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U.K. Nuclear Data Progress Report

January - December 1985

Editors: J P Mason and J A Cookson

Nuclear Physics Division
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PREFACE

This report is prepared at the request of the United Kingdom Nuclear Data Committee (UKNDC) and summarises nuclear data research in the UK between January and December 1985.

Nuclear data are presented by laboratory with contributions this year from the UKAEA establishments at Harwell and Winfrith, from the National Physical Laboratory, from the Universities of Aston, Birmingham, Edinburgh, Liverpool and Oxford, and from the Imperial College Reactor Centre. Also included are descriptions of work from collaborations involving Harwell, Winfrith, the Universities of Oxford and Birmingham, the Los Alamos National Laboratory, the Netherlands Energy Research Foundation (ECN), the Istituto de Fisica Applicata Generale in Milan and the NEA data bank. Collaborations involving the National Physical Laboratory, the Universities of New Mexico and Manchester, the Institute for Nuclear Energy (IPEN) in Peru and Hammersmith Hospital are also reported.

Contributions on Chemical Nuclear Data are grouped under that heading, and have been gathered by the Chemical Nuclear Data Committee of the UKNDC. Much of this work is again the product of collaborative effort involving Harwell, Winfrith, Aldermaston, the Universities of Birmingham and Manchester, Imperial College and the Central Electricity Generating Board.

Where the work is clearly relevant to requests in WRENDA 83/84 (INDC(SEC)-88/URSF), the appropriate numbers are given after the title of the contribution. In addition, a CINDA-type index is included at the end of the report.

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

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* For a key, see page 1

1 NUCLEAR PHYSICS DIVISION, AERE, HARWELL

Division head: Dr J E Lynn (until October)
Dr A T G Ferguson (from October)

Introduction

Nuclear data measurements in the Nuclear Physics Division are diverse and performed on a variety of sources. Individual research items are labelled with a single letter to indicate which out of the Harwell suite of accelerators was used for the relevant measurements. The letters used are:

A	Cockcroft-Walton Generator
D	14 MeV Tandem Generator
E	136 MeV Electron Linac HELIOS
I	500 keV Van de Graaff Generator

These letters are also used for reference in the table of contents.

The material for this contribution is taken from the chapter on Nuclear Data and Technology for Nuclear Power in the 1985 Nuclear Physics Division Progress Report AERE PR/NP 33.

Some of this work was undertaken as part of the Underlying Research Programme of the UKAEA.

1.1 E The 136 MeV electron linear accelerator HELIOS (M S Coates, B P Clear, J Down, R A J Riddle, P W Swinden, F Dutton, D Walkinshaw, R Green, R Dallimore and P Feiven)

Routine operation of HELIOS continued throughout most of the year using the condensed matter, fast neutron and low energy cells. There were planned breaks in the operational programme to make modifications and improvements to the plant.

The high power Litton klystron (30 MW, 60 kW rating), which provided power for the first two accelerating sections of the machine, showed signs of failure and was replaced by the Thomson-CSF type (20 MW, 40 kW rating) used on the other sections of the machine. We had made a decision not to purchase replacement Litton klystrons because of the unfavourable £/$ exchange rate, despite the improved machine performance obtainable with this higher rated valve. However, we have successfully tested a new and equivalent higher rated version of the Thomson-CSF klystron in socket on HELIOS and this type will be ordered in future as the need arises for replacements.

A natural uranium neutron-producing target has been installed in the condensed matter cell to replace the tantalum target which has been used since operations began. The new target increases the neutron output/kWe of electron beam by a factor of ~1.7. There is uncertainty about how long the target will remain useful because of a lack of knowledge of thermal temperature cycling effects in the operating temperature environment. The swelling of uranium due to thermal cycling could lead to the cooling channels in the target closing up with consequent damage, possibly severe, to the Zircaloy-clad uranium plates because of breakdown in the effectiveness of the water cooling mechanism. So far, the target has operated for several weeks at 22 kWe without any apparent ill effect. As far as we know this is the highest beam power at which a uranium-containing target has ever operated.

The pulsed magnet system (see UKNDC(84)P111 p.45) has been considerably improved over the past year and has been successfully tested off-line at the power levels needed to handle electron pulses at an energy of 120 MeV and a repetition frequency of 150 pps which is the required performance for use with the Neutron Booster cell.

1.2 E Measurement of η (^{235}U) in the energy range below 1 eV (M C Moxon and J B Brisland) (WRENDA 964-967)

The experiment to measure the relative variation of η (^{235}U) with neutron energy outlined in last year's report (UKNDC(85)P112 p.35) is almost completed. The use of a PDP-11/34 computer for data collection has allowed the handling of count rates of over 250 events per neutron pulse produced at the linac target. The pulse shape discrimination equipment has been used to obtain data with high statistical accuracy from two separate ^{235}U metal samples. The shape of the incident neutron spectrum has been measured using both a ^{10}B ion chamber and the gamma-ray yield from a standard ^{10}B oxide sample. Sets of resonant filters of suitable materials (Hf, Er, In, Ag, Cd) have been used to determine backgrounds.

Some of these data have been analysed to give a preliminary value of the η (^{235}U) energy variation. Below 0.1 eV our results appear to be consistent with the version used in the WIMS data library, but between ~0.1 eV and 1 eV the energy variation seems to differ from the WIMS shape. However, our data were not corrected for the multiple scattering effects arising from the size of the ^{235}U samples used. In the final analysis we expect to determine the relative η (^{235}U) energy variation to ~0.5% between 10 meV and 1 eV neutron energy, and to come close to this accuracy in the energy ranges 3 meV to 10 meV and 1 eV to 10 eV. A factor affecting the accuracy of the determination at the lowest energies is the background contribution from delayed neutrons produced in the uranium target which is now used for neutron production (see Section 1.1). While the original tantalum target, which the uranium target replaced, had a lower neutron yield by a factor of ~1.7, the signal-to-background ratio at neutron energies below ~10 meV was superior.

1.3 NEANDC Task Force on ^{238}U (M C Moxon, G Shaw and M G Sowerby) (WRENDA 1067-1069)

The work reported previously (UKNDC(84)P111 p.48, UKNDC(85)P112 p.36) has continued. A recommendation of the joint meeting of the ^{238}U and Fe Task Forces held in Paris during October 1984 was that the ORNL

transmission data[1] in the energy range 7.9 to 8.4 keV should be analysed with the shape fitting code REFIT. The neutron widths determined in this analysis differ from the ones obtained by Olsen[2] at ORNL using the SIOB code. The disagreement is probably due to the difference in the shape of the calculated resolution function in the two codes. This is more important in this energy range than it was below 4 keV where the resonance parameters obtained from the two codes were in excellent agreement.

During the year, neutron widths and resonance energies for the main transmission dips of the ORNL data in the energy region from 10 to 15 keV have been determined. In the energy range up to 15 keV, 709 s-wave resonances have been observed. From an analysis of the distribution of neutron widths and level spacings it is concluded that the distribution of reduced neutron widths in general obeys the Porter-Thomas distribution, but that there are more resonances than expected with large neutron widths. If some of the dips are due to two or more s-wave resonances then more small level spacings are observed than predicted. Further investigation of these anomalies is required in order to understand fully the observed data and so use it to deduce the parameters in the unresolved energy range.

Another Task Force recommendation is that to obtain the final recommended resonance parameters, a simultaneous analysis of high resolution transmission and capture data must be carried out. Graphs of unprocessed high resolution capture data obtained using a 150 m flight path have been provided by de Saussure (ORNL). A preliminary examination of these confirmed most of the small resonances already observed below 4 keV, but indicated the presence of many more previously unknown resonances. The simultaneous analysis awaits the arrival of the processed data from ORNL.

A paper summarising the work of the Task Force with the following abstract was presented to the International Conference on Nuclear Data for Basic and Applied Science, Santa Fé, USA, 13-17 May 1985 (Paper IA 04).

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(1) D K Olsen, G de Saussure, R B Perez, F C Difillipo, R W Ingle and H Weaver, Nucl. Sci. and Eng. 69 (1979) 202.

(2) D K Olsen, Private Communication to Task Force (1985).

"The work of the NEANDC Task Force on ^{238}U is reviewed and the progress made in understanding the origin of the discrepancies in the neutron widths of the resolved resonances above 1.4 keV and the capture cross-section between 1 and 30 keV is discussed. The discrepancy in neutron widths appears to be due to the resolution function of the experiments being wider and more complex than assumed. The capture cross-section problem may in part be due to the incorrect normalisation of an experiment in the keV energy range."

In addition to discussing the origin of the discrepancies, which are now understood particularly for the neutron widths, the paper makes recommendations of the work that should be done in the future.

1.4 Evaluation of ^{238}U cross-sections (M C Moxon, B H Patrick and M G Sowerby).

The UK, in cooperation with France and Germany, is responsible for producing a new evaluation of the ^{238}U neutron-induced cross-sections which will be submitted to JEF (the Joint Evaluated File Project which operates in the framework of the NEA Data Bank as a collaboration between laboratories in Member Countries) for inclusion in the JEF-2 library. At a recent technical meeting of the JEF group, agreement was reached on how the work will be shared out. At the present time most of our effort is on the resolved resonance parameters. The work being performed is also relevant to the work of the NEANDC Task Force on ^{238}U (see Section 1.3).

1.5 E High resolution transmission measurements on natural iron (G D James, D B Syme and M C Moxon) (WRENDA 356-358)

Transmission measurements on natural iron have continued over two periods of about six weeks. The first period was devoted to improving the statistical accuracy of data for a 2 mm thick sample under the same conditions as those described previously UKNDC(85)P112 p.38)'. Measurements were made on the 150 m flight path of the fast neutron target of HELIOS at 300 pps with a 30 ns electron pulse width. Neutrons were detected by means of a ^{10}B plug 10 mm thick, viewed by two BGO crystals 110 mm in diameter and 15 mm thick. In the second period, background measurements which bracket the 1.15 keV resonance were made at 0.577 keV and 2.044 keV by using copper samples. The

number of BGO crystals was increased to four and data were taken for 2 mm and 15 mm thick iron samples. To meet the requirements of other experimenters, the pulse rate for these measurements was changed to 500 pps. The background level at 1.15 keV cannot, therefore, be compared directly with that seen previously at 300 pps but these changes in conditions will reveal the effect of systematic errors. Analysis of these data using the code REFIT is in progress.

1.6 E Iron capture cross-section measurements on HELIOS
(D B Gayther, J E Jolly, R B Thom*, C A Burke)**
(WRENDA 356-360,396)

There are considerable discrepancies between reported measurements of the capture cross-sections of structural materials. In particular, recent values for the neutron width of the important 1.15 keV resonance in ^{56}Fe obtained with so-called Total Energy Detectors are as much as 25% greater than the currently accepted value which is based on accurate transmission data. The seriousness of the situation has been recognised by the Nuclear Energy Agency Nuclear Data Committee (NEANDC) in setting up a Task Force[1] with the aim of resolving the discrepancies in the parameters of this resonance.

In a Total Energy Detector, the capture event is observed by detecting the prompt gamma-rays with an efficiency which is proportional to the total excitation energy. Any dependence of the detection efficiency on the shape of the capture gamma-ray spectrum is thus removed, a feature which is essential when studying a structural material where the spectrum is known to differ markedly from one resonance to another. In one type of Total Energy Detector, the required efficiency is achieved by applying a weighting function to the observed pulse amplitude (often called the Maier-Leibnitz technique). The weighting function is usually calculated with a Monte Carlo code. The recently reported discrepant parameters for the ^{56}Fe 1.15 keV resonance suggest the possibility that incorrect weighting functions are being applied for high energy gamma-rays, the gamma-ray cascade from this resonance being particularly "hard". In an attempt to elucidate these discrepancies, and so contribute to the work of the

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* AEE Winfrith

** Imperial College

(1) F G Perey, Int.Conf. on Nuclear Data for Basic and Applied Science, May, 1985, Santa Fé, New Mexico

NEANDC Task Force, a Maier-Leibnitz type of detector is being studied in some detail at Harwell.

The Harwell detector (UKNDC(80)P96 p.22 and UKNDC(81)P100 p.26) consists of two 0.4 ℓ cells of deuterated benzene scintillator, mounted on quartz-windowed photomultipliers and placed on either side of the capture sample. The materials of the detector were selected for their low neutron capture cross-sections so as to achieve a very low sensitivity to background events caused by neutrons scattering from the sample. This consideration is important in structural materials where the probability of resonance neutron scattering is commonly a thousand times larger than the probability of capture.

The pulse amplitude weighting function used at Harwell is based on the Monte Carlo code GAMOC. To assess the validity of this function, the response of the detector to various gamma-ray sources is currently being compared with the predictions of GAMOC. Preliminary results indicate that GAMOC reproduces the observed pulse amplitude spectra reasonably well for gamma-rays below ~1.5 MeV, but that at higher energies the code under-predicts the number of small pulses. The highest energy investigated used the 6.13 MeV gamma-rays from a fluorine target bombarded by 500 keV protons ($^{19}F(p,\alpha\gamma)$). Further measurements and additional developments to GAMOC are planned.

Time-of-flight measurements have been made on the Fast Neutron Target of HELIOS with the Harwell detector and a pure sample of natural iron. Capture data were obtained in the energy range 190 eV - 120 keV using a burst width of 30 ns and a 42 m long flight path. The shape of the incident neutron spectrum was determined by replacing the iron sample with a ^{10}B sample. A suite of computer programs which was written to process two parameter data produced by the Harwell large liquid scintillator has been adapted for use with Total Energy Detector data. Major changes to the codes involved reading data from a new archiving system and the inclusion of weighted summation of the amplitude spectrum. **Fig. 1.1** shows a portion of the data obtained from a summation of eight separate runs with the iron sample, three stages of the analysis being shown. The capture yield (number of capture events per incident neutron) shown in part (c) of **Fig. 1.1** has been normalised for convenience to the data obtained with the large

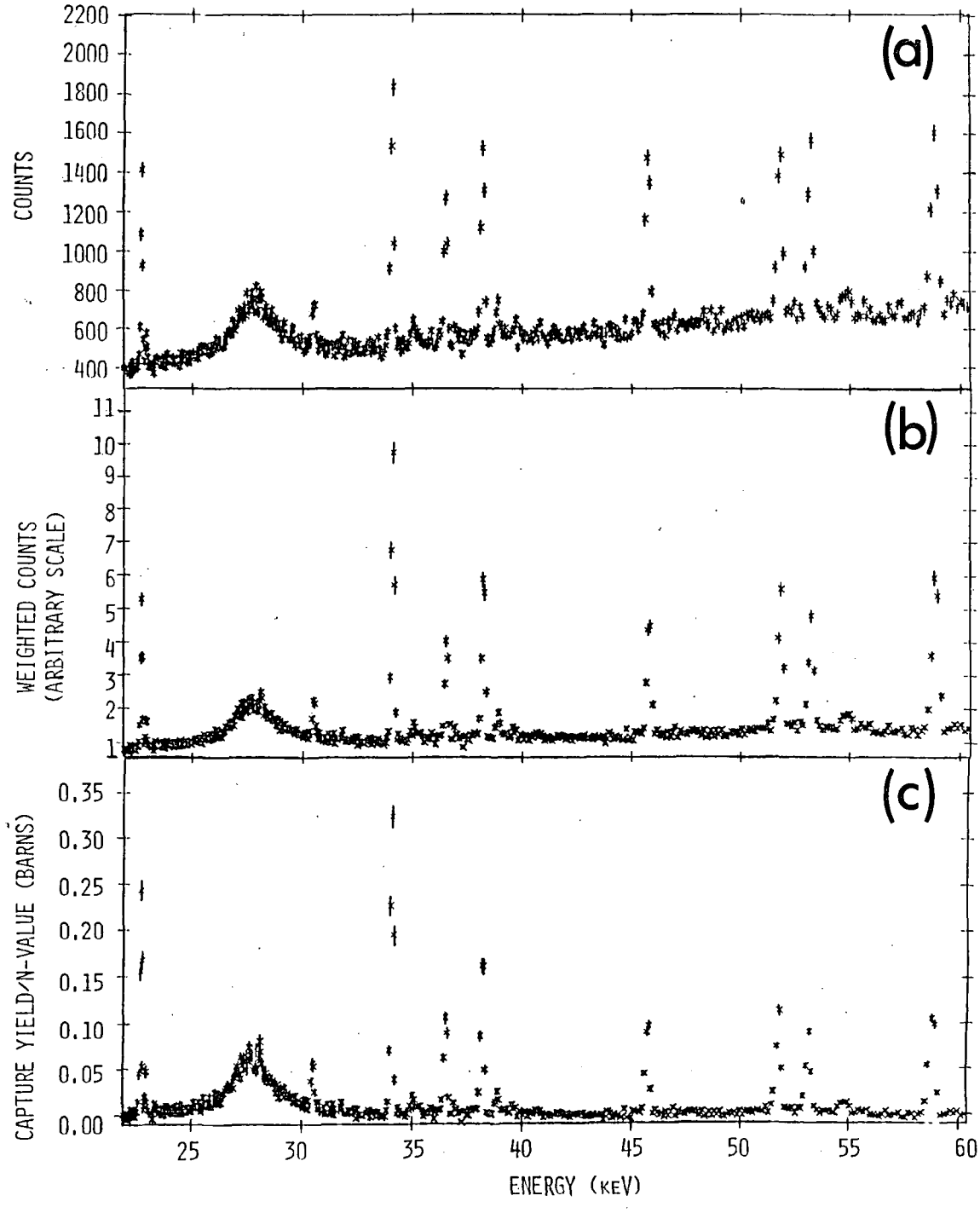

Fig 1.1 Time-of-flight spectra measured with a deuterated benzene capture gamma-ray detector on a 42 m flight path of HELIOS. The sample was a 2 mm thick disc of natural iron ('n' = 0.0169 atoms/b).
(a) Observed counts per time-of-flight channel for capture gamma-rays in the range 1 to 12 MeV.
(b) Spectrum (a) after application of the pulse amplitude weighting problem.
(c) The ratio (capture yield/'n'-value) derived from spectrum (b) after subtraction of background and division by the incident neutron spectrum.

liquid scintillator[1]. The normalisation consisted of matching the areas beneath the 1.15 keV resonance in ^{56}Fe.

As a preliminary check of the internal consistency of the data, the capture areas of two well known resonances in ^{56}Fe were calculated using the capture analysis code CAREA. The ratio of the capture areas of these resonances, at the nominal energies of 22.8 and 1.15 keV, was found to be 2.70±0.25. These resonances have been studied recently by Weston and Todd[2] to highlight possible problems with Total Energy Detectors associated with the shape of the capture gamma-ray spectrum, the spectrum from the 22.8 keV resonance being much "softer" than that from the 1.15 keV resonance. They obtained a value of 2.91±0.17 for the ratio of the capture areas from measurements made with their Total Energy Detector, and quote a value of 2.83±0.16 derived from transmission data. Although the preliminary ratio of the capture areas derived from the present measurements agrees with these figures, further work on the weighting function and a more rigorous resonance analysis are required before a definite conclusion can be drawn.

1.7 E Resonance neutron capture in structural materials (J P Mason and B H Patrick) (WRENDA 391, 486, 487)

Last year it was reported (UKNDC(85)P112 p.39) that measurements had been made of the gamma-ray spectra following resonance neutron capture in ^{54}Fe and ^{62}Ni. The Fast Neutron Target of HELIOS was used as the neutron source, and Ge detectors provided the two parameters recorded for each event: time-of-flight and gamma-ray energy. The analysis of these data has now been completed and, in addition, further data have been collected using the same experimental set-up but with a natural nickel sample. This work was successfully submitted as a Ph.D. thesis to the University of Birmingham[3].

1.7.1 Capture gamma-ray spectra from ^{54}Fe

As reported last year, the relative strengths of the observed transitions from the 7.8 keV s-wave resonance of ^{54}Fe were found to

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(1) D B Gayther, R B Thom, M C Moxon and J E Jolly, UKAEA Report AERE-R 11583 (1985).

(2) L W Weston and J H Todd, Int. Conf. on Nuclear Data for Basic and Applied Science, May 1985, Santa Fé, New Mexico.

(3) J P Mason, PhD thesis, University of Birmingham and AERE-R 12078 (1986)

agree with the predictions of the valence model, confirming the findings of Raman et al[1]. Further analysis of the data was undertaken during the year to establish absolute values for the partial radiative widths of these transitions, in order to provide a more severe test of the valence model predictions. This was achieved by deducing the yield of the ground state transition as a function of time-of-flight, the normalisation being obtained by comparison with the yield of the 478 keV gamma-ray from the $^{10}B(n,\alpha\gamma)^{7}Li$ reaction. A value for the partial radiative width of this transition was then obtained by fitting the yield curve with the code REFIT (see **Fig. 1.2**). Other partial radiative widths were established from the previously known relative strengths.

The results of this analysis are summarised in **Table 1.1**, where it is apparent that there is a satisfactory agreement of the experiment with theory, at least for the transitions to low-lying states with large spectroscopic factors.

Table 1.1

The partial widths for gamma-ray transitions E_γ from the 7.8 keV s-wave resonance of ^{54}Fe to final states E_x, with spin-parity J^π and (d,p) spectroscopic factors θ^2_μ in ^{55}Fe. For comparison, the valence model predictions of the absolute strengths are also given. The values for the gamma-ray energies are those corresponding to capture by thermal neutrons.

				Partial width (eV)	
E_γ(MeV)	E_x (MeV)	J^π	θ^2_μ	Present Measurement	Valence Model
9.298	0.0	$3/2^-$	0.78	1.5 ± 0.3	1.21
8.885	0.413	$1/2^-$	0.6	0.5 ± 0.1	0.38
7.373	1.925	$1/2^-$	0.1	0.08 ± 0.03	0.05
7.240	2.058	$3/2^-$	0.09	0.08	0.1
6.820	2.478	$3/2^-$	0.17	0.10 ± 0.04	0.17
6.263	3.035	$3/2^-$	0.03	0.11	0.03
5.739	3.559	$3/2^-$	0.12	0.09	0.09
5.498	3.800	$1/2^-$	0.6	0.09	0.17
3.523	5.775	$3/2^-$	0.05	0.14	0.01

(1) S Roman, G C Slaughter, J C Wells and B J Allen, Phys.Rev.C22 (1980) 328

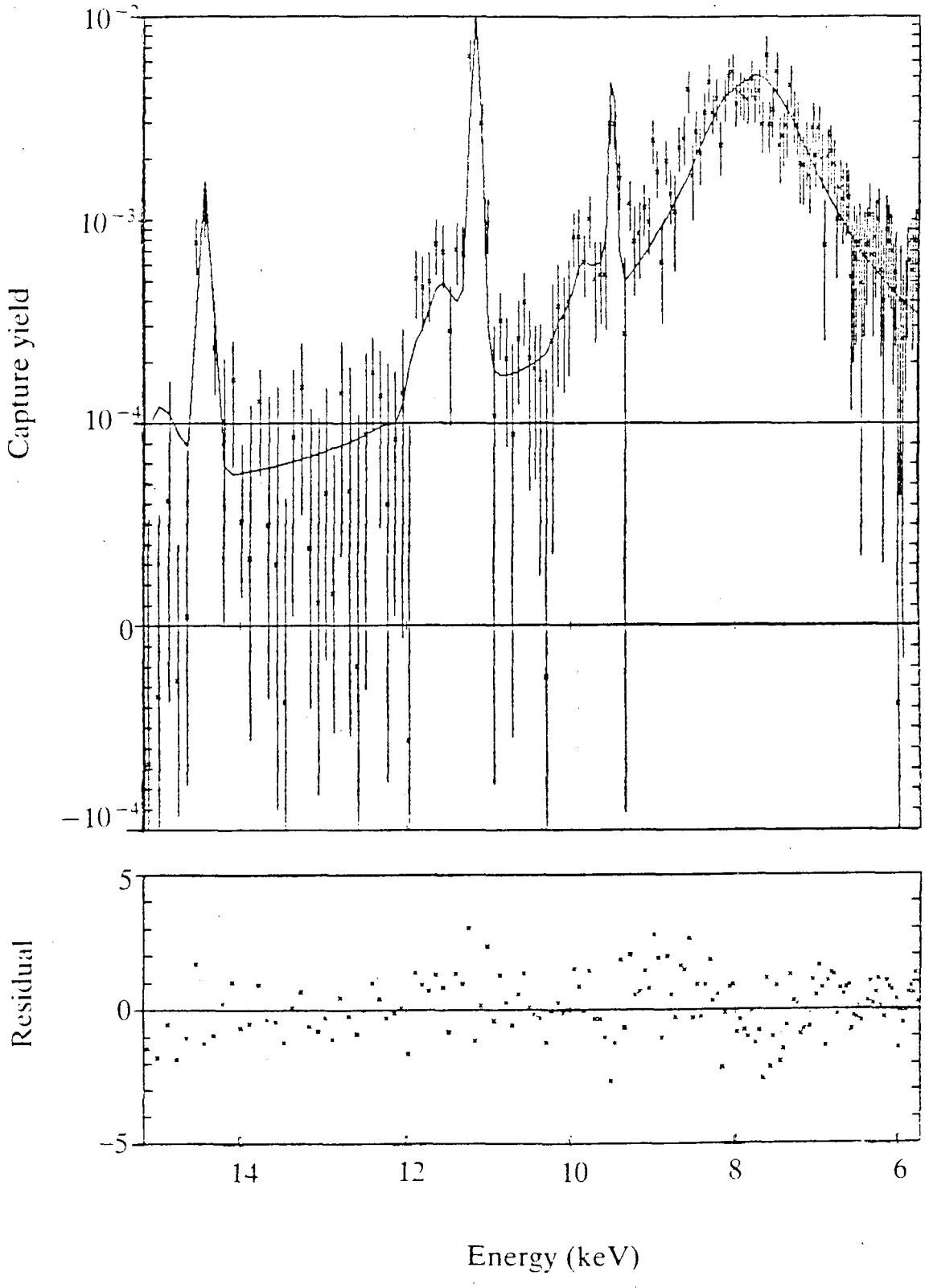

Fig 1.2 The experimentally determined yield for the transition to the ground state following neutron capture in ^{54}Fe. The fit to the data was provided by the code REFIT and the corresponding residuals (deviations of the fit from the data divided by the error) are shown in the lower graph. Note that the abscissa is a descending energy scale and the capture yield is a log scale for values 10^{-4}.

The results of this analysis are shown in **Table 1.2**, where it is clear that the valence model fails to reproduce the observations. This has been interpreted as being due to an interference of the valence capture component with the underlying statistical part. It would appear that, in order for valence model predictions to hold, the statistical capture component must be very small in comparison. Such a condition may be obtained for a nucleus with a closed neutron shell such as ^{54}Fe.

The capture gamma-ray spectrum from the 9.4 keV resonance was also observed and showed strong transitions to states with spin-parities $1/2^-$, $3/2^-$ and $5/2^-$. On the assumption of the dominance of M1 over E2 primary transitions, it was possible to assign a spin-parity of $3/2^-$ to this resonance.

Partial radiative widths were also deduced for three p-wave resonances at 9.5 keV, 11.2 keV and 14.5 keV. The spectra for these resonances appeared to be consistent with a statistical interpretation of the capture reaction and with previous total radiative width measurements.

Table 1.2

The partial widths for gamma-ray transitions E_γ from the 4.5 keV s-wave resonance of ^{62}Ni to final states E_x, with spin-parity J^π and (d,p) spectroscopic factors θ_μ^2 in ^{63}Ni. For comparison, the valence model predictions of the absolute strengths are also given. The values for the gamma-ray energies are those corresponding to capture by thermal neutrons.

				Partial width (eV)	
E_γ(MeV)	E_x (MeV)	J^π	θ_μ^2	Present Measurement	Valence Model
6.838	0.0	$1/2^-$	0.37	3.0 ± 0.6	0.34
6.683	0.155	$3/2^-$	0.28	0.04 ± 0.02	0.57
6.323	0.515	$3/2^-$	0.08	0.08 ± 0.02	0.15
5.835	1.003	$1/2^-$	0.33	0.17 ± 0.04	0.23
5.511	1.327	$3/2^-$	0.06	0.07 ± 0.02	0.04

1.7.2 Capture gamma-ray spectra from ^{62}Ni

The gamma-ray spectrum following capture in the 4.5 keV s-wave resonance of ^{62}Ni (see **Fig. 1.3**), obtained using a separated isotope sample, was analysed and compared with the valence model in the same way as for the ^{54}Fe capture described above.

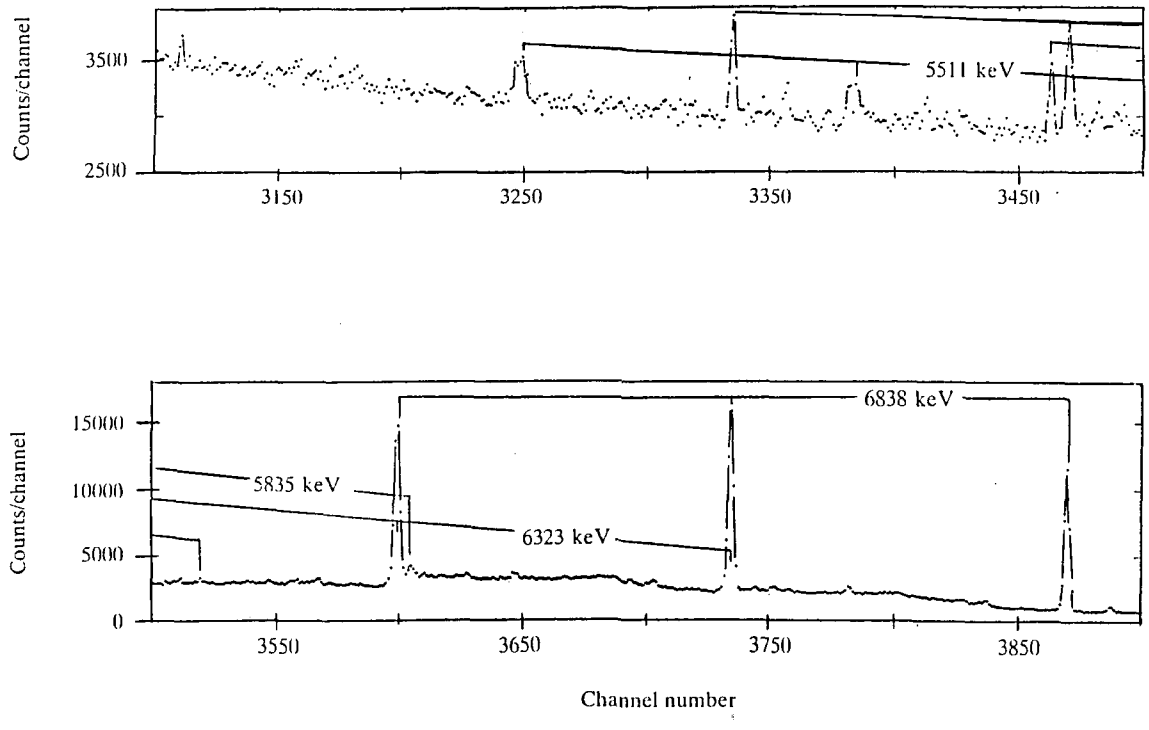

Fig 1.3 The gamma-ray spectrum observed following capture in the 4.5keV s-wave resonance of ^{62}Ni. Strong, high energy primary transitions are marked (with energies corresponding to thermal neutron capture), and the dominance of the 6.838 keV transition to the ground state of ^{63}Ni is evident.

The yield curve for the ground state transition was once more deduced from the time-of-flight spectrum (see **Fig. 1.4**) and the ^{10}B yield, but unfortunately, in this case it was not possible to obtain a good fit with the code REFIT. A likely explanation was that the code was failing to model adequately the large quantity of multiple scattering taking place in this broad s-wave resonance. In order to test this possibility, data were collected using a natural nickel sample in which the isotope ^{62}Ni is only 3.6% abundant. With these data a satisfactory fit to the observed yield was achieved, and it was possible to establish absolute partial radiative widths for five transitions.

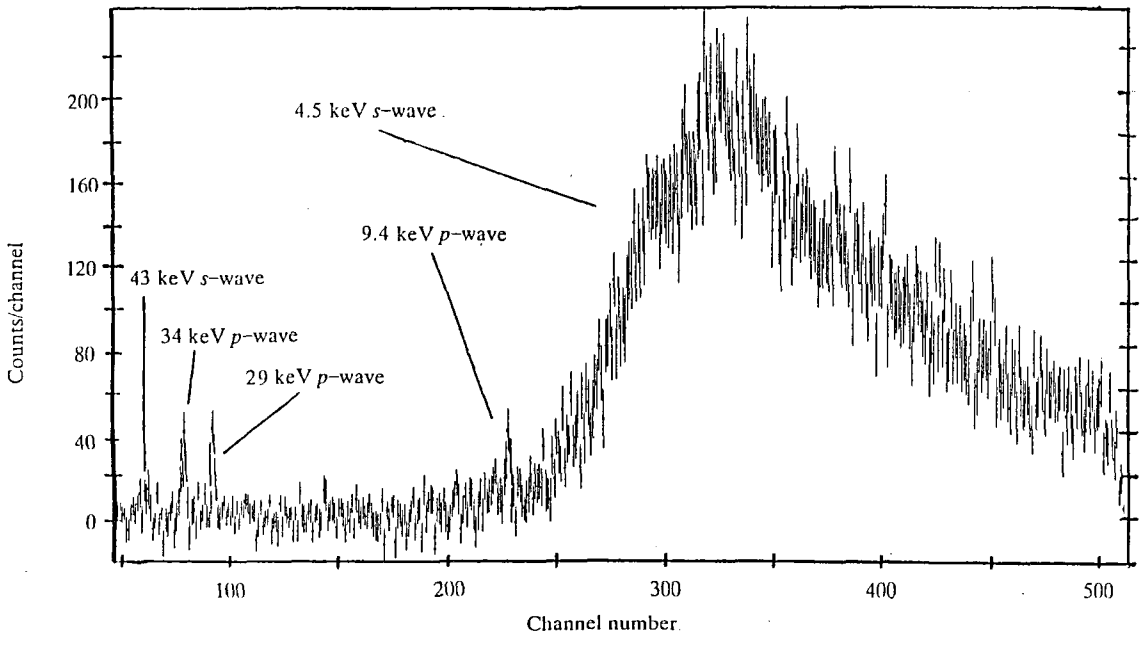

Fig 1.4 The time-of-flight spectrum for the transition to the ground state following capture in ^{62}Ni. The most prominent resonances are marked.

1.7.3 Future developments

In the near future, it should be possible to analyse the natural nickel data further in order to obtain values for partial radiative widths of the low-lying resonances of ^{58}Ni and ^{60}Ni. It may be expected that the results in the case of ^{58}Ni will show some evidence of valence effects, as the predicted widths are large.

A new data acquisition system, incorporating a dedicated PDP-11/23 computer is currently under development and should be ready for use shortly. This will greatly improve the quality of future data, by allowing more information to be recorded for each event (a 24-bit

rather than a 21-bit word), and, with its use of a CAMAC driven time-to-digital converter, by permitting the use of timing channel bin widths down to 1 ns. With this improved system, resolved resonance capture gamma-ray measurements will be possible up to neutron energies of ~100 keV, a previously unexplored area for nuclides in this mass region.

1.8 A 6130 keV gamma-ray source using the $^{13}C(\alpha,n)^{16}O$ reaction (J P Mason)

A high energy gamma-ray source has been produced by mixing the alpha emitter ^{238}Pu with ^{13}C to produce the 6130 keV gamma-ray from the de-excitation of the second excited state in ^{16}O(1). The gamma-ray spectrum has been measured with a Ge detector (see **Fig. 1.5**) and is seen to consist of a line at 6130 keV, well separated from the strong line at 2615 keV which is due to contamination of ^{236}Pu in the ^{238}Pu. The strength of the 6130 keV gamma-ray was determined to be ~770 Bq.

The source also emits neutrons, from the (α,n) reaction and from spontaneous fission. The emission rate and mean energy of these

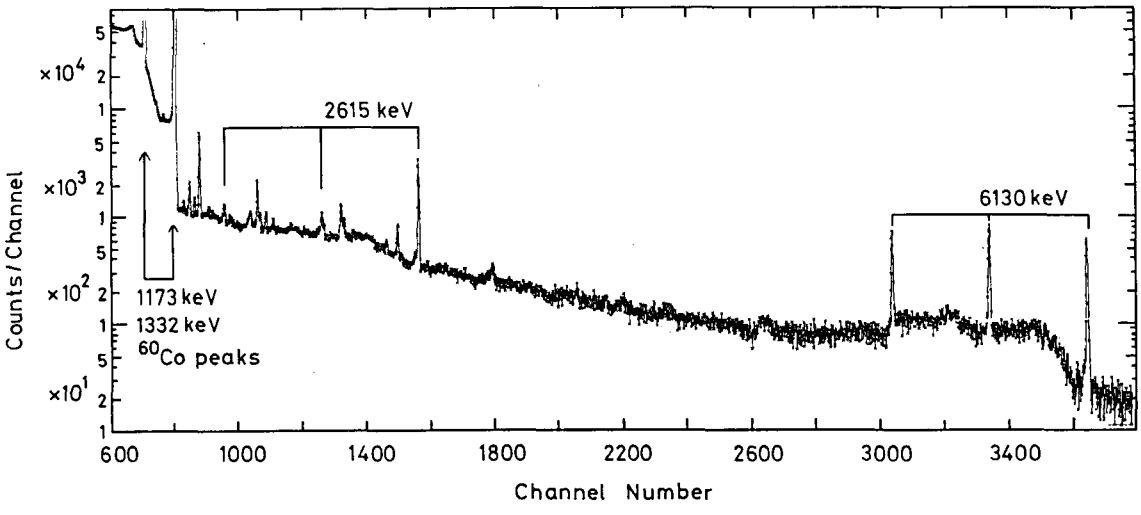

Fig 1.5 The gamma-ray spectrum obtained after ~10 h with the $^{238}Pu/^{13}C$ source 25 cm from the front face of a 110 cm^3 n-type Ge detector. All events detected with energy 1 MeV are shown; no background has been subtracted. The peaks at 1173 and 1332 keV which go off-scale are due to the presence of a ^{60}Co calibration source.

(1) J P Mason, Nucl. Instr. and Meth. for Phys. Res. A241 (1985) 207.

neutrons were found to be 4.5 x 10^4 ($\pm$2%) s^{-1} and 4.0$\pm$0.1 MeV respectively, as determined with the large oil-moderated assembly of $^{10}BF_3$ counters situated on the Low Energy line of HELIOS.

1.9 The $^{93}Nb(n,n')^{93m}Nb$ reaction (D B Gayther and C A Uttley, M F Murphy* and K Randle**) (WRENDA 563-569, 571-573, 582)

A preliminary account of the determination of the cross-section for this reaction by foil activation was presented at the Santa Fé Conference[1]. No further foil activations were made in the period covered by this report. An attempt to make a measurement at 600 keV neutron energy was not successful because of the failure of the LiF targets to withstand the long irradiations required (UKNDC(85)P112 p.41). It is still hoped to make this measurement if sufficiently robust lithium targets can be developed. A measurement at 2.8 MeV neutron energy is to be made on the 6 MV Van de Graaff accelerator at Harwell.

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

Table 1.3 summarises the present state of the measurement programme.

Four measurements have been made since the chambers became available over four years ago, and if the programme continues at its present rate it will take until at least mid-1987 to complete. To speed up the exercise presents an administrative rather than a technical problem. Each measurement requires a participating laboratory to devote to it several man-months of effort and the present rate of progress is accounted for by staff shortages, greater emphasis being given to other programmes of work, and re-scheduling caused by accelerator breakdowns. Some improvement could be expected if participants were to give the Intercomparison a higher priority, thereby allowing greater flexibility in scheduling the programme, and thus avoiding such a hiatus as occurred between July 1983 and February 1984.

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* AEE, Winfrith

** University of Birmingham

(1) International Conference on Nuclear Data for Basic and Applied Sciences, Santa Fé, New Mexico, May 13-17 (1985).

Table 1.3
Current status of the fission chamber intercomparison measurements

LABORATORY +	DATES	ENERGIES	ACCELERATOR	FLUENCE MONITOR	COMMENTS
NBS	Jan.-July 1983	0.5 MeV	Linac, Pulsed Van de Graaff	Black detector	Measurements completed - final report written. Excellent agreement between Linac and Van de Graaff. Collimated beam used on Van de Graaff.
BIPM	Feb.-May 1984	14.65 MeV	Unpulsed D-T generator	Associated particle	Measurements completed - report written. Both chambers used. Open (uncollimated) geometry. Background determined with shadow cone. Cd box around mounting framework.
PTB	Oct. 1984 - March 1985	All	Pulsed Van de Graaff	Proton recoil telescope and proportional counter	Measurements completed. Both chambers used. Preliminary evaluation based on shape of $^{235}U/^{238}U$ fission cross-section ratio satisfactory.
CBNM	April 1985 - February 1986	All	Linac, Pulsed Van de Graaff		Only Van de Graaff measurements completed. Will use linac late in 1986.
ETL	Spring 1986	All	Cockcroft-Walton Pelletron		
NPL	1986	0.565 MeV 14.8MeV	Pulsed Van de Graaff	Calibrated Long Counter	
IRK		14 MeV			Programme not yet arranged.
AERE		All	Linac Pulsed Van de Graaff?		Last measurements

+NBS: National Bureau of Standards (USA); BIPM: Bureau International des Poids et Mesures (France); PTB: Physikalische Technische Bundesanstalt (FRG); CBNM: Central Bureau for Nuclear Measurements (EEC, Belgium); ETL: Electrotechnical Laboratory (Japan); NPL: National Physical Laboratory (UK); IRK: Institut für Radiumforschung und Kernphysik (Austria); AERE: Atomic Energy Research Establishment, Harwell (UK).

1.11 A,D,I Studies of neutron induced charged particle reactions: detector development (R A Jarjis*, M C Scott* and D B Gayther)

Measurements were made on three accelerators during 1985. Initial calibrations of the NE-102A/CsI(Tl) charged particle phoswich detector (UKNDC(85)P112 p.43) were re-examined using ^{1}H and ^{4}He ion beams from the Harwell Tandem Van de Graaff. The results were found to be compatible. In addition, the fundamental studies of NE-102A plastic scintillator were completed. The energy loss results exhibit good agreement with the Bethe formula down to incident energies of 1.0 MeV for protons and 2.6 MeV for α-particles. Measurements of the straggling parameter for charged particles traversing a 0.01 mm film of NE-102A were also concluded. The results are shown in **Fig. 1.6** as a function of the charged particle energy deposition in the scintillator. The data are important for detector design and modification since they represent the energy broadening of charged particle spectra. Another important parameter for the detector design is the light output from the thin scintillator film. The results of our measurements are presented in **Fig. 1.7** as a function of the deposited energy of charged particles. As expected, the data exhibit a saturation behaviour due to quenching effects in the scintillation process.

Measurements of charged particle spectra from fast neutron-induced reactions were continued using at first the Harwell 500 kV Van de Graaff accelerator. The experiments were conducted under low charged particle background conditions, but the relatively weak D-T neutron source required the detector to be placed close to the target and it was not possible to provide good neutron shielding. In spite of this, the detection of charged particles from an aluminium target was demonstrated. In order to improve the experimental arrangement, a second test facility was installed on the Harwell 500 kV Cockcroft-Walton accelerator. The higher deuteron beam currents that are available from this machine allowed adequate neutron shielding to be installed. The initial findings were confirmed, and the detection

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* University of Birmingham

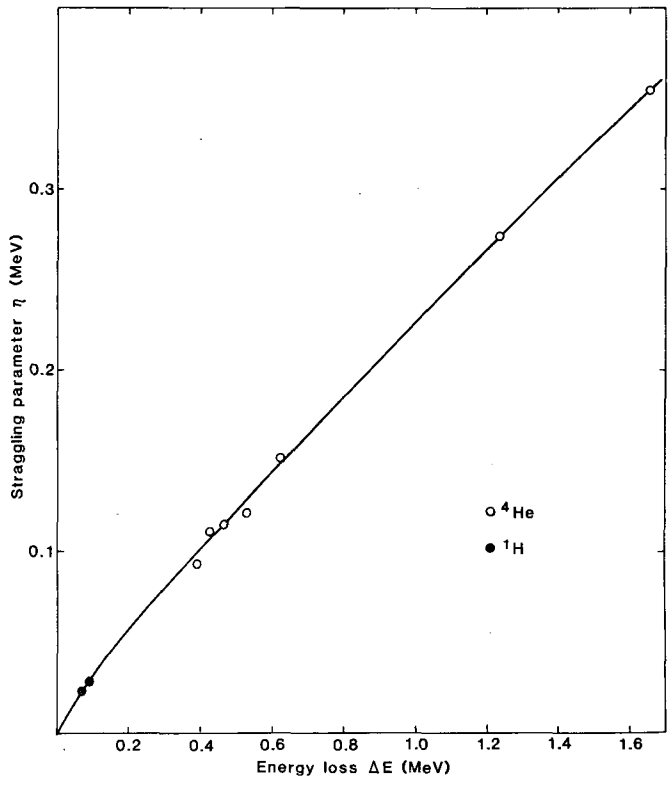

Fig 1.6 The straggling parameter of a 0.01 mm thick NE-102A scintillator versus the energy deposited by charged particles.

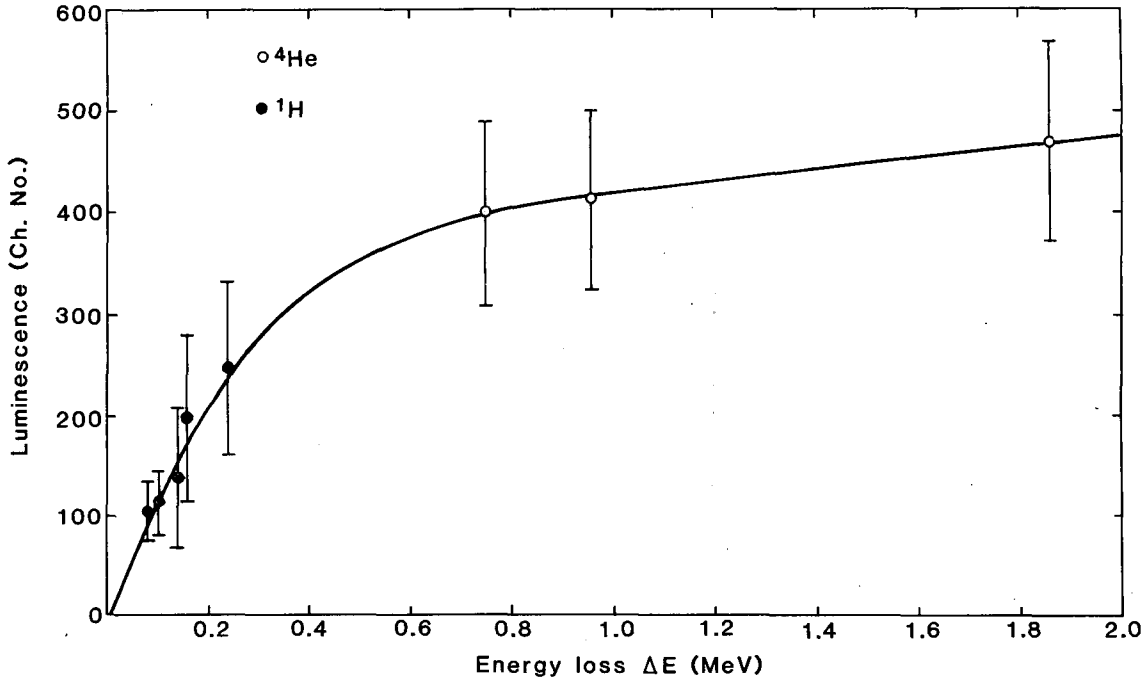

Fig 1.7 The deposited energy dependence of the light output from a 0.02 mm thick NE-102A scintillator.

of different charged particle spectra from aluminium and mylar targets was demonstrated.

The above experiments also indicate that further development is required if the charged particle discrimination at low energies is to be improved. One possibility which is being investigated experimentally is to use a new phoswich detector consisting of NE-102A and NE-115 plastic scintillators. The NE-115 scintillator has a light output decay time of 225 ns, which makes it suitable as a full energy (L) detector. Furthermore, its lower light output compared to CsI(Tl) can be advantageous for this type of detector arrangement. This is because a ΔE (ΔL) signal containing minimum contribution from the (L) detector can produce better charged particle discrimination.

1.12 Activation of fusion reactors (B H Patrick, M G Sowerby, R A Forrest, D W Muir* and E M Bowey).

Nuclear reactions induced by the high flux of 14 MeV neutrons produced by the D-T fusion reaction will cause the first wall and blanket of a Tokamak system to become active and radiation damaged. The latter effect is likely to limit the lifetime of these components to a few years and thus necessitate their replacement. Removal and storage for possible later re-use will be facilitated by low induced radioactivity. A programme aimed at identifying suitable materials is under way, and as part of this we are improving the nuclear data required for assessment, in cooperation with Culham Laboratory (Dr. L. Giancarli), the University of Oxford (Dr. P. E. Hodgson) and ECN Petten (Dr. H. Gruppelaar).

Some years ago, the UKCTRIIIA nuclear data library[1] was generated for this purpose, the emphasis being on the materials of most interest at the time. The interest has now widened to include other materials and their likely impurities, and work has started to extend the library to cover missing elements and reactions and to bring it up-to-date. Where possible, data will be taken from recommended evaluated data files and, where these are lacking, from nuclear systematics and theory.

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* On attachment from Los Alamos National Laboratory, Los Alamos, New Mexico, USA

(1) O N Jarvis, UKAEA Report AERE-R 9601 (Rev) (1980)

The modifications to the library are being made in two phases. In the first, the data for important activation products will be improved, while in the second phase the coverage of the periodic table will be greatly extended and some of the older data will be replaced. In the first phase ECN Petten will put together the revised library. We have provided group cross-sections calculated with NJOY for all materials on the ENDF/B-V activation file (Tape 532) and have helped Culham and Petten to produce an improved version of the code THRESH[1] that can use recommended experimental data to normalise the calculated cross-sections.

In order that the second phase of the work can be carried out, three codes of varying sophistication are being implemented and improved. The Los Alamos pre-equilibrium statistical model code GNASH has been implemented[2] on the Harwell CRAY-1 computer. This code uses Hauser-Feshbach theory to calculate complicated multistep reaction chains and it will only be used for nuclei where accurate calculations are required. At the other extreme, THRESH, which is based on the statistical model plus cross-section systematics, is being further improved by incorporating better systematics into the code (see Section 1.14.4). The code CADE[3] has a more physical basis than THRESH but is not so sophisticated as GNASH. It does not consider reactions to discrete final levels in the nucleus but assumes the final nucleus can be described by a continuum of levels (Weisskopf-Ewing Theory). In cooperation with the University of Oxford, this code is currently being tested against experimental data and being made easy to run.

1.13 Work related to the design of the European Demonstration Reprocessing Plant (EDRP) (R A Forrest, M G Sowerby and D A J Endacott)

The Authority is preparing detailed designs for the EDRP, which is proposed to be sited at Dounreay. It would have the capability to reprocess fuel from Superphenix I and future commercial demonstration fast reactors both in the UK and Europe.

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(1) L Giancarli and H Gruppelaar, UKAEA Culham Report CLM-R 261 (to be issued)
(2) D W Muir, UKAEA Report AERE-R 11877 (1985)
(3) D Wilmore, UKAEA Report AERE-R 11515 (1984)

Since September 1985 we have been carrying out calculations using the FISPIN code to determine the levels of activity that will have to be accommodated within the plant. Fuel from several different reactor types will be reprocessed and the plant must therefore be designed for the most demanding conditions considered likely to arise.

The long term use of fast reactors will necessitate the reprocessing and refabrication of plutonium through several cycles, and the possibility of build-up of highly active or long-lived nuclides has to be studied in order to prove the safety case. An example of this type of study is the fate of neptunium isotopes (specifically ^{237}Np) produced in the fuel during irradiation. These would normally be left in the waste streams, but could be diverted with the plutonium to be refabricated and subsequently placed back in the reactor.

Calculations in which all the ^{237}Np is recycled with the Pu show that by the sixth reprocessing cycle a fractional burn up of 0.988 is achieved. There is no associated build up of particular Pu isotopes and this method of 'nuclear incineration' should be considered as a means of reducing the overall levels of activity from fast reactor operation.

1.14 Nuclear data computer codes

1.14.1 The computer code NJOY (E M Bowey and D W Muir*)

The latest version (6/83) of the evaluated file processing code NJOY was successfully implemented on the Harwell CRAY-1 computer. As a result, the computing costs of processing a typical evaluated file to produce group cross-section data were considerably reduced. The code was used to process the ENDF/B-V activation library into a 100 group form for inclusion in the improved nuclear data library being constructed for estimation of activation and transmutation in fusion systems.

1.14.2 The computer code GNASH (D W Muir* and E M Bowey)

The pre-equilibrium, statistical nuclear model code GNASH, developed at the Los Alamos National Laboratory, has been implemented

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* On attachment from Los Alamos National Laboratory, Los Alamos, New Mexico, USA

on the CRAY-1 computer at Harwell. The opportunity was taken to make some improvements which permit a more flexible and easy use of the code, and to incorporate into the system auxiliary codes required by GNASH (e.g. a code to calculate transmission coefficients for Hauser-Feshbach calculations). A detailed account of the suite of codes is to be found in Ref. 1.

1.14.3 FISPIN on the Harwell computer (D A J Endacott)

The FISPIN code[2] calculates the production and removal of three groups of nuclides in an irradiation: the actinide group, the fission product group and the structural material group. Over the years, the code has gradually been improved by adding extra facilities for users and modifying the calculational method. Since the last report (UKNDC(85)P112 p.46), version 6 of the code, produced at Risley, has been made available on the Harwell mainframe IBM computer. Problems were encountered in converting the coding from ICL FORTRAN to IBM FORTRAN but these have now been resolved. Verification tests on the code show that it agrees with calculations carried out using version 5 on the Harwell computer, and with versions 5 and 6 on the Risley computer. One of the extra options in version 6 is a condensed form of output.

A number of new data libraries have been added to those available at Harwell. These are:-

UKFPTR4 - a thermal reactor fission product library generated from the decay data from UKFPDD2 fission yield data from Crouch[3] and cross-section data.

PWRDAT4 and FRLIB2 - PWR and fast reactor libraries based on cross-section data and UKHEDD-1. They contain information on 129 nuclides and have 23 group gamma spectra.

PWRBUG28, PWRBUG32 and PWRBUG36 - burn-up dependent cross-section libraries based on the Bugey reactor for fuel enrichments of 2.8, 3.2 and 3.6% respectively.

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(1) D W Muir, AERE-R 11877 (1985).
(2) R F Burstall, UKAEA Risley report ND-R-328 (1979).
(3) E A C Crouch (1982) unpublished.

1.14.4 Improvements to the THRESH code (R A Forrest)

As part of the programme to improve the data used to calculate the activation of fusion reactors (see Section 1.12), further improvements are being made to the code THRESH. In the version of the code improved by Giancarli and Gruppelaar[1] the cross-sections derived from a simple statistical theory are normalised either to experimental data or to the value obtained from cross-section systematics. The empirical fits used in the systematics have been improved for the (n,p), (n,α), (n,d) and (n,t) reactions, both in the light of new data and so that they also cover a wider range of nuclei. In addition, an automatic graphics facility has been written which will aid in the checking of the large quantities of computer-generated results which will be produced when the activation library is extended.

1.15 Nuclear Materials Assay

Neutron Systems Group has continued to develop techniques of nuclear materials assay based on active and passive neutron interrogation and on high resolution γ-ray spectroscopy.

1.15.1 Fissile material assay by neutron interrogation (B H Armitage and A C Sherwood)

The programme of work has concentrated on problems associated with the behaviour of neutrons in large volume matrix-filled disposal containers. The experimental study (UKNDC(85)P112 p.47) of matrix effects in 200 ℓ drums has been broadened to include fissile material at any position within the drum. Dense aggregates of fissile material are subject to self-shielding when assayed by the neutron die-away technique. A major advance has been brought about by Monte Carlo computer studies which have shown that the self-shielding problem may be very much reduced if delayed neutron interrogation is used for the assay of fissile material in non-moderating matrices. Work undertaken at G.E.C Avionics has begun to demonstrate that pulsed neutron sources can be constructed with a longer useful life.

1.15.1.1 Matrix effects in the assay of fissile material in 200 ℓ drums (B H Armitage and A C Sherwood)

A neutron die-away chamber at Harwell, capable of accommodating a single 200 ℓ drum, has already been described (UKNDC(83)P109 p.54). To

(1) L Giancarli and H Gruppelaar, UKAEA Culham Report CLM-R 261 (to be issued)

be able to assay fissile material in matrix-filled drums by the neutron die-away technique, it is necessary to define a procedure which does not require a prior knowledge of the matrix. An experimental study involving the use of eighteen different matrices has been reported (UKNDC(85)P112 p.47). On the basis of their neutron absorption and moderating properties, the matrices were placed into four categories. The matrix-filled drums were separated into high/low absorption, high/low moderation categories by the measured lifetimes of thermal neutrons observed in BF_3 detectors. One of these detectors was mounted on the inside wall of the die-away chamber and the other immediately below the drum. Finally, empirical analysis methods were used to obtain matrix-corrected responses for each category.

A more complete account of this work has already been published[1]. The limitation of that study, however, was its confinement to the observation of fissile material at the centre of the drum. The next stage was to extend the study to include fissile material present at other locations within the drum.

At the beginning of this work, a difficulty emerged with the more dense matrices. This was that the response of a 1.02 g ^{235}U sample was greater from the upper regions of the drum than from the lower (**Fig. 1.8(b)**). That this difficulty did not exist with the less dense matrices is illustrated in **Fig. 1.8(a)**, which shows the relatively uniform response obtained with an empty drum. The origin of this problem is not clearly understood. No such effect was observed with model chamber calculations using the Monte Carlo code MORSE.

The problem was overcome by wrapping Cd around the upper end of the ^{3}He detectors so that their effective length was reduced from 95 cm to 63 cm. The geometry was shown in Fig. 1.10(a) of UKNDC(85)P112 p.48.

The spatial variability of response to the dense matrix (35 g water/83 kg iron shot/13 kg polyethylene bottles) after the modification is shown in (c) of **Fig. 1.8.** Following this, a further improvement in spatial variability was obtained (see **Fig. 1.8(d)**) by reducing from 0.7 ms to 0.4 ms the delay between the onset

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

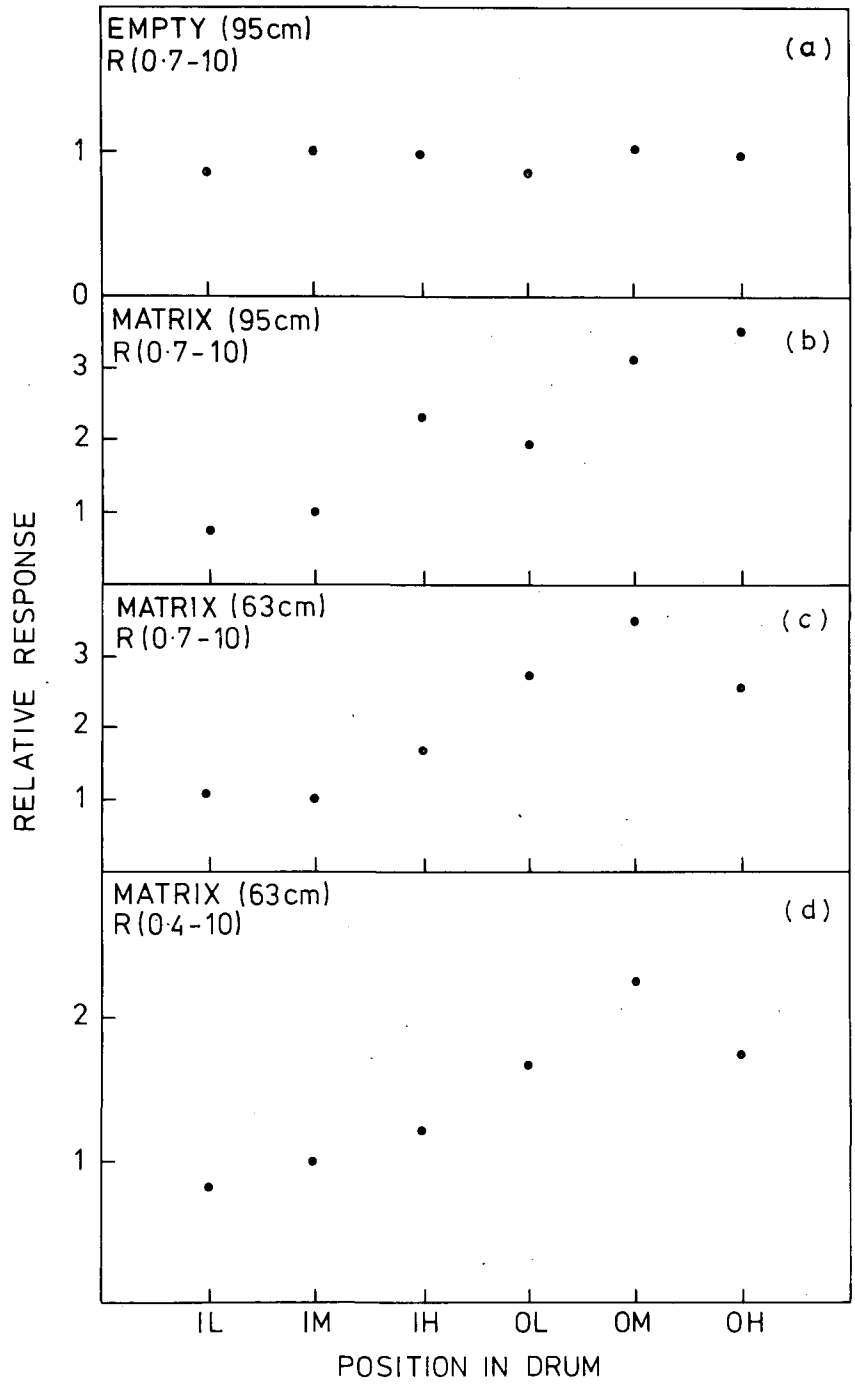

Fig 1.8 Relative response values for fissile material as a function of position in (a) an empty drum (b) a dense matrix-filled drum (c) a dense matrix-filled drum and modified detectors and (d) a dense matrix, modified detectors and fission neutron count delay of 0.4 ms. These data are given for six locations in the drum labelled inner lower (IL), inner middle (IM) inner higher (IH), outer lower (OL), outer middle (OM) and outer higher (OH).

of the 14 MeV interrogating pulse and the recording of fast fission neutrons. Thus in the figure, R(0.4-10) refers to the fast fission neutrons being recorded over the interval 0.4 ms to 10 ms after the 14 MeV neutron pulse.

Measurements of the spatial variability of response have so far been made on nine of the eighteen matrices involved in the previous study. It is planned to complete the experimental programme and examine the implications for the previously proposed empirical methods of analysis.

1.15.1.2 Examination of drums containing Pu and U contaminated waste
(B H Armitage)

Two drums containing Pu and U contaminated waste have been prepared at Harwell. These drums have been assayed by both fission neutron coincidence counting and by high resolution gamma-spectroscopy. This report is concerned with the measurement of the fissile material content by neutron die-away interrogation. The sealed drums contain a large wire mesh basket filled with shredded polythene contaminated with Pu and U. One drum contains 14.7 g of reactor grade Pu while the other contains 12 g of reactor grade Pu plus 20 g of ^{235}U as natural UO_2 powder. Although these drums have been assayed by the neutron die-away technique, the detailed interpretation awaits the completion of appropriate standards, and also the completion of the 200 ℓ drum matrix studies.

1.15.1.3 Neutron interrogation of fissile material in 500 ℓ drums
(B H Armitage and C G Cogbill)

An initial assessment of problems likely to be encountered in assaying fissile material in 500 ℓ disposal containers has already been reported (UKNDC(85)P112 p.51). In particular, a study was made of neutron die-away interrogation of fissile material in iron-filled drums. These calculations indicated that the measured response would be highly dependent both on the location of the fissile material within the drum and also on the density of the iron fill. They also showed that a purely thermal interrogating flux would not penetrate dense aggregates of highly enriched uranium (HEU) or Pu, so that the fissile content would be subject to severe underestimation.

To overcome the self-shielding problem a harder, more penetrating, neutron flux is required. If a pulsed source of 14 MeV neutrons is

used to interrogate HEU or Pu, induced fission may be detected by counting delayed neutrons. The advantage is that in an iron matrix, many of the fissions will be induced by non-thermal neutrons.

Calculations were made with the Monte Carlo computer code MORSE. Initially a conventional graphite and polythene die-away chamber was modelled. This differed from the existing die-away chamber at Harwell mainly insofar as it could accommodate a single 500 ℓ drum.

The calculations show that delayed neutron interrogation will result in a marked reduction in self-shielding. Delayed neutron interrogation of a single 10 g sphere of HEU in a 500 ℓ drum, containing iron at 1.5 g cm^{-3}, will result in a fission rate of 0.6 of that of dispersed material. The corresponding result for neutron die-away interrogation (purely thermal flux) is 0.05. This means that the hardening of the interrogating flux has produced more than a tenfold improvement, so that instead of a 10 g spherical lump being recorded as 0.5 g it will be recorded as 6 g.

As far as delayed neutron interrogation was concerned, the Monte Carlo calculations established that the interrogating neutron flux was considerably less in the inner regions of the drum relative to those nearer the surface. This may be attributed to the absorption of thermal neutrons within the matrix. To try to overcome this problem the 500 ℓ drum was given a 1 mm thick wrapping of Cd. This had the effect of ensuring that only non-thermal neutrons entered the drum matrix, and that a thermal neutron population could only arise after a number of successive scattering events.

The calculations indicated that the spatial variability of response to the presence of fissile material was considerably improved by the Cd wrapping. The calculated values for the delayed neutron response for six regions in the drum showed a reduction in the standard deviation of the spatial variability of response from ±70% to ±15% for HEU.

1.15.1.4 Pulsed neutron source development (B H Armitage and J W Leake*)

The development programme with G.E.C. Avionics (UKNDC(85)P112 p.52) is nearing a successful conclusion, and it is anticipated that an improved neutron source will be available for tests at Harwell in a few months. This 14 MeV neutron source will consist of a sealed tube

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* Instrumentation and Applied Physics Division

within which deuterons are accelerated onto a tritiated target, and will have a separate high voltage transformer and a control unit. The neutron source will be of slightly larger dimensions than that currently in use at Harwell, and should have improved high voltage characteristics.

The objective of the programme is to make available pulsed neutron sources of greater reliability and longevity. Lifetime tests on sealed tubes incorporating new features such as low sputter materials, a suppressor electrode and an alternative target material, have shown that a build-up of gas pressure is the principal failure mode. Because of this, it is hoped that an additional improvement in tube life can be obtained by reducing the tritium content. Experience so far has indicated that the incorporation of the new features has resulted in a progressive improvement in tube lifetime.

1.15.2 The effects of neutron multiplication on neutron coincidence counter measurements (M T Swinhoe)

The importance of neutron multiplication corrections to coincidence counter results was described in UKNDC(85)P112 p.55.The report mentioned there has been issued.[1] This field has developed rapidly over the past year; the correction technique now in common use was produced by Los Alamos[2]. This method has been tested and found to work well on suitable samples, i.e. samples which are sufficiently well characterized that the contribution to the signal from (α, n) events can be calculated. This requires a knowledge of the isotopic composition. An investigation of the uncertainties in the results revealed that the dominant error is usually that due to the uncertainty on the (α, n) production rate.

The use of multiplying reference samples, which was proposed empirically in UKNDC(85)P112 p.55, has been put on a firm theoretical basis by the inclusion of an estimate of the reference sample multiplication. This allows the correction techique to be extended to those situations where multiplying reference samples are needed.

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(1) M T Swinhoe AERE-R 11678 (1985)

(2) N Ensslin in Proc. 7th ESARDA Symposium, Liège, Belgium 1985

An important question in the use of neutron coincidence counters is whether the calibration (which may have been made with plutonium metal of a particular isotopic composition) holds for all types of material (e.g. plutonium oxide, mixed plutonium uranium oxide or samples with different isotopic composition). An investigation has been made into the effects on the response of the coincidence counter of the neutron energy spectrum and of induced fission in various isotopes. The conclusion is that the difference between the various types of sample should be very small. A report of this work is in preparation.

1.15.3 Quality checking of the fissile content of 500 ℓ drums of cement encapsulated waste (M T Swinhoe)

Several progress reports have described the measurement of fissile material using the differential die-away technique (eg. UKNDC(85)P112 p.47). The present work began with a calculational exercise to determine the effect of a very dense hydrogenous matrix on the results of the assay. This investigation led to an arrangement in which the 14 MeV pulsed neutron tube and a fast neutron detector are on opposite sides of the drum, the whole assembly is surrounded by a concrete shield and the drum is rotated as the measurement proceeds. This arrangement balances the variation with position of interrogation flux against the variation of the detection efficiency, the aim being to reduce the variation of response within the drum.

The response of such an arrangement for a drum of CAGR waste has been calculated and the results show differences in the horizontal mid-plane (level with the neutron tube) of about a factor of two. This is acceptable for quality checking purposes. In the vertical direction the response varies by a factor of eight. This value needs to be reduced, and the proposed method is to scan the drum either by moving the neutron source or the drum itself. A report describing this work should be available shortly[1].

An experimental test facility is under construction and should soon be commissioned. This will allow the verification of the computer

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(1) M T Swinhoe AERE-R 12074 (1985).

calculations and enable investigation of methods of reducing the vertical variation of response.

1.15.4 Neutron self-shielding of fissile material up to 750 eV (M J Cogbill* and M T Swinhoe)

Self-shielding, the reduction of reaction rate in bulk samples relative to that in dilute samples, can be important in the assay of fissile material, particularly when thermal neutrons are used. In trying to overcome this problem, it is useful to harden the interrogating neutron spectrum and avoid thermal neutrons by covering the sample with cadmium. In some materials, significant self-shielding can occur above thermal energies, and Monte Carlo calculations have been carried out using the code MORSE to quantify the effect. The materials for which results have been obtained are plutonium metal, plutonium oxide, uranium metal (93% ^{235}U) and uranium oxide (2.5% ^{235}U). The calculations were carried out for various spherical samples with masses in the range of 0.1-100 g. The results show that there are severe self-shielding effects below 100 eV but that they have mostly disappeared by 1 keV. This work has been issued as a report in the safeguards series SRDP-R126.

1.15.5 Marginal effects in the calculation of (α, n) production in mixed Pu/UO_2 and in Pu metal fuel (D West)

The neutron coincidence counting method of assaying the Pu content of material is subject to a background from (α, n) neutrons which induce fissions in the sample. Typically 30% of neutrons arise from (α, n) reactions in mixed oxide fuel, and an accurate estimate of the intensity of (α, n) neutrons is required in order to apply a correction. This has led to concern about the magnitude of effects which could alter the straightforward estimate of (α, n) intensity from measured thick target yields.

The following effects were considered, and detailed calculations of their magnitude were reported in Ref.1:-

- The accuracy of the measurements available.
- Uncertainties arising from applying the data to mixtures or compounds

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* University of Birmingham

(1) D West AERE-R 11779 (1985)

- Neutron production in Al alloyed with Pu metal.
- The magnitude and effect of the difference of stopping powers between Pu and U.
- Neutron production in Al canning material from surface emission of α particles.
- Neutron production in the air spaces of powdered PuO_2 prior to sintering.

Neutron production in Al alloyed with Pu amounts to 6% of the spontaneous fission neutron emission for an alloy containing 2% of Al. The combined effect of ignoring the last three factors given above was shown to be much less than the accuracy (1-2%) to which the best determined (α, n) yields are known. Consequently they can be neglected.

1.15.6 Plutonium dating (D West)

The date of chemical separation of a Pu sample is of use in identification, and for determining the amount of ^{241}Am which has accumulated. A method of dating, using γ-ray analysis, which exploits the branched γ and β decay of ^{241}Pu was proposed in Ref.1. Partial tests using fuel pins have been reported previously (UKNDC(82)P105 p.50 and UKNDC(83)P109 p.63) but these were marred by uncertainties in the ages of available samples.

Samples of ^{241}Pu with well known separation dates have now been inter-compared. In addition, fuel pin measurements have been made at different times separated by several years and a constant date of separation obtained for the "unknown" sample. Both these series of measurements have been assisted by techniques not previously available for the work. These are the use of the GAMANAL γ-ray analysis computer program and the Pulse Processing System NM8800 with an HP Ge detector, the latter enabling counting times to be reduced by one order of magnitude.

Fuel pin samples (WO1, WO2, and WO3) of known separation date (7 Nov. 1980) were used to determine the separation date for fuel pin M120. The results are given in **Table 1.4.**

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(1) D West and A C Sherwood, Annals of Nuclear Energy 8(1981)441, and AERE-R 10020.

TABLE 1.4

Results of the separation date of fuel pin M120 as determined by successive measurements

Date of measurement	Determined date of separation
June 1982	4 July 1977 ± 19 days
October 1984	28 June 1977 ± 17 days
April 1985	4 July 1977 ± 12 days
Weighted mean	3 July 1977 ± 9 days

There is excellent agreement between the separation dates as determined on the three occasions. The only known information about fuel pin M120 is that its constituent material was isotopically analysed on 15 March 1978 and that usually six months elapsed between chemical separation and isotopic analysis.

Laboratory samples of ^{241}Pu were supplied by Mr R A P Wiltshire of Chemistry Division. Two of the six samples (nos. 10 and 29) were used as standards, and the separation dates of the remainder of the samples were determined and compared with the known dates. The results are shown in **Table 1.5.** Satisfactory agreement between measured and known dates of separation is obtained for samples nos. 29, 31 and 27. The agreement is borderline for sample no. 24. In the case of sample no. 36, however, there is a real discrepancy. The difference is in the sense of more ^{241}Am being present in the sample than could have grown in from the ^{241}Pu. One can surmise that, in this case only, contamination with ^{241}Am may have occurred in the glove box.

On the basis of the above two sets of experiments, the dating method proposed in Ref.1 is shown to be valid over an age range of 3 months to 15 years, and capable of measurement accuracy of about ±1% over this range.

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(1) D West and A C Sherwood, Annals of Nuclear Energy 8(1981)441, and AERE-R 10020.

Table 1.5

Separation date measurement made in July - August 1985 for the laboratory-separated ^{241}Pu samples

MEASURED SAMPLES

	No. 36 Separated 25 October 1979	No. 29 Separated 16 October 1979	No. 24 Separated 23 December 1981	No. 31 Separated 4 December 1984	No. 27 Separated 3 May 1985
Using Standard No.10 (separated 19 March 1970):					
Measured Value:	1.0* August 1979	9.2 October 1979	9.7 January 1982		
Uncertainty:	± 13 days or ± 0.6%	± 14 days or ± 0.7%	±6.7 days or ± 0.5%		
(Known - Measured Value):	+ 85.5 days or + 6.6%	+ 7.3 days or + 0.5%	- 17.2 days or - 2.6%		
Using Standard No.29 (separated 16 October 1979):					
Measured Value:	10.1 June 1979**		1.9 January 1982	1.5 December 1984	5.1 May 1985
Uncertainty:	± 24 days or ± 1.1%		± 7.1 days or ± 0.5%	± 4.7 days or ± 1.9%	± 2.8 days or ± 3.3%
(Known - Measured Value):	+ 137.4 days or + 5.8%		- 9.4 days or - 1.3%	+ 3.0 days or + 0.6%	- 1.6 days or - 0.6σ

* Measured dates are quoted in decimal days.

** Measurements made using Ge-(Li) detector.

1.16 Neutron diagnostics for JET*

Over the past six years, Neutron Systems Group has been involved in the design and provision of five sets of neutron diagnostic instrumentation for JET. An overview of these sets was given in UKNDC (83)P109 p.64. The set consisting of resolved neutron yield monitors is now installed and in regular use, providing valuable measurements of the time-dependent neutron output during JET pulses. The remaining four sets are at various stages of development and implementation of these is commented on below.

1.16.1 Time-integrated neutron yield monitor (JET KN2 diagnostic system) G Huxtable, J P Argyle, P Dixon, A R Talbot*, M Calkin, and M Philbin**

The KN2 system (UKNDC(85)P112p.57) is designed to irradiate foils at positions close to the JET torus and to transfer them to the diagnostic hall for measurement. The original system has been further developed prior to its installation at JET.

JET has extended its original requirements for the KN2 pneumatic transfer system by requiring the provision of extra irradiation stations and, to reduce the problem of air activation, the introduction of an air "purge" phase into the operation of fetching a capsule from the torus hall. This work has been covered by a separate contract with JET and is largely complete. It has required the complete rebuilding of the control system as supplied by the subcontractors, and the opportunity has been taken to make a number of major improvements. Much of the pneumatics in the diagnostic hall has been rebuilt under this extension contract, with consequent improvements in performance and reliability.

The pneumatic system will be installed in the JET diagnostic hall, together with its control cubicle, as soon as JET's necessary construction work has been completed to allow it.

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* Joint European Torus, Culham, Oxon.

** Now a student at Trinity College, Cambridge.

Some software has been written to allow simple control of the capsule transfer system by a local LSI-11 computer for testing purposes, simulating the JET computer system in that it controls a CAMAC crate containing the JET line surveyor/driver (LSD) which multiplexes input and output lines. This program will next have to be extended and translated to run on JET's NORD system.

After a considerable delay, JET has approved the detailed design of pipework near the torus, at least for the four lower irradiation stations. This stainless steel pipework is now being built, together with the air-control hardware at these stations.

The gamma detection and counting system comprises a 45 cm^3 high purity Ge detector and a 76.2 mm dia x 76.2 mm NaI detector, both feeding a Canberra-90 analyser having 16kbyte of store. The Ge pulses are interfaced through a Harwell/Link Systems Pulse Procesor type 8800, which uses pulsed optical feedback so that high gamma-ray counting rates (up to 500 kHz) may be used with little degradation of the spectrum. To this system has been added a loss-free counter unit for correcting counting losses. A teething problem, in the form of spurious peaks introduced by this unit at low count rates, has since been identified and corrected.

Software has been written for remote control of the Canberra-90 MCA via the JET CODAS system, and for the transfer of spectrum data from the MCA to CODAS as a data file for further analysis. Due to poor compatibility between the serial interface of the analyser and the CODAS system, this spectrum transfer operation is rather slow (about 45 s for a 4k spectrum) and may be a limiting factor in some operations of the system. It is expected that further modifications will be required as operating experience is gained.

There remains the major task of writing a set of programs on the JET NORD system for user-interface, for analysis of the gamma spectrum in terms of induced activities, and finally for its reduction to neutron flux information.

Using the Harwell 500 keV Van de Graaff, a relative measurement has recently been made of the (n, 2n) cross-section of ^{109}Ag at 14.1 MeV. This is a prospectively useful dosimetry material although

the relevant gamma-ray line is a weak one[1].

The transfer system has recently been tested by using it to expose a capsule containing Al and In foils to 14.2 MeV neutrons and then making a quick transfer to the Ge detector for counting.

1.16.2 Neutron spatial emission profile monitor (M T Swinhoe and P Dixon*)

Experimental tests have been made on the Link Systems 5020 pulse shape discriminator unit. This appears to be working satisfactorily. The collimator/shield assemblies are being manufactured.

1.16.3 2.5 MeV neutron spectrometer for deuterium plasmas (M T Swinhoe, P Dixon* and M Loughlin**)

Experimental work using the Dynamitron accelerator at Birmingham and complementary calculational work have been carried out in an attempt to improve the resolution of NE213 liquid scintillation detectors for fast neutrons. This may enable measurements to be made of the width of the neutron spectrum emitted from JET at high plasma temperatures. The shielding for the detectors is being manufactured.

1.16.4 14 MeV neutron spectrometers for deuterium-tritium plasmas (E W Lees, C A Uttley, D West, A C Sherwood, C W Thompson* and D B Syme)

Different versions of spectrometer systems for 14 MeV neutrons have been designed and costed for JET, as described in previous progress reports (UKNDC(84)P111 p.76 and UKNDC(85)P112 p.60). During this year, it was decided that the cost of providing both the silicon diode and the annular radiator spectrometers in one massive shielding enclosure would be prohibitive. The cost could not be sufficiently reduced, although various economies in the design were considered, including:

(a) the use of only one collimator for the silicon diode detector, so restricting its application to plasma temperatures below about 5 keV.

(b) a reduction in shield thickness by about 20% following upon the restriction to operations below 5 keV plasma temperatures.

(c) the use of a shield material (water, polythene or concrete) cheaper than the 'Premadex' material which had previously been

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* Engineering Projects Division, Harwell

** Physics Department, University of Birmingham

(1) M T Philbin and E W Lees, AERE-R 11902(1985).

favoured in order to minimise the shield mass. However, the use of these materials means various penalties on performance or practicability.

Late in the year, it was announced that the date for tritium injection into JET would be delayed by two years. In the light of this new timescale and the above costing difficulties, it was thought best to complete the present phase of work with the current design and cost estimates.

It is now hoped to pursue separate development of the shield and the detector design for an annular proton recoil detector situated in its own shield in the diagnostic hall. The silicon diode detector will use the existing roof laboratory, viewing the plasma from above, consistent with its more restricted application to the ohmic heating regime ($T < 5$ keV).

1.16.4.1 Annular radiator proton recoil spectrometer (C A Uttley, A C Sherwood and D B Syme)

A preliminary version of the annular radiator proton recoil detector (see UKNDC(85)P112 p.63) has been tested in the 14 MeV neutron flux from the neutron generator in Hangar 7, AERE Harwell. The 6 mg cm^{-2} polythene radiator annulus and the high purity Ge detector are contained in a cylindrical cryostat. The design is intended for an essentially parallel beam of incident neutrons (as at JET) and it was not possible to provide this in the test geometry available. Therefore the recoil proton peak from 14 MeV neutrons was observed to sit on a background due to neutrons scattered into the Ge detector itself. The observed resolution was also higher than that which will be obtained at JET (~350 keV), but this was expected because of the finite angular range of the incoming neutrons and other source effects in these tests.

It is desirable to extend the testing in improved background conditions with parallel neutron beams and also to quantify the background sensitivity. It is possible further to reduce the background (e.g. by improved chamber design and/or the inclusion of a ΔE detector) to confirm that each event is due to a recoil proton. These design changes are under consideration.

2 CHEMICAL NUCLEAR DATA

2.1 Introduction

During 1985 the Chemical Nuclear Data Committee held two meetings (Chairman A L Nichols (AEEW)). With effect from December 1985, F G Etham (AEEW) took over from R Bett as Secretary of this committee. The Data Library Sub-committee (Chairman A Tobias (CEGB), Secretary H E Simms (AERE)) also met twice during the year.

Relevant experimental studies at AERE Harwell have been concentrated within the Actinide Chemistry and Analysis Group of the Chemistry Division. Studies within this group involve the measurement of decay data identified with the IAEA Coordinated Research Programme on Transactinium Nuclear Decay Data (particularly with respect to ^{237}Np, ^{237}Pu and specific Cm isotopes). Contractual negotiations during the year have involved a greater involvement in such work by the National Physical Laboratory and certain universities (e.g. Imperial College and Manchester).

Evaluation effort continues to be linked to the development and needs of the European Joint Evaluated File. Members of the Data Library Sub-committee have assisted in the final adoption of decay and fission yield data for the first issue of the file (JEF-1). There has also been a significant increase in effort for the evaluation of fission yield data following the establishment of a multi-funded contract involving University of Birmingham personnel based at AEE Winfrith.

Support for chemical nuclear data stands at between two and three scientist-years in the UK, shared over many people. The small increase on previous years can be attributed to various contracts between the nuclear power community and the universities, an important development that needs to be encouraged further. The work covers such diverse activities as the measurement of half-lives, decay data, neutron dosimetry, neutron cross-sections and fission yields in PFR, as well as data evaluation and decay heat assessments.

2.2 Measurement work

2.2.1 Fission yield of tritium (J W McMillan* and D H Rowe*)

An experimental programme is being planned at Harwell to measure the ternary fission yield of tritium from uranium and plutonium nuclides, particularly during fast neutron irradiation. The programme essentially comprises the completion of work commenced several years ago on ^{235}U and ^{239}Pu, plus its extension to other nuclides.

In the original programme, aqueous specimens of ^{235}U and ^{239}Pu were irradiated in GLEEP with thermal neutrons, and metallic specimens of ^{235}U and ^{239}Pu were irradiated in ZEBRA with fast neutrons. Despite post-irradiation storage for more than five years, calculation shows that tritium should not have escaped from the original irradiation capsules. Consequently, steps are being taken to construct and commission a chemical separation system in a glove box for the recovery and measurement of the tritium in the irradiated specimens. This equipment would then be available for the examination of further fast neutron irradiated nuclides including ^{238}U, ^{240}Pu, ^{241}Pu and ^{242}Pu. As ZEBRA is no longer available, future irradiations will be undertaken using the Harwell electron linac HELIOS, or MASURCA at Cadarache. The continuation of this programme is dependent on the availability of adequate funding during the financial year 1986/87.

2.2.2 Absolute fission yields of selected fission product nuclides (T W Kyffin**)

Absolute fission yield studies are under way in PFR, and the experimental capsules are still being irradiated in the reactor. Because of the changes to the programme, the expected burn-up values of the samples have increased significantly and, along with the measurement accuracies, these are given in **Table 2.1**

The proposed fission yield measurements are for Nd nuclides, $^{95}Nb/Zr$, ^{106}Ru, ^{137}Cs and ^{144}Ce. The capsules will not be removed from the reactor until late 1986, and the measurements could not be completed before the end of 1987. However, current circumstances indicate that the necessary analysis cannot be undertaken unless there is a strong representation from interested parties.

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* AERE Harwell

** DNPDE

Table 2.1

Materials used in the fission yield studies at PFR.
The corresponding accuracy in the measurements is shown, together with the expected burn-up

Material	Accuracy	Burn-up
^{235}U	2%	35%
^{238}U	6%	1.5%
^{239}Pu	2%	35%
^{240}Pu	6%	10%
^{241}Pu	6%	50%

2.2.3 Decay scheme data of specific actinides (A J Fudge* and M F Banham * (WRENDA 1072)

^{237}U

A quantity of ^{237}U was made by irradiating ^{236}U with thermal neutrons. After irradiation the material was purified radiochemically by ion exchange. Two aliquots of the final solution were sealed in glass ampoules. One was used for the half-life measurements, using a high pressure ion chamber, and the other was sent to the National Physical Laboratory (NPL) for an accurate assay of the ^{237}U using the β-γ coincidence method. Further aliquots were prepared in the standard 10 cm^3 counting geometry for the gamma-ray intensity measurements. NPL also used the solution supplied to make an independent measurement of the half-life. The processing of the data obtained is almost complete.

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* AERE Harwell

^{233}Pa

A quantity of ^{233}Pa was made by irradiating a small amount of ^{232}Th with thermal neutrons in the DIDO reactor. The ^{233}Pa was purified radiochemically by ion exchange and aliquots of the final solution were prepared in a similar manner to that used for the ^{237}U measurements. Aliquots were supplied to NPL for measurements of the ^{233}Pa concentration, and calculation of the P_γ values for all of the γ-rays observed is close to completion. An aliquot of the original solution was also sent to Hasten at the University of Cambridge, who measured a half-life of 26.96 ±0.03 days.

The half-life measurement at AERE was interrupted by failure of the ion chamber electronics and a new measurement will be started shortly when a new supply of ^{233}Pa becomes available.

^{237}Np

The alpha branching ratios and hence the overall decay scheme for ^{237}Np needs to be re-measured. The three most abundant alpha emissions at 4766.1, 4771.1 and 4788.1 keV are too close in energy to be resolved by the use of conventional solid state detectors. A joint programme of work has been started with G Bortels of CBNM Geel, aimed at using computer codes for the analysis of a ^{237}Np spectrum to resolve the overlapping peaks. Nuclides with a different energy and a much simpler decay scheme (and hence simpler energy spectra) have been added to ^{237}Np in order to obtain the shape factor for the peaks for computer fitting. Sources of ^{237}Np and ^{240}Pu have been prepared by vacuum evaporation. Measurements will be carried out at AERE, CBNM and JEN Madrid.

Half-life measurements on ^{237}Np have been resumed and preliminary results are in close agreement with the value of 2.14×10^6 years obtained by Brauer et al[1]

2.2.4 Decay scheme studies of ^{239}U and ^{243}Am (T D MacMahon* and S P Holloway**)

See Section 11.1

(1) F P Brauer, R W Stromatt, J D Ludwick, F P Roberts and W L Lyon, J.Inorg. Nucl. Chem. 12(1960)234.

* Imperial College

** AWRE

2.2.5 Evaluation of the half-life of ^{90}Sr (P W Gray* and T D MacMahon*)

See Section 11.2

2.2.6 Single nucleon transfer reactions in the system (^{12}C, ^{14}N, ^{16}O) on ^{197}Au (H Wilkinson**, G W A Newton**, V J Robinson**)

Cross-sections for the quasi-elastic single nucleon transfer products in the system (^{12}C, ^{14}N, ^{16}O) on ^{197}Au have been measured using off-line gamma-ray spectroscopy. The projectiles were accelerated in the Harwell Variable Energy Cyclotron (VEC) to energies ranging from below the coulomb barrier up to approximately twice the barrier. The products of interest are shown in **Table 2.2.** All have spin isomers which allow some insight to be obtained into the angular momentum transfer involved in the reactions.

Table 2.2

Target-like single nucleon transfer products in ^{12}C, ^{14}N, ^{16}O on ^{197}Au

Nuclide	Half-life	Spin-parity	Transfer reaction
^{197}Hg	64.1 h	$1/2^-$	p in n out of target
^{197m}Hg	23.8 h	$13/2^+$	p in n out of target
^{196g}Au	6.18 d	2^-	n out of target
^{196m}Au	8.2 s	5^-	n out of target
$^{196m2}Au$	9.7 h	12^-	n out of target
^{198g}Au	2.7 d	2^-	n in to target
^{197g}Pt	18.3 h	$1/2^-$	p out n in to target
^{197m}Pt	94 m	$13/2^+$	p out n in to target
^{198}Hg	stable	0^+	p in to target
^{196}Pt	stable	0^+	p out of target
^{199}Hg	stable	$1/2^-$	p in n in to target
^{195}Pt	stable	$1/2^-$	p out n out of target

* Imperial College

** University of Manchester

Table 2.3 gives the results obtained so far which indicate that the reactions are "direct" and the yields should therefore be described by the Distorted Wave Born Approximation (DWBA). Due to the large number of levels available for transfer in the gold nucleus, a DWBA calculation is difficult to perform for this system. However, plans are being made to obtain some theoretical values for comparison with experiment using the DWBA code DAISY.

2.3 CNDC Data Library Sub-committee

(Current Membership: A Tobias (Chairman, CEGB), H E Sims (Secretary, AERE), A L Nichols (AEEW), M F James (AEEW), A Whittaker (BNFL), and J Banai (University of Birmingham))

2.3.1 Data library development

The current status of the UKCNDC data libraries is summarised in **Table 2.4.** Evaluation efforts have been severely restricted during the past year with relatively little progress being made towards revisions of the decay data files.

2.3.1.1 Heavy elements (A L Nichols*)

The published data for specified actinides have been critically evaluated as part of the UKAEA contribution to the IAEA Coordinated Research Programme on the Measurement and Evaluation of Transactinium Isotope Decay Data. The nuclides and evaluated decay parameters were as follows:

^{231}Pa	gamma-ray emission probabilities and alpha-particle emission probabilities,
^{234}U	half-life, gamma-ray emission probabilities and alpha-particle emission probabilities,
^{239}U	half-life and gamma-ray emission probabilities,
^{242m}Am	half-lives.

Many complex decay schemes were produced during the evaluation of the data for ^{231}Pa and ^{239}U.

An extensive report is being prepared in conjunction with IAEA personnel, describing all of the measurements and evaluations made under the auspices of the Coordinated Research Programme on the Measurement and Evaluation of Transactinium Isotope Decay Data. Half-lives, branching fractions, and alpha and gamma-ray emission probabilities have been assessed for 26 heavy elements and actinides. At various times throughout the year the tabulations for this report

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* AEEW

Table 2.3

Cross-sections for the quasi-elastic single neucleon transfer products in the system (^{12}C, ^{14}N, ^{16}O) on ^{197}Au

Projectile Centre of Mass Energy (MeV)	Cross-sections (mb)		
	^{197m}Hg	^{196g}Au	^{198}Au
^{12}C			
72.7	3.8	44.7	-
91.3	13.4	72.7	0.9
106.1	23.5	120.1	3.8
144.1	31.7	120.1	9.7
150.7	44.4	174.2	15.2
161.4	39.8	147.1	15.1
^{14}N			
71.1	10.1	55.7	5.8
77.3	15.8	65.6	8.2
92.0	27.5	84.1	12.9
116.5	42.4	110.4	19.0
132.1	49.4	135.2	23.2
137.6	48.8	129.9	20.9
^{16}O			
80.0	-	6.8	-
113.9	24.6	102.8	3.7
123.2	30.4	124.7	7.2
169.0	48.1	163.9	20.4

Table 2.4
UK Chemical Nuclear Data Libraries. Status as at November 1985

Data	Present Status	File Development
1 Fission Product Decay Data	Exists as UKFPDD-2 (ENDF/B-IV format) - replaces UKFPDD-1 Total no. of nuclides = 855 Radioactive nuclides = 736 Ground state = 175 1st excited state = 133 2nd excited state = 5 Nuclides with spectra = 390 Total no.of gamma lines = 11,978 Total no.of beta$^-$ lines = 3,592 Total no.of beta$^+$ lines = 91	Data acquisition for future revision. Some data have been converted to ENDF/B-V format. Adoption of delayed neutron emission probabilities from Reeder (BNL)
2 Activation Product Decay Data	Available in ENDF/B-IV and V format for 91 nuclides as UKPADD-1. Now includes detailed K x-ray spectra.	60 nuclides have been evaluated for UKPADD-2, 56 are in ENDF/B-V format. Temporarily suspended. References are being brought together for the evaluation of ^{51}Cr, ^{65}Zn, ^{75}Se and ^{198}Au as part of a programme of work identified with IAEA.
3 Heavy Element and Actinide Decay Data	Completion of UKHEDD-1, including spontaneous fission data in June 1982. Data in ENDF/B-V format for: 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 = 3,475 Total no.of discrete electrons = 6,755 Total no.of x-rays = 381	
4 Fission Yields	Available in ENDF/B-V format, based on James/Crouch data called Crouch 4A (adjusted) and Crouch 4U (unadjusted).	Crouch's data files and programs have been used (in ENDF/B-IV and V formats) to produce updated libraries of both unconstrained and constrained yields including uncertainties. These will also generate most of the necessary documentation. Ternary fission has been included and the work is described in CNDC(85)P3 and CNDC(85)P4. Further development has begun in collaboration with Birmingham University.

have been reviewed in preparation for the final proofs. The intention is to include these improved data in a new version of the UKCNDC heavy element decay data library (UKHEDD-2) when the IAEA document has been published.

2.3.1.2 Fission products (A Tobias*)

With the exception of a detailed evaluation of the decay scheme of ^{129}I, requested by BNFL, there have been no evaluations made specifically for UKFPDD-3. All efforts have been directed towards the JEF collaboration.

2.3.1.3 Activation products (A L Nichols**)

Gamma-ray emission probability data have been evaluated for ^{51}Cr, ^{65}Zn and ^{198}Au (and are planned for ^{75}Se), following the IAEA consultants' meeting on Gamma-ray Standards for Detector Calibration held at Grenoble, May 1985. An assessment was made of the requirements for an internationally-accepted file of x- and gamma-ray standards, and a provisional list of nuclides was produced at this meeting.

2.3.1.4 Fission yields (M F James**, P S Whitworth**and J Banai***)

The new libraries of fission yields (C4U and C4A) have been tested and compared with other sets in decay heat calculations, and a draft report has been issued on the results. Yields for 14 MeV fission have been added, and some errors found and corrected.

2.3.2 Fission yields (J Banai***, D R Weaver*** and M F James**)

The evaluation code of Crouch that was used to produce the original version of C4U has been altered to improve the statistical method, and to produce clearer tables in which discrepant measurements can be more easily detected.

The database of measurements is being checked and brought up to date. A detailed study is being made of any measurement shown to be particularly discrepant and to give a large contribution to χ^2 by the computer-produced tables. Additionally, an evaluation of ternary fission measurements has begun.

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* CEGB

** AEEW

*** University of Birmingham

2.3.3 Joint Evaluated File (JEF)

A preliminary version of the JEF-1 Decay Data File has been constructed by the Data Library Sub-Committee from UK and French evaluations. The selection of decay data from UK and French data sources was made on a nuclide-by-nuclide basis, using the agreed decay scheme consistency checks. The preliminary JEF-1 Decay Data File has been processed by the ENDF/B-V checking code FIZCON. A number of errors were subsequently identified in the section of FIZCON which examines the decay data. After taking these into account, minor differences in interpretation of the ENDF/B-V format between UK and French evaluators were found to be the cause of the bulk of the remaining 'errors' identified by FIZCON. Agreement on a consistent interpretation of the ENDF/B-V format has now been agreed and the JEF-1 Decay Data File is being revised accordingly. This is expected to be completed early in 1986.

The JEF-1 Decay Data File has been compared with ENDF/B-V evaluations where available, and with UKFPDD-2 for the fission products. The majority of the differences found are due to the inclusion of more recent experimental data. It is aimed to use the revised JEF-1 Decay Data File with the corresponding JEF fission yields in decay heat testing.

2.3.4 CASCADE (G Evangelides*)

All of the CASCADE reports have been completed and have been critically reviewed by the Data Library Sub-Committee. They are awaiting final vetting prior to publication by AERE Harwell.

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* Daresbury Laboratory

3 REACTOR PHYSICS DIVISION, AEE WINFRITH

(Division head: A J Briggs)

3.1 Nuclear data evaluation and validation

3.1.1 Decay heat calculations (M F James)

The new fission yield library C4A (see Section 2.3.1) has been used in decay heat calculations. As a covariance matrix was produced for the library, it has been possible to calculate the fission yield contribution to the overall standard deviation of the calculations. Total standard deviation at different irradiation and cooling times, and correlations between different decay heats have been calculated.

3.1.2 Fission product yields (M F James, P S Whitworth, J Banai)

(See Section 2.3.1.4)

3.1.3 Few-group capture cross-sections of ^{153}Eu and ^{133}Cs in FISPIN (R W Smith)

An in-depth review of the three group (thermal, resonance and fast) capture cross-sections of ^{153}Eu and ^{133}Cs, as used in FISPIN, has been completed for MAGNOX and PWR fuels. Error estimates have been derived by comparing calculated values with an evaluation of all available experimental data.

3.1.4 Benchmark testing of the JEF-1 library (C R Eaton, C J Dean and M J Grimstone)

Benchmark testing of this library has continued. The 71-group version of the library provided by the NEA Data Bank has been used in calculations with the MURAL code for a number of zero leakage systems. These included the Zebra 8 series of plate cells, and a series of PROTEUS pin lattices containing PuO_2 + UO_2 fuel and steel. Some intermediate spectrum systems have been examined as possible benchmarks and have been calculated with the 71-group data, although it is recognised that this data set is not suitable for the treatment of these systems in its present form. Further benchmark tests of this data set have also been carried out on spherical homogeneous representations of fast critical assemblies.

3.2 Cross-section processing codes

3.2.1 REMO (R W Smith)

The code REMO (a version of SIGAR7 with a multi-channel fission Reich-Moore option) has been used to process resonance parameter data for ^{60}Ni and ^{241}Pu, supplied by the IAEA. The results, in the form of files of cross-section against energy at 0 K, have been forwarded to the IAEA in Vienna as the UK contribution of an international intercomparison exercise.

3.2.2 NJOY (C J Dean and C R Eaton)

The latest version of NJOY has been successfully implemented on the CRAY computer at AERE Harwell. By using the Update facility and the reference version of the program (in this case 6/83), changes originating from Los Alamos, NEA, AERE Harwell and AEE Winfrith have been included. The Update system provides a convenient means of cataloging and exchanging information on modifications and improvements, and the UK would like to see its universal adoption by all NJOY users.

3.3 New data files (C J Dean and P S Whitworth)

The ENDL file for ^{31}P has been converted into ENDF/B-V format.

4 DIVISION OF RADIATION SCIENCE AND ACOUSTICS
NATIONAL PHYSICAL LABORATORY
(Superintendent: K C Shotton)

4.1 Neutron source emission rate and fast neutron fluence intercomparisons

The intercomparison exercises described below are held under the auspices of the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) of the CIPM*

4.1.1 NBS neutron source SR144 (^{252}Cf) (co-ordinator: E J Axton (NPL, BIPM))

Analysis of the results has been completed and shows satisfactory agreement between most of the participating groups, including NPL. A report has been prepared.

4.1.2 Transfer method using the ^{115}In(n,γ)^{116m}In reaction for 144 and 565 keV neutron fluences (co-ordinator: T B Ryves (NPL))

All groups have finished the measurements and submitted results which have been analysed by NPL. A report has been prepared with a view to publication in 1986.

4.1.3 Transfer method using twin ^{235}U and ^{238}U fission chambers (co-ordinator: D B Gayther (AERE))

(See Section 1.10)

4.1.4 Transfer method using two moderating sphere detectors (co-ordinator: J B Hunt (NPL))

Section III of CCEMRI recommended that the two-sphere technique, proposed by NPL, should be tested in a mini-intercomparison. The sphere diameters are 88.9 mm and 241.3 mm, and a spherical ^{3}He proportional counter will be used. A detailed protocol has been prepared by NPL. The measurement cycle will begin at BIPM in early 1986 and it is envisaged that NBS, CBNM, PTB and NPL will also participate. The test will be carried out at neutron energies of 2.5 and 14.65 MeV.

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* For abbreviations see UKNDC(82)P105 p.71

4.2 Nuclear decay scheme measurements (P Christmas, D Smith, M J Woods, S M Judge, S A Woods, S Waters*, W Gelletly** and J Pearcey**)

4.2.1 Half-lives

The half-life measurements of ^{152}Eu and ^{154}Eu have continued. The results have not changed significantly from those reported previously (UKNDC(85)P112 p.90), and the latest values will be submitted for publication this year.

Measurements have also been completed for the half-lives of ^{237}U, ^{233}Pa (in collaboration with AERE, Harwell), ^{47}Sc (in collaboration with CBNM and LMRI) and ^{82}Rb (in collaboration with MRC). The results for ^{82}Rb and ^{47}Sc have been submitted for publication and it is expected that similar action will take place for ^{237}U and ^{233}Pa.

A co-ordinated research survey programme under the auspices of the IAEA and involving members of ICRM is now surveying the decay data for a selected group of radionuclides which are commonly used in the calibration of gamma-ray detector systems. NPL and PTB are contributing to this programme with a survey of half-life data; a preliminary report is expected early in 1986.

4.2.2 ^{82}Rb decay scheme

The measurements reported previously (UKNDC(85)P112 p.91) have now been completed and the results have been submitted for publication.

4.2.3 ^{93m}Nb decay scheme

A measurement has been made of the absolute K X-ray emission from ^{93m}Nb, as part of an international collaborative effort by NBS, PTB, LMRI, INEL, AERE, CBNM and NPL. The NPL measurements taken in conjunction with the activity estimate by CBNM gave a value of $P_k\omega_k = 0.1081 \pm 1.3\%$, where ω_k is the fluorescence yield.

4.2.4 Beta-ray spectrometry

A collaborative study is continuing with Manchester University to obtain improved decay data and nuclear structure information for

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* MRC Cyclotron Unit, Hammersmith Hospital

** Manchester University

actinide nuclei. Conversion electron studies on the NPL iron-free beta-ray spectrometer (which utilizes a multi-wire proportional counter and a Bergqvist-type multi-element source) and conventional gamma-ray spectrometry are employed. Measurements of the decay of ^{237}Np have been completed and a study of ^{241}Am is under way.

An electron-gamma coincidence system has been developed for the beta-ray spectrometer and a start has been made on using the system to measure the end-point energies of beta-decay branches from the decay of ^{47}Ca. Precise values of beta-decay end-point energies are needed for certain strategic nuclides near stability in order to resolve discrepancies in the table of atomic mass differences.

4.3 The thermal neutron capture cross-section ratios of manganese, sulphur and boron to hydrogen (A. Arbildo*, J. C. Robertson** and T. B. Ryves)

The manganese bath technique has been extended to measure the thermal neutron capture cross-section ratios of Mn, S and B to H. Experimental measurements have finished and the results are now being analysed, taking fully into account the covariances which exist between data. For the ratio of the S to the H cross-section, a result of (1.621 ± 0.033) has already been obtained, and an account of this work has been accepted for publication in Annals of Nuclear Energy.

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* Institute for Nuclear Energy (IPEN), Lima, Peru

** University of New Mexico, USA

5 DEPARTMENT OF PHYSICS RADIATION CENTRE, UNIVERSITY OF BIRMINGHAM

(Director: Professor J Walker)

5.1 Delayed neutron measurements (S J Chilton, D R Weaver, J G Owen and J Walker)(WRENDA 979)

Measurements of spectra of delayed neutrons from the fission of ^{235}U induced by neutrons from the Be(d,n) reaction (UKNDC(85)P112 p.92) have continued during the year. Different beam-pulsing timing cycles have been employed to provide information according to the Keepin scheme[1] on the temporal variation of the spectra. In addition, a new data recording system has recently been employed to record pulse height and time-of-arrival of pulse, rather than pulse height and pulse rise-time.

Four earlier measurements of delayed neutron spectra from fast fission in ^{235}U, produced by bombarding a ^{235}U sample with monoenergetic neutron beams of different energy, have been compared using a rebinning technique[2]. The analysis showed a systematic variation in the portion of the delayed neutron spectra below about 150 keV, as reported at the Santa Fé meeting in May 1985[3] (see **Fig 5.1**). The variations were statistically significant based on error calculations using a full covariance matrix analysis.

At the same time a further spectrum unfolding method[4], which does not rely on dual parameter (pulse height versus pulse rise-time) discrimination of ^{3}He recoil events, was applied to all of these ^{235}U measurements, and also to measurements with an Am/Li neutron source. Some differences between the results from the two methods of unfolding and, in particular, differences in the systematic variation of the spectra reported at Santa Fé, led to a study being made of the low energy part of the spectra. From the Am/Li source measurements, where the spectrum cannot have been different for measurements made at different times, it has become clear that instability in the rise-time parameter of the dual parameter analysis can have a disproportionate effect on the unfolded spectra. The criterion for setting up the

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(1) G R Keepin, Physics of Nuclear Kinetics, Addison Wesley (1965).

(2) D R Weaver, J G Owen, J Walker and S J Chilton, University of Birmingham, Department of Physics Radiation Centre Annual Report (1984), BRC 84/01 p.3.

(3) J Walker, D R Weaver, J G Owen and S J Chilton, Proceedings of the International Conference on Nuclear Data for Basic and Applied Science, Santa Fé, May 1985.

(4) S J Chilton, D R Weaver, J Walker and J G Owen, University of Birmingham, Dept. of Physics Radiation Centre Annual Report (1984), BRC 84/01 p.4.

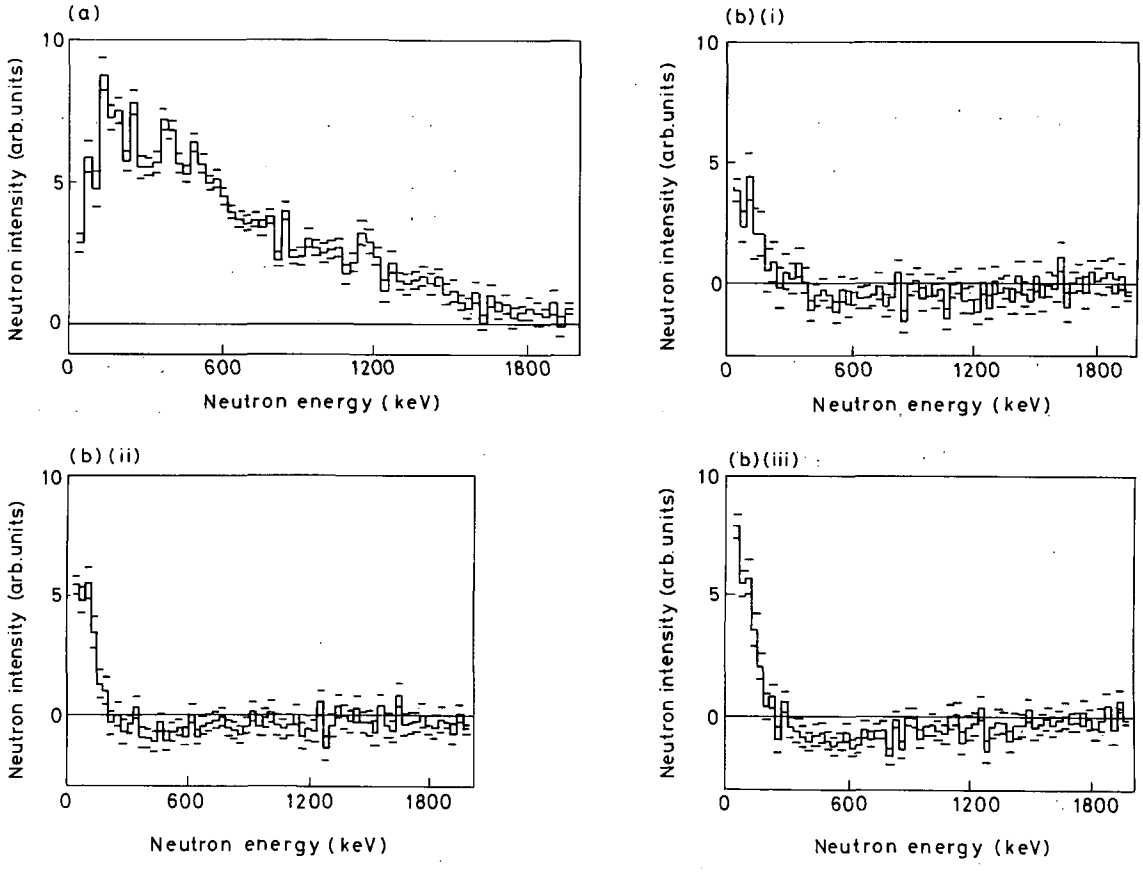

Fig 5.1 (a) Rise-time discriminated data for the normalised delayed neutron spectrum following fission produced by 0.49 MeV neutrons. (b) Differences in delayed neutron spectra produced by different incident neutron energies: (i) 0.94 MeV - 0.49 MeV, (ii) 1.44 MeV - 0.49 MeV, (iii) 1.76 MeV - 0.49 MeV.
The lines above and below the histogram indicate the errors.

rise-time analysis has always been a 10:1 ratio in the contribution from thermal neutrons between two adjacent rise-time slices in the spectrum. It appears that the older of our two ^{3}He spectrometers and its electronics are less stable in rise-time discrimination than the newer, Seforad detector. Further measurement of its rise-time discriminated efficiency has shown a significant change from that determined in the early stages of this project, whereas its total undiscriminated response has remained unchanged. The new analysis without rise-time discrimination (1) appears not to suffer from these effects; therefore the spectrum unfolding from the ^{235}U

(1) S J Chilton, D R Weaver, J Walker and J G Owen, University of Birmingham, Department of Physics Radiation Centre Annual Report (1984), BRC 84/01 p4.

measurements has been repeated using the newer method. The results (see **Fig 5.2**) cast some doubt on the systematic variation seen in the low energy portions of the delayed neutron spectra.

The analysis method without rise-time discrimination has been extended to the newer detector so that measurements taken earlier on ^{239}Pu fission, without the benefit of dual parameter data collection, can be analysed, as can the recent measurements on ^{235}U, where pulse height and time-of-arrival were recorded.

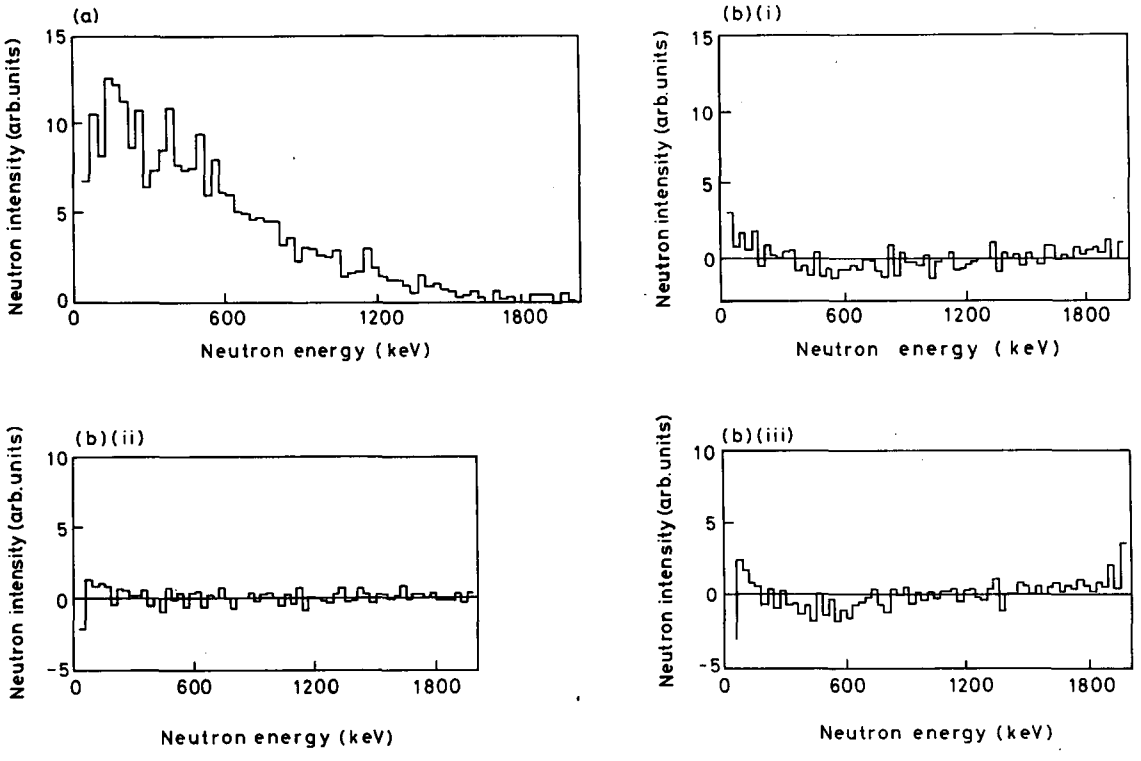

Fig 5.2 (a) Undiscriminated data for the delayed neutron spectrum following fission produced by 0.49 MeV neutrons.
(b) Differences in the delayed neutron spectra produced by different incident neutron energies: (i) 0.94 MeV - 0.49 MeV, (ii) 1.44 MeV - 0.49 MeV, (iii) 1.76 MeV - 0.49 MeV.

6 DEPARTMENT OF PHYSICS, UNIVERSITY OF BIRMINGHAM

6.1 Neutron physics measurements relating to fast neutron cancer therapy (N R Crout, J G Fletcher, M C Scott and G C Taylor)

The M.R.C. Neutron Cancer Therapy facility at Clatterbridge, a 60 MeV proton machine, is currently just starting clinical trials. These trials involve assessment of the effectiveness of neutrons for curing, or regressing, different cancers in comparison with other methods of treatment. However, such trials have to be conducted over a number of years - because of the time span of the disease - and intercomparison with the results from other facilities is therefore important in speeding up these evaluation procedures. Unfortunately, such intercomparisons are often difficult because of differences in beam characteristics and irradiation conditions. The objective of our M.R.C. supported programme is therefore to provide as detailed characteristics as possible of the Clatterbridge facility.

Ideally one wants the spectrum of each of the charged particles produced for different beam sizes and positions within a subject. Lack of data in the neutron energy range 20-60 MeV for charged particle producing reactions in, principally, carbon and oxygen, preclude calculation of this, although in a related Harwell supported programme we are developing a new detector system for charged particle production measurements. Our objectives in the current measurements are therefore (a) to measure neutron spectra, and (b) to measure linear energy transfer (LET) distributions (or event size spectra).

In order to perform neutron spectrometry in situ, one has to unfold the detector response. This requires knowledge of the response functions of the detector which in this case is an NE213 scintillator 6.0 cm in diameter and 6.0 cm high, mounted on a perspex light guide. Because of the high carbon content of this scintillator, if pulse shape discrimination is used the response function might also be analysed to provide charged particle production data. We are therefore undertaking a series of response function measurements on the Harwell 136 MeV electron linac, using the 150 m fast neutron flight path. A CAMAC-based 3-dimensional data acquisition system has been commissioned to provide a 1 mega-channel storage for an array of 128 pulse height channels, 64 pulse shape channels and 128 time-of-flight channels.

Thus, at each neutron energy one obtains a 2-parameter response function array of pulse height against pulse shape (i.e. particle type).

One result from our preliminary measurement is shown in **Fig. 6.1** which illustrates the response function at 30.7 MeV summed over all particle types. **Fig. 6.2** shows the light output curve for the neutron energy range 15 to 40 MeV, derived from the proton recoil edges of the same data.

In a related programme we have developed a Monte Carlo light photon transport code to predict the pulse height spectra of scintillation counters. This models the light reflection and transmission properties of cells of different geometries, and allows the reflecting paint to be "banded", since this has been shown to improve resolution by minimising the importance of the spatial dependence of pulse height. Associated with this is the implementation of the high energy neutron data set HILO, which has cross-section information in the ANISN/MORSE format up to 400 MeV.

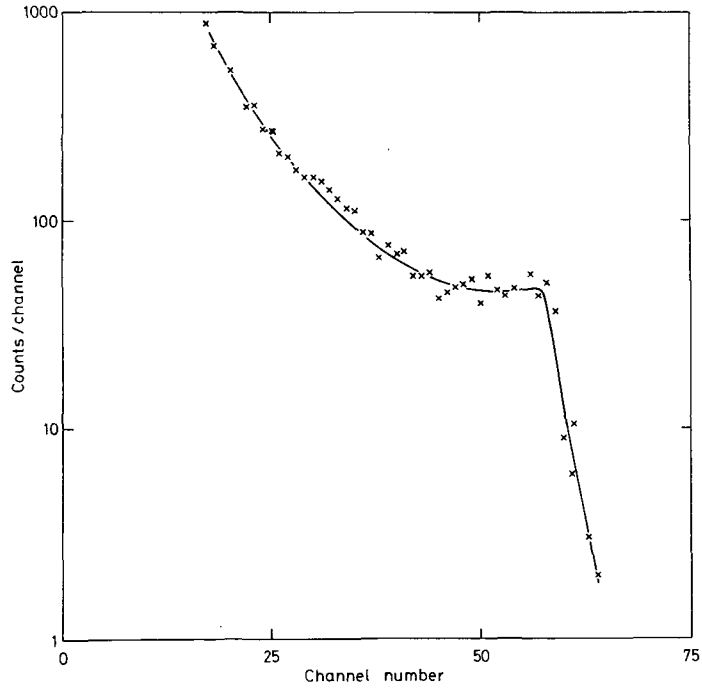

Fig 6.1 The detector response function for 30.7 MeV neutrons

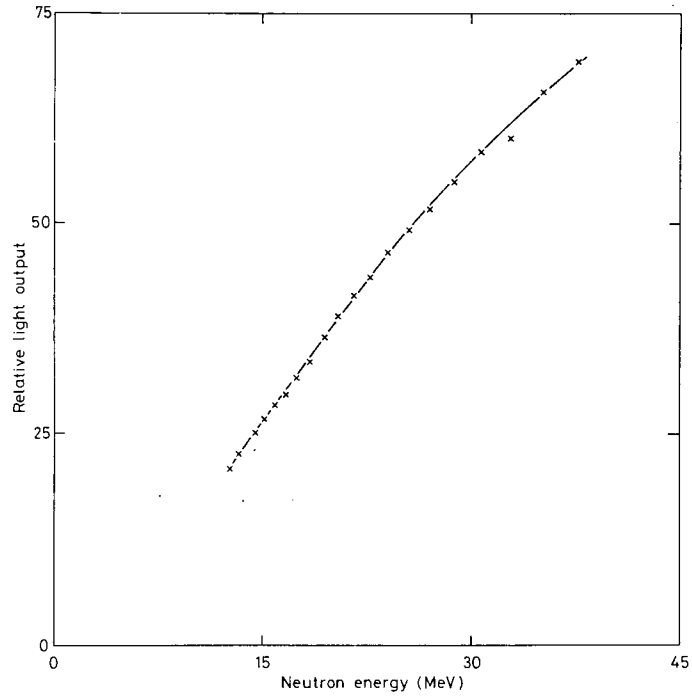

Fig 6.2 Plot of the relative light output (given by the channel number of the proton edge half height) versus neutron energy (from the time-of-flight).

7 DEPARTMENT OF MATHEMATICS AND PHYSICS, UNIVERSITY OF ASTON IN BIRMINGHAM

7.1 Multiple neutron scattering effects in lead (A J Cox and M H Jasim) (WRENDA 814)

The work reported last year (UKNDC(85)P112 p.98) has been extended to study neutron multiple scattering effects in lead. In the present work, neutron differential scattering cross-sections for both elastic and inelastic scattering have been measured for different sample thicknesses using an associated particle time-of-flight system. It is found in both cases that the neutron production cross-sections, σ_x, increase with increasing sample thickness x. This behaviour is described by the phenomenological formula

$$\sigma_x = \sigma_0 \exp(\alpha x),$$

where α and σ_0 are constants.

A SAMES accelerator produced 140 keV deuterons which were incident upon a titanium tritide target. The alpha particles produced in the $^3H(d,n)^4He$ reaction were detected at 90° to the deuteron beam, using an NE102A plastic scintillator coupled to a 56AVP photomultiplier tube. The alpha particle aperture was 1.09 cm x 1.89 cm, defining an associated neutron beam of mean angle 83° ± 4° to the deuteron beam.

Samples were positioned 25 cm from the target, and neutrons were detected at scattering angles between 30° and 90°. The neutron detector was a 10 cm x 10 cm cylindrical NE102A scintillator, coupled to a 56AVP photomultiplier tube shielded from the earth's magnetic field by a mu-metal shield. In addition, the photomultiplier was shielded by a cylinder consisting of concentric layers of 15 cm of paraffin wax, 2 cm boric oxide and 5 cm of lead. The detector was placed 85 cm from the scattering sample to optimise the counting statistics while maintaining an acceptable energy resolution, the timing resolution being 2.5±0.2 ns.

The signal from the anode of the neutron detector photomultiplier tube, after discrimination in a constant fraction discriminator, was used as a start signal for a time-to-pulse-height converter. The alpha particle detector signals were first passed through a 100 MHz

discriminator and then fed into a gate and delay generator whose output produced the stop signal.

The output of the time-to-pulse-height converter was fed into a multi-channel pulse height analyser. The experimental uncertainties were estimated by adding the percentage errors in quadrature.

The scattering samples consisted of slabs of elemental lead. Measurements were made at 10° intervals for angles between 30° and 90° and for thicknesses between 0.9 cm and 7.5 cm (i.e. between 0.19 and 1.5 mean free paths).

A typical time spectrum is shown in **Fig. 7.1.** It can be seen that the peak due to elastic scattering is well resolved from those due to inelastic scattering.

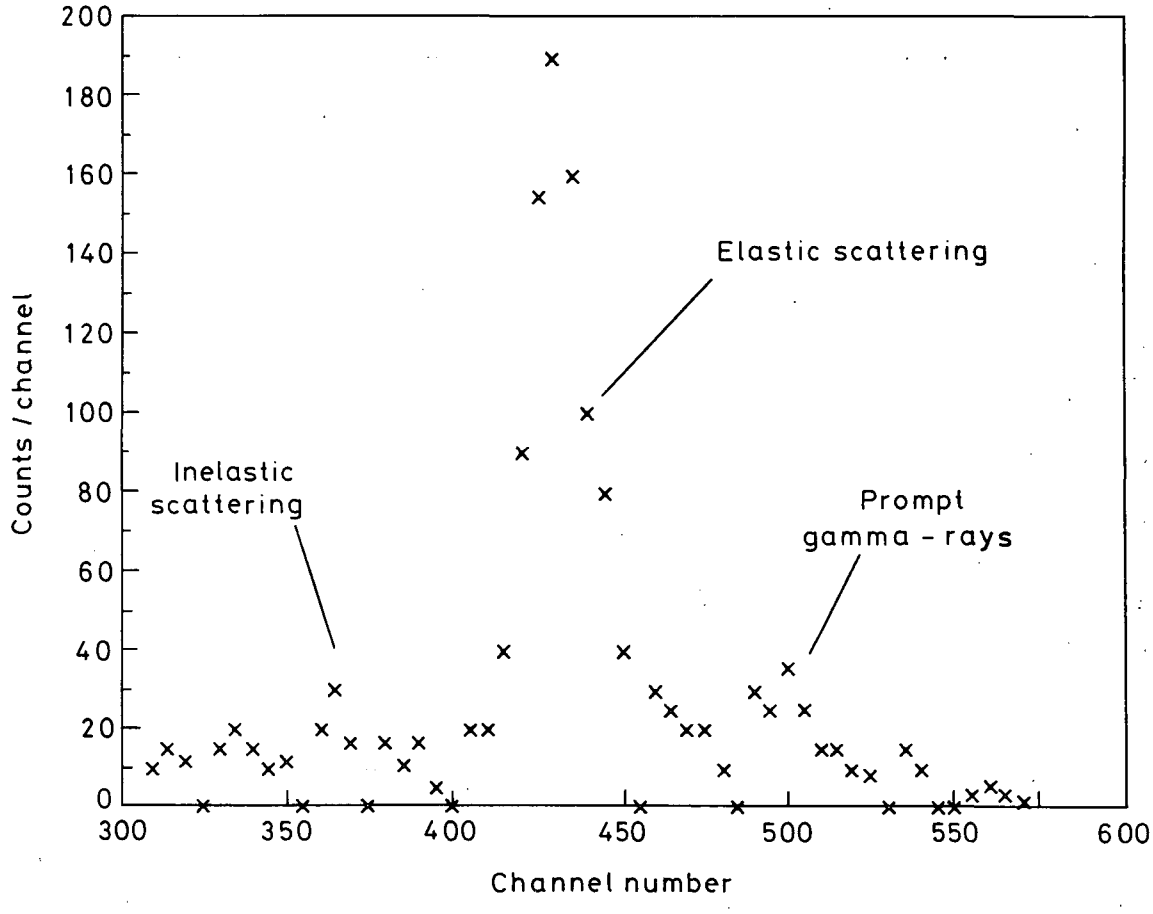

Fig 7.1 A typical time spectrum obtained using a 0.9 cm thick Pb sample, observed at a scattering angle of 40°. The timing calibration is 0.244 ns/channel.

Differential cross-sections were calculated for both elastic and inelastic scattering. The results for the elastic scattering are given in **Fig. 7.2**, which shows the values for the 0.9 cm thick sample, and **Table 7.1** which shows their variation with sample thickness.

Because the inelastic peaks were not resolved, the effective cross-sections for 3 MeV neutron energy ranges between 2 MeV and 14 MeV were calculated. The variation of these cross-sections with sample thickness is given in **Table 7.2**, together with the associated uncertainties.

For the thickness range studied, the variation of the effective cross-sections with thickness was found to be described by the empirical formula

$$\sigma_x = \sigma_0 \exp(\alpha x)$$

where α has the value 0.36±0.1/ mean free path.

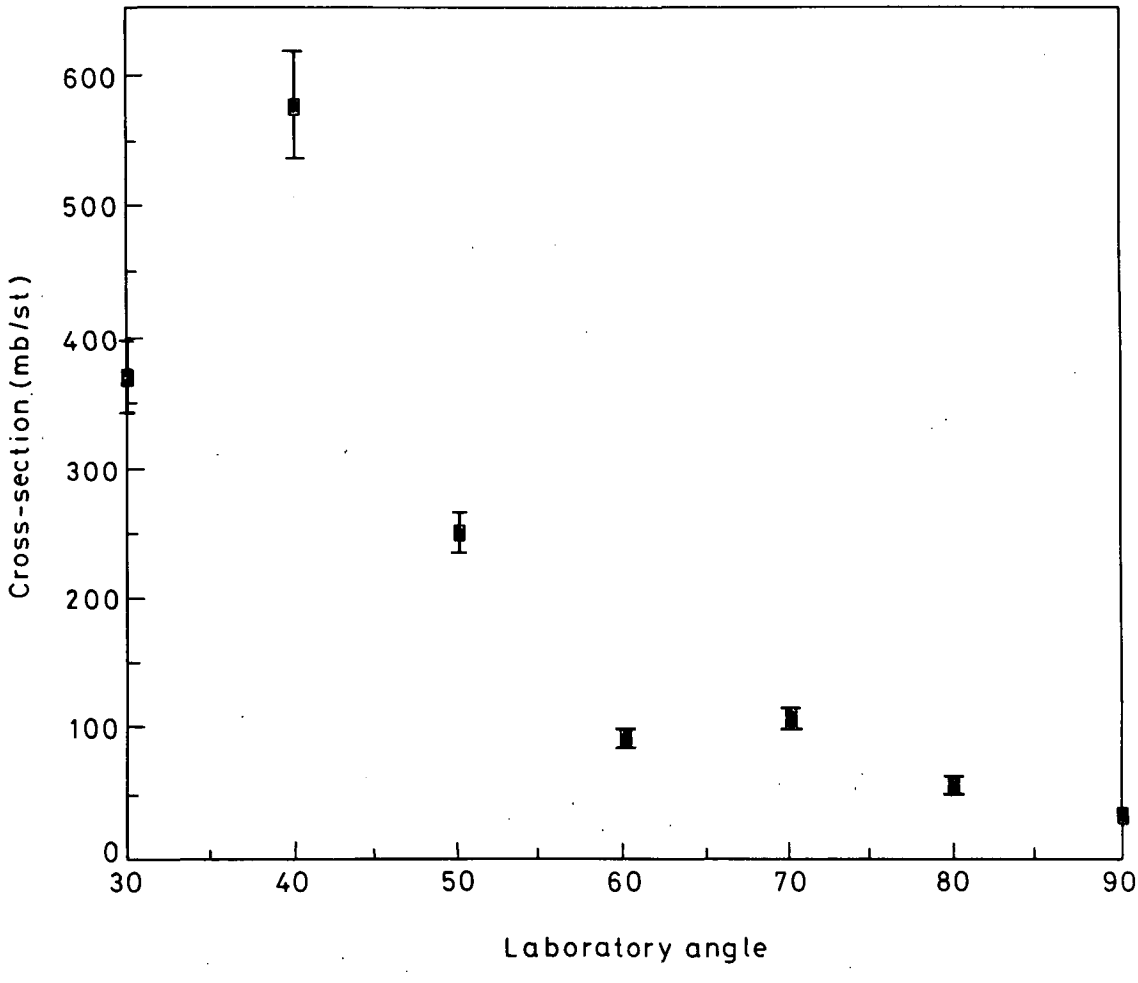

Fig 7.2 The elastic scattering differential cross-section for the 0.9 cm thick Pb sample.

The fit of this equation to results for the elastic scattering is shown in **Fig. 7.3**, and the value of α agrees with the measurements of Anvarian[1], Al-Shalabi[2] and Warner[3].

The increase in the elastic scattering cross-section in the angular range measured is caused by neutrons being scattered out of the angular range 0° to 20° (where a decrease would be observed) into the 30° to 90° range.

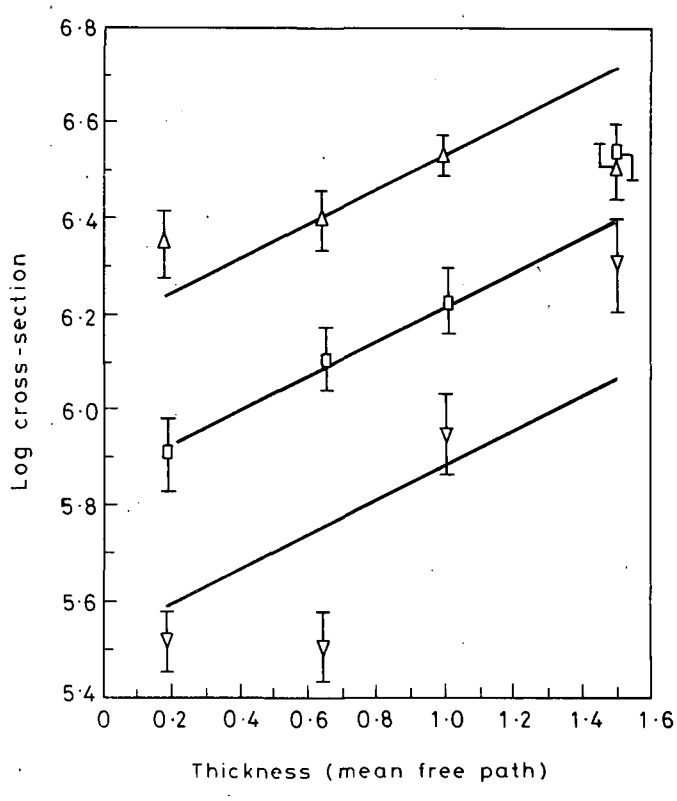

Fig 7.3 The variation of differential cross-sections with thickness for laboratory angles of 30° (Δ), 40° ([]) and 50° (∇). The lines are fits to the empirical formula given in the text.

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(1) S T P Anvarian and A J Cox, Int.J.App.Rad.& Isot., 35(1984)45.

(2) B Al-Shalabi and A J Cox, Nucl.Inst.& Meths., 205(1983)495.

(3) P C Warner and A J Cox, Nucl.Inst.& Meths., A241(1985)245.

Table 7.1

Elastic scattering cross-section for lead

Angle (deg)	Thickness (cm)	Cross-section (mb/sr)
30	0.9	367±31
	3.2	449±33
	5	503±37
	7.5	686±44
40	0.9	574±46
	3.2	600±42
	5	687±33
	7.5	670±44
50	0.9	247±18
	3.2	245±20
	5	380±35
	7.5	544±55
60	0.9	90±11
	3.2	103±19
	5	93±10
	7.5	263±30
70	0.9	104±12
	3.2	130±20
	5	260±31
	7.5	385±44
80	0.9	54±7
	3.2	133±15
	5	334±34
	7.5	432±48
90	0.9	33±5
	3.2	140±19
	5	184±23
	7.5	192±28

Table 7.2

Inelastic scattering cross-sections for lead

Angle (deg)	Thickness (cm)	Differential cross-sections (mb/sr) for given energy range			
		2-5 MeV	5-8 MeV	8-11 MeV	11-14 MeV
30	0.9	14.3±2.1	51.6±8.4	46.1±7.2	371±24
	3.2	34.8±5.3	42.5±6.3	52.0±6.5	439±27
	5	40.0±5.4	75.2±8.0	56.6±6.4	629±33
	7.5	42.0±4.3	62.6±6.7	47.0±6.5	679±50
40	0.9	30.4±2.4	53.5±6.7	32.2±4.7	545±24
	3.2	40.0±3.8	60.9±9.0	50.1±6.2	542±38
	5	40.2±5.1	67.0±7.4	53.7±4.1	642±28
	7.5	47.6±6.0	58.3±5.1	64.0±6.9	551±37
50	0.9	14.1±2.8	20.2±4.0	22.0±3.7	230±18
	3.2	11.9±2.4	21.1±3.2	33.2±4.3	261±18
	5	22.2±4.1	19.5±2.4	52.0±4.7	368±24
	7.5	32.4±6.8	40.1±4.9	58.4±7.7	508±44
60	0.9	14.3±6.8	29.0±3.2	24.1±3.0	118±8
	3.2	51.8±6.6	52.1±6.2	32.5±3.2	157±10
	5	35.1±6.5	38.0±6.1	42.0±4.2	188±17
	7.5	34.4±5.5	60.8±6.5	63.2±9.4	246±31
70	0.9	59.6±9.6	40.5±4.8	18.6±2.5	105±9
	3.2	60.7±8.6	42.1±4.8	14.7±2.1	115±9
	5	67.8±8.2	72.3±7.7	44.7±6.3	270±18
	7.5	67.8±7.4	41.8±5.0	66.0±8.0	390±65
80	0.9	42.5±5.1	13.2±1.4	10.4±1.4	26±4
	3.2	63.8±7.5	65.6±8.2	32.0±4.1	116±10
	5	57.1±6.9	54.2±7.9	18.0±4.1	110±14
	7.5	78.0±9.6	79.8±11.6	66.0±6.5	143±17
90	0.9	20.1±4.4	22.3±3.1	15.0±2.5	35±3
	3.2	48.8±6.3	46.0±6.2	28.3±5.4	113±6
	5	58.0±7.3	26.0±4.7	40.0±7.1	82±9
	7.5	87.0±9.2	48.0±6.2	28.3±5.7	83±9

8 DEPARTMENT OF PHYSICS, UNIVERSITY OF EDINBURGH

8.1 The analysing power and differential cross-section for elastic scattering of 3 MeV neutrons (R. B. Galloway and H. Savalooni)

The programme of measurements of the angular dependence of polarization due to elastic scattering and of the elastic differential cross-section for 3 MeV neutrons is continuing (see UKNDC(85)P112, p.102), the measurements being made at 7° intervals from 20° to 167° using a 24 detector fast neutron polarimeter[1]. The measurements and comparative optical model analyses of W, Hg, Tℓ, Pb, Bi and U have been published[2]. Current concern is with Cd, Sn, Sb, Te and I.

8.2 2.5 MeV neutron elastic and inelastic differential scattering cross-sections (M N Erduran and R B Galloway) (WRENDA 660,812)

These measurements using proton recoil spectrum unfolding[3] have provided elastic and inelastic differential cross-sections at 10° intervals from 20° to 150° for Bi, Hg, I, Sn and In. Final stages of comparison with model calculations are in progress.

8.3 Inelastic scattering of 14 MeV neutrons by Bi (R B Galloway and R J Rahighi)

The associated particle time-of-flight system described previously (UKNDC(85)P112, p.102), has been used in 14 MeV neutron scattering studies of Bi. Measurements have been made of the differential cross-section for inelastic scattering by 10 states up to 7.9 MeV excitation, and the data are being compared with coupled channels calculations.

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(1) J R M Annand and R B Galloway, Nucl. Instr. Meth. 206(1983)431.

(2) J R M Annand and R B Galloway, J. Phys. G 11(1985)1341.

(3) M N Erduran and R B Galloway, Nucl. Instr. Meth. A238(1985)83.

9 NUCLEAR PHYSICS LABORATORY, UNIVERSITY OF OXFORD

9.1 Neutron inelastic scattering

9.1.1 The inelastic scattering of neutrons by ^{238}U (P E Hodgson and A M Kobos)

This work, described previously (UKNDC(84)P111, p.111) has now been published[1].

9.1.2 The inelastic scattering of neutrons by ^{232}Th (A M Street and P E Hodgson)

This work, described last year (UKNDC(85)P112, p.103), is being published in Nuclear Science and Engineering.

9.2 The neutron optical potential

9.2.1 The phenomenological neutron optical potential (P E Hodgson)

This work, described last year (UKNDC(85)P112, p.103) has now been published[2].

9.3 Intercomparison of optical model computer programs

9.3.1 International nuclear model code comparison study of the spherical optical model for charged particles (P E Hodgson and E Sartori*)

The results of several calculations of cross-sections and polarisations made with specified input parameters using different programs have been compared[3]. The differences have been investigated, and where possible the programs have been corrected. With care, it is possible to obtain the same cross-sections and polarisations to within about 0.1% using different programs. In addition the results of calulations for neutrons have provided a standard test for neutron optical model calculations.

9.4 Neutron reaction cross-section calculations

9.4.1 Neutron scattering and reactions on ^{59}Co from 1 to 20 MeV (D Wilmore**and P E Hodgson)

This work, described last year (UKNDC(85)P112, p.104) has now been published[4].

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* NEA Data Bank, Gif-sur-Yvette, France

** AERE Harwell

(1) P E Hodgson and A M Kobos, Nucl. Sci. Eng. 89(1985)111.

(2) P E Hodgson, AIP Conf. on Neutron-Nucleus Collisions - A Probe of Nuclear Structure (Ohio, 1984)p.1.

(3) P E Hodgson and E Sartori, NEANDC-198-U, INDC(NEA)5(1985).

(4) D Wilmore and P E Hodgson, J.Phys. G:Nucl. Phys. 11(1985)1007

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

An analysis of neutron reactions on ^{93}Nb is in progress using the methods previously applied to ^{59}Co.

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

The Weisskopf-Ewing theory, which provides a very simple way of estimating statistical compound nucleus cross-sections, has been used to calculate differential cross-sections of neutron-induced reactions on the medium weight nuclei ^{54}Fe, ^{56}Fe, ^{59}Co and ^{55}Mn. These calculations are much faster than the corresponding Hauser-Feshbach calculations.

A paper describing this work is in preparation.

9.5 Pre-equilibrium processes

9.5.1 Pre-equilibrium processes in the reactions of neutrons on ^{59}Co and ^{93}Nb (G M Field, R Bonetti** and P E Hodgson)

This work, described last year (UKNDC(85)P112, p.104) is being published in Journal of Physics G.

9.5.2 The interactions of neutrons with ^{59}Co (P E Hodgson)

An invited paper [1] with the following abstract was presented to the 4th International Conference on Nuclear Reaction Mechanisms in Varenne:

"The cross-sections of all the more important reaction channels for neutrons on ^{59}Co are calculated and the results compared with the experimental data. The optical model is used to obtain the differential elastic scattering cross-section and the total and reaction cross-sections, and the Weisskopf-Ewing, Hauser-Feshbach and Feshbach-Kerman-Koonin theories for the compound and statistical multistep compound contributions to the neutron emission cross-section. Several other reaction channels, in particular (n, 2n), (n,p) and (n,α) are also studied using one or more of these theories."

9.5.3 Analysis of cross-sections of neutron-induced reactons from 1 to 20 MeV (P E Hodgson)

An invited paper [2] with the following abstract was presented to the Specialists' Meeting on the use of the Optical Model for the

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* AERE Harwell

** Istituto di Fisica Applicata Generale, Milano, Italy

(1) P E Hodgson, Int. Conf. on Nuclear Reaction Mechanisms (Varenne, 1985).

(2) P E Hodgson, Proceedings of Specialist Meeting on the Use of the Optical Model for the Calculation of Neutron Cross-sections below 20 MeV (to be published).

Calculation of Neutron Cross-sections below 20 MeV, held in Paris:

"The calculated cross-sections of all the more important reactions of neutrons on ^{59}Co and ^{93}Nb are compared with the experimental data. The optical model is used to obtain the differential elastic scattering cross-section and the total and reaction cross-sections, and the Weisskopf-Ewing, Hauser-Feshbach and Feshbach-Kerman-Koonin theories for the compound and the statistical multistep compound contributions to the neutron emission cross-section. Several other reactions, in particular the (n,2n), (n,p) and (n,α), are also studied."

9.5.4 Analysis of neutron inelastic scattering from ^{59}Co and ^{93}Nb using the multistep compound pre-equilibrium theory (R Bonetti* and P E Hodgson)

A contributed paper[1] was presented to the Specialists Meeting on the use of the Optical Model for the Calculation of Neutron Cross-sections below 20 MeV, held in Paris.

The paper summarises the multistep compound pre-equilibrium theory and presents some comparisons with experimental data for neutron inelastic scattering and reactions on ^{59}Co and ^{93}Nb at 14 MeV.

9.5.5 Pre-equilibrium processes in nuclear reaction theory: the state of the art and beyond (H Gruppelaar**, P Nagel*** and P E Hodgson)

A review paper[2] has been written with the following abstract:

"The semi-classical and quantum-mechanical theories of pre-equilibrium processes in nuclear reactions are reviewed, with special attention to the exciton, hybrid and unified models, and the Feshbach-Kerman-Koonin quantum mechanical theory. The results of the

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(1) R Bonetti and P E Hodgson, Proceedings of Specialist Meeting on the Use of the Optical Model for the Calculations of Neutron Cross-sections below 20 MeV (to be published).

(2) H Gruppelaar, P Nagel and P E Hodgson to be published in Rivista del Nuovo Cimento.

* Istituto di Fisica Applicata Generale, Milano, Italy.
** Netherlands Energy Research Foundation ECN, Petten, Netherlands.
*** NEA Data Bank, Gif-sur-Yvette, France.

'International Nuclear Model and Code Comparison on Pre-equilibrium Effects' carried out under the auspices of the NEA Data Bank are presented and the physical bases and approximations of the models are discussed. The quantum-mechanical theory is described and compared with the semi-classical models. Selected data for pre-equilibrium processes in ^{59}Co and ^{93}Nb are analysed using both the semi-classical models and the quantum mechanical theory and their reliabilities for fitting and prediction are compared. The future development of analyses of pre-equilibrium processes is discussed with particular reference to the scopes of the various models and their optimum areas of applicability."

9.6 Calculation of optical potentials (A M Street)

Optical potentials and the corresponding elastic scattering cross-sections are being calculated from a microscopic first-order Brueckner theory using self-consistent fields in a Hartree-Fock method.

To test the computer program the elastic scattering of 30.3 MeV protons by ^{40}Ca is being calculated. This will enable the effect of long-range Coulomb terms on the scattering cross-section and on the imaginary potential to be investigated.

It is planned to study the isospin dependence of the potential, and the problems of complex binding energies, the non-zero temperature approximation and overcounting in the Born approximation. These calculations should provide a reliable method of determining optical potentials for reaction calculations.

It is also planned to extend the work to neutron reaction calculations.

10 DEPARTMENT OF PHYSICS, UNIVERSITY OF LIVERPOOL

10.1 Nuclear data evaluation (P D Forsyth)

Evaluation work at Liverpool terminated in the Autumn of 1984 when our one full-time evaluator, Dr Naomi J Ward, resigned. The mass chain A = 65 which was submitted in September 1984 is in the process of being published.

The termination of evaluation work in the UK is regretted, and Liverpool University would gladly try to restart the work if sufficient funds were available to support at least two full-time evaluators, the minimum number needed to form a viable group.

11 IMPERIAL COLLEGE REACTOR CENTRE

11.1 Decay scheme studies of ^{239}U and ^{243}Am (T D MacMahon and S P Holloway*)

The beta decay of ^{239}U and the alpha decay of ^{243}Am both populate excited states in ^{239}Np. It is possible, therefore, to measure the beta branching ratios in ^{239}U decay by comparing the gamma-ray spectra of ^{239}U and ^{243}Am and making use of the well-known alpha branching ratios in ^{243}Am. This technique avoids the need to know precisely the conversion coefficients of the transitions in ^{239}Np

The results for beta branching ratios in ^{239}U are given in **Table 11.1**, where the ground state value was obtained by assuming a total feeding of 1.4% to ^{239}Np levels above 117.7 keV. **Table 11.2** gives the observed gamma-ray transition probabilities in ^{239}U and ^{243}Am.

Table 11.1

Beta branching ratios in ^{239}U decay

Populated ^{239}Np level	Absolute beta intensity
117.7 keV	1.80 ± 0.24 %
74.7 keV	69.1 ± 1.4 %
31.1 keV	10.2 ± 1.9 %
ground state	17.5 ± 2.4 %

Table 11.2

Gamma-ray emission probabilities in ^{239}U and ^{243}Am decay

E_γ(keV)	^{239}U P_γ	^{243}Am P_γ
31.1	(6.5 ± 0.7) x 10^{-4}	(4.68 ± 0.22) x 10^{-4}
43.5	(4.18 ± 0.13) x 10^{-2}	(5.87 ± 0.17) x 10^{-2}
46.8	-	(5.12 ± 0.16) x 10^{-4}
74.7	0.482 ± 0.010	0.670 ± 0.012
86.7	(5.2 ± 0.6) x 10^{-4}	(3.34 ± 0.06) x 10^{-3}
117.7	(1.3 ± 0.4) x 10^{-3}	(0.73 ± 0.16) x 10^{-2}
141.8	-	(1.05 ± 0.02) x 10^{-3}

* AWRE

11.2 Evaluation of the half-life of ^{90}Sr (P W Gray and T D MacMahon)

A chi-squared consistency test on nine measurements of the half-life of ^{90}Sr reported between 1955 and 1985 gives a value of 73.0 for 8 degrees of freedom, indicating a very high degree of inconsistency in the data. A consistent subset of these data can be obtained by omitting three measurements. However, it is not considered acceptable to reject as many as three measurements out of nine, especially when two of the three rejected measurements are amongst the most recent.

A statistical procedure for extracting a recommended value from this set has been described[1]. This procedure involves adjusting the information content of two measurements, followed by a uniform inflation of the uncertainties and gives a recommended value for the half-life of 28.7 ± 0.2 years.

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(1) P W Gray and T D MacMahon, Imperial College Reactor Centre Report ICRC/85/2. (1985)

12. CINDA-TYPE LISTING

Element Name	A	Quantity	Energy Min	Energy Max	LAB	TYPE	References NEANDC(E) 272 Vol.8, Jan.87, Page:	AUTHOR	COMMENTS
B	nat	N, Gamma	Thermal-		NPL	Expt.prog.	53	Arbildo +	capture SIG relative to hydrogen
S	nat	N, Gamma	Thermal		NPL	Expt.prog.	53	Arbildo +	capture SIG relative to hydrogen
Mn	55	N, Gamma	Thermal		NPL	Expt.prog.	53	Arbildo +	capture SIG relative to hydrogen
Fe	nat	Total SIG	1.0+2	1.0+5	HAR	Expt.prog.	5	James +	transmission measurements on natural iron samples at 150 m
Fe	nat	N, Gamma	1.15+3		HAR	Expt.prog.	6	Gayther +	measurement of the parameters of the 1.15 keV resonance in Fe-56
Fe	54	Spec N,Gamma	1.0+3	1.0+5	HAR	Expt.prog.	9	Mason +	γ ray spectra from neutron capture
Ni	62	Spec N,Gamma	1.0+3	1.0+5	HAR	Expt.prog.	13	Mason +	γ ray spectra from neutron capture
Nb	93	N, Inelastic	1.0+3	1.0+5	HAR/BIR	Expt.prog.	16	Gayther +	foil activation
Sr	90	Half-life			LON	Expt.prog.	43	Gray +	half life = 28.7 $\pm$0.2 years
Cd	nat	Analys.power + diff. elastic	3.0+6		EDB	Expt.prog.	66	Galloway +	measurement and comparison with theory
In	nat	Diff.elastic + inelastic	2.5+6		EDB	Expt.prog.	66	Erduran +	- " " -
Sn	nat	- " " -	2.5+6		EDB	Expt.prog.	66	Erduran +	- " " -
Sn	nat	Analys.power + diff. elastic	3.0+6		EDB	Expt.prog.	66	Galloway +	- " " -
Sb	nat	- " " -	3.0+6		EDB	Expt.prog.	66	Galloway +	- " " -
Te	nat	- " " -	3.0+6		EDB	Expt.prog.	66	Galloway +	- " " -
I	nat	Diff.elastic + inelastic	2.5+6		EDB	Expt.prog.	66	Erduran +	- " " -
I	nat	Analys.power + diff. elastic	3.0+6		EDB	Expt.prog.	66	Galloway +	- " " -
Hg	nat	Diff. elastic + inelastic	2.5+6		EDB	Expt.prog.	66	Erduran +	- " " -
Bi	209	- " " -	2.5+6		EDB	Expt.prog.	66	Erduran +	- " " -
Bi	209	Diff.inelastic	1.4+7		EDB	Expt.prog.	66	Galloway +	DIFFSIG for 10 states upto 7.9 MeV
Pa	233	Half-life			HAR	Expt.prog.	42	Fudge +	Half life = 26.96 $\pm$ 0.03 days
U	235	ETA	1.0-2	1.0+1	HAR	Expt.prog.	3	Moxon +	variation with energy
U	235	Fission yield	Fast		HAR	Expt.prog.	40	Kyffin	
U	235	Ternary fisson	Thermal		HAR	Expt.prog.	40	McMillan and Rowe	
U	235	Delayed N Spec			BIR	Expt.prog.	54	Chilton +	Spectra of delayed neutrons
U	237	Half-life			HAR	Expt.prog.	41	Fudge and Banham	
U	238	Evaluation	1.0+1	1.5+4	HAR	Eval.prog.	5	Moxon +	analysis of data from various laboratories to obtain resonance params.
U	238	Fission yield	Fast		HAR	Expt.prog.	40	Kyffin	
U	239	Beta decay etc			LON	Expt.prog.	72	MacMahon +	$\beta-\gamma$ branching ratios - Np 239
Np	237	Half-life	-		HAR	Expt.prog.	42	Fudge +	half life + alpha branching ratios
Pu	239	Ternary fission	Thermal		HAR	Expt.prog.	40	McMillan and Rowe	
Pu	239	Fission yield	Fast		HAR	Expt.prog.	40	Kyffin	
Pu	240	Fission yield	Fast		HAR	Expt.prog.	40	Kyffin	
Pu	241	Fission yield	Fast		HAR	Expt.prog.	40	Kyffin	