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United Kingdom Atomic Energy Authority

RESEARCH GROUP

U.K. NUCLEAR DATA PROGRESS REPORT

For six month period up to mid-1967

Editor: E. R. RAE

Nuclear Physics Division,

Atomic Energy Research Establishment,

Harwell, Berkshire.

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CONTENTS

PREFACE

This document was prepared following discussion at the Harwell Nuclear Data Committee. It is intended to bring together reports on the nuclear data work carried on in the various Divisions at A.E.R.E. and A.W.R.E. and later on, work at N.P.L. and any relevant University contributions may also be added. This provides a single document for submission to EANDC and INDC. The present document contains extracts from the Progress Reports of Nuclear Physics, Chemistry and Analytical Sciences Divisions at A.E.R.E. and Nuclear Research Division at A.W.R.E.

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

(Division Head: Dr. B. Rose)

EDITORIAL NOTE

Since the results obtained from the various machines are no longer easily classified according to the energy of the charged beams, individual research items have been labelled with a single letter indicating on which machine the experiments were performed. These labels are as follows:-

Cockcroft Walton Generator (A. T. G. Ferguson)	A
3 MV pulsed Van de Graaff Generator IBIS (A. T. G. Ferguson)	B
5 MV Van de Graaff Generator (A. T. G. Ferguson)	C
13 MV Tandem Generator (J. M. Freeman)	D
45 MeV Electron Linac (E. R. Rae)	E
50 MeV Proton Linac : S.R.C.	F
Variable Energy Cyclotron : Chemistry Division	G
Synchrocyclotron (A. E. Taylor)	H
Nimrod Proton Synchrotron · S.R.C.	I

The running analyses for the various machines operated by the division are presented as far as possible in a uniform format, but some differences remain in the way in which the scheduling is arranged, and machines such as the Electron Linac can accommodate several experiments simultaneously.

NUCLEAR DATA FOR FAST REACTORS

(A) Elastic and inelastic neutron scattering from ^{239}Pu (D. A. Boyce, P. E. Cavanagh, C. F. Coleman, G. A. Gard, A. G. Hardacre, J. C. Kerr and J. F. Turner)

To check our absolute neutron cross section calibration against an accepted substandard we have interleaved over the energy range of our earlier measurements[1] observations of the 90° elastic scattering from our ^{239}Pu sample and from a carbon sample. Since substantial additions to the Maggie[2] Monte Carlo program would be required before it could be used to correct for the mutual shielding of the plutonium sample and its stainless steel can, we have preferred to take an approximate analytical method for multiple scattering corrections used by Cranberg[3], and to adapt this to our problem. This gives satisfactory agreement with measurements made on a tungsten sample with and without a similar can[4], and corrections for the plutonium sample are now being calculated.

The experimental program on neutron scattering from ^{239}Pu is virtually complete, apart from a proposed attempt to resolve scattering from the 8 keV level by making use of narrow resonances in Ca at 130 and 160 keV, and a report on the measurements is being prepared.

GENERAL REACTOR TECHNOLOGIES AND STUDIES

GENERAL NUCLEAR DATA FOR REACTORS

Fission cross section analysis (G. D. James and D. A. J. Endacott)

(a) Fluctuation analysis

Possible causes of the significantly high values of the serial correlation coefficient $r_k(W)$, first noted by Egelstaff[5] in an analysis of low energy fission cross section data and confirmed in a previous report[6], are being investigated. Three sets of resonance parameters each containing about 1700 levels have been generated by the program RMAT (by J. E. Lynn) in such a way that they have the same average properties as the ^{241}Pu resonance levels. Both single level Breit-Wigner and R-matrix fission cross sections and also their Doppler broadened values were calculated for the 3700 energy values in the range 17 eV to 1700 eV encountered in a typical time-of-flight measurement. The serial correlation coefficients $r_k(W)$ for the twelve sets of simulated fission cross section data show that (a), results for the R-matrix cross sections do not differ significantly from those for the single level Breit-Wigner cross sections (b), no significant change in $r_k(W)$ occurs when the cross sections are Doppler broadened and (c), the time-of-flight energy mesh does not lead to significantly high values of $r_k(W)$. By chance, one set of parameters gave some values of $r_k(W)$ above the 5% significance level. The cause of these high values will be investigated.

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(1) A.E.R.E. report PR/NP 10, p. 1 (1966).

(2) Parker J. B., Towle J. H., Sams D., Gilboy W. B., Revnell A. D. and Stevens H. J. Nuclear Instrum. and Methods 30, 77 (1964).

(3) Cranberg L. Los Alamos report LA-2177 (1959).

(4) A.E.R.E. report PR/NP 9 (1966).

(5) Egelstaff P. J. Nuc. Energy 7, 35 (1958).

(6) James G. D. and Endacott D. A. J. Nuc. Phys. Div. Progress Report AERE - PR/NP 10, p. 1 (1966).

(b) Multilevel analysis of ^{239}Pu fission cross section near 85 eV

A comprehensive single level analysis of the ^{239}Pu total and fission cross sections below 250 eV has been reported by Derrien et al.[7]. At some energies several closely spaced wide single levels are required to explain the cross sections. When used in a multilevel formalism such levels would lead to large interference effects and produce cross sections incompatible with the data. A least squares multilevel fit to the fission cross section data of Derrien et al. over the energy range 78 eV to 88 eV has been made to determine the R-matrix parameters of the wide levels. All wide levels were assumed to have spin zero and the effect of the levels at 60.94 eV, 96.49 eV and 100.25 eV was taken into account. The cross sections calculated for three wide levels in a single fission channel occurring in the energy range 78 eV to 88 eV disagreed with the experimental data by factors as large as ten at some energies as a result of severe interference effects. It was found that a good fit to the data could only be obtained by omitting the wide level at 83.52 eV and by introducing a second fission channel for the spin zero levels. Fig. 1 shows by a solid line the multilevel fission cross section obtained from the parameters of Table I and also the data of Derrien et al. The parameters in Table I are as given by Derrien et al. except for the two levels at 81.37 eV and 85.13 eV and the absence of a level at 83.52 eV. At 60.94 eV, 96.49 eV and 100.25 eV the fission widths have been divided equally between the two fission channels.

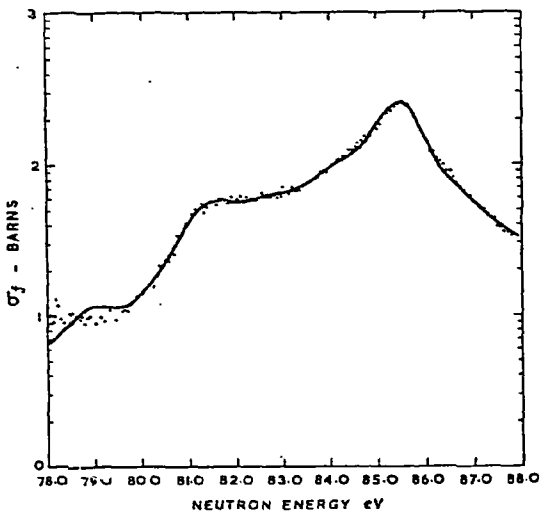

Fig. 1. Multilevel fit to ^{239}Pu fission cross section between 78.0 and 88.0 eV.

TABLE I

E_λ (eV)	Γ_n^o (meV)	Γ_{f1} (meV)	Γ_{f2} (meV)	Γ_γ (meV)	J
60.95	3.843	2976	2976	40	0
78.95	0.012	140	-	40	1
81.37	0.527	-0.154	837.8	40	0
82.68	0.055	29.5	-	40	1
85.13	6.34	3157	-136.4	40	0
85.48	0.85	37.0	-	40	1
96.49	1.36	819	819	40	0
100.25	1.11	2976	2976	40	0

(H) Fission cross sections in the 20 keV to 20 MeV region (A. Langsford, M. S. Coates, D. B. Gayther, G. D. James and G. C. Cox)

An exploratory run to study the feasibility of fission cross section measurements on the synchrocyclotron has shown that:-

(a) With the present neutron intensities the counting rate is approximately one event per second in the fission detector and adequate for cross section measurements.

(7) Derrien H., Brons J., Eggermann C., Michaudon A., Paya D. and Ribon P. Proc. I.A.E.A. Conf. on Nuclear Data, Paris (1966). Paper CN-23/70 to be published.

(b) Backgrounds, measured by placing filters of boric oxide or aluminium in the beam, are at most 1 to 2% over the energy region.

(c) These counting rates and backgrounds roughly equal those in corresponding experiments on the Electron Linear Accelerator but the measurements can be made to higher energies and with better energy resolution.

(E) Neutron cross section measurements on sodium (M. C. Moxon, N. J. Pattenden, V. S. Brown and J. E. Jolly)

Continuing the work previously reported[8,9] further transmission measurements have been performed on another sample, a solution containing 0.214 g/ml of NaCl in heavy water enclosed in a silica cell. The measured minimum transmission at the 2.85 keV Na resonance peak was 0.098 ± 0.015, corresponding to an observed peak cross section of 350 ± 20 b. The corresponding figures for the other solution sample[9] were 0.34 ± 0.02 and 350 ± 25 b. Hence the previous results are confirmed, and further weight is given to the assignment J = 1 for this resonance.

(E) Neutron partial cross sections of ^{98}Mo, ^{100}Mo, ^{107}Ag and ^{109}Ag (A. Asami and M. C. Moxon)

Neutron scattering and capture measurements on ^{98}Mo and ^{100}Mo have been completed, but preliminary analysis of the results suggests that further measurements on much thinner samples of these isotopes may be required.

The results for ^{107}Ag and ^{109}Ag are now being analysed. Figs. 2 and 3 show the observed neutron capture cross sections for ^{107}Ag and ^{109}Ag respectively for neutrons in the energy range 100 eV to 200 eV. The isotopic assignment of the small resonances previously observed is clearly established.

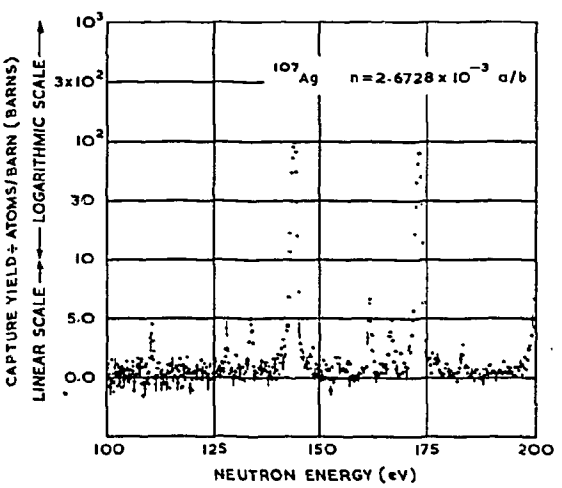

Fig. 2. Neutron capture yield from ^{107}Ag.

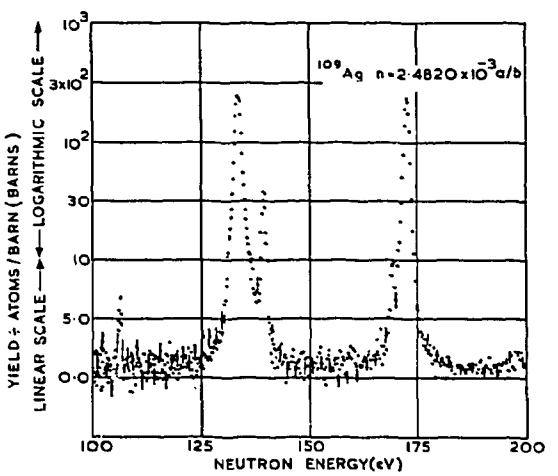

Fig. 3. Neutron capture yield from ^{109}Ag.

The rebuilding of the neutron scattering detector is nearly complete and preliminary measurements on lead and carbon samples indicate an improvement in the signal to background ratio for neutrons with

(8) Moxon M. C., Pattenden N. J., Brown V. S., Jolly J. E. and Pratt J. S. Nuc. Phys. Div. Progress Report AERE - PR/NP 11 (1967).

(9) Moxon M. C. and Pattenden N. J. The low energy neutron cross section of sodium. Proc. I.A.E.A. Conf. on Nuc. Data, Paris (1966), Paper CN-23/27.

energies above 1 keV. This improvement makes it feasible to measure the scattering cross sections of ^{10}B with reasonable accuracy in a reasonably short time, and such measurements will be carried out in the near future.

(E) Total cross section measurements on ^{6}Li and Au (K. M. Diment and C. A. Uttley)

1. Gold

The average neutron total cross section of gold has been measured between 7 keV and 7 MeV using the 120 m and 300 m spectrometers of the electron linear accelerator. The primary object was to determine the p-wave neutron strength function by the methods discussed in previous reports[10] and elsewhere[11]. The low energy s-wave potential scattering length $R'(= R(1 - R_0^\infty))$ and the distant level parameter R_0^∞ were determined separately by correcting the between resonance cross section obtained from thick sample, high resolution transmission measurements for the effects of local resonances, the parameters of which have been determined by Julien et al.[12]. However only some 30 resonances on each side of the chosen energy have been used to correct the observed potential scattering length so that the value of R_0^∞ obtained is uncertain because of the effects of local resonances which have not been resolved and measured. The variance $(\Delta R_0^\infty)^2$ which arises through considering only (m) resonances on either side of the chosen energy can be calculated in the uniform level density approximation to be

$$\overline{\Delta R_0^{\infty 2}} = 6\left(\frac{\lambda_0}{2R}\right)^2 S_0^2 \left(\frac{\pi^2}{6} - \sum_{r=1}^{m} \frac{1}{r^2}\right)$$

where λ_0 is the reduced neutron wavelength at 1 eV, R is the nuclear radius parameter $1.35A^{1/3}$ fm and S_0 is the s-wave neutron strength function $\overline{\Gamma_n^0}/D$ familiar in the experimental literature. Thus $(\Delta R_0^\infty)^2$ is large both when m is small and for those nuclei with large strength functions. Gold has a strength function in the range $(1.5 \rightarrow 2.0) \times 10^{-4}$, which is large compared with the values for nuclei in the 3P and 4P size resonances previously studied. As a result of the uncertainty in the distant level parameter (value – 0.127 ± 0.039) the potential scattering cross section of 9.85b is uncertain by ± .70 barns. Most of this uncertainty will be reflected, through the s-wave shape elastic scattering cross section, as an uncertainty in the p-wave compound nucleus cross section and therefore in the p-wave neutron strength function in the least squares fit to the total cross section below about 300 keV. Table II lists the average p-wave parameters S_1 and R_1^∞ and the s and d wave strength functions S_0, S_2 obtained from least squares fits to the total cross section between 7 keV and 1 MeV when the value of R_0^∞ is altered up or down by one standard deviation.

TABLE II

Average resonance parameters of Gold

R_0^∞	$S_0 \times 10^4$	R_0^∞	$S_1 \times 10^4$	$S_2 \times 10^4$
– 0.166	1.4	+ 0.081	0.38	0.93
– 0.127	1.53	+ 0.078	0.70	0.26
– 0.088	1.75	+ 0.109	1.27	– 0.12

(10) Uttley C. A. and Diment K. M. A.E.R.E. report PR/NP 10 (1966).

(11) Uttley C. A., Newstead C. M. and Diment K. M. I.A.E.A. Conference on Nuclear Data, Paris (1966). Paper CN-23/36.

(12) Julien J., De Barros S., Bianchi G., Corge C., Huynh V. D., Le Poittevin G., Morgenstern J., Netter F., Samour C. and Vastel R. Nucl. Phys. 76, 391 (1966).

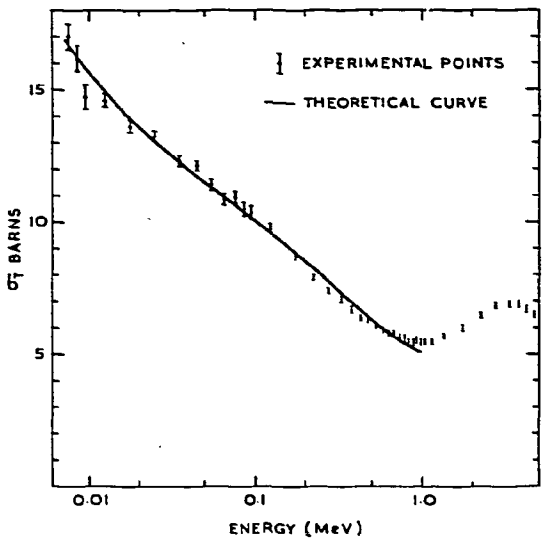

Fig. 4. Total cross section of gold.

In the fitting procedure it was assumed that $R_2^\infty = R_3^\infty = 0$ and $S_3 = S_1$. The fit to the data obtained using the observed value – 0.127 for R_0^∞ is shown in Fig. 4. This fit leads to a value for the p-wave strength function of $(0.70 \begin{smallmatrix}+0.57\\-0.32\end{smallmatrix}) \times 10^{-4}$. The large uncertainties should be considerably reduced when the thick sample average transmission data up to 50 keV have been analysed to determine R_0^∞ and, independently, S_1. The value for the p-wave strength function obtained here is significantly smaller than the predictions ($\sim 1.7 \times 10^{-4}$ and $\sim 1.5 \times 10^{-4}$) of the collective and spherical optical models respectively, and furthermore the parameters in row 1 of Table II associated with the low value of S_1 give the best fit to the experimental data.

2. Lithium 6

The total cross section of ^{6}Li is being measured, initially over the energy range 70 eV to 7 MeV, in an attempt to determine the extent of the $1/\sqrt{E}$ variation in the absorption cross section, the low energy scattering cross section, and the parameters of the 250 keV resonance. Three samples have been fabricated and canned in aluminium. The ^{6}Li to ^{7}Li ratio for these samples has been determined and they have been analysed for chemical impurities. The transmission measurements are alternated with further measurements on ^{10}B and ^{12}C. The preliminary data confirm the positions of the 2.08 MeV and 2.95 MeV resonances in carbon, but suggest that the peak of the p-wave resonance in ^{6}Li lies at about 247 keV, which is below the energy previously observed in the total cross section.

(E) The measurement of alpha, eta and the neutron cross sections of ^{239}Pu (B. H. Patrick, M. G. Schomberg and M. G. Sowerby)

Analysis of the data obtained in the two experiments in which eta and the fission and total cross sections of ^{239}Pu were measured has continued. The magnitude of the scattering cross section σ_s is of particular importance in this analysis both in correcting the fission cross section for the effects of multiple scattering and in determining the capture cross section σ_c from the formula

$$\sigma_c = \sigma_T - \sigma_F - \sigma_s \,, \qquad (1)$$

where σ_T and σ_F are the measured total and fission cross sections respectively. As described in the last progress report[13], the average fission cross section falls abruptly to about half of the expected value at $\sim$ 600 eV, whereas the average total cross section shows little change. These facts cast doubts on the validity of the assumptions that the average elastic scattering cross section is energy independent and that the compound elastic part can be calculated from the s-wave strength function combined with averages of resonance parameters obtained from the resolved region below $\sim$ 300 eV. This problem has been examined in detail and the results and conclusions are briefly described below.

In the energy region where only s-wave interactions are important (i.e. below $\sim$ 10 keV) states with spin 0 and 1 contribute to the ^{239}Pu cross sections. Average cross sections have been calculated in 100 eV intervals from 100 eV to 1 keV and in 1 keV intervals up to 10 keV. In these calculations the

(13) Patrick B. H., Schomberg M. G. and Sowerby M. G. Nucl. Phys. Div. Progress Report AERE - PR/NP 11 (1967).

average resonance parameters of Derrien et al.[14] and the s-wave strength function values of Uttley[15] were used. It was assumed that the neutron widths Γ_n obeyed a Porter-Thomas distribution and the fission widths Γ_f were described by χ^2 distributions with two degrees of freedom for the spin 0 states and one degree of freedom for the spin 1 states[14]. The radiation width Γ_γ was taken to be constant. Using these distributions, the appropriate fluctuation factor was calculated in each case for the particular cross section being estimated. The calculations have shown that the fission cross section is divided almost equally between the two spin states whereas the scattering cross section is almost entirely due to the spin 1 states.

Now the sudden drop in the fission cross section at ~ 600 eV may be caused by (a) a change in one of the partial widths Γ_n, Γ_f or Γ_γ, (b) an increase in the level spacing (c) the opening of another exit channel, or a combination of any of these. The experimental evidence indicates that the fission cross section and the quantity $\frac{\sigma_F\sqrt{E}}{S_o}$ both fall but the total cross section is only slightly affected. The scattering data of Asghar[16] have been examined and although it is not possible to deduce absolute values, it is clear that there is no significant change in the scattering cross section in the region of 600 eV. By comparing the experimental evidence with the effects of the changes (a), (b) and (c) it is found that the only changes consistent with the experimental data are an increase in the spacing of the J = 0 levels or a decrease in the average neutron width Γ_n for these levels.

Since the compound elastic scattering takes place mainly through the spin 1 states we conclude that it is reasonable to calculate the compound elastic scattering cross section above 600 eV using averages of resonance parameters obtained from the resolved region below ~ 300 eV. The total scattering cross section is then obtained by adding the accurately measured value[15] of the shape elastic scattering cross section.

On this basis the capture cross section has been deduced from equation (1), and average values of alpha, the ratio of capture to fission cross sections, have been calculated at energies up to 10 keV, using the total cross section measurements of Uttley[15] and the fission cross section data of James[17]. The results indicate that alpha is about 1.0 from 600 eV to ~ 7 keV and then falls to ~ 0.6 at 10 keV.

(E) <u>The direct measurement of alpha (E) for ^{239}Pu over the energy range 10 eV to 30 keV (M. G. Schomberg, M. G. Sowerby and F. W. Evans)</u>

The quantity $\alpha(E)^*$ is of importance in fast reactor design, and a decision was taken some years ago to attempt a measurement of this quantity over the energy range 10 eV - 30 keV by making use of the Electron Linac with its boosted pulsed-neutron target and associated time of flight equipment. In order to carry out this measurement it has been necessary to develop a special detector system with the following main properties:-

(a) The ability to distinguish between radiative neutron capture and neutron induced fission events.

(b) A constant efficiency for the detection of radiative capture events irrespective of the form of the gamma ray cascade.

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(14) Derrien H., Blons J., Eggerman C., Michaudon A., Paya D. and Ribon P. I.A.E.A. Conference on Nuclear Data, Paris (1966). Paper CN-23/70.

(15) Uttley C. A. EANDC(UK)40'L' (1964).

(16) Asghar M. EANDC(UK)70'S' (1967) Revised.

(17) James G. D. To be published.

*$\alpha(E)$ is the ratio of capture cross section to fission cross section at the neutron energy E.

(c) Adequate time resolution.

A neutron interaction resulting in fission generates a gamma ray cascade, of similar total energy to a radiative capture event, together with short range fission fragments and energetic fission neutrons. To distinguish between fission and capture events it is therefore necessary to observe either the fission fragments or the fission neutrons produced in fission in addition to the gamma rays generated in both fission and capture. The alpha activity of the ^{239}Pu and count rate considerations make it impracticable to detect fission fragments. A detector has therefore been constructed which can distinguish the energetic fission neutrons from scattered neutrons and gamma rays, and which also has the characteristics described in (b) and (c) above.

The detector, which is shown in section in Fig. 5, is a development of the system devised at C.B.M.N. Geel[18], which is itself an improved version of the Moxon-Rae detector[19]. It uses the

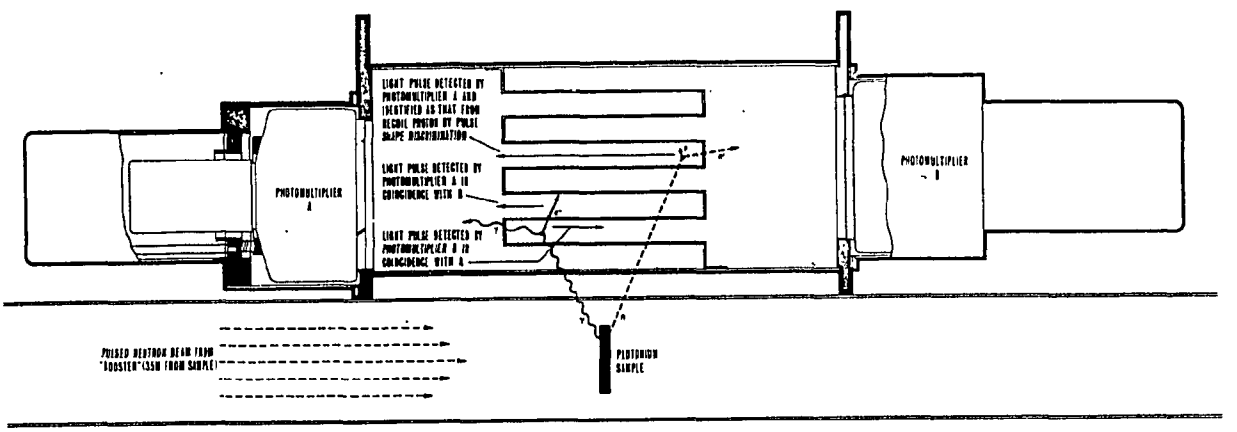
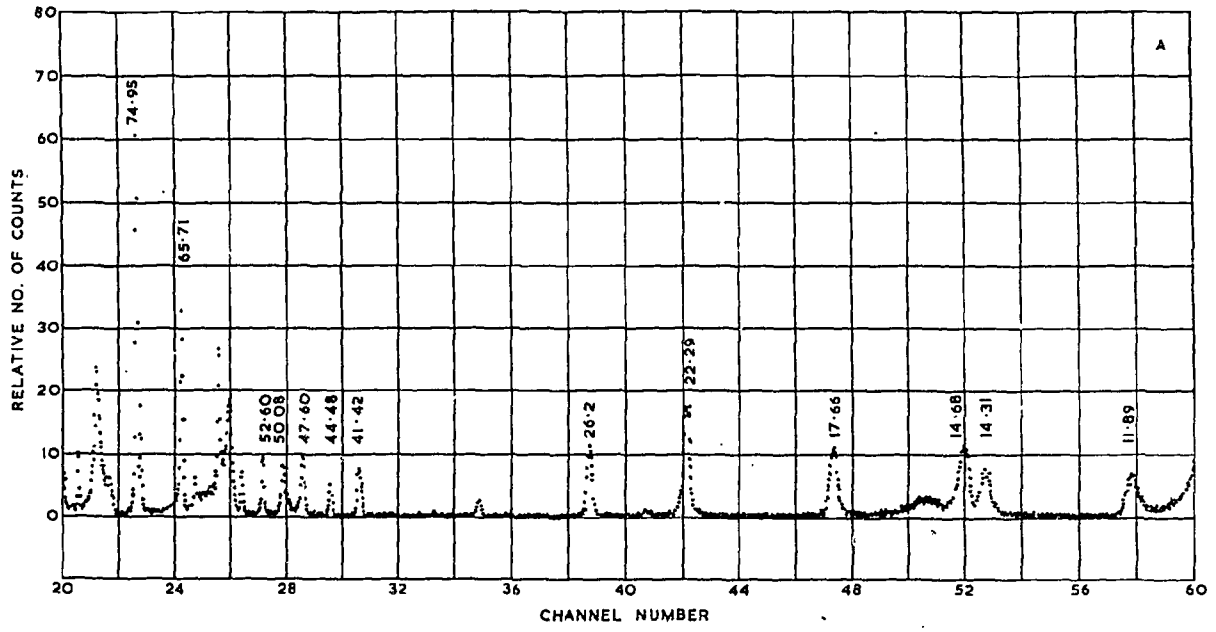


Fig. 5. A detector for the measurement of alpha (E).

liquid scintillator NE213. The main body of the counter is divided into two parts by means of a specially shaped aluminium separator, each part being viewed by its own photomultiplier. When the counter responds to fission neutrons each half acts as an independent system and pulse shape discrimination is used to distinguish recoil protons produced by neutron interactions within the scintillator from electrons produced by gamma ray interactions. As a capture detector it can be given an efficiency for the detection of radiative capture events independent of the nature of the resulting gamma ray cascade, in a similar fashion to the Moxon-Rae detector, by ensuring that the efficiency is proportional to the gamma ray energy - i.e. that $\frac{E_\gamma}{\epsilon(E_\gamma)}$ = constant, where E_γ is the gamma ray energy and $\epsilon(E_\gamma)$ is the efficiency at that energy. A fast coincidence is required between the outputs of the photomultipliers which view the two sides of the separator. As the energy of the incident gamma ray increases the number of secondary photons and recoil electrons produced also increases, while at the same time they are projected progressively more into the forward cone. By suitable design these facts can be exploited to make the probability of a coincidence increase linearly with gamma ray energy. The critical design features are the width of the separator divisions and the low energy bias on the phototube outputs. One must also consider the effect of the thin lead absorber which provides a low energy cut off, thus reducing the counting rate from the intense soft gamma ray background from the natural activity of the samples, which would otherwise disturb the operation of the pulse shape

(18) Carraro G. and Weigman H. EANDC(E)76 'u', p. 133.

(19) Moxon M. C. and Rae E. R. Nucl. Instr. Meth. 24, 445 (1963).



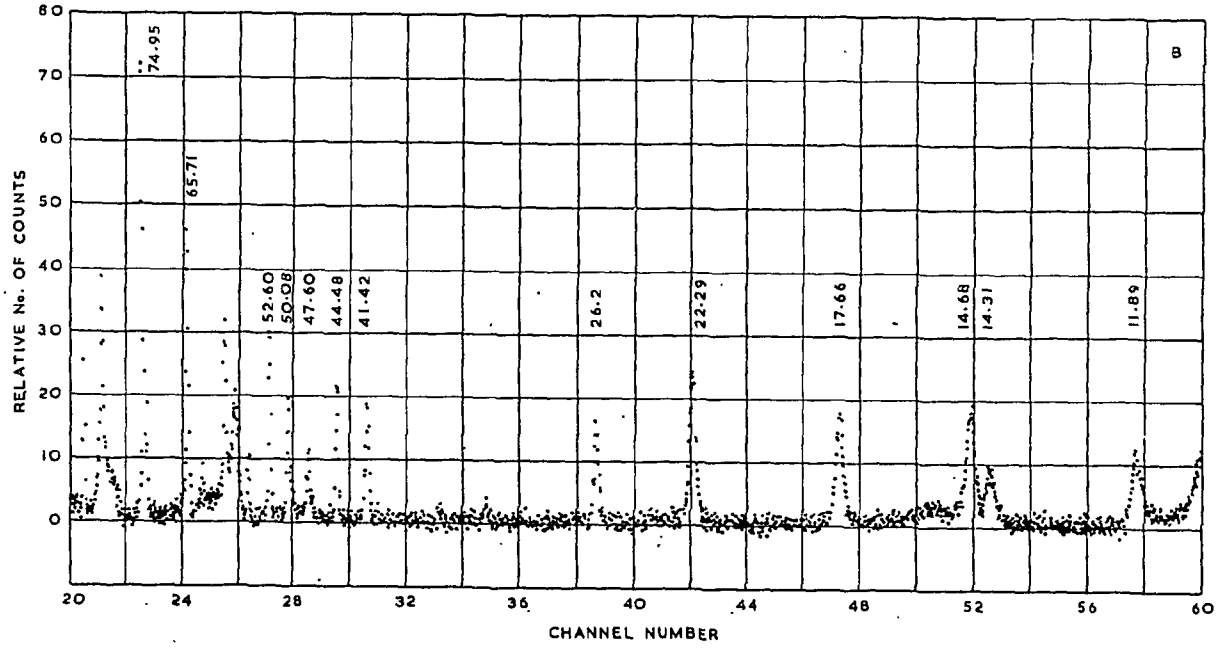


Fig. 6. Fission (A) and gamma-ray (B) counts per timing channel from a ^{239}Pu target.

discrimination system. Because the efficiency of the detector is small both for gamma rays and for neutrons the probability of neutrons and gamma rays from the same event being detected simultaneously is small. Many of the design calculations were performed using a Monte Carlo computer program written for this purpose by M. J. Hopper of the Theoretical Physics Division.

The detector is now operating, but some further work is necessary on the calibration and final adjustment of the gamma ray detection part of the system. Test results with ^{239}Pu, untreated except for background subtraction, are shown in Fig. 6, in which observed counts are plotted against neutron energy. If $N_f(E)\delta E$ is the number of fission events in the internal $E \rightarrow E + \delta E$ and $N_c(E)\delta E$ is the number of capture events, then the number of counts per unit energy interval from the neutron output of the detector, which is shown in the upper curve, is given by

$$n_f(E) \sim F_1 N_f(E)$$

and the number of counts per unit energy interval from the gamma ray output of the detector, shown in the lower curve, is given by

$$n_\gamma(E) \sim F_2 N_f(E) + F_3 N_c(E)$$

where F_1, F_2 and F_3 are constants determined by normalisation. F_1 contains as a multiplying factor the quantity $\bar{\nu}(E)$, but experimental results on other materials suggests that the variation of this quantity from resonance to resonance is $\lesssim 4\%$.

The quantity alpha(E) can then be found from the equation

$$\text{alpha}(E) = \frac{N_c(E)}{N_f(E)} = \frac{\dfrac{n_c(E)}{n_f(E)} - \dfrac{F_2}{F_1}}{\dfrac{F_3}{F_1}}$$

These are only preliminary results, but even a cursory glance at, for example, the resonances at 52.60, 50.08, 47.60, 44.48 and 41.42 eV shows that alpha is varying noticeably from resonance to resonance.

(E) Determination of ^{240}Pu resonance parameters (M. Asghar, M. C. Moxon, N. J. Pattenden and J. E. Jolly)

The work reported previously[20] has been continued, and further transmission and capture measurements have been performed on additional samples. The thickest transmission sample contained 2.82×10^{-3} Pu atoms/b. Resonance analysis of the new measurements is proceeding. The sum of the number of resonances below a given energy as a function of energy is shown in Fig. 7 (overleaf). The total corresponds closely to that obtained at the Geel linac[21]. This indicates that in this region few resonances are missed due to our limited resolution, 2.5 ns/m compared with 0.9 ns/m used in the Geel measurements.

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(20) Asghar M., Moxon M. C., Pattenden N. J., Jolly J. E. and Pratt J. S. Nuc. Phys. Div. Progress Report AERE - PR/NP 11 (1967).

(21) Bockhoff K. H. et al. Conference on Nuclear Data, Paris (1966). Paper CN-23/89.

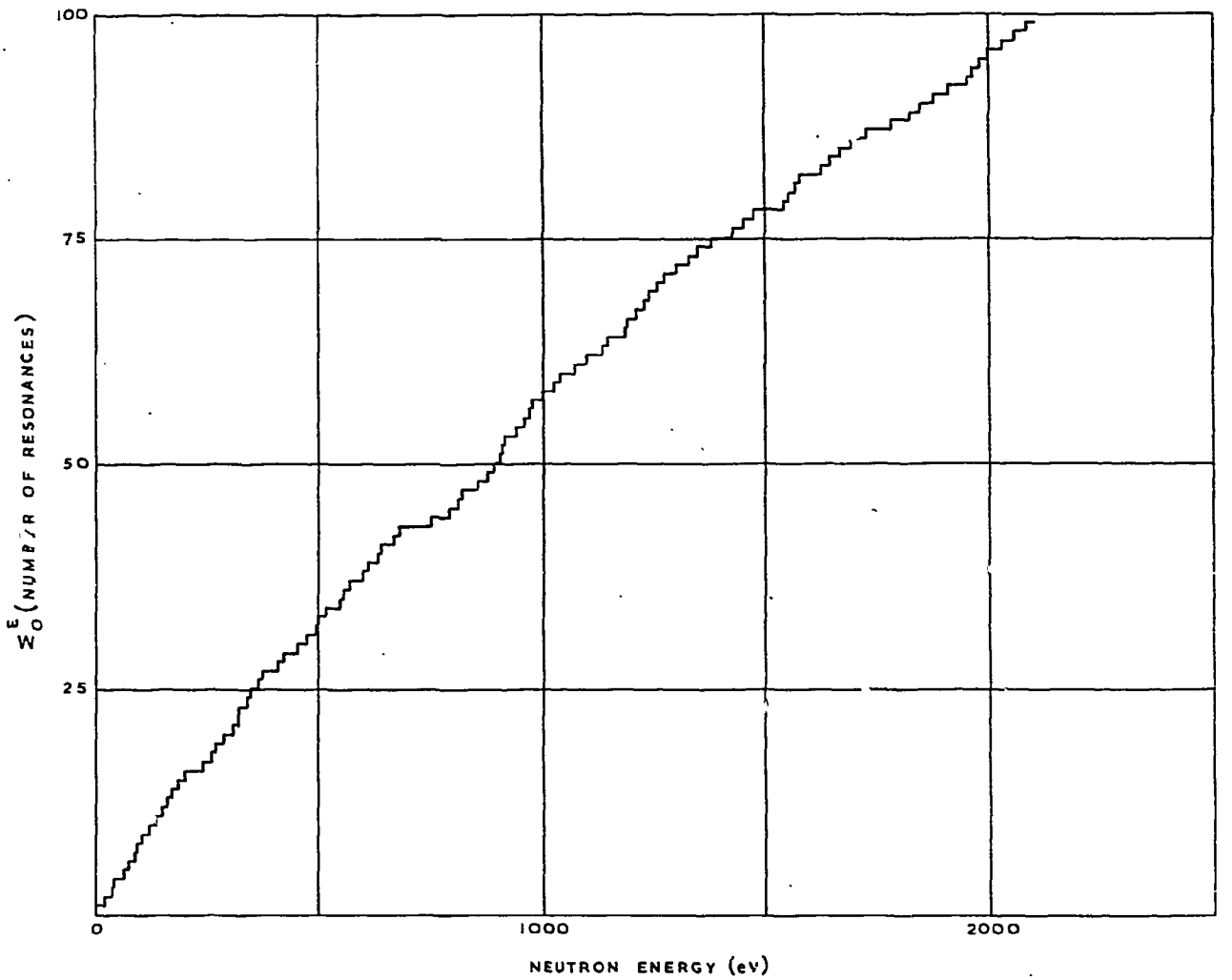

Fig. 7. Observed number of resonances below the energy E for ^{240}Pu.

Relationships between R-matrix and S-matrix reaction theories (J. E. Lynn)

A number of different formalisms are now available for the theoretical discussion of nuclear reactions. Perhaps the two most commonly used are the R-matrix theory of Wigner and Eisenbud[22] and the S-matrix theory of Humblet and Rosenfeld[23]. The former employs, as a basic set for its expansions, the eigenvalues and eigenfunctions of the nuclear hamiltonian within an internal region bounded by specified channel radii and constrained by real, energy independent boundary conditions. These channel radii and boundary conditions have been criticized by the S-matrix school as being artificial and arbitrary. The S-matrix expansions are about the poles of the collision matrix in the complex energy plane. A simple physical interpretation of these poles identifies them with radioactive decaying states. The two theories have their own advantages and disadvantages. The R-matrix theory can be cumbersome to handle in computations, particularly in computations of average cross sections, and the interpretation of its parameters is not always straightforward. On the other hand it gives expressions for the collision

(22) Wigner E. P. and Eisenbud L. Phys. Rev. 72, 29 (1947).

(23) Humblet J. and Rosenfeld L. Nuclear Physics 26, 529 (1961).

matrix which are unitary in form; this is an important property that provides for the conservation of flux in the stationary wave representations of the nuclear reaction. The S-matrix theory is simpler to handle in computations, and the individual terms of the expansion can be immediately interpreted as resonance forms. It does, however, have more parameters than the R-matrix theory, and this immediately implies (since both theories must describe the same collision matrix) that some of its parameters are redundant, or, in other words, are correlated with the others. This brings out the most fundamental difficulty of this theory, namely, that the expression for the collision matrix is not unitary in form. This imposition of unitarity governs the correlations among the parameters, and introduces difficulties into the practical use of the theory which are not immediately apparent in its simple form. Part of our work is directed towards a better understanding of the relationships between the two theories.

A number of nuclear cross section data have been analysed in the S-matrix formalism, and often striking agreement has been obtained between the data and the fitted curve. This agreement has been used as evidence of the validity of the S-matrix theory. However, to our knowledge, no attempts have been made to reconcile such fitting procedures with the demands of unitarity, and it is therefore worth taking a closer look at such fits. A particularly good example is the two-level fit by Mahaux[24] to the $^{15}N(p,\alpha_0)$ reaction to 1.1 MeV. His fit employed seven parameters and is very good. We have fitted the same data with a two-level approximation from R-matrix theory. The fit is every bit as good as if not better than Mahaux's, and it employs only six parameters. As we have explained, these parameters give a collision matrix that is unitary, and it is possible to transform this particular collision matrix into the S-matrix form in order to find a "unitary" set of S-matrix parameters. This has been done and the resulting set differs very considerably from Mahaux's set (for many parameters by several times the statistical error allowable by the R-matrix fit). Studies are also being made of the $^{51}V(n,n)$ reaction at energies up to 25 keV. In this case with two non-zero spins the extra freedom of the S-matrix theory (ignoring unitarity) makes it extremely difficult to obtain a satisfactory determination of the background parameters, although the equivalent R-matrix parameters were found quite ambiguously some years ago[25].

We have also begun to study the statistical properties of S-matrix parameters. For this purpose two computer programmes have been written. Both start from a given set of R-matrix parameters. One is used to find the poles of the collision matrix that can be generated from this set, and the other performs numerical contour integrations around these poles to find their factorised residues (the "partial widths"). The first case to be considered is a 60-level example simulating low energy neutron-induced fission through a single fully open statistical model channel. Through such studies it is hoped to obtain statistical distributions and correlations of parameters so that one can compute, among other things, theoretical average cross sections.

PDP-4 data processor (E. M. Bowey, G. B. Dean and J. L. Wilbourn)

The computer operated for 1380 hours during this period. The main processor has operated satisfactorily at all times, but some delays have occurred through failure of peripheral equipment.

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INTEGRAL DATA MEASUREMENTS

(E) The energy dependence of the $^6Li(n,\alpha)^3He$ cross section in the energy range 10 eV to 100 keV (M. S. Coates, K. M. Diment, D. B. Gayther, B. H. Patrick, M. G. Schomberg and M. G. Sowerby)

We have continued our investigation of the energy dependence of the $^6Li(n,\alpha)$ cross section through the comparison of neutron spectra measured with detectors making use of the $^6Li(n,\alpha)$ and $^{10}B(n,\alpha)$ reactions respectively, assuming a $^1/v$ dependence for the latter reaction. The emphasis has been placed on the region below 30 keV and the question whether or not the cross section follows the $^1/v$ law. Shapiro[26] showed that the s-wave parts of the $^6Li(n,\alpha)$ and $^{10}B(n,\alpha)$ cross sections cannot show a strict $^1/v$ energy dependence, but are more correctly written as

$$\sigma = \text{const. } E^{-1/2} + \Delta\sigma + \beta E^{1/2} + \ldots$$

where the first term represents the $^1/v$ law, the constant term $\Delta\sigma$ is determined only by the absorption cross section at zero energy and the spin of the reaction channel, and β is a constant determined by the states of the compound nucleus excited by s-wave neutrons. Bergman and Shapiro[27] show that for ^{10}B $(\Delta\sigma)_B = -0.40 \pm 0.03$ barn, and deduce that $(\Delta\sigma)_{Li} = -0.03 \pm 0.01$ barn. Since there are no s-wave levels in ^7Li close to the neutron binding energy, β will be very small. However for $^{10}B(n,\alpha)$ $\beta E^{1/2}$ is expected to be significant where the cross section is low, and it is probably this fact which maintains the $^{10}B(n,\alpha)$ cross section at approximately the $^1/v$ level up to ~ 100 keV[28]. These terms have not been taken into account in our present calculations, in which we have so far assumed that the $^{10}B(n,\alpha)$ cross section is proportional to $^1/v$.

The Monte Carlo programme of Lynn[29] which was used to calculate multiple scattering corrections to the lithium glass data has been checked against the Gem code at Risley[30]. It has been found that the results from the two programmes agree within 2%.

A further determination of the $^6Li(n,\alpha)$ cross section between 50 eV and 30 keV has been made using the "no sample" data obtained in a transmission measurement on the 97 m flight path. The data were treated in the same way as the data for thin lithium glass described in the last progress report[31]. The detector was a lithium glass disc 1 inch thick and 2½ inches in diameter coupled to a photomultiplier by a ½ inch thick Perspex light guide, the symmetry axis of the system lying along the direction of the neutron beam. The Gem code was used to calculate the multiple scattering corrections for neutrons interacting in the lithium glass and in the light guide. With this system the correction varied from 25% at 50 eV to ~ 200% at 30 keV. Even with this extremely large and rapidly varying correction the results for the $^6Li(n,\alpha)$ cross section agreed with those deduced from the ⅛ inch thick glass specimen within ~ 10% at 30 keV. Although the thick glass data will not be used in the final calculation of the $^6Li(n,\alpha)$ cross section, the fact that the results are in good agreement with those from the thin glass specimen adds to our confidence in the validity of the corrections.

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(26) Shapiro F. L. Soviet Physics JETP 34, 1132 (1958).

(27) Bergman A. A. and Shapiro F. L. Soviet Physics JETP 13, 895 (1961).

(28) Spaepen J. I.A.E.A. Conference on Nuclear Data, Paris (1966). Paper CN-23/119.

(29) Lynn J. E. Private communication.

(30) Hart W. Private communication.

(31) Coates M. S., Diment K. M., Gayther D. B., Patrick B. H., Schomberg M. G. and Sowerby M. G. Nucl. Phys. Div. Progress Report AERE - PR/NP 11 (1967).

The effects of the resonance at ~ 255 keV on the $^6Li(n,\alpha)$ cross sections below 100 keV have been calculated using the resonance parameters of Bergstom et al.[32]. At present if the $^{10}B(n,\alpha)$ cross section is assumed to be proportional to $^1/v$ the data show that the $^6Li(n,\alpha)$ cross section is consistent with a $^1/v$ term plus the tail of the resonance.

(E) Time of flight neutron spectrum measurements on a sub-critical fast reactor assembly (M. S. Coates, D. B. Gayther and P. D. Goode)

Preliminary data have been presented[33] from an experiment in which the neutron spectrum emerging from the centre of a sub-critical VERA 7A assembly was measured using the pulsed source time of flight method on the 45 MeV electron linac. This spectrum has now been re-evaluated with a more reliable efficiency calibration for the ^{10}B-Vaseline plug[34] used in the measurements. Previously the response (relative detection efficiency) below 100 keV was obtained by comparison with a thick ^{10}B-plug the response of which had been calculated from a Monte Carlo program. In this case the calculation could be in error since multiple scattering effects were evidently important, and these would be sensitive to uncertainties in the ^{10}B scattering cross section. In consequence a further comparison has been made with a much thinner ^{10}B-plug, in which the effects of multiple scattering are small enough for corrections to be applied with confidence. The measurements were made in the energy range 100 eV to 250 keV by the time of flight method, using the electron linac as a primary neutron source, and two different flight paths. The $^{10}B(n,\alpha)$ cross section is assumed to varry in this region as $^1/v$. Available experimental evidence[35] indicates that this assumption is correct to about ± 5% up to at least 100 keV, although theoretically a strict $^1/v$ dependence cannot be justified[36]. Since the detector observes the γ-rays from the first excited state of ^7Li produced in the (n,α) reaction, allowance was made for the slight change (4%) in the branching ratio $^{10}B(n,\alpha_1)^7Li^*/[^{10}B(n,\alpha_0)^7Li + {}^{10}B(n,\alpha_1)^7Li^*]$ between 80 keV and 200 keV[37]. The response curve is shown in Fig. 8 (overleaf). The absolute efficiency is obtained by normalising to the high energy data obtained on the pulsed Van de Graaff IBIS using the technique previously described[38]. The normalisation was made in the region of 100 keV, but it was found that within the accuracy of the measurements the energy variation of the detector efficiency in the range 100 → 200 keV, assuming a $^1/v$ variation in the $^{10}B(n,\alpha)$ cross section, was in agreement with the IBIS measurements. The structure in the response curve at 35, 90 and 150 keV is due to resonances in the 0.5 mm Al can which contains the ^{10}B-Vaseline mixture; the detailed behaviour in this region was obtained with higher energy resolution than is indicated by the experimental points in the figure. The results show that an overall error of about 10% was present in the theoretically extrapolated response used previously.

The re-evaluated VERA 7A spectrum shown in Fig. 9 (overleaf). The spectrum has been corrected for the experimental resolution using an iterative procedure which makes use of the measured shape of the neutron pulse in the assembly. This correction was only significant above 500 keV and had a maximum value of 10% at 3 MeV. A correction has also been applied for the effect of neutron slowing down which causes the slower neutrons to leave the assembly later than the faster ones. The magnitude of the effect was determined from the apparent shifts in the energies of known resonances in Mn and Fe (constituents of the stainless steel fuel element containers) - and gave rise to a barely significant

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(33) Coates M. S., Gayther D. B., Goode P. D. and Tripp D. J. Nuc. Phys. Div. Progress Report AERE - PR/NP 11 (1966).

(34) Coates M. S., Gayther D. B., Goode P. D. and Tripp D. J. Nuc. Phys. Div. Progress Report AERE - PR/NP 10, p. 22 (1966).

(35) Spaepen J. Paper CN23/119, Proc. I.A.E.A. Conf. on Nuclear Data, Paris (1966).

(36) Coates M. S., Diment K. M., Gayther D. B., Patrick B. H., Schomberg M. G. and Sowerby M. G. This report.

(37) Mooring F. P., Monahan J. E. and Huddleston C. M. Nuc. Phys. 82, 16 (1966).

(38) Gayther D. B. and Goode P. D. Nuc. Phys. Div. Progress Report AERE - PR/NP 7, p. 14 (1964).

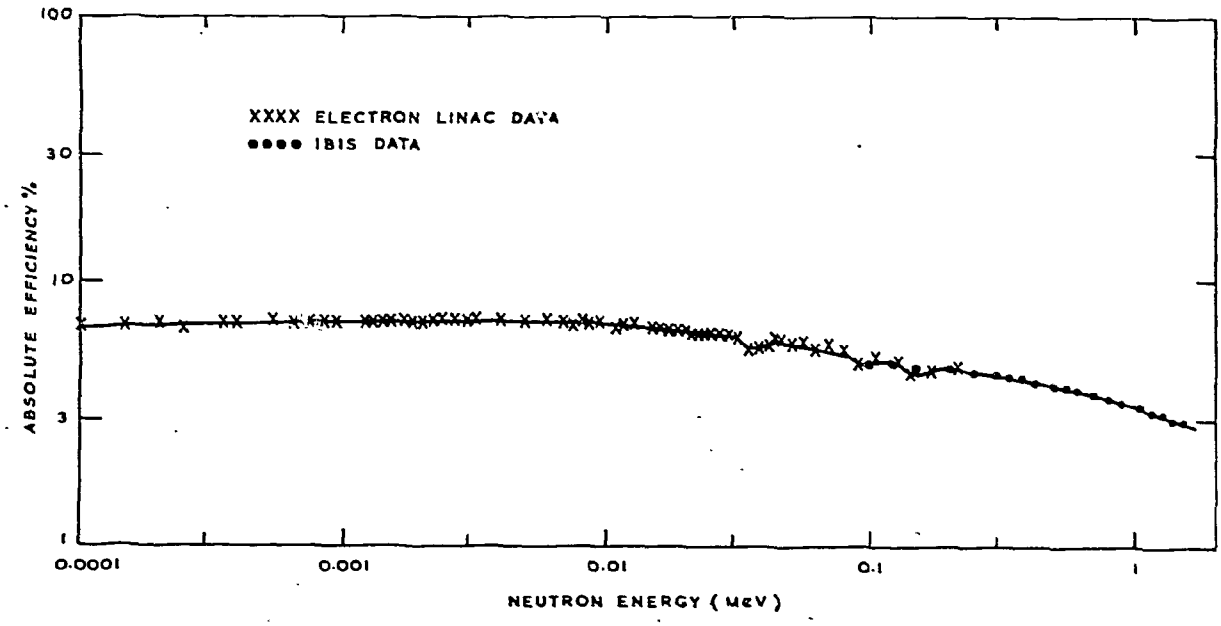

Fig. 8. B-vaseline plug energy response.

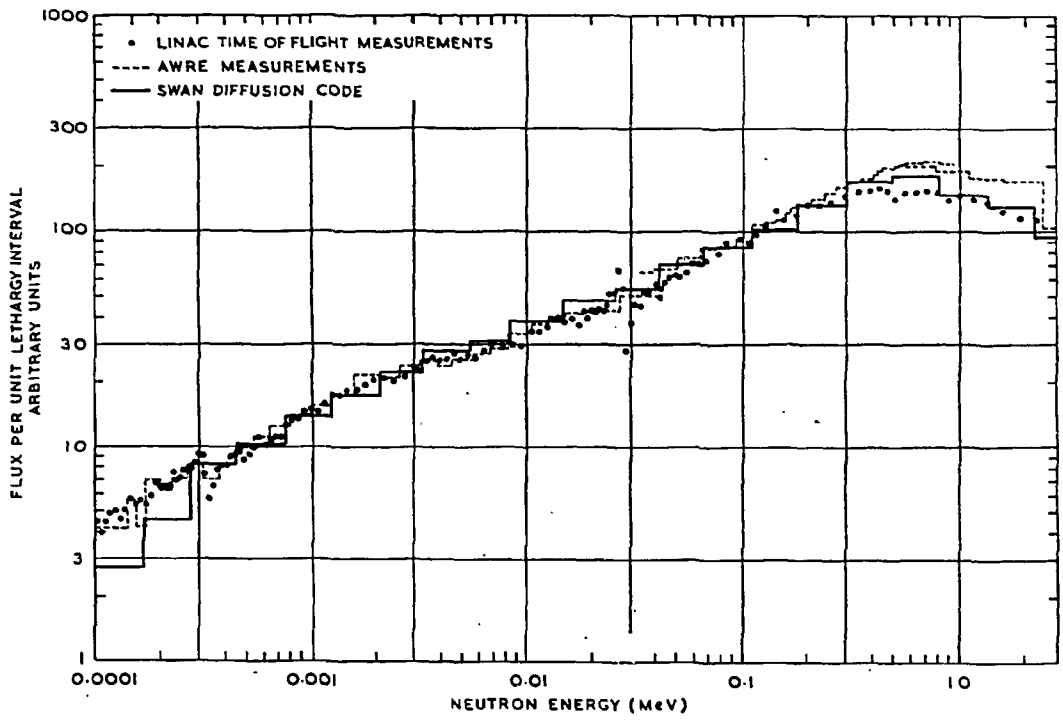

Fig. 9. Re-evaluated spectrum measurements on a VERA 7A assembly.

change in the shape of the spectrum. Fig. 9 also shows the spectrum determined in a similar assembly at A.W.R.E. using the composite technique[39], together with a 35 group SWAN calculation made for the critical system using FD2(R) nuclear data. The linac data and the composite data have the same shape in the region below 80 keV, and in the figure they have been normalised to one another. This is the energy region which was covered by the time of flight technique in the composite measurement. However at higher energies the linac spectrum is still considerably softer than the A.W.R.E. experimental data, although only slightly softer than the theoretical spectrum. The cause of the discrepancy between the two experiments is not yet resolved. The A.W.R.E. measurements are to be repeated and it is also hoped to investigate theoretically possible perturbations arising from differences between the various techniques. Probably the most important of these will be the dependence of the shape of the spectrum on the value of k_{eff}. The A.E.R.E. measurement was made on a sub-critical system, while in the composite technique the system was critical for measurements made at energies greater than 50 keV and sub-critical for measurements below this energy. A detailed account of the A.E.R.E. measurements will be published shortly[40].

(E) Measurements of fast neutron spectra in reactor materials (M. S. Coates, D. B. Gayther and P. D. Goode)

The series of time of flight measurements of fast neutron spectra in geometrically simple arrays of pure materials has been completed. The measurements are intended to provide a basis for comparison with reactor calculations using specific nuclear data in well defined and easily calculable conditions. Table III lists the measurements which have been made. The experimental arrangement and preliminary

TABLE III

Materials and Geometrical Arrangements used to study Fast Neutron Spectra

Material	Shell Outside Diameter (cm)	Shell Wall Thickness (cm)	Radial Distance of measurement point from outside of shell (cm)	Angle of Beam to Radius Vector (deg.)
Natural Uranium	23.9	6.1	0.0	0
	23.9	6.1	0.0	45
	28.4	8.4	0.0	0
	28.4	8.4	0.0	45
	28.4	8.4	4.3	0
	32.0	11.5	0.0	0
	32.0	11.5	0.0	45
Graphite	40.6	15.2	0.0	0
	40.6	15.2	0.0	45
	40.6	15.2	10.2	0
	40.6	15.2	5.2	0
Sodium	90.7	41.6	0.0	0
Polythene	20.3	5.1	0.0	0
	20.3	5.1	0.0	45

(39) Weale J. W., Benjamin P. W., Kernshall C. D., Paterson W. J. and Redfearn J. Berkeley Conf. on Radiation Measurements (1966).

(40) Coates M. S., Gayther D. B., Goode P. D. and Tripp D. J. A.E.R.E. Report R 5330 (1967).

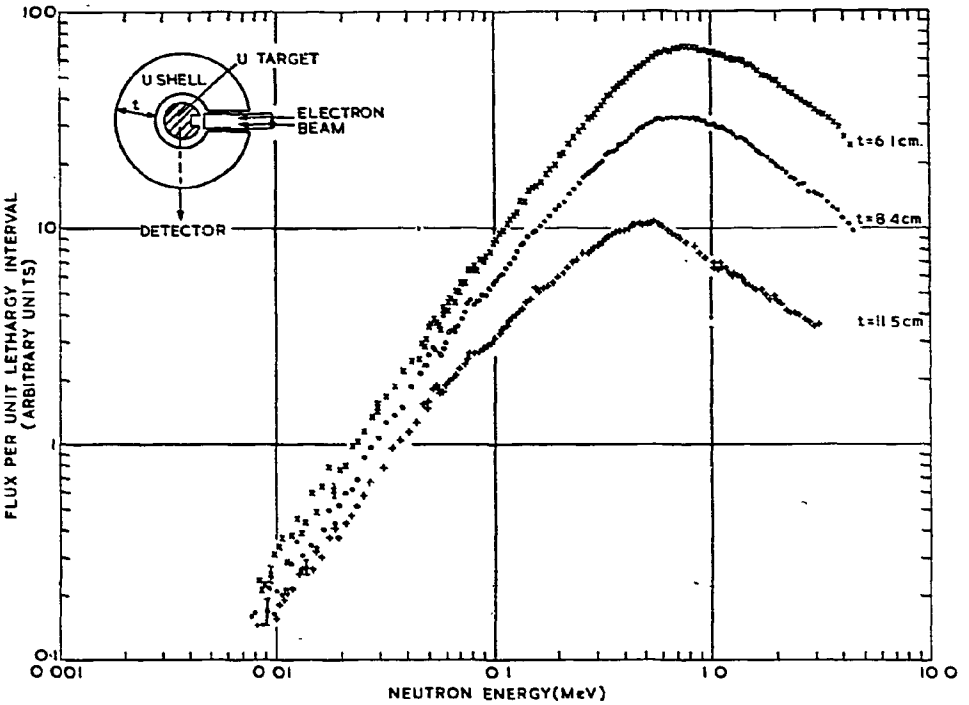

Fig. 10a. Measured 0° leakage spectra from natural uranium shells.

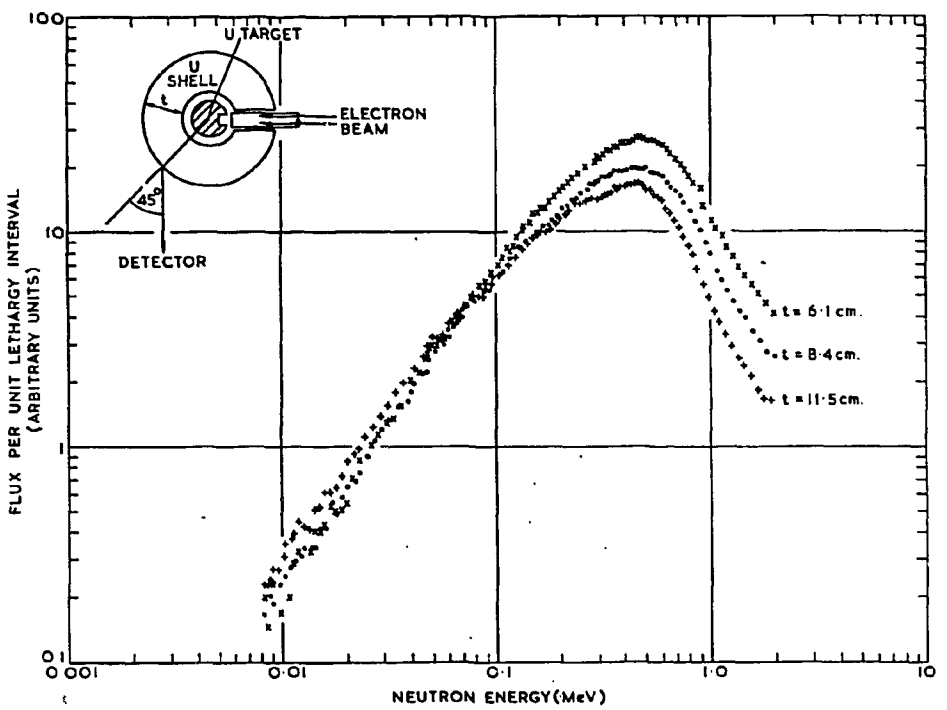

Fig. 10b. Measured 45° leakage spectra from uranium shells.

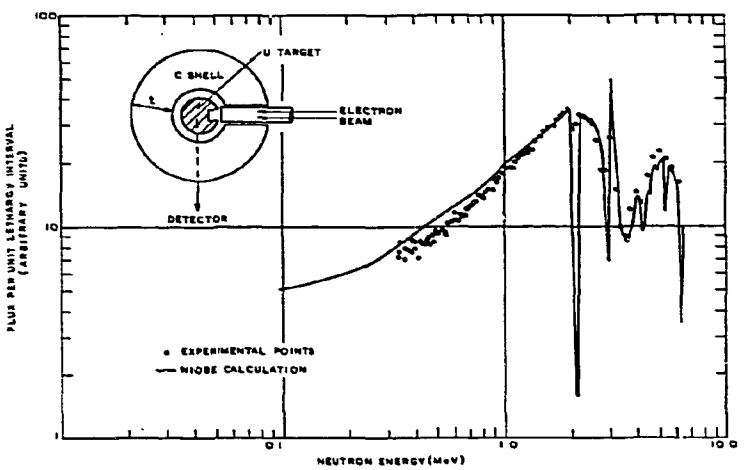

Fig. 11. Measured and calculated 0° leakage spectrum from a graphite shell.

spectra have been reported previously[41]. The materials were used in the form of spherical shells with a central nearly isotropic source of fast neutrons of known energy distribution[42]. We measured the energy spectra of beams of neutrons emerging from small areas on the surface of the shell (leakage) and at particular depths within the shell, the beams making angles of either 0° or 45° to the radius vectors at the appropriate points. Analysis of the experimental data is now almost complete and the work is to be published[43]. Calculations for comparison with the experimental spectra are in progress. Carlson Sn calculations are being carried out by E. D. Pendlebury (A.W.R.E.) and A. F. Avery (Shielding Group) is providing calculations using the NIOBE code.

Fig. 10 shows the leakage spectra for the three uranium shells at 0° and 45° to the radius vector and Fig. 11 shows a comparison of a NIOBE calculation on graphite with the high energy part of the experimental spectrum.

(41) Gayther D. B. and Goode P. D. Nuc. Phys. Div. Progress Report AERE-PR/NP 10, p. 20 (1966).

(42) Gayther D. B. and Goode P. D. A.E.R.E. Report R 5331 (1966).

(43) Coates M. S., Gayther D. B. and Goode P. D. A.E.R.E. Report R 5364 (1967).

(B) The measurement with a Ge(Li) spectrometer of gamma-rays following inelastic neutron scattering (B. H. Armitage, T. Braid*, A. T. G. Ferguson, G. C. Neilson+ and W. Pritchard✓)

In an attempt to exploit the improved gamma-ray energy resolution offered by Ge(Li) detectors we have begun a programme of measurements on the de-excitation gamma-rays following inelastic scattering of fast neutrons. We used the nanosecond pulsed beam system of IBIS with time of flight gating to reduce the effective neutron induced backgrounds in a 30 cc. Ge(Li) detector. A time resolution of 6 ns has been obtained with gamma-rays of 0.5 MeV and above, using a time compensation system in which the output of the time-to-pulse-height converter is mixed with a compensation pulse obtained from the output of a second time-to-pulse-height converter in which the "start" and "stop" pulses are derived from the fast pulse by means of two discriminators set at "low" and "high" levels respectively. At gamma-ray energies greater than 0.5 MeV the application of this time compensation system has decreased the time resolution from 30 ns to 6 ns.

Gamma-ray spectra have been obtained from samples of about 200 gm of natural U and natural Th at several neutron energies between 1 and 2 MeV, using a tritium target and a 50 cm flight path. Analysis of the data is not yet complete and as might be expected the spectra are rather complex.

(H) Neutron total cross sections (A. Langsford, P. H. Bowen, G. C. Cox and P. J. Clements (Nuclear Physics Laboratory, Oxford))

(a) Hydrogen

A description of the aims and methods of this experiment, a measurement of the total cross section in the energy range 300 keV to 5 MeV, appeared in the preceding progress report[93]. The residual uncertainty in the measurement attributed to after-pulsing of photomultiplier tubes, which was discussed in that report and also by White[94], has been overcome by viewing the plastic scintillator of the detector with two photomultiplier tubes whose outputs are taken in coincidence. Unfortunately this has at the same time introduced a smaller, rate dependent, systematic variation in the measured cross section. However, by applying calculated corrections to measurements at different beam intensities, a rate independent cross section has been obtained. Now that the major sources of systematic uncertainty are understood, further running should achieve the required accuracy, 0.2%, in the neutron-proton total cross section.

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*On leave from Argonne National Laboratory.

+On leave from University of Alberta.

✓On attachment from University of Exeter.

(93) Nuc. Phys. Div. Progress Report AERE PR/NP 11 (1967).

(94) White G. A.E.R.E. Report R 5316 (1967).

(b) Carbon

In order to be able to correct for any mismatching of the hydrocarbon samples used in the above measurement the carbon total cross section was determined in the same energy range, 300 keV to 5 MeV. The results agree with those obtained earlier[95], but depart significantly from the preferred BNL 325 (2nd Ed., Supp. 2) values. They are, however, in agreement with work at Rensselaer[96]. At this time it is not possible to rule out a 0.5% systematic error caused by non-uniformity in the carbon sample. Our results are presented in Fig. 26a (overleaf).

(c) Sodium

A further measurement of the sodium total cross section has been made in the 300 keV to 10 MeV region with the same samples as before[95], and with higher statistical accuracy. The results are shown in Fig. 26b. After the completion of the synchrocyclotron improvement programme further measurements will be made with a reduced lower energy limit in order to investigate the cross section variations reported by Hibdon[97].

(d) Holmium

The total cross section of a 7 cm long (0,2261 atoms bn^{-1}) sample of holmium has been measured in the energy range 2 MeV to 130 MeV and the results are presented in Fig. 26. These data were taken as part of a study to be made with Dr. H. Marshak (N.B.S. Washington) of the total cross section for longitudinally polarized holmium nuclei.

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(95) Nuc. Phys. Div. Progress Report AERE PR/NP 9, p. 34 (1967).

(96) Yergin P. F. et al. Proc. Conf. on Neutron Cross Section Technology, A.E.C. CONF-660303, Book 2, p. 690 (1966).

(97) Hibden C. T. Phys. Rev. 118, 514 (1960).

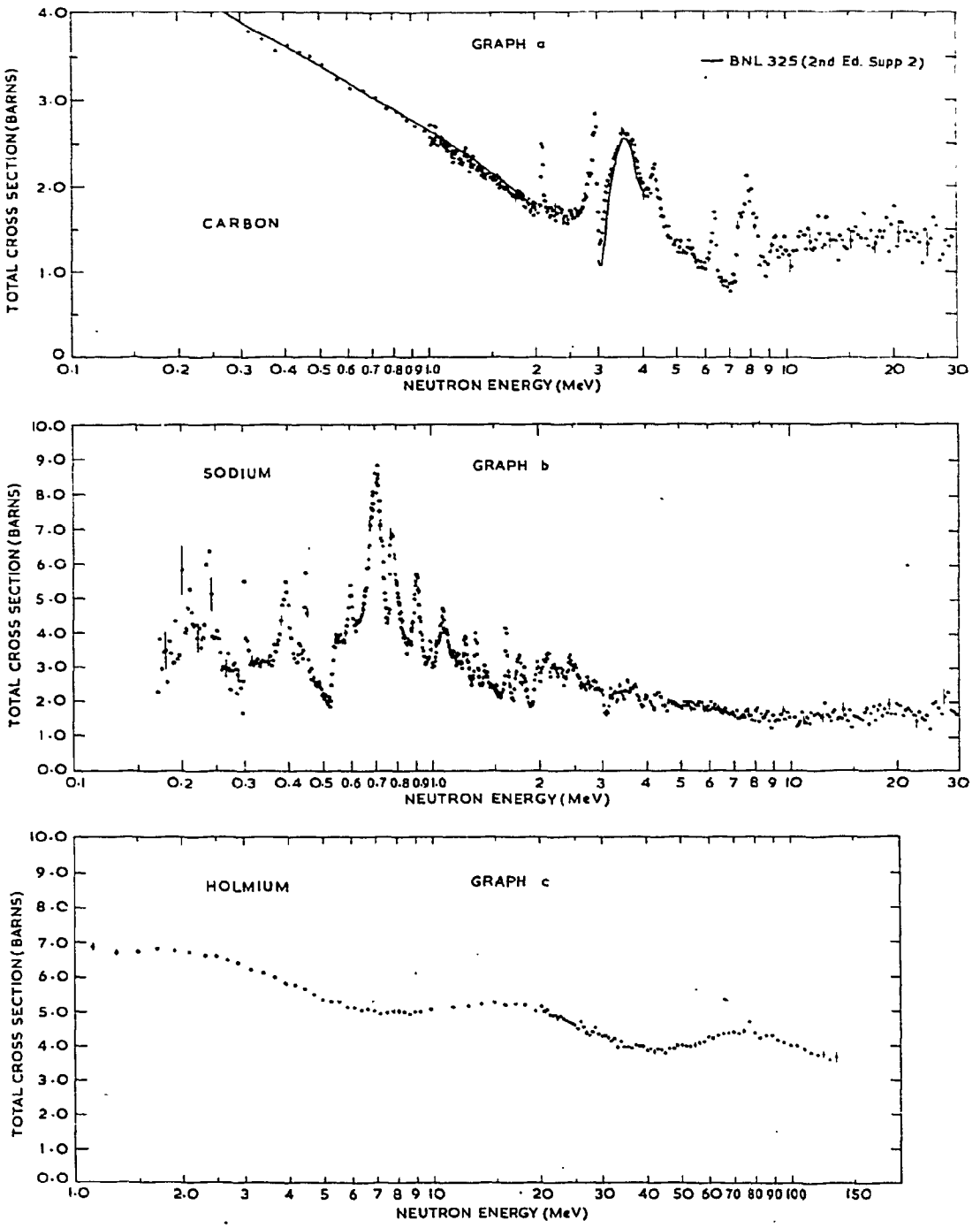

Fig. 26. Neutron total cross sections in the MeV region for (a) carbon, (b) sodium and (c) holmium.

REPORTS AND PUBLICATIONS

REPORTS

AERE - R 5331 Neutron Energy Spectra and Angular Distributions from Targets bombarded by 45 MeV Electrons. D. B. Gayther and P. D. Goode.

CHEMISTRY DIVISION, A.E.R.E.

(Division Head: Dr. W. Wild)

^{106m}Rh in Low Energy Fission (I. F. Croall, T. A. Eastwood and H. H. Willis)

This work is now complete and has been written up for publication. Additional measurements of the yield of ^{105}Rh in the thermal neutron fission of ^{235}U and ^{239}Pu have been made. On the basis of the independent yield, predicted by the equal charge displacement rule, at ^{106}Rh, it is found that the low spin isomer of ^{106}Rh (30 sec.) is favoured in independent formation in the thermal neutron induced fission of ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu. In all the other isomer ratios investigated the high spin isomer has been found to predominate, and this example of ^{106m}Rh is the first to show that the fission process does not necessarily produce high spin in the products.

The Decay of ^{142}Ba and ^{142}La (I. F. Croall, Miss L. Halliday and H. H. Willis)

As a first stage in this work we have measured the half-lives of ^{142}Ba and ^{142}La, as particularly for the former, there are considerable discrepancies in the literature. The half-lives obtained are 11 ± 1 mins. for ^{142}Ba and 92.5 ± 1 mins. for ^{142}La. A search is now being made for possible isomerism in ^{142}Ba or ^{142}La.

Fission Yield Measurements (I. F. Croall and H. H. Willis)

In preparation for measurements of absolute yields from fast neutron induced fission, determination of the absolute yields produced in the thermal neutron fission of ^{235}U have been carried out in BEPO. The absolute yield of ^{99}Mo and nuclides of the elements Zr, Sr, Cs, Ce, Ba and Ag have now been measured. The results have not yet been completely analysed, but the observed ^{99}Mo absolute yield appears to be in good agreement with the value of 6.14%, the 'best' value derived from other measurements.

Multiple Neutron Capture in ^{239}Pu (E. A. C. Crouch and M. Brownsword)

The 24 month irradiated sample of ^{239}Pu alone remains to be chemically separated and mass-analysed. Using a method previously outlined (PR/Chem 10) the solution of the equations of formation of the fission products by all the nuclear processes which occur in fissile materials, has been programmed for the light mass peak of ^{239}Pu fission. Using known fission yields and nuclear data (roughly that of the 1964 Chart of the Nuclides), the irradiation history of the 15 month irradiation sample, and an estimate of the flux at the irradiation position in DIDO, the isotopic composition of the products was calculated. As examples of the first results obtained, the following comparisons are given:

Ratio	Calculated	Found
$^{85}Rb/^{87}Rb$	.4664	.4549
$^{88}Sr/^{90}Sr$	.7909	.9232
$^{91}Zr/^{96}Zr$	.4847	.4587
$^{92}Zr/^{96}Zr$	.6094	.6115
$^{93}Zr/^{96}Zr$	.7675	.7236
$^{94}Zr/^{96}Zr$	.8665	.8669
$^{239}Pu/^{241}Pu$	.2729	.2682

Discrepancies between the found and calculated ratios and relative quantities will indicate missing or incorrect nuclear data. It is emphasized that these are initial results and numerical errors may still be present.

Delayed neutrons from antimony and arsenic isotopes. In-pile experiments using the Zn + H_2SO_4 system have now been completed. Neutron count rates were 10 times larger than those obtained with the best electrolytic system. The results have confirmed those reported previously (PR/Chem 10 and 11) and have also shown 11-second ^{134}Sb to be a delayed neutron precursor. The delayed neutron activity is very weak (Pn ~ 0.1%), but ^{134}Sb is the first delayed neutron precursor discovered which has only 1 neutron in excess of a closed shell - the neutrons actually being emitted from a nuclide (^{134}Te) containing a "magic" number of neutrons (82). Although earlier theories excluded the possibility of delayed neutron emission from such a nuclide, more recent theoretical treatments (Pappas and Rudstom, Nuc. Phys. 21 (1960) 353 and our own assessment described above) include ^{134}Sb as a potential delayed neutron precursor.

This work is now completed and the data is being analysed prior to writing up.

Search for delayed neutrons from selenium isotopes. A series of reactor experiments have been carried out to search for delayed neutron precursors amongst the fission product selenium isotopes. The method, based on the formation of H_2Se (PR/Chem 11), gives a chemical yield of 0.3 to 2.0%. Because of arsenic and antimony contamination and the growing in of bromine isotopes, the decay curves are difficult to sort out and a complete analysis has not yet been performed. However the results show that any delayed neutron emission from the selenium isotopes must be rather weak. By counting the neutrons from ^{87}Br (grown in from ^{87}Se) it has been possible to make the first half-life measurement of ^{87}Se. A preliminary value is 6 ± 1 seconds. This finding is highly relevant to overall delayed neutron kinetics.

New methods of obtaining a high yield of H_2Se from a mixture of fission products are also being investigated.

ANALYTICAL SCIENCES DIVISION, A.E.R.E.

(Division Head: Dr. A. A. Smales)

Capture cross sections of neodymium isotopes (M. J. Cabell and M. Wilkins)

The experiment has yielded the following values:-

Nuclide	Mean cross section for reactor neutrons, in barns	Cross section for Maxwellian neutrons (T = 82 ± 13°C), in barns	Cross section for 2200 m/sec neutrons, in barns
^{142}Nd	16.18 ± 0.37	18.76 ± 0.73	-
^{143}Nd	319.7 ± 8.4	316.1 ± 13.5	318.0 ± 13.6
^{144}Nd	3.58 ± 0.30	3.58 ± 0.30	-
^{145}Nd	59.0 ± 6.7	42.9 ± 2.2	40.5 ± 2.1

In addition Westcott's S_0 (Ref. A.E.C.L. Report CRRP960) for ^{142}Nd and ^{145}Nd was found to be –(2.05 ± 0.69) and 6.4 ± 0.9 respectively.

These results go a long way towards explaining the discrepancies which previously existed between the values obtained for these nuclides by pile oscillator and neutron transmission measurements on the one hand, and by activation methods on the other. Only in the case of ^{145}Nd does a real discrepancy still exist. The values for Maxwellian and 2200 m/sec neutrons given here are appreciably lower than those obtained previously, although the value of S_0 is in line with previous findings.

REPORTS AND PUBLICATIONS

AERE - R 5520 "Mass Spectrometric Measurements of the Neutron Capture Cross Section of ^{142}Nd, ^{143}Nd, ^{144}Na and ^{145}Nd for Reactor and Maxwellian Neutrons" by M. J. Cabell and M. Wilkins (July 1967).

This report has been accepted for publication in Journal of Inorganic & Nuclear Chemistry.

NUCLEAR RESEARCH DIVISION, A.W.R.E.

(Chief of Nuclear Research: Dr. H. R. Hulme)

1. Accelerator and Neutron Physics (R. Batchelor)

1.3 Fast Neutron Physics and 6 MV Accelerator (J. H. Towle)

1.3.1 Time of Flight Measurements

(a) Neutron Scattering on Reactor Elements at 7 MeV (J. H. Towle, G. J. Wall)

In earlier (90°) measurements of inelastic spectra at this energy (paper entitled "Absolute Level Densities from Neutron Inelastic Scattering" now in press), strong direct reaction contributions were seen to certain levels of a collective nature. A programme of angular distribution measurements is now commencing in order to throw further light on this effect.

The 5 in. diameter counter is now fully operational. A time resolution of 3 ns FWHM was obtained for a neutron peak in the TOF spectra. This should be reduced further by two-dimensional (time x energy) recording currently being set up in the intertechnique + PDP7 system.

Scattering runs at 7 MeV on Si^{28} and S^{32} were made in order to examine the new shield and collimator arrangements for 5 m flight path runs. In these measurements the detector is in the collimated water-tank at 5 m flight path and the short flight path tank is used as a fore-collimator. Some 10 ft of collimator is utilised in this system. Accurate lining up of the two collimators at each angle is achieved using a laser beam. Backgrounds were very satisfactory, and breakthrough of direct source neutrons at this energy was very small. Angular distribution measurements will commence in the next machine run.

(b) Inelastic Scattering at 5, 6 and 7 MeV in the Rare Earths (R. O. Owens*, J. H. Towle)

Further least squares fits to the inelastic spectra of 15 elements by evaporation formulae have been made and values of the temperature T or level density constant a determined. Some progress has been made in preparing a final paper.

(c) Elastic and Inelastic Scattering by V^{51} and Y^{89} (J. H. Towle, W. B. Gilboy)

The Y^{89} elastic scattering data are being corrected for a small oxygen contamination of the Y^{89} sample. The analysis and interpretation of the other neutron data is complete and will be reported in conjunction with further data obtained from the $(n,n'\gamma)$ process with a Li-Ge γ-ray counter (see Section 1.3.2(b)).

(d) Neutron Scattering by Ni^{58} and Ni^{60} (J. H. Towle, R. Batchelor, W. B. Gilboy)

The final report on this work is not yet completed.

(e) Neutron Scattering from B^{10}, B^{11}, U^{235}, Pu^{239}

Owing to the development of the new detector and shielding system, no further measurements have been made on these isotopes in this period.

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*Now at University of Glasgow.

1.3.2 γ-Ray Spectroscopy with Li Drifted Ge Detectors

(a) $Bi^{209}(n'\gamma)$ Reaction (W. B. Gilboy, R. E. Coles)

Six levels of a theoretically predicted septuplet near 2.6 MeV in Bi^{209} have been exhibited by γ-ray transitions direct to the ground state. Interfering backgrounds make it difficult to establish the extent of possible cascades through lower levels. Improvements to the γ-spectrometer should shortly enable more definite conclusions to be made.

(b) $V^{51}(n,n'\gamma)$, $Y^{89}(n,n'\gamma)$ Reactions (W. B. Gilboy, R. E. Coles)

These reactions were recently re-measured over the neutron energy range 0.4 - 3.2 MeV using a 40 cc GE-Li counter (GL46) with 4.2 keV resolution for Cs^{137}. The data are of much better quality than that of earlier measurements and greatly improved excitation functions can be derived.

(c) $Cr(n,n'\gamma)$ Reaction (W. B. Gilboy, R. E. Coles)

γ-Rays from a ring scatterer of natural Cr were observed with GL46 over a neutron energy range 0.6 - 3.2 MeV. γ-Ray transitions from several isotopes of Cr were identified and in conjunction with earlier neutron data reliable inelastic cross sections should be derived.

1.3.3 Measurement of (n,2n) Cross Sections Using Large Liquid Scintillation Counter (D. S. Mather, P. J. Nind)

Further work was carried out to assist in making corrections to the measured cross sections, particularly those for nuclides of low mass number. The effect of elastic scattering in the samples was simulated by the use of water, polyethylene and perspex which should yield effectively zero (n,2n) cross sections but have elastic scattering representative of the light elements.

The prompt system has been used with the Pu^{239} samples. Measurements of the random gating were made by lowering the target below the collimator thus giving background but no beam through the sample. Because of the low background levels a short series of non-prompt measurements was also attempted for Pu^{239}. The results are now being analysed.

1.4 Fast Neutron Physics: Miscellaneous

1.4.1 The Doppler Effect on the $U^{238}(n,\gamma)$ Reaction at Different Neutron Energies and at High Temperatures (P. Fieldhouse, J. L. Perkin, G. P. Warner, A. Brickstock, A. R. Davies)

Doppler effect measurements have now been completed and a paper has been submitted to the Journal of Nuclear Energy with the following abstract and table of results:-

Measurements of the Doppler effect on the $U^{238}(n,\gamma)$ reaction have been made on uranium metal samples heated to 770°K with neutrons of different energies in the range 0 - 54 keV from the $Li^{7}(p,n)$ reaction. The measurements made in one particular energy range (0 - 10 keV) were extended to temperatures of up to 1960°K using uranium dioxide samples. The results obtained were compared with computer calculations.

In the uranium metal samples the Doppler effect at different neutron energies was found to agree within the rather large experimental errors with the theoretical calculations. In the uranium oxide samples the measured Doppler effect over the temperature range 290-1960°K agreed with that calculated, except for the first 200°K of this range when the measured effect was greater than that calculated.

Sample	Temperature Range, °K	Incident Neutron Energy Range, keV	Doppler Effect Expressed as the % Change in Reaction Rate over the Temperature Range	
			Experimental	Theoretical
Uranium Sphere	290-770	0-10	11 ± 5.7	7.3
		3-15	2.8 ± 2.5	5.4
		6-23	3.8 ± 2.4	3.5
		10-33	3.4 ± 2.3	2.7
		27-54	5.3 ± 1.7	-
Uranium Oxide Cylinder	200-500	0-10	8.6 ± 3.8	3.4
	500-1960	0-10	6.3 ± 3.3	7.9

1.4.2 (n,α) Cross Sections for Cr, Fe, Ni and Mo for Fission Neutrons (J. F. Barry, N. J. Freeman)

The samples have been irradiated in DFR but have not yet been sent to AWRE. Cr and Mo samples have been irradiated with α particles from the 6 MV accelerator and measurements of the helium extraction efficiency will shortly be carried out.

1.5 Neutron Cross Section Measurements Using Bomb Neutrons (A. Moat, E. Moss*, J. Pugh, D. G. Piper)

The LASL shot Persimmon of 23rd February 1967 provided the AWRE team with its first opportunity of making cross section measurements with a bomb source. Three experiments were attempted:-

(a) Fission cross section of Pu^{238}, and the angular distribution of fission fragments (detectors at 15°, 55° and 90°).

(b) Fission measurements on a 1 μg sample of Pu^{239} to assess the feasibility of experiments on small quantities of short-lived isotopes.

(c) Recording of the fission fragments from U^{235} under similar conditions to a LASL record, but using AWRE detector, amplifier and recording system.

All the records appear satisfactory except for the 15° Pu^{238} which was lost due to detector failure.

Some delay in reading the records was caused by teething troubles of the polar co-ordinate digital assessing machine. Readings have now been made on the 55° and 90° Pu^{238} film discs, and some preliminary plots of signal level versus energy have been obtained showing a considerable quantity of new data.

The team wishes to record its gratitude to the Los Alamos Scientific Laboratory for the invitation to participate in the Persimmon shot, and for making available its field facilities.

*Member of CPA Division.

Preparations for the next shot are under way. We expect to mount a neutron spectrometer to study the purity of the neutron beam in the energy region above 1 MeV. This spectrometer is in the final stages of manufacture; tests are expected to be completed by the end of October. Most of the difficulties of making a Be^7 sample have now been resolved, and it appears to be possible to prepare a 1 μg foil for the next shot for measurement of the (n,p) cross section; also planned for the next shot is a measurement of α for Pu^{241} in collaboration with Dr. Rae's group at Harwell.

The recording equipment will again be provided and operated by CPA; that division is currently manufacturing a 16 channel recording facility for the neutron spectrometer, designing a multi-linear amplifier system to replace the logarithmic amplifier used on Persimmon, and designing a modified disc camera to record four channels per film disc. The date of the next shot will determine how much of this new equipment can be mounted.

2. Tandem Van de Graaff (J. H. Towle)

2.4 Neutron Time of Flight Studies

2.4.1 Neutron Scattering (J. A. Cookson, J. G. Locke, J. L. Wankling)

Preliminary measurements on the scattering of 10 MeV neutrons from B^{10}, B^{11} and U^{238} have been made. One set of Ni^{58} separated isotope gas cell windows has been obtained which should make it possible to obtain a more monochromatic source of 10 MeV neutrons than hitherto.

2.6 Cross Sections of $O^{16}(n,\alpha)$ and $C^{12}(n,\alpha)$ for the Medical Research Council (D. Dandy, G. Garner, J. L. Wankling)

The reaction $O^{16}(n,\alpha)$ has been studied using a hemispherical geometry in the neutron energy range $6.5 < En < 11.5$ MeV at 0.5 MeV intervals. Signal to backgrounds of approximately 1:4 were obtained and the analysis of the results is well under way. The excitation function and α energy spectra will be extracted from the data.

Because of its unfavourable Q-value the reaction $C^{12}(n,\alpha)$ is not considered to be feasible using the existing equipment and has not been pursued.

3. Research Reactor Herald; Integral Neutron Data; Mass Spectrometry and Atomic Physics; Solid State Physics (Division Head: J. J. McEnhill)

3.3 Neutron Physics (A. L. Rodgers)

3.3.2 Fission Physics

(a) Ternary Fission (A. Clarke, E. E. Maslin)

Preliminary measurements on ternary fission events have shown that the anomalous events observed in the earlier work [1] are not associated with ternary fission. Collection of further data is continuing to obtain an accurate energy/mass surface so that α particle emission may be studied as a function of fission mass division.

The techniques of analysing the data have been improved by transferring most of the analysis which had previously been performed on STRETCH to the PDP8 computer. The analysis of the fission events now produces two matrices, one for binary and one for ternary fission events. Each

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[1] CNR/PR/8.

matrix gives the number of events as a function of the mass and kinetic energy of the fragments, and these are fed into ATLAS for the final analysis and plotting of contour diagrams.

(b) Fission Fragment Time of Flight Measurements (W. G. F. Core, E. Finch*)

The apparatus has been re-assembled and fission fragments have been observed with the surface barrier detectors at each end of the flight tube but no pulses have yet been detected from the VYNS film detector.

A new rotating counter holder has been installed to enable the response of various counters to fission fragment to be readily observed.

4. Integral Neutron Data Experiments (J. W. Weale)

4.1 VIPER Pulsed Reactor (L. J. Dalby, H. Goodfellow, R. L. Long, W. B. McCormick, M. H. McTaggart, G. V. Stupart, E. G. Warnke)

Construction and test of the reactor mechanisms in the AWRE workshops were completed satisfactorily and the reactor was rebuilt in its working position in the A70.1 cell during the first half of this period. In parallel with the mechanical construction the instrumentation has been tested and the reactor was finally coupled to its control circuitry in April.

Approval to proceed with nuclear commissioning was given by the Safety Panel at its meeting on 25th April subject to review by a sub-panel at various stages. A Safety Document was issued in March 1967. Fuel was first loaded on 19th May and the reactor first went critical on Friday, 26th May at 4.37 p.m. Preliminary indications are that the reactor behaves as designed. The control rod worths and safety blocks worths were predicted correctly within 10%. The critical mass is somewhat higher than predicted by about 5-10%. Measurements in the steady state mode of operation which precedes pulsed operation are proceeding. Pulsing is expected to start in July.

4.2 VERA Assemblies (P. W. Benjamin, H. Goodfellow, W. B. McCormick, M. H. McTaggart, W. J. Paterson)

No experiments on the VERA machine have been done during the installation of VIPER. The opportunity has been taken to revise the instrumentation for VERA and rebuild the control desk in an improved form. The building ventilation system has also been revised and improvements made to the automatic filtered venting system.

4.2.1 Assemblies 18A and 18B [1] (VERA Assemblies Built to Simulate DFR)

Further comparison of the results of these experiments with the multigroup methods in use in Dounreay confirm the earlier conclusions, namely that:-

(1) Best agreement is obtained using the FD2 [2] data set with Ravier's nickel data [3] and the CRAM diffusion code [4].

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[1] J. C. Smith and H. Atkinson, DERE, M. H. McTaggart, AWRE: "Theoretical and Experiment Analysis of Reaction Rate Distributions in the Dounreay Fast Reactor". Presented at the Conference on Fast Critical Experiments and their Analysis, Argonne (October 1966) TRG Report 1384(D).

[2] R. W. Smith et al.: "The FD2 Group-Averaged Cross Section Set for Fast Reactor Calculations". AEEW-R491.

[3] R. Ravier and M. Vastel: "Sections Efficaces Neutroniques due Nickel dans le Domaine d'Energie 0.0001 eV a 15 MeV". PNR/SEPR/CA/65.101.

[4] A. Hassitt: "A Computer Program to Solve the Multigroup Diffusion Equations". TRG Report 229(R).

*Oxford University.

(2) Improved agreement is obtained if the calculation is made to treat geometric detail of the core construction as closely as possible. A form of synthesis of a three dimensional system using the two-dimensional form of CRAM is better than a simple cylindrical simulation of the experimental assembly.

(3) There is need to improve methods of dealing with resonance reactions such as $U^{238}(n,\gamma)$ either by better methods of calculation or by devising experiments more amenable to calculation.

(4) Although in this sample the agreement is good, the range of capture data for nickel which forms the inner reflector is wide and is worthy of study by more definite experiments.

4.2.2 Assembly 19A

Analysis of results is complete except for some re-scanning of the photo-plate exposures. Between 6 eV and 500 keV the spectrum measurements agree very well with a SWAN calculation using FD2R data. From 0.8 to 6 eV the measured fluxes are about 20% larger than those calculated and above 500 keV the measured fluxes are smaller than those calculated by an average amount of about 20%. The measured U^{238}/U^{235} fission cross section ratio is 15% smaller than the value derived from the SWAN calculation and supports the indication given by the spectrum measurements that the calculated spectrum is too hard. Present spectrum results indicate a U^{238}/U^{235} fission cross section ratio about 20% smaller than the calculated value, i.e. 5% smaller than the measured ratio.

The prompt neutron decay constants exhibit a linear variation with reactivity which passes through $\alpha = 2.65 \times 10^3\ s^{-1}$ at delayed critical. This agrees well with the value $2.52 \times 10^3\ s^{-1}$ given by the SWAN calculation. This degree of agreement with calculated decay constants is unusual and it is probably significant that this core is more homogeneous than all previous VERA cores. This result supports the conclusion from an earlier investigation on VERA 7A that a considerable part of the discrepancies between calculated and measured prompt neutron lifetime arises from the heterogeneity of the assemblies. The linear relationship of decay constant and reactivity extrapolates to $\alpha = 0$ at $\rho = 0.425\%$ above delayed critical, which is 1.30 times the calculated effective delayed neutron fraction. This type of discrepancy has been observed frequently and seems to confirm that a linear extrapolation to $\alpha = 0$ is not justified in many multi-zone assemblies.

4.3 Fast Neutron Spectrometry (P. W. Benjamin, W. Paterson, J. Reedfearn)

4.3.1 Development of Techniques

(a) Time of Flight Methods

Additional shielding around the detector in the extracted beam at 30 m has reduced the time-dependent neutron background in time of flight experiments to an acceptable level.

An investigation has shown that source and beam hole geometry have little effect on the extracted beam spectrum below 30 keV. No discernable difference was found between spectra in beams extracted parallel and perpendicular to the assembly flux gradients.

An integrated circuit digital sequence control unit has been built to control the timing of the accelerator and the detector system.

(b) Gas Counter Techniques

Tests on the reproducibility of the measured spectrum in the PANDA assembly 7A when different counters and fillings are used have shown that the maximum spread of the results from the mean is 3%.

The RIDL 400 channel analyser was found to have ~10% change in differential linearity from channel 15 to 400 with the largest error below channel 100. This can cause a large error (~20%) in the measured neutron spectrum. The LABEN analyser was found to have a much better (< 1%) differential linearity and is now being used for all gas counters spectrum work.

The head amplifier with reduced non-linearity on the output stage has been further developed and a number of new designs are being tested.

4.3.2 ARGUS Computer

The ARGUS 400 computer was delivered on the 10th April 1967. It worked satisfactorily on delivery and no serious faults have occurred.

A symbolic program assembly system called ASPAL has been written and has now been fully tested. This language greatly facilitates the optimum programming of the computer for real time data collection and analysis problems. AEE, Winfrith will be using ASPAL as the main language system for their ARGUS 400.

Several AWRE built peripheral items have been connected to the computer and it is now in use as a twin 1000 channel analyser and for reactor period measurements.

4.4 SCAMP (H. Goodfellow, R. C. Lane)

Mechanical completion of the rig has been delayed by functional difficulties with pumps, dump valves etc. which became apparent during water commissioning tests. The rig is almost complete but it is unlikely that second stage commissioning with concentrated nitric acid will commence before the end of June 1967.

The experimental program has been extended to include critical volume measurements at H/Pu ratios of about 660 and 1320. The attendant difficulties of bagging out and transporting very dilute solutions to Windscale will be avoided by incorporating a solution evaporator within the SCAMP rig. The evaporator is now installed and is ready for final testing.

A safety evaluation of the safety circuits and control instrumentation has been conducted by AHSB, Risley and their report is in preparation. The VERA and Criticality Facilities Safety Panel approved the experimental program, the addition of the solution evaporator and the proposed commissioning tests at their meeting on 30th March 1967.

GEM calculation of the k values for a variety of pyrex tube configurations in plutonium nitrate cylindrical cores have been performed. Some computer program difficulties still exist but progress is being made on the specification of an efficient heterogeneous poison arrangement as a basis for an experimental program with solid absorbers.

4.5 Development of High Current Accelerators as Neutron Sources

4.5.1 VERA Accelerator

Current tests with the modified ion source and injector lens have been completed. A maximum pulsed ion current of 40 mA was obtained from the accelerator tube and the purpose of the tests was to establish what proportion of this could be transmitted through strong focus lenses (one electro-magnetic and one electrostatic) to targets at the VERA and VIPER reactor positions. At the nearer VERA one, 30 mA was obtained, and 25 mA was obtained at the VIPER position. These currents are three times those available with the undeveloped arrangement and will provide a very significant reduction in time of flight data collection time.

Large ion currents reduce the life of the Von Ardenne ion source filaments to 2 to 3 hours and some development work is in hand with oxide coated filaments which are reported to be superior to metallic ones.

5. Mass Spectrometry and Atomic Physics (N. R. Daly)

5.2 High Sensitivity Gas Analysis Mass Spectrometer (N. J. Freeman, Miss N. L. Campbell)
(See 1.4.2)

5.2.1 (n,α) Cross Sections for Fe, Ni, Mo and Cr

The samples have been irradiated in DFR. The removal of the samples from the irradiation capsule has been delayed owing to the capsule activity. Techniques to measure the helium from the Mo and Cr samples are being developed.

Further samples of stainless steel for Dounreay and Culcheth have been analysed for helium content. Work is also being done on the analysis of helium and fission gas mixture in connection with the development of reactor fuel elements.

PAPERS PUBLISHED BY THE NUCLEAR RESEARCH DIVISION

1. P. Fieldhouse, E. R. Culliford and D. S. Mather: "Calibration of Aldermaston Spontaneous Fission Source". J. Nuclear Energy, 21, 131 (1967).

2. S. A. Cox and F. R. Pontet: "Measurement of the Li^6(n, absorption) and B^{10}(n, absorption) Cross Section by the Shell Transmission Method". J. Nuclear Energy, 21, 271 (1967).

18. E. E. Maslin, A. L. Rodgers and W. G. F. Core: "Prompt Neutron Emission from U^{235} Fission Fragments". AWRE Report No. 0-43/67.

20. A. McNair, F. Bannister, R. L. G. Keith and H. W. Wilson: "β Decay Energy from the Fission Products of U^{235}". EANDC(UK)78S.

21. A. McNair and R.L.G. Keith: "β Decay Energy from the Fission Products of Pu^{239}". EANDC(UK)82S.

U.K. Progress Report

The status of nuclear data work in the U.K. up to mid-1967 is summarised in the progress report (EANDC(UK)91 AL) circulated to members of INDC. Such progress reports should in future appear at six monthly intervals, and the next report is due shortly.

In the meantime more recent progress in a number of important specific measurements is listed briefly below. At AWRE work on the thermal fission cross sections of ^{233}U, ^{235}U and ^{239}Pu by Keith, McNair and Rodgers[1] has been prepared for publication and a new determination of the half life of ^{233}U has been made by Keith[2]. A joint AWRE, NPL remeasurement of the value of $\bar{\nu}$ for ^{252}Cf has also been reported[3]. At AERE a measurement has been completed by Uttley and Diment[4] of the total cross section of carbon from 100 eV to 10 MeV. This has been used as a standard for a measurement of the scattering cross section of ^{10}B (Asami and Moxon) from 1 to 80 keV[5]. This latter measurement has confirmed the deviation from a "1/v" shape of the reaction cross section of ^{10}B in this energy range as noted by Bergman and Shapiro[6], the constant term in the reaction cross section being -0.25 ± 0.12 b. Also on the subject of standard cross sections, a measurement of the ^{6}Li total cross section (Uttley and Diment) from 70 eV to 1 MeV has been completed[7] and a fit made to the cross section in terms of s- and p-wave components.

Average values of the fission cross section and alpha have been obtained for ^{239}Pu in the energy range 100 eV to 30 keV from high resolution fission and total cross section measurements[8] (Patrick, Sowerby and Schomberg) and work continues on the direct measurement of alpha for ^{239}Pu in the same energy range[9] (Schomberg and Sowerby). Measurements of elastic and inelastic scattering by ^{239}Pu have been completed to a neutron energy of 1.5 MeV[10] (Cavanagh, Coleman, Gard and Turner) and a new mass spectrometric measurement of the half life of ^{241}Pu has been carried out by Cabell[11].

(1) R. L. G. Keith, A. McNair and A. L. Rodgers, EANDC(UK)92 AL

(2) R. L. G. Keith, EANDC(UK)83 S

(3) P. H. White and E. J. Axton, EANDC(UK)87 AL to be published

(4) C. A. Uttley and K. M. Diment, EANDC(UK)94 AL

(5) A. Asami and M. C. Moxon, EANDC(UK)99 AL

(6) A. H. Bergman and F. L. Shapiro, JETP 40, 1270 (1961)

(7) C. A. Uttley and K. M. Diment - to be published

(8) B. H. Patrick, M. G. Sowerby and M. G. Schomberg, EANDC(UK)96 AL

(9) M. G. Schomberg, M. G. Sowerby and F. W. Evans, EANDC(UK)100 AL

(10) P. E. Cavanagh, J. F. Coleman, J. Gard and J. F. Turner, EANDC(UK)105 AL - to be published

(11) M. J. Cabell, EANDC(UK)104 AL