides = 736 Ground state = 715 1st excited state = 133 2nd excited state = 5 Nuclides with spectra = 390 Total no. of gamma lines = 11978 Total no. of beta$^-$ lines = 3592 Total no. of beta$^+$ lines = 91	Delayed neutron emission probabilities to be inserted into UKFPDD-2 on completion of evaluation by Crouch (AERE)
2. Activation Product Decay Data	Available in ENDF/B-IV format for 91 nuclides	Maintenance and improvements are in hand (Nichols, AEEW)
3. Heavy Element and Actinide Decay Data	Exists as UKHEDD-1 (ENDF/B-V format) - Total no. of nuclides = 125 Ground state = 111 1st metastable state = 13 2nd metastable state = 1 Total no. of alpha lines = 767 Total no. of beta$^-$ lines = 527 Total no. of beta$^+$ lines = 39 Total no. of gamma lines = 3474 Total no. of discrete electrons = 6755 Total no. of X-rays = 381	Spontaneous fission data being evaluated (James, AEEW) - completion expected by end of 1980
4. Fission Yields	Available in ENDF/B-IV format, based on Crouch's second round of adjustment (Crouch 3). 60 new compilations have been added. Yields to isomeric states have been calculated on basis of ENDF/B-IV ratios and are included	It is hoped to publish this evaluation by the end of 1980
5. Delayed Neutrons	Tomlinson data are still recommended.	Delayed neutron emission probabilities and half-lives of precursors have been evaluated. Neutron spectra await evaluation.
6. (α,n) cross sections	None in library	Data being evaluated by James (AEEW)

based on other data sets and experimental results[2]. The new data file contains considerably fewer theoretical values than the old, and spectral data is now included for 390 nuclides compared with 302 previously.

An extensive review of decay heat evaluation has also been published[3].

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(1) A. Tobias and B.S.J. Davies, CEGB Report RD/B/N4942, (1980).

(2) A. Tobias, CEGB Report RD/B/N4949, (1980).

(3) A. Tobias, Prog. in Nucl. Energy, 5, (1980), pp.1-93.

2.5.2 Fission product yield assessments and consistent sets (E.A.C. Crouch)

(a) The fission product library has been augmented with newly published yields, and values for the isomeric ratios have been incorporated into the routine used for outputting the fission yields in ENDF/B-IV format. These ratios were calculated in the manner of Madlard and England[1]. When no data is available the independent yields have been divided equally between the ground state and the first excited states.

(b) A sub-library of neutron emission probabilities and half-lives of precursors has been made and will be included with the fission product yields until a separate delayed neutron evaluation has been completed.

(c) The computer routines used in this work have been cast into a suitable form to output data for a typesetting system ("TCCD"), which produces typeset output ready for printing.[2] This process does not involve reproduction of computer line-printer output nor hand setting of mathematical material, and should therefore save much proof reading.

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(1) Madlard and England, LA-6595, (1975).

(2) M.J. Hopper, AERE R-8574, (1976).

3. REACTOR PHYSICS DIVISION, AEE, WINFRITH
(Division Head: Dr. C.G. Campbell)

3.1 The UK Nuclear Data Library (R.W. Smith and J.S. Story)

New editions of the general purpose tape NDL1, fission-product tape NDL-2 and dosimetry tape NDL-3 were distributed to AERE, AWRE, Risley and the NEA Data Bank during the year.

Work continues in the re-evaluation of the resonance parameters of the iron isotopes.

In the light of comments received from the NEA Data Bank, the resonance cross section program SIGAR7 has been further revised and has been implemented on the ICL-2976 computer. Implementation on the IBM-3033 computer at Harwell is proposed.

3.2 The calculation of the sensitivities of nuclide inventories to nuclear data (M.F. James)

The inventory program FISPIN has been modified to calculate the sensitivities of actinide inventories to variations in half-lives and cross-sections. Sensitivities can be completed for either constant flux or constant power during irradiation periods.

Similar modifications are in hand to calculate sensitivities for fission product inventories.

3.3 AEE Counting Laboratory (W.H. Taylor)

3.3.1 Actinide fission rate measurements

Absolute fission rates of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and ^{244}Cm have been determined in the fissile and fertile regions of a heterogeneous (annular) fast reactor core in Zebra. The comparison of these measured with calculated values is in progress.

3.3.2 Studies of the $^{93}Nb(n,n')^{93m}Nb$ reaction (Relevant to request number 704)

Absolute determinations of the $^{93}Nb(n,n')^{93m}Nb$ reaction rates in EBRII (USA) and BR2 (Belgium) reactors have been made by six European laboratories (including AEE Winfrith) as part of a niobium dosimetry intercomparison experiment. The estimated accuracy of these determinations was $\sim\pm3\%$ and the preliminary conclusion (based on the spread of results) was that the absolute reaction rate could be determined with an accuracy $\sim\pm6\%$. A proposal has been made to measure the differential cross section for this reaction (which at present is only inferred from integral experiments) using the DYNAMITRON machine at Birmingham University as the source of monoenergetic neutrons and

with the absolute levels of induced activities being determined at AEE Winfrith. It is proposed to start this work during 1981.

3.3.3 β and γ decay power from fast fission

Further measurements[1] of β decay power from the fragments from the fast fission of ^{239}Pu and ^{235}U have been made following an intermittent irradiation in Zebra over a period ∿1 month during which the fissile deposits experienced a total fluence of $\sim 10^{16} n/cm^2$. Attempts to measure the γ-ray energy were made using a large liquid scintillator tank at AERE and measurements of the X and γ-ray spectra were made at different cooling times. The analysis of this work is expected to be completed during 1981.

3.3.4 Activation cross sections of fast reactor core materials and coolant impurities

The absolute activities induced in the components of fast reactor steels and coolant impurities (K, Zn) (normalised to the absolute ^{239}Pu fission rate) have been determined after the samples had been irradiated in the fissile and fertile regions of a heterogeneous fast reactor core in Zebra. Preliminary comparisons between experimental values and values calculated using the MURAL code and the FGL5 or FD5 cross section file, show agreement, for the majority of reactions, to within ∿30%. A report summarising the results and analysis of the component activation experiments that have been made in three Zebra cores should be produced during 1981.

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(1) M.F. Murphy, W.H. Taylor, D.W. Sweet and M.R. Marsh, AEEW R1212 (1978).

4. PHYSICS DEPARTMENT, NATIONAL RADIOLOGICAL PROTECTION BOARD

(Head of Department: J.A. Reissland)

4.1 Neutron cross section and Kerma calculations from 20 to 50 MeV (P.J. Dimbylow)

A calculation of kerma values for C, N and O from 20 to 50 MeV[1] has been completed. An optical model program, NOPTIC has been used to calculate total and elastic cross secions whilst reaction cross sections have been computed using an evaporation model program, SMOLDERS[2]. The emitted particle and recoil nucleus spectra have been converted from the centre-of-mass system into the laboratory system so as to obtain kerma values. Multiple particle cascade chains are treated as sequential two-body break-up reactions and in all processes the angular distribution of emitted particles is assumed to be isotropic in the centre-of-mass system.

The evaluation of neutron cross section data has been extended to Al, Mg, P, S, Ar and Ca. Available total and elastic cross section data have been fitted using NOPTIC.

A more complete approach to the calculation of reaction cross sections requires the inclusion of discrete energy levels and precompound effects. This approach has been followed in the form of a multi-step Hauser-Feshbach code, GNASH[3]. The residual nuclei are composed of a set of discrete energy levels of known energy, spin and parity at low excitation energies joined to a continuous level density description at the higher energies. The program uses a simplified pre-equilibrium expression which does not include spin and parity effects. The reaction cross sections for Mg, Al, P, S, Ar and Ca as well as for C, N and O have been calculated using GNASH.

Work is in progress to calculate the direct reaction components of inelastic scattering to low lying levels in C and O which are produced by collective modes of excitation, using the Distorted Wave Born Approximation code, DWUCK[4]. These are, in particular, the 2^+ level at 4.43 MeV and the 3^- level at 9.64 MeV in C and the 2^+ (6.92 MeV), 3^- (6.13 MeV) levels in O. Direct components of (n,d) and (n,p) reactions are also being investigated.

Kerma values from the combined GNASH and DWUCK results will be calculated.

This project was part-funded by CEC contract 164-76 B10 UK.

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(1) P.J. Dimbylow, "Neutron cross sections and kerma values for carbon, nitrogen and oxygen from 20 to 50 MeV." Phys. Med. Biol., 25 (4), 637-649, (1980).

(2) P.J. Dimbylow, "The high energy neutron cross section programs NOPTIC and SMOLDERS", NRPB-M44, (1980).

(3) P.G. Young and E.D. Arthur, "GNASH: A pre-equilibrium statistical nuclear model code for calculation of cross sections and emission spectra", LA-6947, (1977).

(4) P.D. Kunz, Private communication.

5. DIVISION OF RADIATION SCIENCE AND ACOUSTICS
NATIONAL PHYSICAL LABORATORY
(Supt. Dr. W.A. Jennings)

5.1 Neutron source calibrations (E.J. Axton, A.G. Bardell)

Following the acquisition of high purity $MnSO_4$ solution for the manganese bath facility, a series of measurements have been completed at ten different manganese concentrations, with a RaBe photoneutron source in the 50 cm diameter bath and a ^{252}Cf source in the 100 cm diameter bath. Analysis of the results should yield values for the source strength and for the H/Mn thermal neutron capture cross section ratio. These may be compared with historic values corrected for the effects of recently discovered chemical impurities in the old solution.

In view of the importance of the S/Mn thermal neutron capture cross section ratio in absolute neutron source strength measurements using the manganese bath technique, an experiment has been designed to determine this parameter by varying the concentration of sulphur in the solution.

5.2 International comparison of neutron source strength

The comparison organised by the International Bureau of Weights and Measures(1) (BIPM) is in progress. Measurements are expected to be completed during 1981. Seven laboratories have now completed their measurements. A list of participants is given below.

National Bureau of Standards (NBS) USA
Bureau International des Poids et Mesures (BIPM)
Physikalisch-Technische Bundesanstalt (PTB) Federal Republic of Germany
Comitato Nazionale Energia Nucleare (CNEN) Italy
Centre d'Etudes Nucleaires (CEN) France
Laboratoire de Metrologie des Rayonnements Ionisants (LMRI) France
Amt fur Standardisierung, Messwesen und Warenprufung (ASMW) German Democratic Republic
V.G. Khlopin Radium Institute (VG KRI) USSR
D.I. Mendeleev Institute of Metrology (VN IIM) USSR
Electrotechnical Laboratory (ETL) Japan
Bhabha Atomic Research Centre (BARC) India
National Physical Laboratory (NPL) UK

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(1) NPL represents the UK upon the various consultative committees of the Comite International des Poids et Mesures (CIPM) which surveys the work of BIPM.

5.3 International comparison of neutron fluence rate organised by BIPM

Details of the neutron energies and transfer methods were given in the previous report (UKNDC(80)P96, p.89). The majority of participants were not ready to start in April 1980, and proving of some of the transfer devices was not complete. Measurements are now expected to commence in April 1981.

5.4 Neutron cross sections at energies near 14 MeV (T.B. Ryves, P. Kolkowski)
(Relevant to request numbers 707, 704, 715, 1020, 1293)

Some activation cross sections have been measured with a calibrated Ge(Li) detector, and the final results, which supersede those given in the previous UKNDC progress report[1], are given in Table 5.1. The uncertainties are 1σ.

Table 5.1

Neutron cross sections at about 14 MeV

Reaction	Neutron Energy MeV	Cross Section mb	Reference
$^{93}Nb(n,2n)^{92m}Nb$	14.68	453 ± 11	(2)
$^{93}Nb(n,\alpha)^{90m}Y$	14.68	5.56 ± 0.18	(2)
$^{93}Nb(n,n')^{93m}Nb$	14.3	36.5 ± 3.0	(2)
$^{181}Ta(n,2n)^{180m}Ta$	14.68	1307 ± 40	(3),(4)
$^{197}Au(n,2n)^{196g+m}Au$	14.68	2170 ± 67	(5)
$^{197}Au(n,\gamma)^{198}Au$	14.3	1.09 ± 0.10	(5)
Isomeric ratio for ^{196}Au	14.3	0.068 ± 0.003	(5)

In addition, the provisional cross section for $^{238}U(n,2n)^{237}U$ was 778 ± 23 mb at the re-evaluated energy of 14.59 MeV. Other measurements have been completed for Zr, Ag and In.

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(1) UKNDC(80)P96, p.87.

(2) T.B. Ryves and P. Kolkowski (1981), J. Phys. G. 7, to be published.

(3) T.B. Ryves (1980), J. Phys. G., 6, 763.

(4) T.B. Ryves and P. Kolkowski (1980), J. Phys. G. 6, 771.

(5) T.B. Ryves and P. Kolkowski (1981), J. Phys. G. 7, 115.

5.5 Evaluation of neutron cross sections at 14.7 MeV (T.B. Ryves)

A simultaneous evaluation of eight inter-related cross sections by the method of least squares has been started. The cross sections, selected for their importance as neutron standards, are those for the reactions $^{1}H(n,n)$, $^{32}S(n,p)$, $^{27}Al(n,\alpha)$, $^{56}Fe(n,p)$, $^{63}Cu(n,2n)$, $^{65}Cu(n,2n)$, $^{93}Nb(n,2n)$ and $^{197}Au(n,2n)$. The theoretical model has been formulated and a FORTRAN program written to handle the data. Work is now in progress to incorporate reliable published data. It is hoped to achieve a data set with 1σ uncertainties of 1-3%, which can be compared with other evaluations.

5.6 Neutron time-of-flight spectrometry (J.B. Hunt)

The commissioning of the nanosecond pulser system on the 3.5 MV Van de Graaff accelerator has been completed. Preliminary measurements have been made of the neutron spectra from the reactions Li(p,n), T(p,n), Sc(p,n), D(d,n), Be(d,n) and T(d,n). Contributions from competing reactions, in scatter and target scattering are being investigated with a view to decreasing their magnitude.

5.7 Nuclear decay scheme measurements (P. Christmas, D. Smith, M.J. Woods, R.A. Mercer, L.E.H. Stuart, A.E.M. Hodgson)

A paper has been published(1) on the determination of the relative intensities of γ-rays from pure E2 transitions in the decay of ^{180m}Hf.

On behalf of BIPM, the laboratory has organised an international intercomparison of the absolute counting of ^{55}Fe. A draft report has been prepared. From the results a preliminary value of 0.282 with a standard error of the order of $\pm$ 0.003 has been deduced for $p_k w_k$ (the probability of producing a K X-ray per nuclear decay).

The NPL magnetic separator is being used to prepare isotopically pure samples of $^{151,153}Eu$ required for accurate determinations of the half-lives of $^{152,154}Eu$ using ionisation chambers.

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(1) P. Christmas and P. Cross, Nucl. Instr. Meth., 174, (1980) 571.

6. UNIVERSITY OF BIRMINGHAM, DEPARTMENT OF PHYSICS

6.1 Fast neutron spectrometry and its application in fusion reactor data evaluation and medical physics (M.C. Scott, J.W. Bennett, R. Koohi Fayegh and J.S. Petler)

Further development work has been undertaken on the miniature (∿1.5 cc) NE213 neutron spectrometer described in earlier reports[1]. This had centred on two aspects, the first being the prediction of response functions, allowing the use of matrix unfolding codes, and the second has been to build a probe suitable for medical physics applications.

The two main problems relating to response function prediction are (i) knowing the alpha to proton light output ratio, and (ii) determining the cross section and reaction branches for the $^{12}C(n,n'3\alpha)$ reaction. Although we have undertaken some preliminary work to determine the alpha light output directly, using an organic compound of astatine-211 (which emits alphas of 5.8 and 7.2 MeV), for the present work the value at an energy point was determined by adjusting the predicted $^{12}C(n,\alpha)$ peak in the response function to obtain agreement with an absolute measurement at 14 MeV. We obtained a value for the alpha-proton light output ratio which was 20% higher than that of Verbinski[2]. However, since related photon transport studies indicate that this ratio could be geometry dependent, this result is not unexpected.

The $^{12}C(n,n'3\alpha)$ branches used in the O5S response function prediction code were increased to include the reactions via ^{9}Be, and to include more excited levels of ^{12}C. The branching ratios were then adjusted to obtain the best fit to the measured response: this occurred with 45% of the decays via $^{9}Be^{*}$ and with the following percentages going via the $^{12}C^{*}$ levels for 14 MeV neutrons: 4% via the 9.63 and 10.1 MeV levels, 16% via 10.84 MeV, 14% via 11.82 and 17% via 12.73 MeV. The resulting agreement between prediction and measurement is shown in Fig. 6.1, the two diverging only below a proton energy of about 1.5 MeV.

Calculated response functions using this data were then used with the matrix unfolding code FERDOR to measure spectra from a 14 MeV source in bare Be shells and in Be shells surrounded by a large integral assembly of lithium fluoride[3]. A typical result is shown in Fig. 6.2, where it is compared with a P_7S_{16} transport calculation using the ENDF/B-IV data set and the ANISN S code.

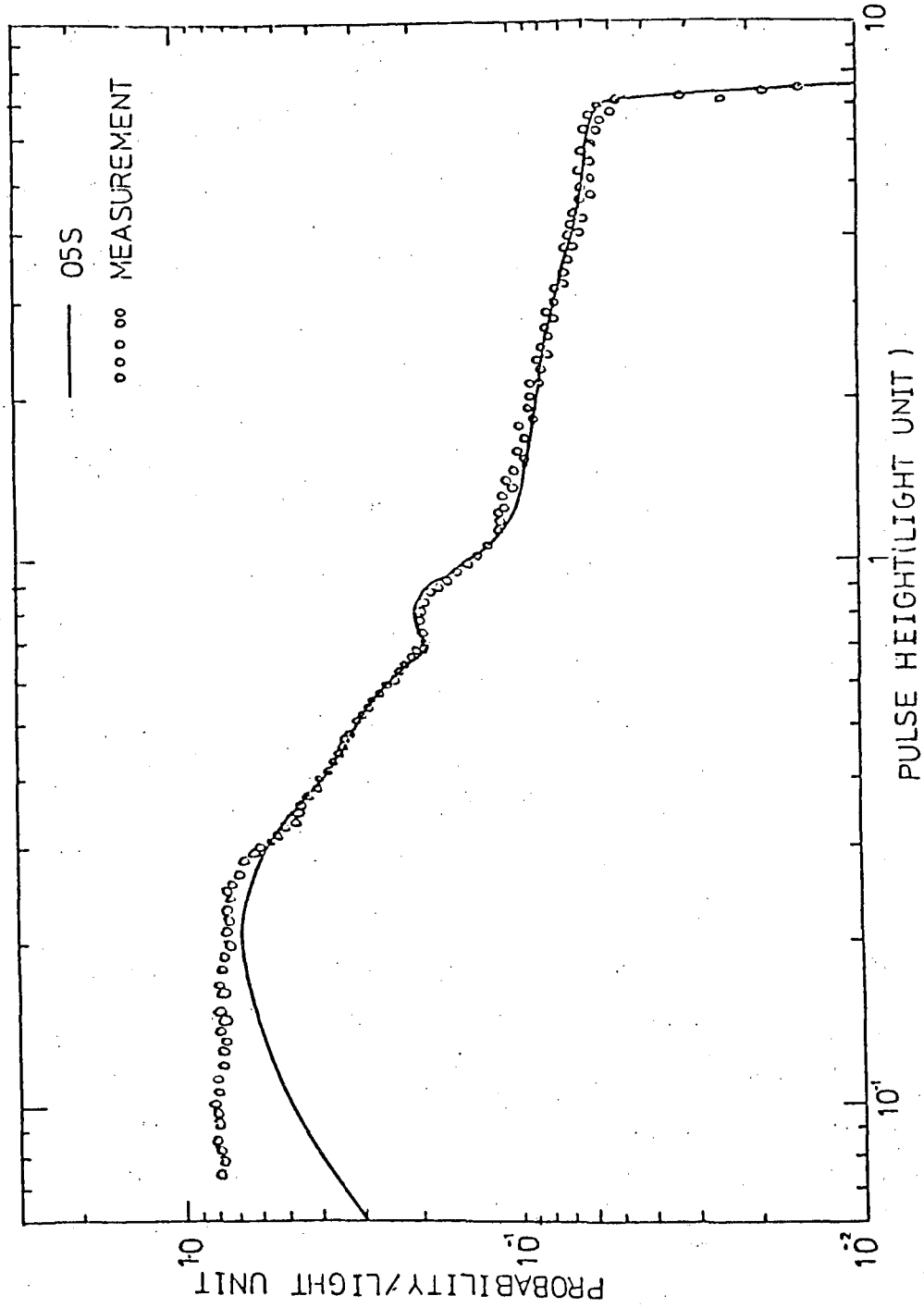

Fig 6.1 Comparison of prediction and measurement of a 14.3 MeV response function

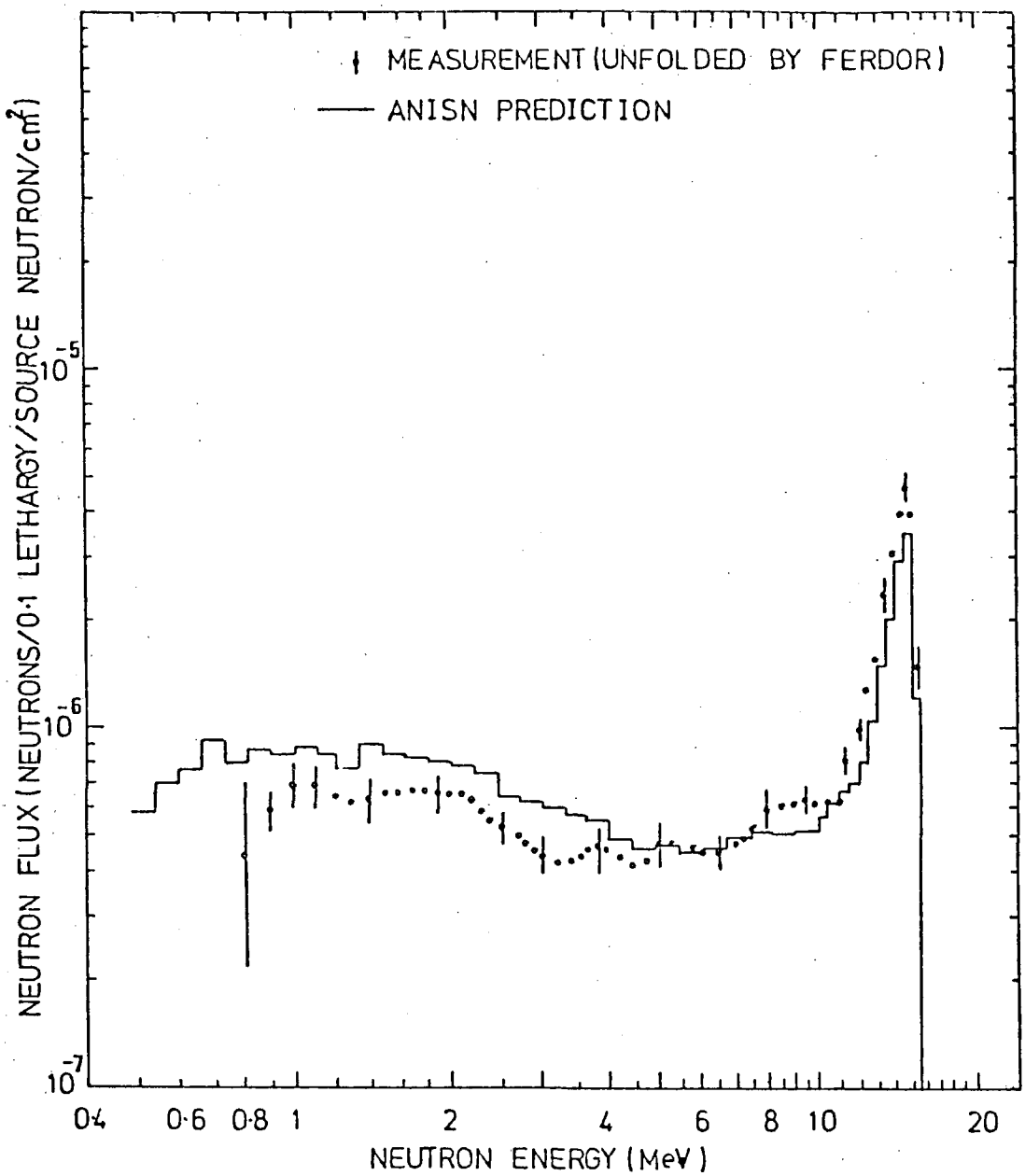

Fig 6.2 Neutron flux in the assembly at (r = 55.3 cm, θ = 0°) for t = 9.65 cm

For medical physics applications, where we want a water-tight probe for making measurements in phantoms, the cell has been placed at the end of a 235 mm long, 15 mm diameter optical quartz light guide, surrounded with aluminium foil and encapsulated in stainless steel. The effect of the light guide was to attenuate the light output signal by a factor of 0.55. However the resolution measured using gamma sources improved by 20-25%. A series of neutron spectra measurements from 14 MeV sources have been made on a simple water phantom using a detector without a light guide, and comparison with a Monte Carlo calculation using ENDF/B-IV data gives excellent agreement.

Some work has also been carried out to determine the response of spherical proton recoil proportional counters to 14 MeV neutrons, since we wish to use these to make

measurements in the 10 keV to 2.5 MeV range. Preliminary Monte Carlo calculations indicate that (n,p) and (n,α) reactions in the stainless steel walls are significant in determining the response.

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(1) L.J. Perkins and M.C. Scott. Nucl. Instr. Meth. 166 (1979) 451-464.

(2) V.V. Verbinski et al. Nucl. Instr. Meth. 65 (1968) 8.

(3) R. Koohi-Fayegh, Ph.D. Thesis, University of Birmingham, 1980, "Neutron Spectrum Measurements in a Be-LiF Assembly Using an NE 213 Scintillator".

7. BIRMINGHAM RADIATION CENTRE, UNIVERSITIES OF BIRMINGHAM AND ASTON

(Director: Professor J. Walker)

7.1 The neutron spectrum from an Am/Li source (D.R. Weaver, J. Walker and J.G. Owen)
(Relevant to request numbers 16, 17)

As reported last year (UKNDC(80)P96, p.101), the neutron spectrum (Fig. 7.1) from

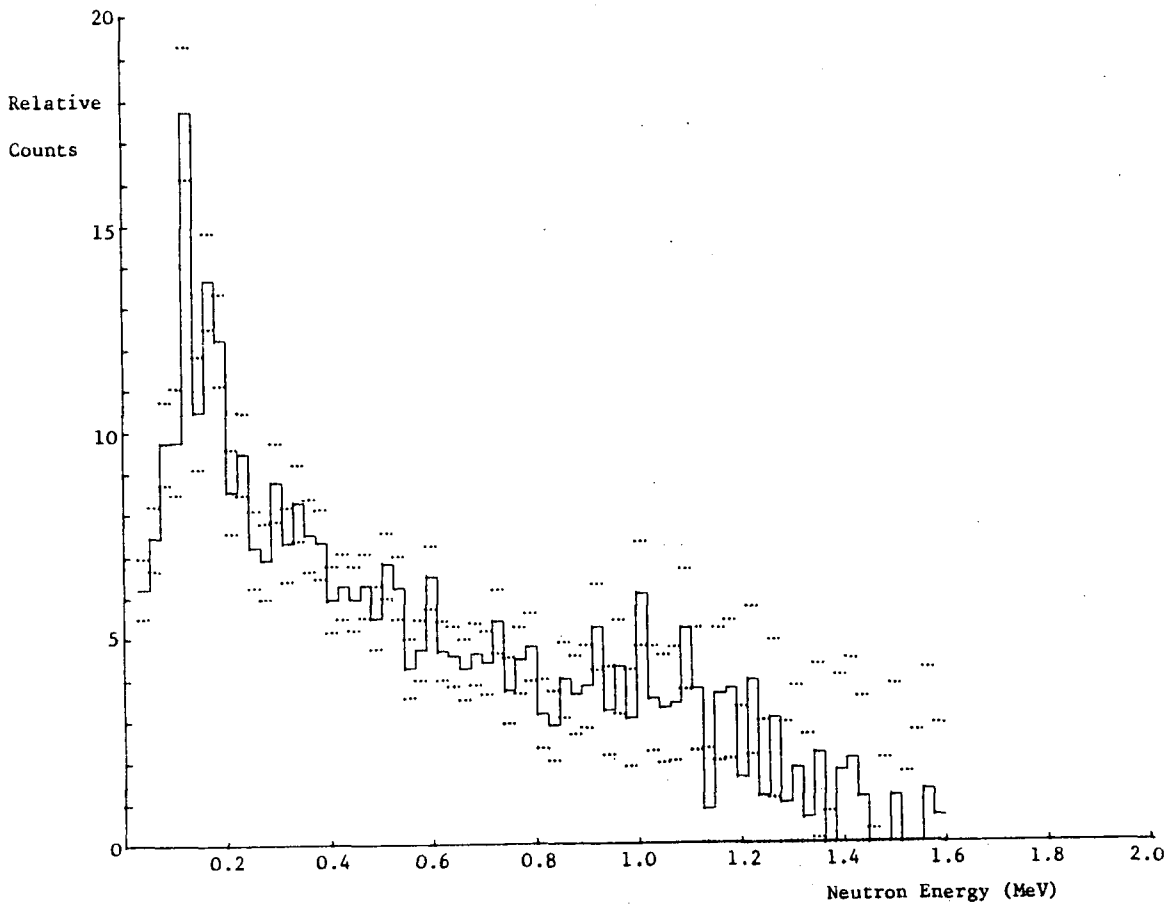

Fig 7.1 The neutron spectrum from an Am/Li source

an Am/Li source has been measured. This differs from that shown previously in that a full correction has now been made for protons recoiling within the counter volume. In addition the groups for unfolding the energy structure are slightly broader, each being 21.7 keV wide compared with 15 keV used previously. This latter change has been incorporated to avoid rebinning the data prior to unfolding. The errors shown in the

figure (standard deviations of approximately ± 10% below 500 keV, ± 10-30% between 500 and 1000 keV, and increasing to ± 100% at about 1300 keV) include the contributions from counting statistics and from errors in the spectrometer response function used in the unfolding code. A full account of this measurement and the method of error analysis is in preparation[1].

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(1) J.G. Owen, J. Walker and D.R. Weaver. The calibration of a ^{3}He spectrometer and its use to measure the neutron spectrum from an Am/Li source. (To be published)

7.2 Delayed neutron energy spectra from ^{239}Pu (J.G. Owen, J. Walker and D.R. Weaver)
(Relevant to request number 1438)

The bulk of the experimental programme during the past year has been centred on the IBIS accelerator at AERE, Harwell, where the spectrum of delayed neutrons emitted following fast fission of ^{239}Pu has been measured for two different energies of the neutrons inducing fission. The sample was a 63 g metallic cylinder, and the accelerator beam was pulsed repetitively with the beam on for 0.8 s and off for 1 s; delayed neutron counting took place for 0.8 s during the beam-off period. Two gridded ^{3}He ionisation chambers were used to collect the spectral information.

Fig. 7.2(a) and (b) shows the delayed neutron spectra obtained for energies of the neutrons inducing fission in ^{239}Pu of approximately 2 MeV and 0.5 MeV respectively; each spectrum is the result of about 6 days continuous operation of the accelerator. A full analysis of the errors on the data, including correlation effects, is in progress.

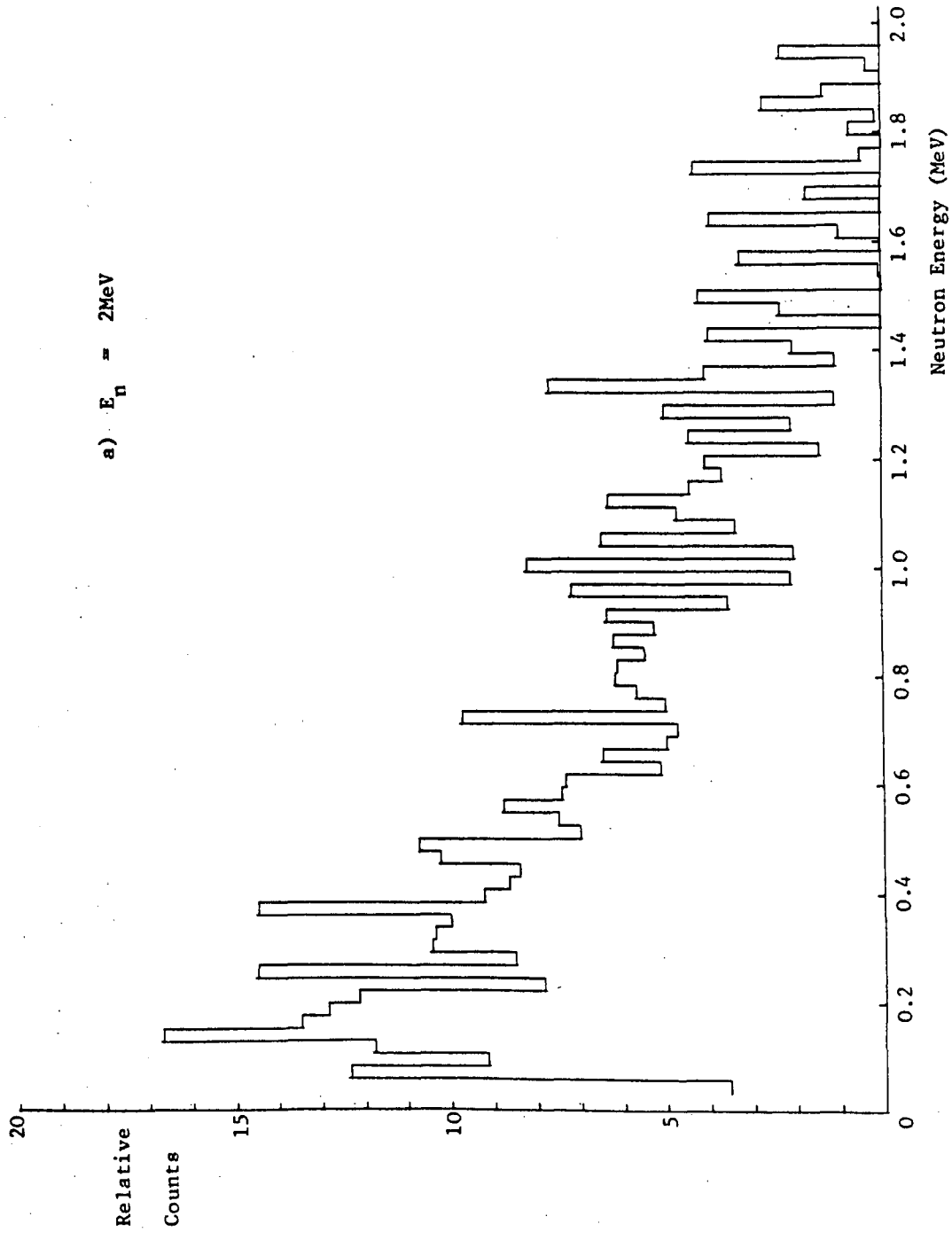

Fig. 7.2 The delayed neutron spectrum from ^{239}Pu fission at mean primary neutron energies of approximately (a) 2 MeV and (b) 0.5 MeV

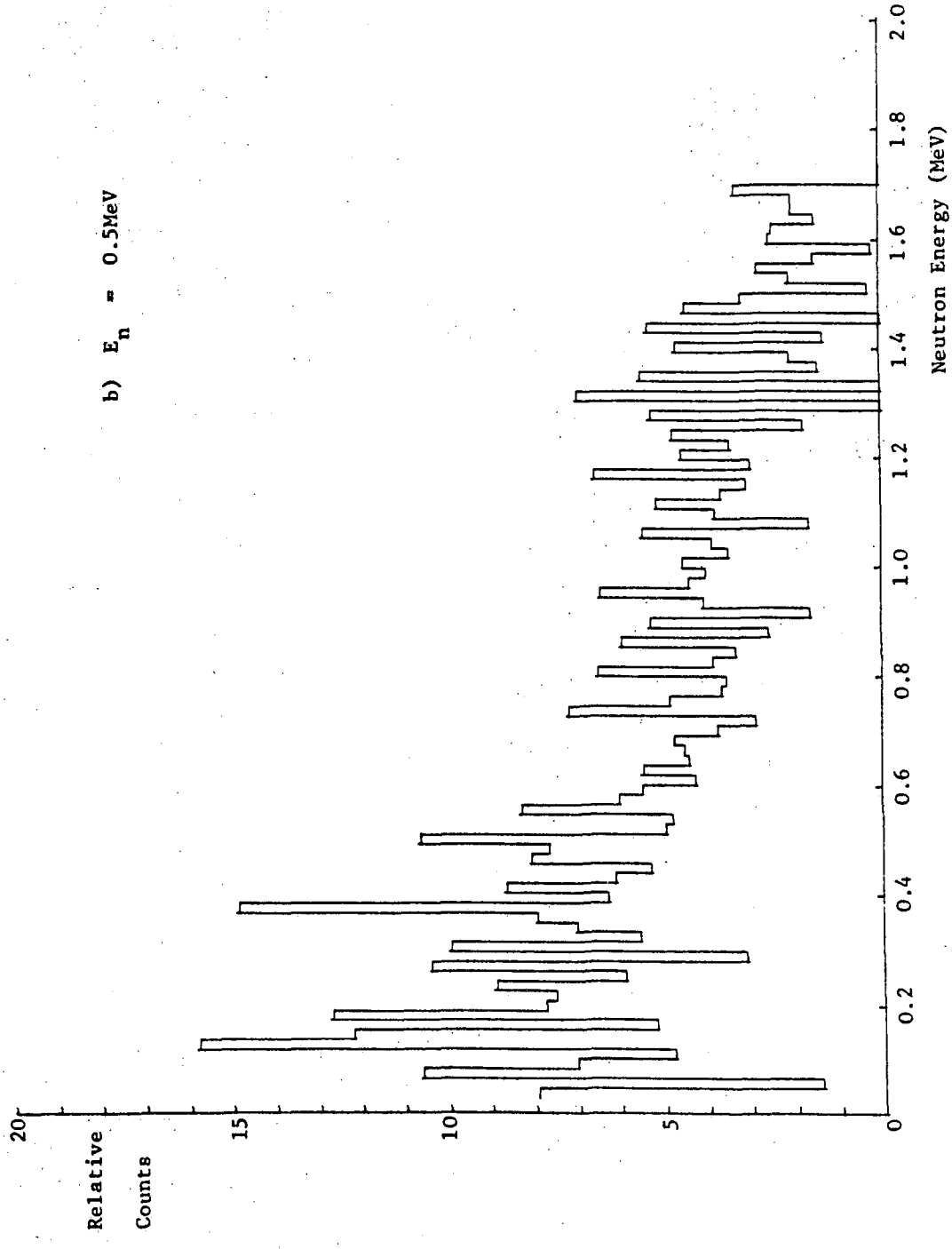

Fig. 7.2 The delayed neutron spectrum from ^{239}Pu fission at mean primary neutron energies of approximately (a) 2 MeV and (b) 0.5 MeV

8. UNIVERSITY OF EDINBURGH, DEPARTMENT OF PHYSICS

8.1 The polarisation and differential cross section for the elastic scattering of 2.9 MeV neutrons by heavy nuclei (J. Annand and R.B. Galloway)
(Relevant to request numbers 454 and 986)

Simultaneous measurements of the angular dependence of polarisation due to elastic scattering and of the elastic differential cross section for 2.9 MeV neutrons scattered by Fe, Cu, I, Hg, Pb[1] and by W, Tl, Bi, U[2] have been used to test the results of combining many different optical model and Hauser-Feshbach calculations, and optimum optical model parameter sets have been found. The calculated angular dependence of polarisation for the heavier nuclei fitted the experimental data less well than for Fe and Cu. It was decided to make further measurements on heavy nuclei to significantly higher accuracy and at angular intervals of 7° instead of 14° to investigate the quality of the model fits in more detail.

Much of the work of the past year has concerned the proving tests on a new neutron scattering polarimeter, with which simultaneous scattering asymmetry measurements can be made at 11 scattering angles instead of 6 in the past and with which the efficiency intercalibration of the 22 detectors can form part of the computer controlled measurement sequence. Related work on long term scintillation counter stability has been undertaken[3]. Preliminary measurements on scattering by W and Pb indicate that an improvement in accuracy of polarisation measurement of a factor of 5 may be expected.

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(1) R.B. Galloway and A. Waheed, Nucl. Phys. A318 (1979) 173.

(2) Amena Begum and R.B. Galloway, J. Phys. G (1981) in press.

(3) R.B. Galloway, Nucl. Instr. and Meth. 172 (1980) 431.

8.2 Neutron polarisation in the $^{7}Li(d,n)^{8}Be$ reaction (R.B. Galloway and A.M. Ghazarian)

The angular dependence of the polarisation of the ground state neutrons from the $^{7}Li(d,n)^{8}Be$ reaction is being measured in the expectation that this reaction may provide a useful source of polarised 14 MeV neutrons from a low energy accelerator. The results for 450 keV incident deuterons are illustrated in Fig. 8.1. The deuteron energy dependence of the neutron polarisation and of the neutron yield are now being investigated along with DWBA analysis of the data.

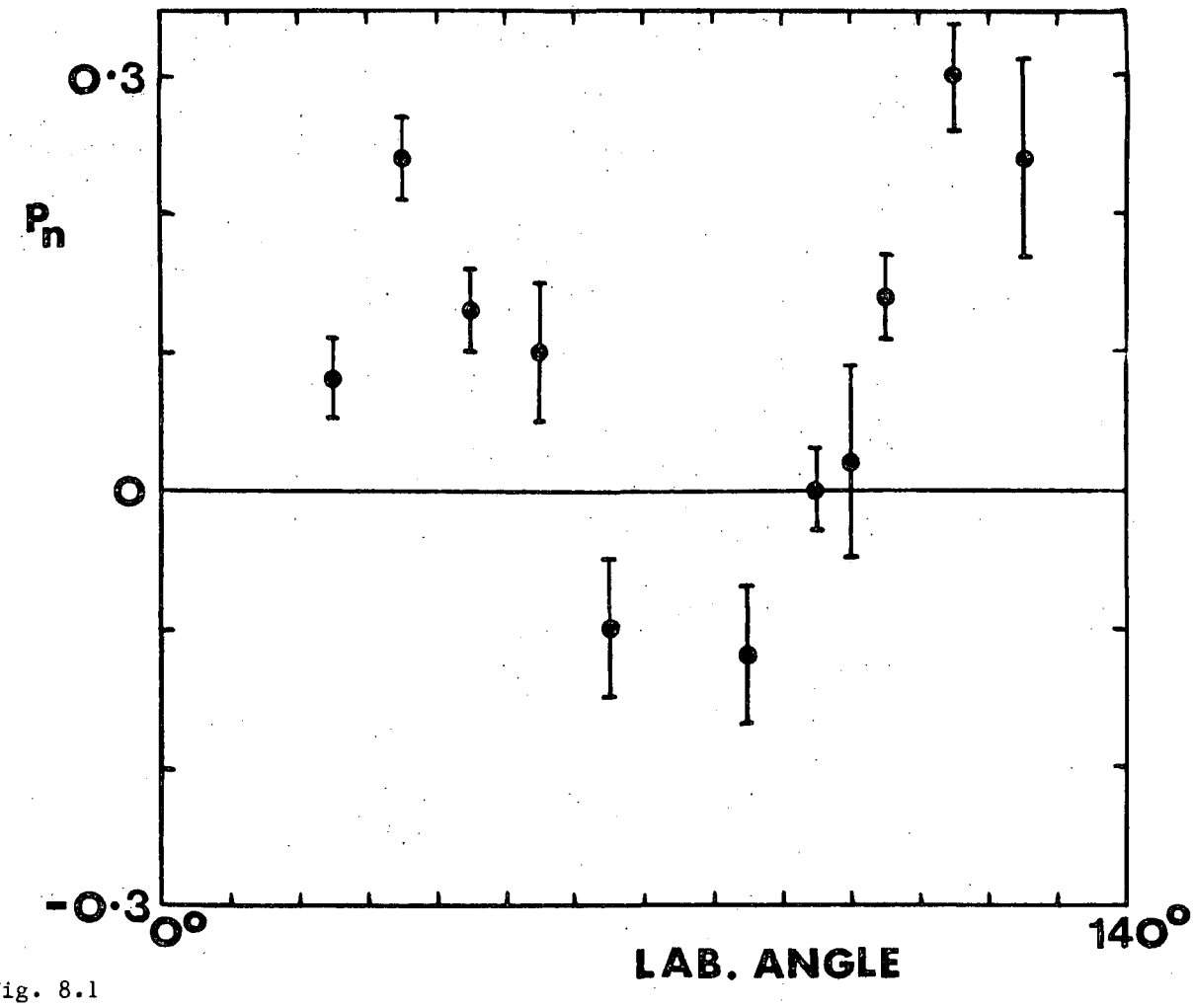

Fig. 8.1

8.3 <u>The polarisation of neutrons from the $^2H(d,n)^3He$ reaction (R.B. Galloway and A.S. Hall)</u>

The measurements and interpretation of the angular dependence of the polarisation of the neutrons from the reaction $^2H(d,n)^3He$ for 290 keV and 460 keV deuterons (UKNDC(80)P96, p.96) have been published(1). This completes a sequence of measurements(2-7) on the polarisation of the neutrons from the $^2H(d,n)^3He$ reaction over the deuteron energy range 35 keV to 5.5 MeV.

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(1) R.B. Galloway and A.S. Hall, Phys. Rev. C21 (1980) 453.

(2) R.B. Galloway and R. Martinez Lugo, Nucl. Instr. and Meth. 158 (1979) 153.

(3) A.M. Alsoraya and R.B. Galloway, Nucl. Phys. A280 (1977) 61.

(4) R.B. Galloway, A.S. Hall, R.M.A. Maayouf and D.G. Vass, Nucl. Phys. A242 (1975) 122.

(5) R.M.A. Maayouf and R.B. Galloway, Nucl. Instr. and Meth. 118 (1974) 343.

(6) H. Davie and R.B. Galloway, Nucl. Instr. and Meth. 108 (1973) 581.

(7) H. Davie and R.B. Galloway, Nucl. Instr. and Meth. 92 (1971) 547.