UNCLASSIFIED

UKNDC(71)P28
EANDC(UK)134A
INDC(UK)12/G

INDC-412

U.K. NUCLEAR DATA PROGRESS REPORT

Mid 1969 – Mid 1970

Editor: E. R. Rae

This document contains information of a preliminary or private nature and should be used with discretion. Its contents may not be quoted, abstracted, or transmitted to libraries without the explicit permission of the individual authors.

Nuclear Physics Division,
U.K.A.E.A. Research Group,
Atomic Energy Research Establishment,
HARWELL.

April 1971

HL 71/2044

IAEA
NUCLEAR DATA SECTION
MASTER COPY

PREFACE

This document is prepared at the request of the U.K. Nuclear Data Committee. It brings together progress reports on nuclear reactor data from AERE, AWRE and NPL. This issue contains in addition, for the first time, a contribution from the Kelvin Laboratory of the University of Glasgow.

CONTENTS

	Page No.
Nuclear Physics Division, A.E.R.E.	1
Analytical Sciences Division, A.E.R.E.	44
Chemistry Division, A.E.R.E.	46
Nuclear Research Division, A.W.R.E.	49
Radiation Science Division, N.P.L.	52
Kelvin Laboratory, University of Glasgow	54

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

(Division Head: Dr. B. Rose)

EDITORIAL NOTE

Since the results obtained from the various machines are not easily classified according to the energy of the charged beams, individual research items are labelled with a single letter indicating on which machine the experiments were performed. These labels are as follows:

Cockcroft Walton Generator (G. Dearnaley)	A
3 MV pulsed Van de Graaff Generator IBIS (A. T. G. Ferguson)	B
6 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 exist 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

E. Angular fluxes and energy spectra of neutrons from targets and shells of reactor materials (A. J. H. Goddard and J. G. Williams (Imperial College) and H. Lichtblau (University of Birmingham)

Following the measurements of hemisphere integrated leakage spectra from targets of natural uranium and lead[1], energy spectra of angular fluxes from these targets and from spherical shells of natural uranium surrounding them have been studied. Spectra have been normalised to hemisphere integrated target measurements with the complementary records of integrated target electron current and activation from ^{58}Co formed by (n,p) reactions in several small ^{58}Ni foils, symmetrically distributed over the target surface during irradiation. The experimental arrangements and methods used were essentially the same as those developed by Gayther and Goode[2] and Coates et al.[3].

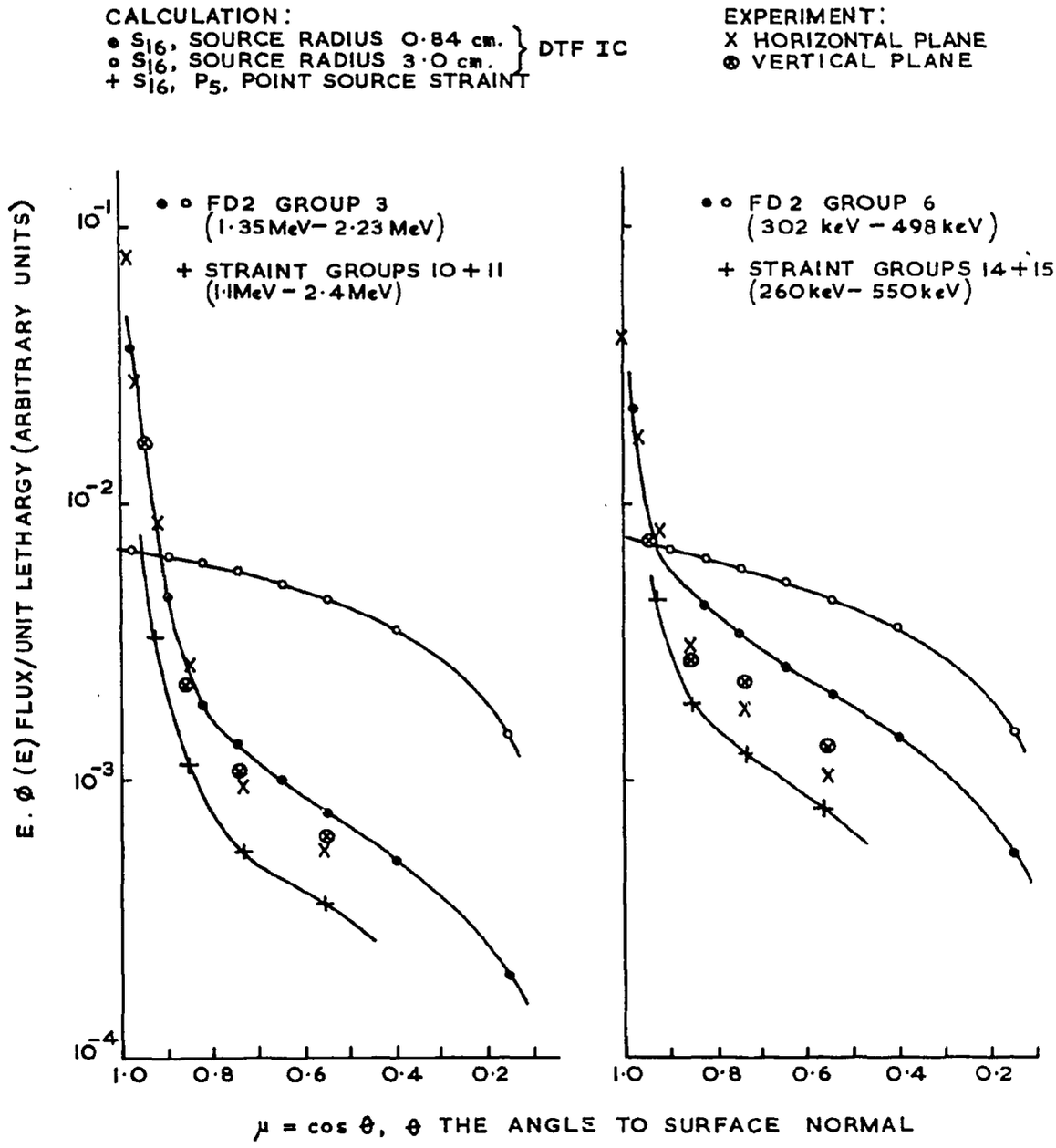


Fig. 1 Comparison between calculated target angular flux distributions and experiment.

Vector flux measurements of neutrons emerging at angles θ with the surface normal from the 3.0 cm radius target of natural uranium have been obtained. Neutrons from two sets of target surface elements, lying both in horizontal and in vertical planes, were observed. The measurements were compared with results of S_{16} calculations, based on the Imperial College version of the DTF IV transport code using FD 2 data and $S_{16}P_5$ calculations using STRAINT[4]. In Fig. 1 the results of STRAINT calculations for a point source and DTF IV calculations assuming uniform sources of radius 3 cm and 0.84 cm (i.e. 3 radiation lengths in ^{238}U) are shown together with experimental points for two ranges of neutron energy. While the point source and the smaller source give roughly equally good approximations on either side of the measured values, the extended source leads to considerably larger disagreement with experiment.

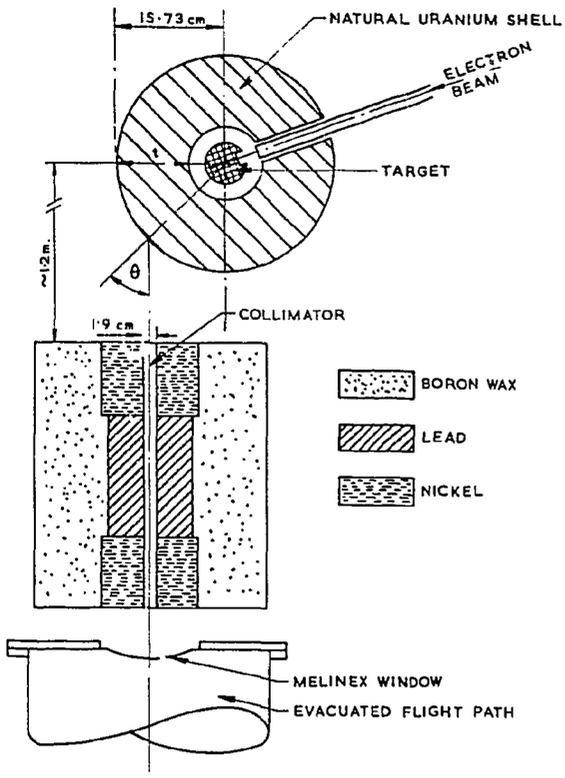


Fig. 2 Experimental arrangement for measuring neutron spectra from shells.

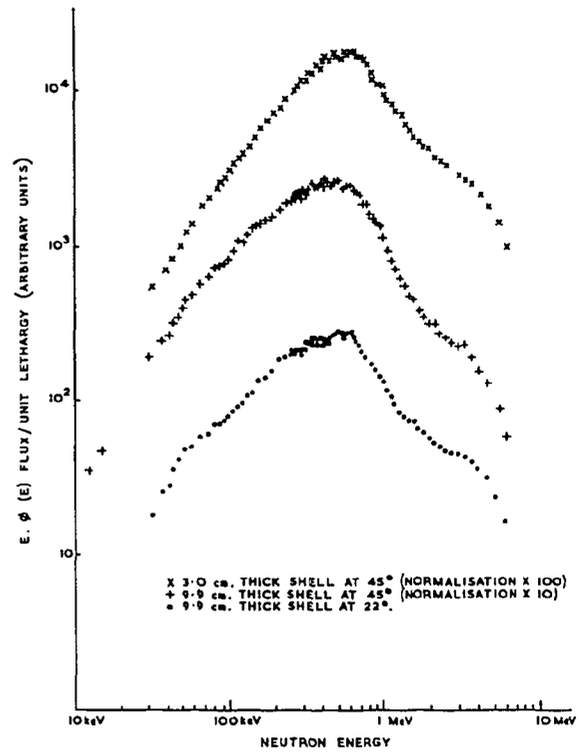


Fig. 3 Neutron spectra from natural uranium shell with 6.0 cm diameter uranium target.

Fig. 2 represents part of the experimental arrangement for the shell spectra measurements. Table I lists shell thicknesses t and angles θ between the normal to the surface element of shell "seen" by the neutron detectors and the direction of the flight path, at which spectra from natural uranium shells of outer radius 15.73 cm have been measured.

Normalised shell spectra measured under the conditions set out in Table I are shown in Figs. 3 and 4. The -45^0 measurement, which is not included in the figures, was made in order to check source symmetry and reproducibility compared with the $+45^0$ spectrum and found to agree with the latter within ±3% or within random errors, where these exceed ±3%, i.e. below 40 keV. Measurements extend to a low energy limit of 10 keV, but require corrections for room return in the range 10 keV - 40 keV. Spectra shown here do not include this part of the energy range. Calculations of these corrections are nearly complete.

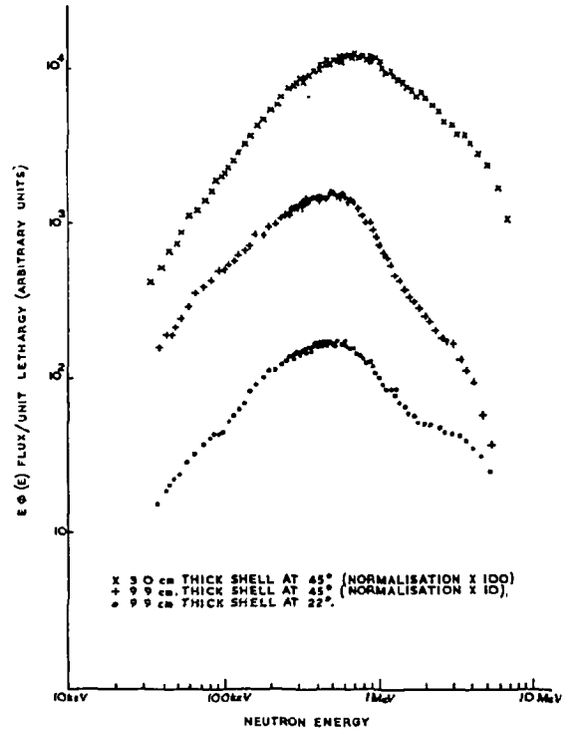


Fig. 4 Neutron spectra from natural uranium shell with 7.2 cm diameter lead target.

TABLE I

Conditions under which spectra of neutrons leaking from natural uranium shells of outer diameter 15.73 cm were measured

shell thickness t cm	angle between normal to surface element and flight path θ^{o}	target
3.0	45	U_{nat}, Pb
9.9	45	U_{nat}, Pb
9.9	42	U_{nat}, Pb
9.9	-45	U_{nat} only

Currently we are co-operating with E. D. Pendlebury of AWRE in making data adjustments from the experimental spectra by calculational techniques[5,6], based on the S_n transport code STRAINT[4]. Other adjustment schemes have been reported[7,8,9] but these have not been capable of dealing with angular fluxes. The work is still at an early stage.

(1) Goddard A. J. H., Williams J. G. and Lichtblau H. AERE - PR/NP 16, p. 1 (1969).

(2) Gayther D. B. and Goode P. D. J. Nucl. Energy 21, 733 (1967).

(3) Coates M. S., Gayther D. B. and Goode P. D. AERE - R 5364 (1968).

(4) Wade R. D. AWRE 0/12/63 (1963).

(5) Pendlebury E. D. Second Conf. on Neutron Cross sections and Technology, Washington March 1968, NBS Special Publication 299, Vol. 11, p. 1177.

(6) Ballance B. M. O., Pendlebury E. D., Price J. A. and West P. H. Proc. of Int. Conf. on the Physics of Fast Reactor Operation and Design, B.N.E.S. report, p. 149 (1969).

(7) Bitelli G., Cecchini G., Gandini A. and Salvatores M. Proc. of Int. Conf. on the Physics of Fast Reactor Operation and Design, B.N.E.S. report, p. 149 (1969).

(8) Barre J. Y., Heindler N., Lapacelle T. and Ravier J. Proc. of Int. Conf. on the Physics of Fast Reactor Operation and Design, B.N.E.S. report, p. 165 (1969).

(9) Rowland J. L. and Macdougall J. D. Proc. Int. Conf. on the Physics of Fast Reactor Operation and Design, B.N.E.S. report, p. 180 (1969).

E. A neutron detector with flat energy response for use in time-of-flight experiments (M. S. Coates and G. J. Hunt)

The spherical ^{10}B-Vaseline detector described earlier[1] has been constructed. Four 10.8 cm diameter, 5 cm thick Na-I crystals view the surface of the sphere to detect the 478 keV γ-rays produced in the $^{10}B(n,\alpha)^7Li^*,\gamma^7Li$ reaction. Table I gives a list of relevant detector parameters. Measurements have been made on the 300 m flight path of the neutron booster. A detailed description of the relevant booster construction has been given[2]. The only significant alteration is that the 2 cm thick water moderator and Al containers described in the reference have been replaced by 2.5 cm thick polyethylene slabs. The neutron beam was collimated at the booster end of the flight path so that the detector viewed a 12.5 cm diameter circle at the centre of the moderator face. A collimator of 90 cm borated resin and 20 cm Pb set ~3 metres from the detector limited the beam to fall within the diameter of the re-entrant hole. Alignment was checked by removing the insert from the centre hole (see Table I) and ensuring that the beam passed completely through without striking the remaining part of the detector. The detector was shielded with surrounding walls of 5 cm thick Pb inside 15 cm thick borated wax. The flight path had two breaks at 60 m and 120 m positions to allow measurements to be made on shorter flight paths. The six vacuum windows through which the neutron beam passed were each of 0.0125 cm thick Melinex. Air gaps in the flight path totalled ~10 metres. The response of the detector has been calculated using the GEM 4 Monte Carlo code on the IBM 7090 at Risley[3]. A detailed study was made of the γ-rays emerging from the five equal areas on the surface of the sphere defined in Fig. 1. With the NaI crystals viewing regions (2 + 3) the efficiency for neutron detection is expected to be flat to within 4%[1] over the energy range (100 eV → 700 keV). To test this prediction experimentally requires comparison measurements with detectors of accurately known response such as 1/v detectors at low energies and the Harwell long counter[4] at high energies. These measurements will be made in the near future. However, as a first test of the predicted response of the spherical detector, measurements have been made with the NaI crystals viewing two different regions of the sphere surface and the ratio of the responses as a function of neutron energy compared with the calculated ratio. The two regions measured were (2 + 3) and (3 + 4) of Fig. 1. Fig. 2 shows the calculated ratio together with the experimental results. In order to obtain better statistical accuracy the timing channel counts have been suitably grouped. Normalisation of the data to the calculated ratio was made at ~1 MeV. The accuracy at low energies is limited by background due to cosmic rays and it should be possible to reduce this in future measurements by anti-coincidence techniques. Time dependent background as determined using black resonance filters was insignificant.

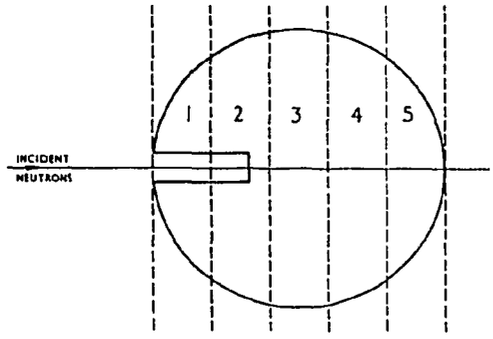


Fig. 1 Five equal areas on sphere surface. Areas defined by intersection with surface of equally spaced planes perpendicular to neutron beam direction.

The agreement between theory and experiment is encouraging. In the region above ~100 keV where the accuracy of the experimental points is $\lesssim \pm 2\%$, there is some indication of a small systematic discrepancy (<2% overall) with theory. Since, however, the points determing the theoretical curve have errors of 1-2% it is probably fair to conclude that theory and experiment agree within the respective errors. This work was reported in detail in paper CN-26/35 presented at the IAEA Conference on Nuclear Data for Reactors, Helsinki (June, 1970).

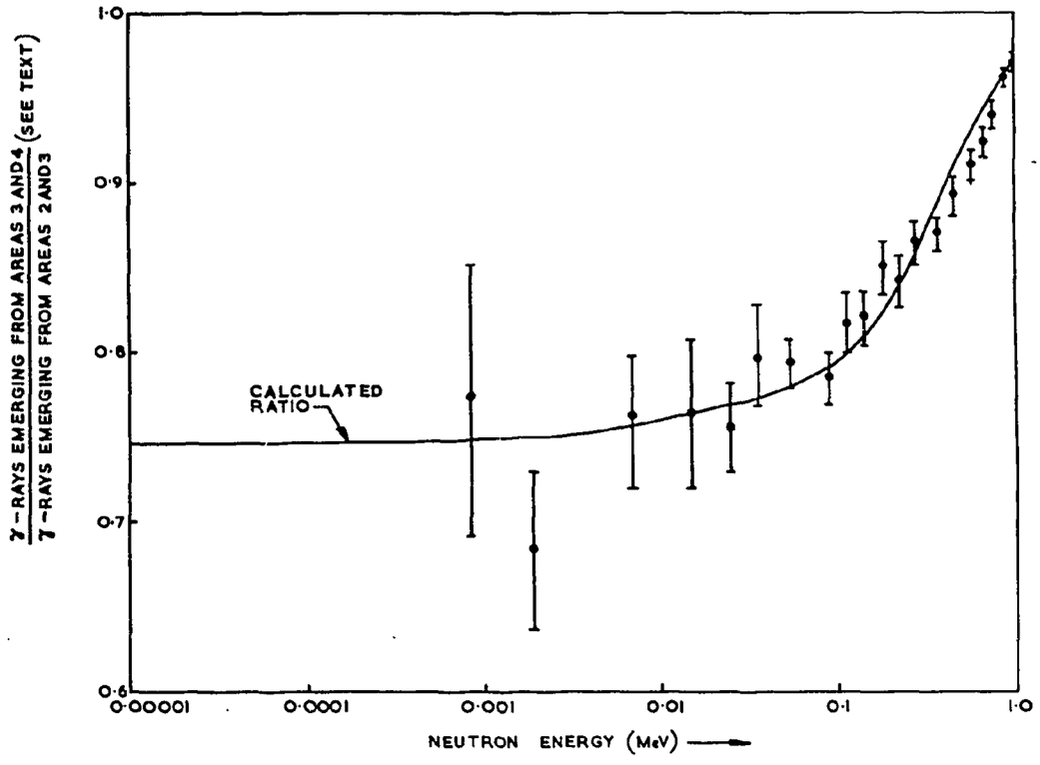


Fig. 2 Calculated and experimental ratio of detector response under different operating conditions.

TABLE I

Experimental Detector Parameters

Sphere radius	:	12 cm nominal
Re-entrant hole depth	:	8 cm nominal
Re-entrant hole diameter	:	2.5 cm nominal
Containment shell	:	Aluminium 0.175 cm thick
*Boron content	:	1059 gms powder (nominally 90% pure B) with 90% ^{10}B content. Impurities C(2%), Fe(0.7%), Ni(0.3%), Si(2.4%), O_2(1%), Cr+Al+Co+Cu(1.0%)
Vaseline content	:	5389 gms
NaI crystals	:	Four crystals symmetrically placed about the neutron beam direction and essentially in contact with the sphere surface. Each crystal 10.8 cm diameter and 5 cm thick.

Comments — The re-entrant hole is formed by having a thin walled (0.0125 cm) stainless steel tube crossing the sphere on a diameter and inserting into this a cylinder of ^{10}B-Vaseline contained in aluminium 0.025 cm thick. The NaI crystals have lead collars 2.5 cm thick, to ensure that they detect only γ-rays from the required area on the sphere surface.

*The isotopic content and the presence of impurities were included in the calculations.

---

(1) Coates M. S. and Hart W. Nuclear Physics Division Progress Report AERE - PR/NP 16, p. 2 (1969).

(2) Coates M. S. and Tripp D. J. Nuclear Physics Division Progress Report AERE - PR/NP 7, p. 12 (1964).

(3) Coates M. S and Hart W. Nuclear Physics Division Progress Report AERE - PR/NP 15, p. 1 (1968).

(4) Adams J. M., Ferguson A. T. G. and McKenzie C. D. Nuclear Physics Division Progress Report AERE - PR/NP 14, p. 16 (1967).

E. Capture measurements with a large liquid scintillation counter (M. S. Coates and M. C. Moxon)

Experiments have been carried out on the 270 litre, 76 cm diameter liquid scintillation tank[1] set up on a 100 m flight path of the neutron booster to determine its suitability as a capture detector up to high (~1 MeV) neutron energies. Background has been considerably suppressed by replacing the liquid scintillator used for the first trials with NE 211 containing 10% of methyl borate and lining the central stainless steel tube through which the neutron beam passes with ^{10}B and polyethylene layers. The counts to background at the 1 keV capture resonance in Fe, observed in a channel accepting pulses due to γ-rays in the energy range 3 MeV → 11 MeV, was improved by a factor of 100 to 15/1. (The detector was unshielded apart from the 2 ft thick concrete walls of the containment cell). Background up to 1 MeV neutron energy was low enough to distinguish on the time-of-flight distributions obtained with a Ni sample in the beam much of the structure observed by Block et al.[2] on the large liquid scintillator at Rensselaer Polytechnic Institute. Further measurements however, using resonance filters and a carbon scattering sample, showed that part of the structure observed by us was due to scattered neutrons being promptly captured in the stainless steel of the central tube, making accurate (±10%) measurement of capture cross sections in the few millibarns range impossible until the tube has been replaced with one of lower capture cross section. This will be done as a next step, probably using a borated resin sleeve with a thin Al coating to prevent contamination of the scintillation liquid.

(1) Colvin D. W. and Bowen P. H. Nuclear Physics Division Progress Report AERE - PR/NP 15, p. 5 (1967).

(2) Block R. C., Hockenbury R. W., Bartolome Z. and Fulwood R. R. IAEA Conf. on Nuclear Data for Reactors Vol. 1, p. 565 (Paris) (1966).

E. Neutron capture cross-section measurements (M. C. Moxon, P. Riehs (Seibersdorf) J. E. Jolly and M. B. Hughes)

(a) Energy range 5 eV to 100 keV

Capture measurements on several samples of V and Ni have been completed in the neutron energy range from 5 eV to 100 keV using the capture detector at the 32 metre station on the 'booster' target of the Harwell 45 MeV linear accelerator. The data are in the process of being analysed and preliminary indications are that the radiation widths for the first three s-wave resonances in vanadium lie between 1 and 3 eV. In the case of nickel, the presence of several isotopes complicates the analysis and correction of the data for self-screening and multiple scattering, but the use of several sample thicknesses may enable us to approach the true capture cross section and obtain some idea of the resonance parameters.

Peter Riehs, on a short visit from Austria in March and April of this year, brought with him samples of the erbium isotopes which were on loan to the A.A.E.C. from the U.S.A.E.C. During the period he was at Harwell, capture measurements were carried out on all the samples and the data are now being reduced to capture yield and it is hoped to obtain resonance parameters and average capture cross-sections from the data as well as isotopic allocation of many of the resonances.

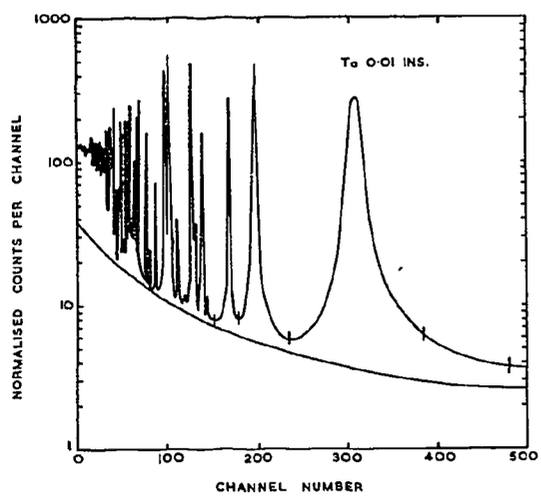


Fig. 1 Counts from a Moxon-Rae detector using a 0.01 in thick tantalum sample.

(b) Energy range 0.01 eV to 1 keV

A 'Moxon-Rae' capture detector has recently been set up at 4.5 m from a natural uranium target in Cell III of the linac. This is primarily to measure capture cross sections in the energy range from 0.1 eV to 100 eV. The high signal to background (~100/1 at 5 eV (see Fig. 1)) will enable us to measure capture yields, i.e. $n\sigma_\gamma$, as low as 0.01 with reasonable accuracy. In two sessions each lasting about two days capture measurements were carried out on samples of U, Au, Ta, Ag, Rh, Fe and the erbium isotopes. The high count rate obtained from some of the samples required the use of the time-of-flight analyser, developed by D. V. Morris (see contribution to this report by Boyce et al.) which feeds the information directly into the PDP-4 computer and can handle count rates as high as 100,000 counts per second during the counting period.

E. The direct measurement of alpha for ^{239}Pu (M. G. Schomberg, M. G. Sowerby, D. A. Boyce, K. J. Murray and D. L. Sutton)

The experiment[1] to measure the ratio of the capture and fission cross sections (α) for ^{239}Pu in the energy range 100 eV to 30 keV has been completed. The final results, which are shown in Fig. 1, are presented in a paper with the following abstract submitted to the Helsinki Conference on Nuclear Data for Reactors.

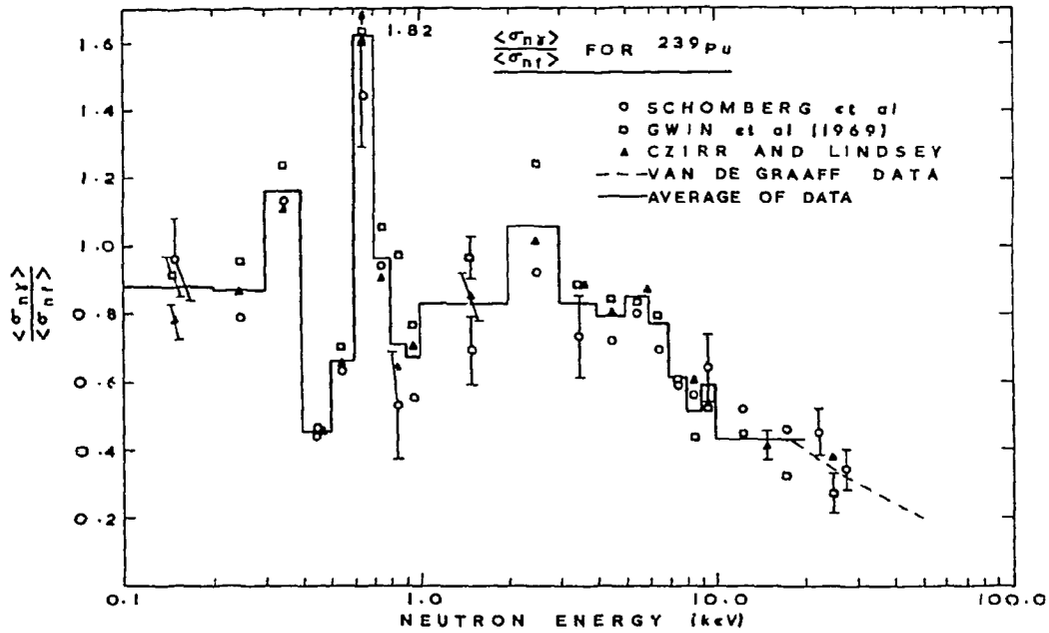


Fig. 1 Energy variation of α for ^{239}Pu.

"The ratio of the capture to fission cross sections (alpha) of ^{239}Pu in the energy range 100 eV to 30 keV has been measured using the Harwell 45 MeV Linear Accelerator time-of-flight spectrometer. The method used has been described by Schomberg et al. in Fast Reactor Physics 1, 289 (1968) together with provisional results. In this paper the final results are presented and compared with the other available data. Most experiments to measure alpha in this energy range are normalised to the values of alpha at the peaks of the low energy resonances. It was recognised at the meeting of specialists organised by the International Working Group on Fast Reactors in July 1969 that some of the discrepancies between the various experiments were due to differences in the values used for normalisation. It was therefore recommended that a best set of normalisation values should be obtained and that, for comparison purposes, all experiments should be normalised to these. An evaluation to produce a best set has been performed and the results are discussed in this paper".

(1) Schomberg M. G., Sowerby M. G., Boyce D. A., Murray K. J. and Sutton D. L. AERE - PR/NP 16, p. 14 (1969).

B. Prompt fission neutron spectra from Uranium and Plutonium (J. M. Adams and J. L. Rose Borough Polytechnic)

Following the work of Barnard[1], preliminary experiments have been initiated for a further study of the prompt fission neutron spectra with particular attention to the higher secondary neutron energies where the previous results are inaccurate due to interference from gamma rays.

An improved neutron detection system, consisting of an NE213 liquid scintillator† (bubble free encapsulation) coupled to a 2 in. diameter low noise photomultiplier‡, has been developed for use with a stabilised version of the Harwell pulse shape discrimination system. With this system, neutron-gamma discrimination is still effective at neutron energies of less than 50 keV, which is well below the lowest neutron energy of interest.

Using IBIS, the Harwell 3 MeV pulsed Van de Graaff, two complementary methods are being employed in order to calibrate the relative neutron efficiency of the detector as a function of neutron energy. One method relies on knowledge of the relative angular distributions of the standard neutron producing reactions (e.g. $^{7}Li(p,n)^{7}Be$, $T(p,n)^{3}He$, $^{9}Be(\alpha,n)^{12}C$ and $T(d,n)^{4}He$) while the other method depends on the well known hydrogen cross-section. The latter method involves scattering neutrons from a suitable hydrogenous material (e.g. polythene) and using the resulting observed angular distributions to determine the relative detection efficiency. A Monte-Carlo programme (Maggie)(3) will be used to correct for multiple scattering events in the scattering sample. The resultant neutron efficiency calibration will be compared with the results from another Monte-Carlo programme, (Lucifer)(4), which calculates the theoretical neutron detection efficiency of hydrogenous scintillators.

Preliminary results have indicated that the hydrogen scattering method will work from 300 keV to 6 MeV; at high energies, where the backgrounds involved are unpredictable due to the lower hydrogen scattering cross section, further work has to be done to establish the feasability of this approach.

Work has also been started on building a Xenon gas scintillator fission chamber based on the work of Sayers(5). This, it is hoped, will replace the short-lived solid state fission detectors now in use and allow for higher counting rates in fission experiments.

---

†Supplied by Nuclear Enterprises (G.B.) Ltd.

‡Type C3100D supplied by RCA.

---

(1) Barnard E., Ferguson A. T. G., McMurray W. R. and Van Heerden I. J. Nuclear Physics, 71, 228 (1965).

(3) Parker J. B., Towle J. H., Sims D. and James P. G. Nuc. Instr. & Methods 14, 1 (1961).

(4) Batchelor R., Gilboy W. B., Parker J. B. and Towle J. H. Nuc. Instr. & Methods, 13, 76 (1961).

(5) Sayers A. and Wu C. S. Rev. Sci. Inst., 28, 758 (1957).

E. Study of γ-rays emitted following neutron resonance capture in ^{240}Pu, ^{238}U and ^{103}Rh
(M. S. Coates and M. C. Moxon)

Experimental evidence has recently been reported by Nisle and Stepan(1) for the existence of a short lived component in the decay rate of ^{241}Pu as deduced from reactivity measurements. A possible explanation is the existence of a shape isomer in ^{241}Pu, and, in the hope of observing evidence for this, measurements have been made of the pulse height spectra produced by γ-rays emitted in the $^{240}Pu(n,\gamma)$ reaction. The presence of a shape isomer might be expected to give rise to two distinct energy groups in the distribution, corresponding to transitions in the first and second minima respectively of the double humped energy vs. nuclear deformation curve. Two NaI scintillation counters* each with crystals 15 cm diameter and 10 cm thick were set up on a 14 m flight path of the neutron

---

*We are grateful to Mr. D. Newton of Health Physics and Medical Division for the loan of these counters.

booster. The counters were operated in coincidence each with a bias setting of 250 keV. A time gate allowed the system to detect γ-rays emitted following neutron capture in the large resonance in ^{240}Pu at 1.05 eV. The plutonium oxide sample (99.28% ^{240}Pu of Pu content), 2.5 cm diameter, 118 mg weight, was placed between the two counters which lay outside the neutron beam. Pulse height distributions were recorded on a 100 channel analyser. For comparison purposes similar measurements were made with a ^{238}U sample at the 6.67 eV and 36.7 eV resonances and with a ^{103}Rh sample at the 1.1 eV resonance. No shape isomerism effect is expected in these nuclei. The spectra are shown in Fig. 1 normalised on the energy axis to the binding energy of ^{104}Rh and to equal area under the respective curves. The presence of a shape isomer in ^{241}Pu would show as a marked discontinuity in the pulse height distribution near 2-3 MeV (near channel No. 50). There is no evidence of this.

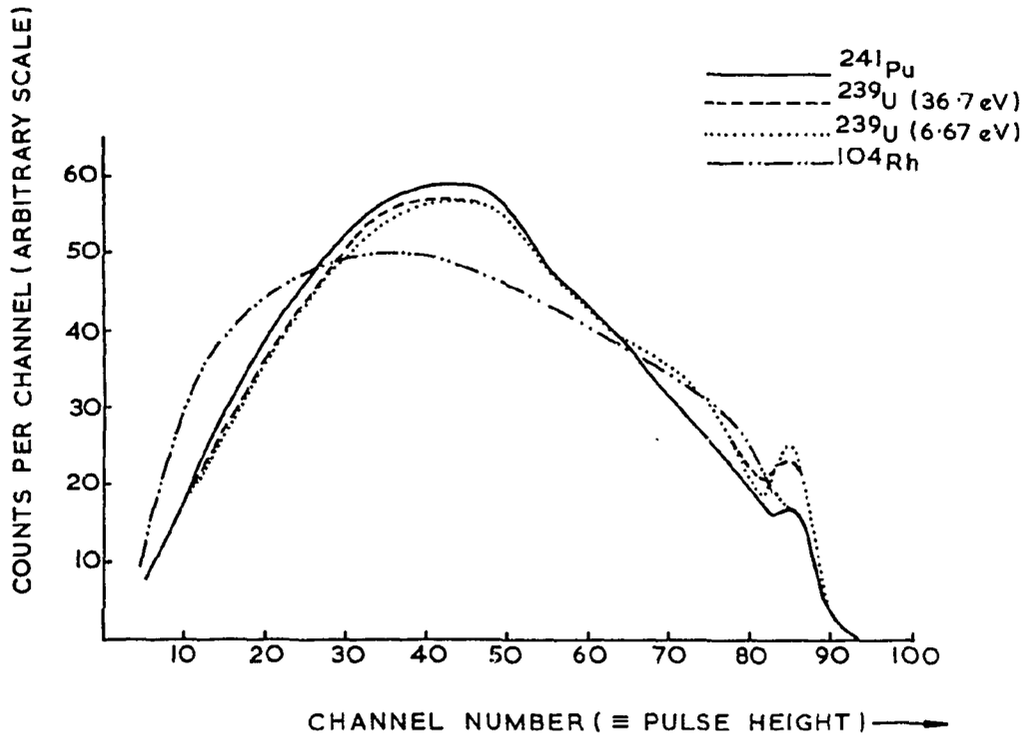


Fig. 1 Normalised γ-ray pulse height distributions.

It is interesting that the ^{241}Pu spectrum is significantly different from that of ^{239}U despite the similarity of their level schemes. The strong transitions near the binding energy in ^{239}U appear to be absent in ^{241}Pu. The measurements show the reduced strength of these transitions for the 36 eV resonance in ^{239}U compared to that for the 6.7 eV resonance. Qualitatively this agrees with the high resolution measurements of Thomas et al.[2] using a Ge-Li detector.

In addition to the pulse height distribution measurements an attempt was made to measure the multiplicity of the γ-rays in the cascade following capture. It is easily shown[3] that the mean value $\bar{\nu}$ of the multiplicity is given from $c/\bar{s} = k(\bar{\nu} - 1)$ where c is the coincidence count rate in the two NaI detectors, $\bar{s}$ is the mean single count rate and k is a constant whose value is in principle dependent on γ-ray energy. In practice k turns out to be insensitive to γ-ray energy over the region of interest. Its value is determined by using γ-ray sources whose multiplicity is known to be 2 (e.g. ^{60}Co and ^{24}Na). The object of the multiplicity measurements was to see if that in ^{241}Pu was anomalously high. This would indicate the possibility of a conventional isomeric state with a very high spin value, since a large

number of γ-ray transitions is needed to arrive at such a state. The existence of this state at a suitable energy level could give an alternative explanation for the Nisle and Stepan reactivity measurement. No anomaly was observed however in the ^{241}Pu multiplicity determination. The mean multiplicity values were:

^{241}Pu	(1.05 eV resonance)	=	2.80 ± 0.14
^{239}U	(6.67 eV resonance)	=	3.00 ± 0.15
^{104}Rh	(1.1 eV resonance)	=	3.20 ± 0.16

An isomeric state with a half life ~ μsecs is known to exist[4] at 134 keV in ^{239}U. No anomalously high multiplicity in the γ cascade following neutron capture in ^{238}U is expected in this case since the spin difference between the isomeric state and the ground state is only ~2.

---

(1) Nisle R. S. and Stepan I. E. Nuc. Sci. and Eng. 39, 257 (1970).

(2) Thomas B. W., Uttley C. A. and Rae E. R. Nuclear Physics Division Progress Report AERE - PR/NP 14, p. 23 (1968).

(3) Muehlhause C. O. Phys. Rev. 79, 277 (1950).

(4) Thomas B. W., Murray J. and Rae E. R. This report, p. 19.

B. The production of spontaneously fissioning isomers in the (n,γ) reaction on targets of ^{233}U, ^{234}U, ^{235}U, ^{238}U, and ^{239}Pu (A. J. Elwyn* and A. T. G. Ferguson)

Spontaneous fission with an anomalously short half-life was first reported[1] in 1962. Subsequent experiments[2,3] established that the observed activity (14 ms) was associated with an isomeric state in ^{242}Am having relatively low spin and relatively high excitation energy (~3 MeV), but yet no observable γ- or α-decaying branch. Further studies[4,5] have since revealed the existence of short-lived spontaneously fissioning isomers in other isotopes. Calculations by Strutinsky[6] and others[7] suggest that the potential-energy surface along the fission degree of freedom has two maxima separated by a secondary minimum at a value of prolate deformation larger than that of the ground state. The spontaneously fissioning isomeric states are thought to be formed in this second minimum. The present report describes the results of a search for short-lived spontaneously fissioning isomers formed in neutron-induced reactions. Production cross sections, isomer ratios and half-lives determined in such measurements supplement, with perhaps less ambiguity, the results based on some charged-particle-induced measurements.

The current experiments were carried out using IBIS at a neutron energy of 2.2 MeV. A preliminary search at 0.55 MeV was also made. The fissile samples were separated isotopes of U and ^{239}Pu. The time distribution of fission fragments detected by a surface barrier detector was measured relative to the time of arrival of a burst of protons at the target. A typical time distribution for a target of ^{239}Pu is shown in Fig. 1 in which the intense peak is the "prompt" fission while the tail is attributed to the weakly excited isomeric branch. A numerical analysis of the tail indicated the presence of two half lives and gave their intensity relative to prompt fission. The results obtained are summarized in Table I. The isomeric half lives, together with data on spontaneous fission from the ground state, enable one to set limits on the excitation energies of the isomeric states. The results of such estimates are shown in Table II. These estimates are consistent with those derived by other methods.

---

*On leave from Argonne National Laboratory.

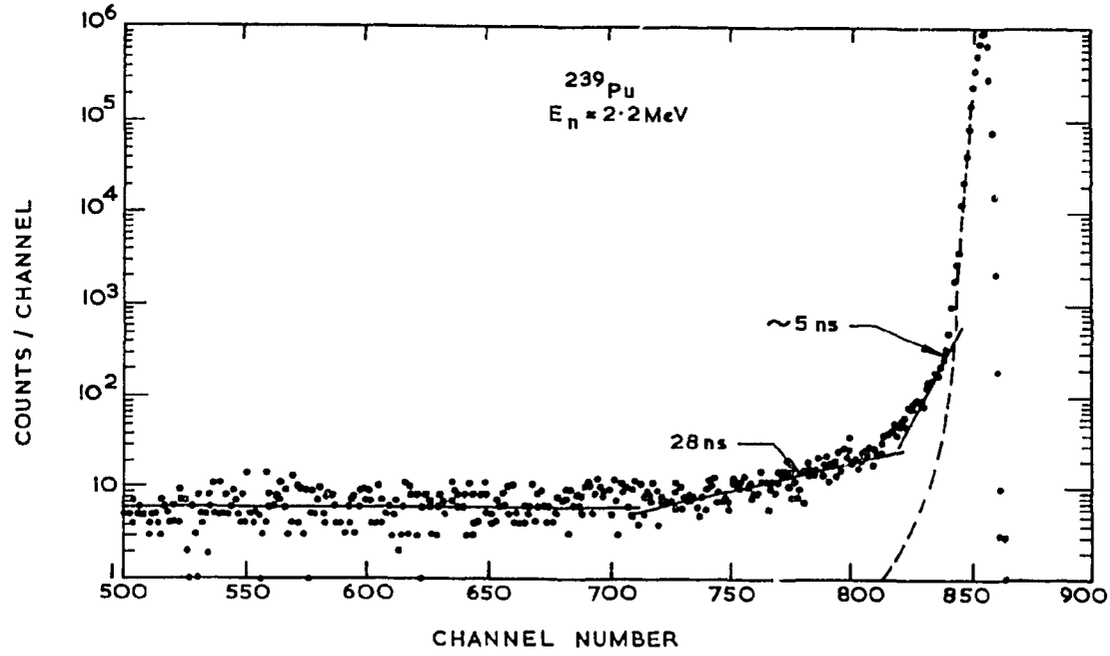


Fig. 1 Time distribution of fission fragments from a ^{239}Pu target.

TABLE I

Experimental results

Energy (MeV)	Target nucleus	Final nucleus	$\tau_{1/2}$ ($\times 10^{-9}$ sec)	$R^{a)} = \frac{\text{delayed}}{\text{prompt}}$ ($\times 10^{-4}$)	σ(delayed)$^{a,b)}$ ($\times 10^{-27}$ cm^2)
2.2	^{239}Pu	^{240}Pu	29.0 ± 3.8	4.1	0.82
			4.1 – 5.2	39	7.8
	^{233}U	^{234}U	30.4 ± 4.9	4.7	0.96
	^{234}U	^{235}U	19.7 ± 4.9	1.2	0.18
	^{235}U	^{236}U	66.6 ± 8.7	3.1	0.4
	^{238}U	^{239}U	No lifetime observed		
0.55	^{233}U	^{234}U	34.9 ± 4.5	7.4	1.5

a) Error about ± 50%.

b) Calculated from the ratios R and the neutron induced fission cross sections.

TABLE II

Excitation energies of isomeric states

Final nucleus	$\tau_{1/2}$ ($\times 10^{-9}$ sec)	E_i (upper limit) (MeV)	E_i a) (MeV)
^{234}U	30.4 ± 4.9	2.97	
^{235}U	19.7 ± 4.9	3.32	2.7
^{236}U	66.6 ± 8.7	2.96	>2.6
^{240}Pu	29.0 ± 3.8	2.44	
	4.1 – 5.2	2.64	2.3 – 2.4

a) Results based on other fission experiments. See ref. [10]

The cross section for isomer production is sensitive to the spin and excitation of the isomeric state as well as to the heights of the outer and intermediate barriers. Current work is aimed at exploring more fully the variation of cross sections with neutron energy.

(1) Polikanov S. M., Druin V. A., Karnaukhov V. A., Mikheev V. L., Pleve A. A., Skovelev N. K., Subbotin V. G., Ter-Akop'yan G. M. and Fomichev V. A. Zh. Eksperim. i Teor, Fiz. 42, 1464 (1962) (English transl.: Sov. Phys. – JETP 15,1016 (1962)).

(2) Polikanov S. M. Usp. Fiz. Nauk 94 (1968) 43 (English transl.: Sov. Phys. – Usp. 11, (1968) 22); Flerov G. N., Pleve A. A., Polikanov S. M., Tretyakova S. P., Martalogu N., Poenaru D., Sezon M., Vilcov I. and Vilcov N. Nucl. Phys. A97, 444 (1967); Flerov G. N., Gangrskii Yu. P., Markov B. N., Pleve A. A., Polikanov S. M. and Yungklaussen Kh. Yad. Fiz. 6, 17 (1967) (English transl.: Soviet J. Nucl. Phys. 6,12 (1967); Flerov G. N., Ivanov E., Martalogue N., Pleve A. A., Polikanov S. M., Poenaru D. and Vilcov N. Revue Roumaine Phys. 10,217 (1965).

(3) Flerov G. N., Pleve A. A., Polikanov S. M., Tretyakova S. P., Boca I., Sezon M., Vilcov I. and Vilcov N. Nucl. Phys. A102,443 (1967); Boca I., Martalogue N., Sezon M., Vilcov I., Vilcov N., Flerov G. N., Pleve A. A., Polikanov S. M. and Tretyakov S. P. Rev. Roumaine Phys. 13, 181 (1968).

(4) Borggreen J., Gangrskii Y. P., Sletten G. and Bjørnholm S. Phys. Letters 25B, 402 (1967); Bjørnholm S., Borggreen J., Westgaard L. and Karnaukhov V. A. Nucl. Phys. A95, 513 (1967); Boca I., Martalogu N., Sezon M., Vilcov I., Vilcov N., Flerov G. N., Pleve A. A., Polikanov S. M. and Tretyakova S. P. Nucl. Phys. A134, 541 (1969).

(5) Lark N., Sletten G. and Bjørnholm S. Nuclear Structure: Dubna Symposium 1968 (IAEA, Vienna, 1968); Lark N., Sletten G., Pedersen J. and Bjørnholm S. Nucl. Phys. (to be published).

(6) Strutinsky V. M. Nucl. Phys. A95,420 (1967); A122, 1 (1968).

(7) Nilsson S. G., Nix J. R., Sobiczewski A., Szymanski Z., Wycech S., Gustafson C. and Möller P. Nucl. Phys. A115, 545 (1968); Nilsson S. G., Tsang C. F., Sobiczewski A., Szymanski, Z., Wycech S., Gustafson C., Lamm J. L., Möller P. and Nilsson B. Nucl. Phys. A131, 1 (1969).

(8) Vandenbosch R. and Wolf K. L. 2nd. IAEA Symposium on Physics and Chemistry of Fission, Vienna 1969.

(9) Metag V., Repnow R., von Brentano P. and Fox J. D. Z. Physik 226, 1 (1969); Metag V., Repnow R., von Brentano P. and Fox J. D. ref. 8.

(10) Lynn J. E. 2nd IAEA Symposium on Physics and Chemistry of Fission, Vienna 1969.

B. Inelastic neutron scattering from ^{238}U (B. H. Armitage and W. Spencer)

Work has begun on the measurement of inelastic neutron scattering from ^{238}U using time-of-flight techniques. This work is intended to complement the measurements already made in this laboratory[1] over the neutron energy range 0.07 to 1.6 MeV, and measurements made at AWRE at higher primary neutron energies[2]. The availability of low noise RCA C3100D photomultipliers enables neutrons to be detected to below 50 keV without having recourse to a twin-photomultiplier system[3]. The pulse shape discrimination system is being used to suppress the gamma-ray background, and so far the emphasis of the work has been on the achievement of an optimum geometry for the minimization of the neutron background in the time spectrum.

(1) Barnard E., Ferguson A. T. G., McMurray W. R. and Van Heerden I. J. Nucl. Phys. 80, 46 (1966).

(2) Batchelor R., Gilboy W. B. and Towle J. H. Nucl. Phys. 65, 236 (1965).

(3) Adams J. H. et al. Nucl. Instr. and Meth. 34, 21 (1965).

Evaluation of the fast neutron cross sections of ^{238}U: some theoretical considerations (J. E. Lynn)

Certain basic data on the microstructure of the ^{238}U cross sections have been obtained from studies in the resonance and kilovolt region; these are essentially the s-wave neutron strength function, the $J^{\pi} = {}^{1}/_{2}{}^{+}$ resonance spacing, the total radiation width of the same ${}^{1}/_{2}{}^{+}$ levels, and the p-wave neutron strength function. It is common to use such data together with information of the low-lying levels of the target nucleus, to calculate neutron cross sections to considerably higher energies (~1 MeV), and it may be thought that such calculations may be a useful guide in selecting the most reliable of divergent data when evaluating neutron cross sections.

To some extent this is true, but it is important to be aware of all the factors that may affect the theoretical calculation, and of the uncertainties in the theoretical concepts. A typical set of calculated cross sections and data are shown in Figs. 1(a) and (b). In these it has been assumed that all the odd neutron orbital angular momentum waves have strength-functions equal to the measured p-wave value below 100 keV, and that the even waves have the s-wave strength-function value. The radiation width of all compound nucleus states is assumed independent of total angular momentum and parity but the energy dependence is given by Fig. 2 while the level density variation is given by the formula $p \propto \exp\sqrt{[125(U(\text{in MeV}) - 0.7)]}$. The radiative capture cross section as calculated agrees remarkably well with what a recent evaluator considers to be the best data, but in fact the radiation width behaviour shown in Fig. 2 is a rather special one in which the radiation mechanism rather strongly favours high energy transitions (of about 3 MeV in energy). The usual type of statistical model gives a radiation width behaviour similar to that shown in Fig. 3 and this would give a much increased capture cross section towards the higher energies in Fig. 1a. However, recent basic studies on neutron resonance capture spectra are beginning to demonstrate non-statistical features and encourage us to believe that behaviour something like Fig. 2 may be realistic.

As far as the calculation of inelastic scattering is concerned, there are two extreme alternative assumptions to be considered even after the basic strength-function data are adopted. The usual assumption is that there is no correlation from resonance to resonance between elastic and inelastic scattering widths. If this assumption is abandoned in favour of full correlation the calculated cross section is increased as shown in Fig. 1b. The possibility that the second assumption may in fact be the correct one is implied by the coupling of single particle and rotational properties through the rotating deformed nuclear field as in the coupled-channel optical model. This coupling first creates special

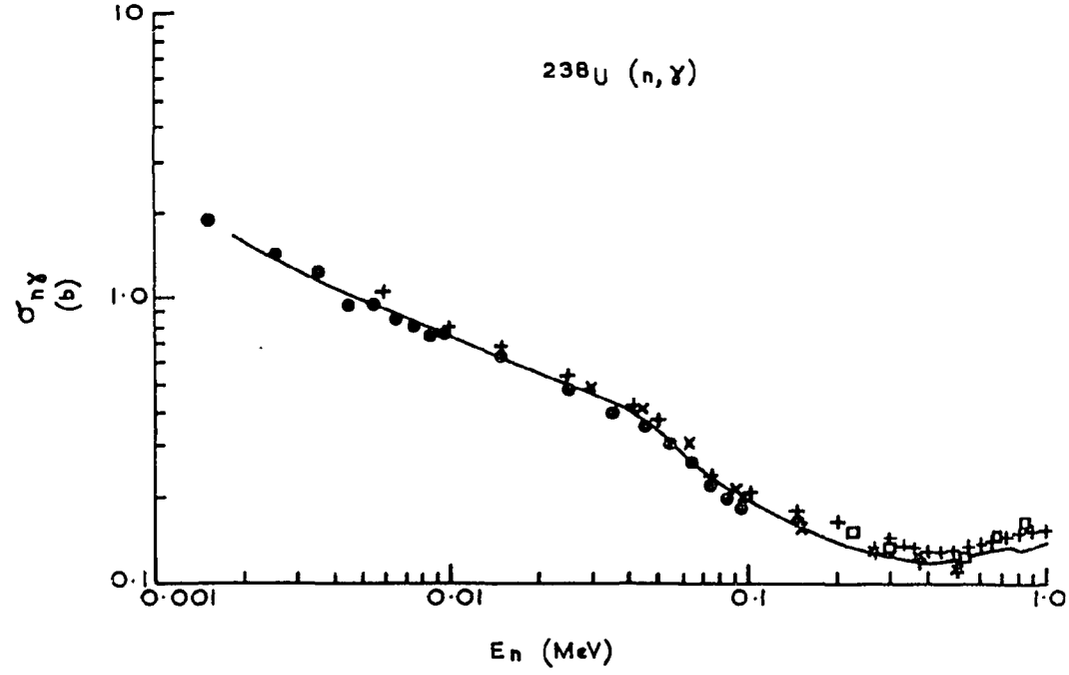


Fig. 1(a) The calculated capture cross section of ^{238}U compared with some measured (•, x) and evaluated (+) data.

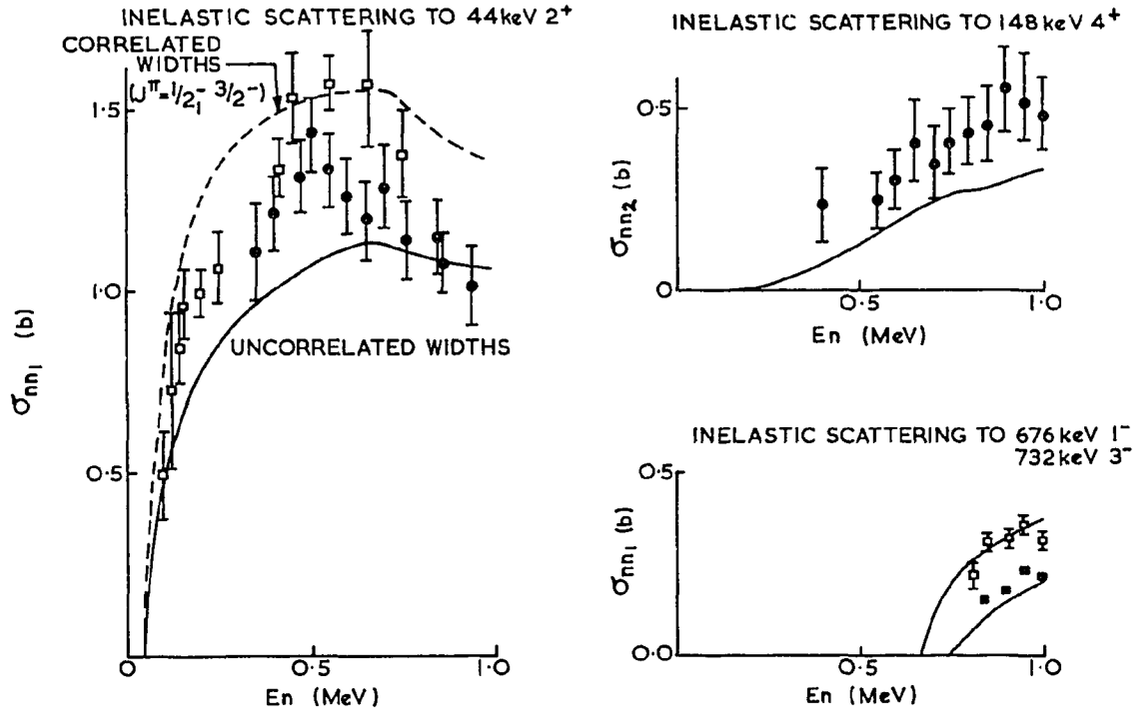


Fig. 1(b) Calculated neutron inelastic scattering cross section to some low lying states in ^{238}U.

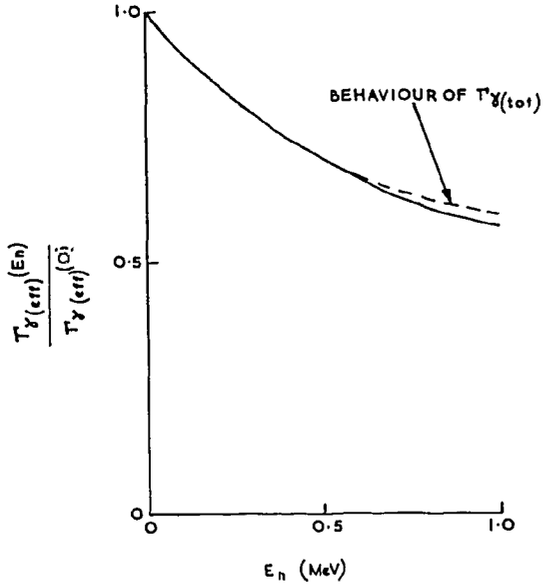


Fig. 2 Calculated radiative capture width behaviour of $^{238}U + n$ based on a shell model level density law.

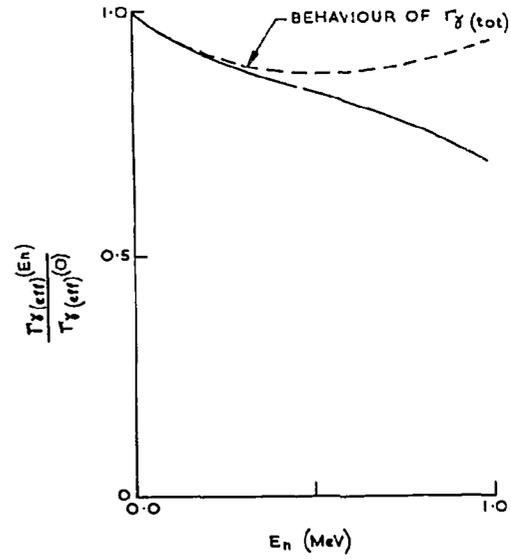


Fig. 3 Calculated radiative capture width behaviour of $^{238}U + n$ based on the statistical model.

states that are mixtures of a 1p (single particle) state in a non-rotating nucleus, a 1p state in a nucleus rotating in a 2^+ state, etc. The first component corresponds to elastic scattering, the second to inelastic scattering to the 2^+ rotational state and so on. These special states are then mixed (by the residual particle-particle forces) into the fine-structure states of the cross section. If the mixing is rather less than the spacing between special states the ratio of reduced widths in the special state is carried over into the nearby fine structure states i.e. correlation of these reduced widths in the resonances occurs. If the fine-structure states receive appreciable admixtures from more than one special state this correlation is obliterated. The contribution of direct inelastic scattering to the cross section is also greatly affected by the degree of spreading of the special states. Until we understand the role of these special modes better we cannot estimate cross sections by nuclear theory (even starting with some of the basic parameters) to better than 20% or even possibly 50%.

A more complete account of this work is being written for the IAEA Helsinki Conference on Nuclear Data for Reactors[1].

(1) Lynn J. E. IAEA Conference on Nuclear Data for Reactors, p. CN-26/105, Helsinki, 15-19 June 1970.

B. Effective neutron penetration depth into the standard Harwell long counter (J. M. Adams)

Measurements have been carried out in order to determine the effective depth, R_0, to which neutrons penetrate into the standard Harwell long counter[1]. This work was initiated in order that the recently re-calibrated Harwell long counters[2,3] could be used quantitatively at any distance from a source of monoenergetic neutrons. The method involved producing monoenergetic neutrons using the $^7Li(p,n)^7Be$ and $T(p,n)^3He$ reactions in the energy range from 120 keV to 2.8 MeV, and recording the number of neutrons detected at various distances, R, from the neutron source between 75 cm and 400 cm.

Experimentally the number of neutrons detected, N, can be written in the form

$$N = N_o + N_{bgd} + N_{in} - N_{out} - N_{abs}$$

where N_o is the number of neutrons starting within the cone defined by the long counter from the source, N_{bgd} is the number of background neutrons, N_{in} is the number of neutrons outside the defining cone that are scattered into the long counter and detected, N_{out} is the number of neutrons within the defining cone that are scattered and not detected and N_{abs} is the number of neutrons within the defining cone that are absorbed. By using a suitably shaped piece of paraffin wax, measurements were also carried out at each distance with the paraffin between the source and the long counter in an attempt to determine $N_{bgd} + N_{in}$: it was not possible however to determine N_{out} and N_{abs} experimentally. In addition measurements of N_{bgd} alone were made.

Assuming that the neutron yield varies inversely as the square of the distance, $R + R_o$, it is then possible to determine R_o as a function of neutron energy. However although N_{in}, N_{out} and N_{abs} are small by comparison with N_o it was found necessary to take them all into account in the analysis. For this purpose a computer programme was written employing Monte Carlo techniques, in which individual neutrons are tracked from the source, using the known cross sections for oxygen and nitrogen, in order to compute the quantities N, N_o, N_{in}, N_{out} and N_{abs}. From this analysis, which is at present being completed, it is apparent that N_{out} is significantly larger than N_{in} and N_{abs}.

In addition, theoretical estimates of R_o are also being undertaken using the Monte Carlo programme Monk at Risley[4]. It is hoped that a comparison of the experimental determinations corrected for air scattering with the Monk calculations will result in a better understanding of the neutron detection within the standard Harwell long counter.

The results, together with those of the recent neutron efficiency recalibration[2], should provide a much better foundation for the determination not only of neutron fluxes but also of the detection efficiency of any neutron counter using the standard Harwell long counter.

(1) Allen W. D. AERE - NP/R 1667.

(2) Adams J. M., Ferguson A. T. G. and McKenzie C. D. AERE - PR/NP 14, 15, and 16.

(3) Adams J. M. AERE - PR/NP 16.

(4) Hemmings P. J. and Moore J. G. private communication.

GENERAL NUCLEAR DATA FOR REACTORS

E. A measurement of the ratio of the $^6Li(n,\alpha)$ and $^{10}B(n,\alpha)$ cross sections from 10 eV to 80 keV and recommended values of the $^{10}B(n,\alpha)$ cross section up to 200 keV (M. G. Sowerby, B. H. Patrick, C. A. Uttley and K. M. Diment)

Measurements of the neutron spectrum produced by the Harwell 45 MeV Linear Accelerator have been made, using time-of-flight techniques, with detectors based upon the $^6Li(n,\alpha)$ and $^{10}B(n,\alpha)$ reactions. A 2 inch diameter $^{10}BF_3$ counter, a "boron plug" detector with 0.003547 ^{10}B atoms/barn and a ⅛ inch thick ^6Li glass scintillator were used in the experiments and their relative efficiencies as a function neutron energy were calculated by Monte Carlo methods. Since these detectors were "thin" ($n\sigma < 0.3$) the multiple scattering corrections are small and almost energy independent and hence the experimental data can be used to obtain the ratio of the $^6Li(n,\alpha)$ to $^{10}B(n,\alpha)$ cross sections in the energy range 10 eV to 80 keV. The ratio is normalised at 10 eV to a value of 0.245. The absorption cross section of ^6Li has been obtained from total and scattering cross section of data. By combining these values with the data from the ratio measurement, the $^{10}B(n,\alpha)$ cross section has been deduced with estimated errors ranging from 2-3%. The results are compared with other measurements in Fig. 1 and there is very good agreement over the entire

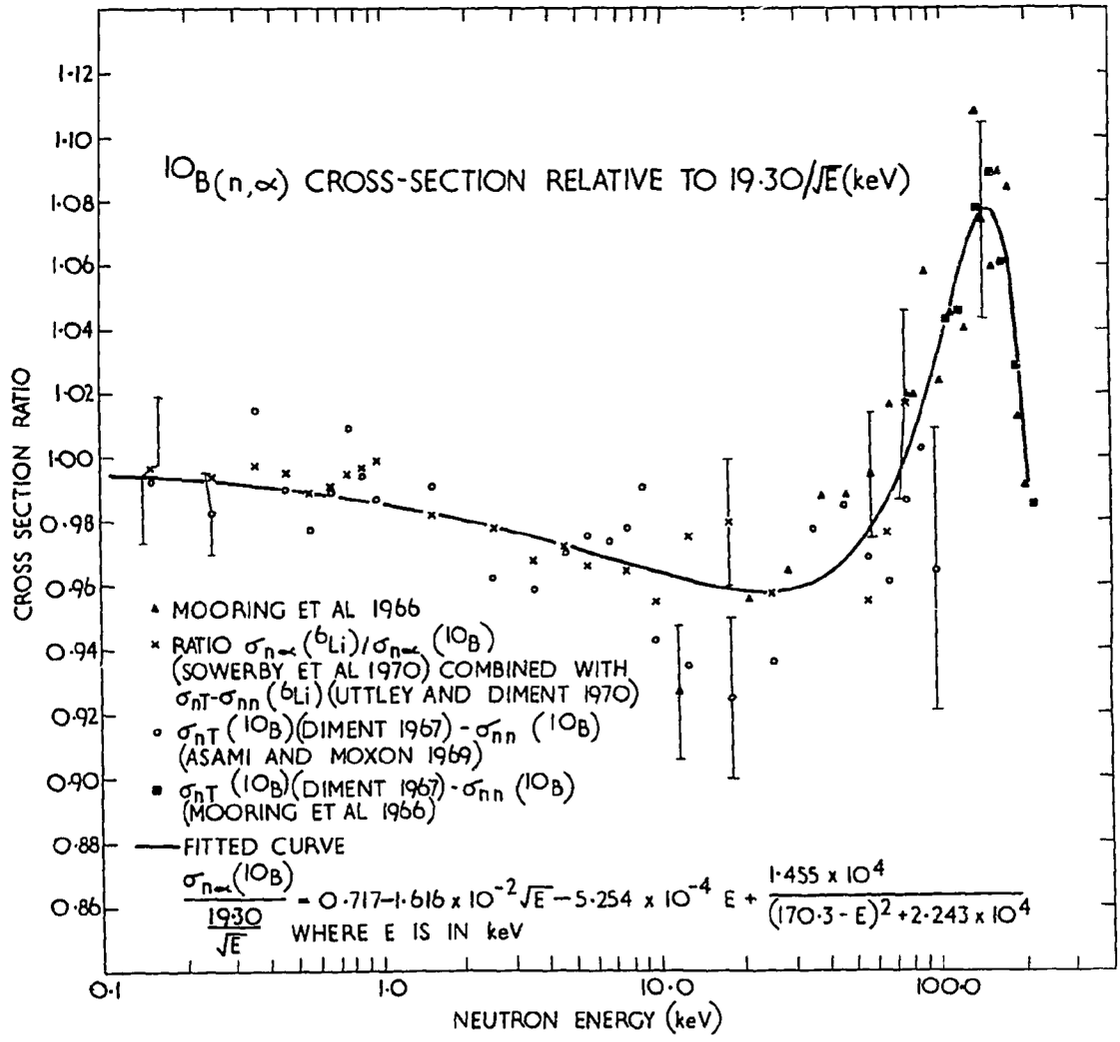


Fig. 1 The $^{10}B(n,\alpha)$ cross section relative to $19.80/\sqrt{E}$(keV) from 100 eV to 200 keV.

energy range. The data are all consistent with the $^{10}B(n,\alpha)$ cross section falling below the $1/\sqrt{E}$ level, reaching a minimum at ~25 keV, where the deviation is about 4%. Above this energy the cross section relative to the $1/\sqrt{E}$ level rises and passes through a resonance at ~170 keV. The complete set of data has been fitted by an analytic expression which includes the first three terms of the Shapiro[1] expansion describing the low energy dependence of such cross sections together with an s-wave resonance at 170 keV. A least squares fitting procedure was used with five free parameters, two of which are the energy and total width of the resonance. It is concluded that the $^{10}B(n,\alpha)$ cross section up to 200 keV is given by

$$\sigma_{n\alpha} = \frac{13.837}{\sqrt{E}} - 0.312 - 1.014 \times 10^{-2}\sqrt{E} + \frac{2.809 \times 10^5}{\sqrt{E}[(170.3-E)^2 + 2.243 \times 10^4}. \quad \text{barns}$$

where E is in keV. This expression has an estimated accuracy ranging from ~1.5% at low energies to ~3% at the high energy end, this being a considerable improvement in accuracy over previous determinations. A paper on this work has been accepted for publication in the Journal of Nuclear Energy,

and a paper was presented at the IAEA Conference on Nuclear Data for Reactors, Helsinki, June, 1970 (Paper CN-26/26).

(1) Shapiro F. L. Soviet Physics JEPT 7, 1132 (1958).

E. Observation of an isomeric level in ^{239}U by means of the $^{238}U(n,\gamma)^{239}U$ reaction (B. W. Thomas, J. Murray and E. R. Rae)

A detailed measurement of the low energy gamma-ray spectrum (<1 MeV) produced in thermal neutron capture by ^{238}U has been published by Maier[1]. The strong gamma-ray observed at 134 keV was thought to depopulate a level in ^{239}U at the same excitation energy. Data from (d,p) measurements[2] and high energy resonance capture spectra[3] confirm this assumption and suggest that the transition is of E2 character. Time-of-flight measurements have been made on a 20 metre flight path of the Harwell 45 MeV electron linear accelerator to study the low energy capture spectra of ^{238}U as a function of neutron energy, using a 25 cm^3 Ge(Li) detector. Data collection has been carried out by a two parameter system using a PDP-4 computer on-line to the experiment, for gamma-rays in the range 70 to 900 keV, and for neutron energies below 350 eV. Suitable analysis of the raw data can yield complete gamma-ray spectra for single resonances or time-of-flight spectra for individual transitions. The gamma-ray spectra are very similar from resonance to resonance, as might be expected, and are in general agreement with the thermal data. The time-of-flight spectrum for the 134 keV transition indicates that the corresponding level in ^{239}U is isomeric, with an experimental half life of approximately 1 microsecond. This is evident from the long tails on the low energy side of each resonance. In Fig. 1 some resonance shapes for the 134 keV transition are compared with those for a smooth portion of the gamma-ray spectrum to demonstrate the effect. The smooth underlying gamma-ray spectrum in this case is a complicated summation of the Compton distributions of all higher energy gamma-rays due to the response function of the detector.

The only process likely to compete with gamma-ray decay of the 134 keV level in this case is internal conversion. Using an internal conversion coefficient of 3.5 we obtain an intrinsic gamma-ray decay half-life for the isomeric state of approximately 4.5 microseconds. This is to be compared with the single particle estimate for an E2 transition of 60 nanoseconds.

This work is described in paper CN-26/36 presented at the IAEA Conference on Nuclear Data for Reactors, Helsinki June 1970.

(1) Maier B. P. K. Zeit. Phys. 184, 143 (1965).

(2) Sheline R. K., Shelton W. N., Udagawa T., Jurney E. T. and Motz H. T. Phys. Rev. 151, 1011 (1966).

(3) Price D. L., Chrien R. E., Wasson O. A., Bhat M. R., Beer M., Lone M. A. and Graves R. Nuc. Phys. A121, No. 3, 630 (1968).

E. Fission fragment angular distributions from resonance fission with oriented nuclei (N. J. Pattenden and J. E. Jolly; H. Postma, R. Kuiken and K. Ravensberg (F.O.M., Netherlands); J. C. Waldron (Chemistry))

During the period covered by this report, the analysis of the ^{235}U data referred to previously[1] has continued and is now almost completed. Measurements have also been made on ^{233}U and ^{237}Np. On ^{233}U the data-taking has finished and the results are being analysed, and for ^{237}Np the data-taking is continuing.

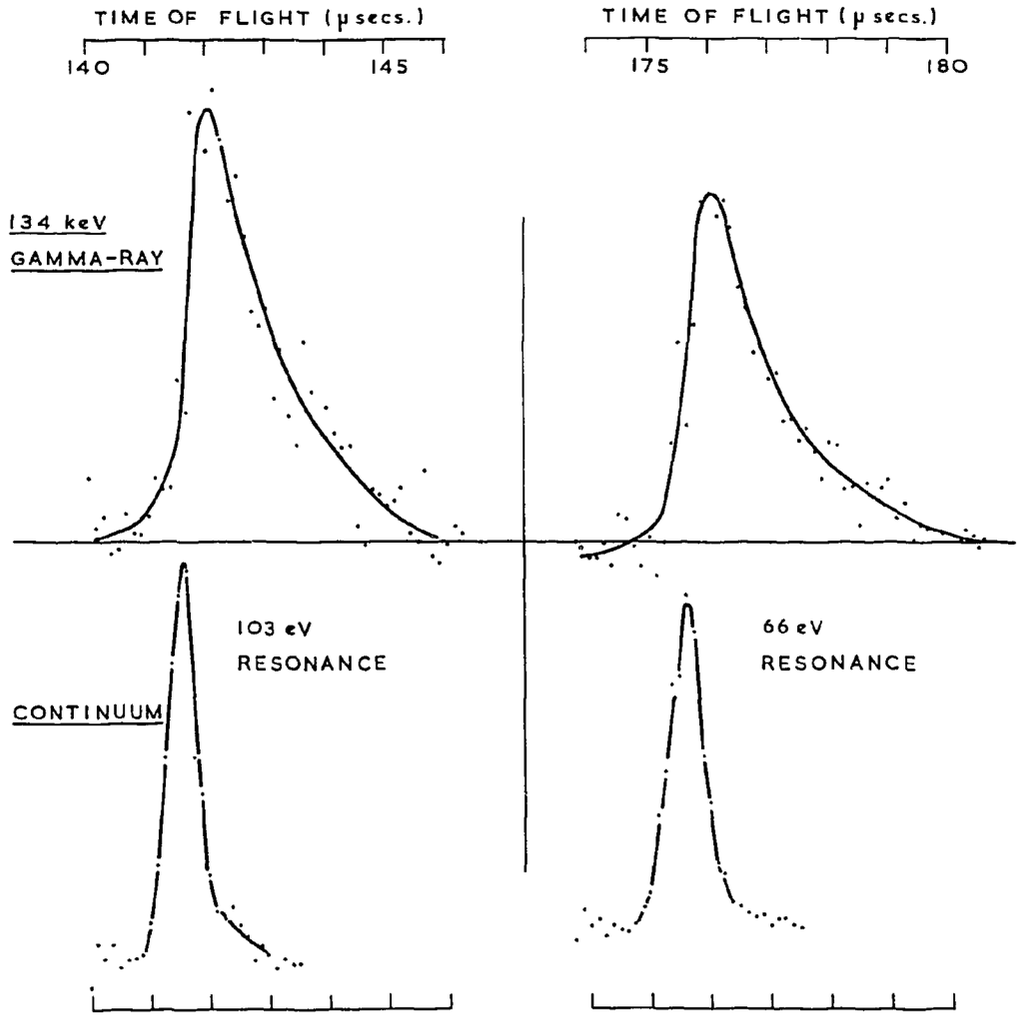


Fig. 1 *Neutron resonance shapes for the 134 keV capture gamma-ray produced in the reaction* $^{238}U(n,\gamma)^{239}U$.

In the case of ^{235}U, the A_2 values[1] of 55 resonances in the region below 100 eV are shown in Fig. 1, plotted in the form of a weighted histogram, given by the relation

$$Y = \frac{1}{\sqrt{2\pi}} \sum_{res} \left[\exp\left(-\frac{1}{2}\left(\frac{A_2 - A_{2\,res}}{\Delta A_{2\,res}}\right)^2\right) \right] / \Delta A_{2\,res}$$

where $A_{2\,res}$ and $\Delta A_{2\,res}$ refer to the experimental resonance values and statistical errors of the anisotropy parameter A_2. Systematic errors, changing the position of the distribution, have not yet been fully evaluated. Also included in the figure are calculated A_2 values for various possible J,K combinations. The channel theory of fission, as developed by Bohr[2], together with the liquid drop model, predicts that the predominant K values should be 0 and 1 for J = 3 and 1 for J = 4. Clearly our results do not agree with this prediction.

Measurements on ^{233}U were done during May, June and October 1969. Two RUN[1] samples having different thicknesses of the isotope were used, one contained 22.1 mg and the other 25.3 mg of ^{233}U. The α-activity of ^{233}U is rather high and this resulted in a much higher sample temperature (0.27°K and 0.32°K for the light and heavy coated samples respectively), while the cooling-plate was constantly at 0.16°K. Another complication raised by the α-activity was a deterioration of the diffused junction detectors due to radiation damage. After completion of the data taking on ^{233}U the efficiency had decreased to less than half the original value and it was necessary to replace the complete set of eight detectors.

A weighted hisotogram of the A_2 values for 67 resonances of ^{233}U from 0-60 eV is given in Fig. 2 together with the theorectical A_2-values, in a similar way to ^{235}U. Generally, ^{233}U shows a similar behaviour to ^{235}U but the distribution appears to be broader.

The ^{237}Np nucleus can also be oriented in RUN. The hyperfine splitting in this case is due to a combination of magnetic dipole and electric quadrupole couplings. Fission in ^{237}Np resonances is a sub-threshold process attributed to coupling with class II states[3]. During June-July 1969 and January-February 1970 data have been taken but due to the extremly low counting rate it will be necessary to continue for at least 3 months more. Preliminary results for the group of resonances at 40 eV are shown in Fig. 3. Interpretation in terms of a double humped fission barrier suggests single J and K values for resonances in one group. The statistical accuracy is not yet good enough to confirm this. The indication is that the 40 eV group has (J,K) = (2,2) but because of systematic errors (uncertainty in f_2-values, normalisation of detectors, etc.) the value (3,3) cannot be excluded.

During September 1969 the cryogenic equipment was improved and partially serviced.

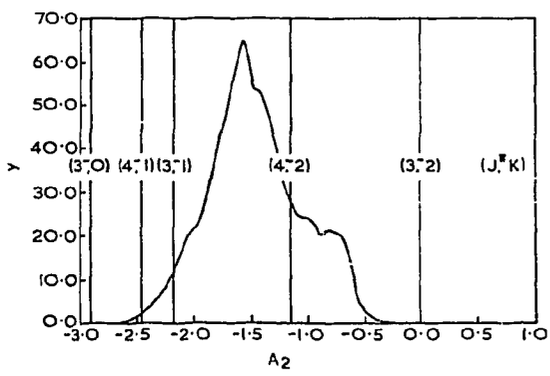


Fig. 1 ^{235}U: frequency distribution of A_2-values for 55 resonances in the region 0-100 eV.

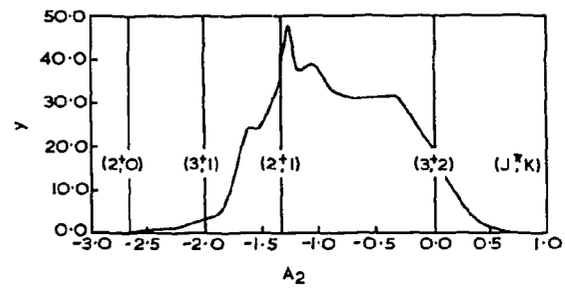


Fig. 2 ^{233}U: frequency distribution of A_2-values for 67 resonances in the region 0-60 eV.

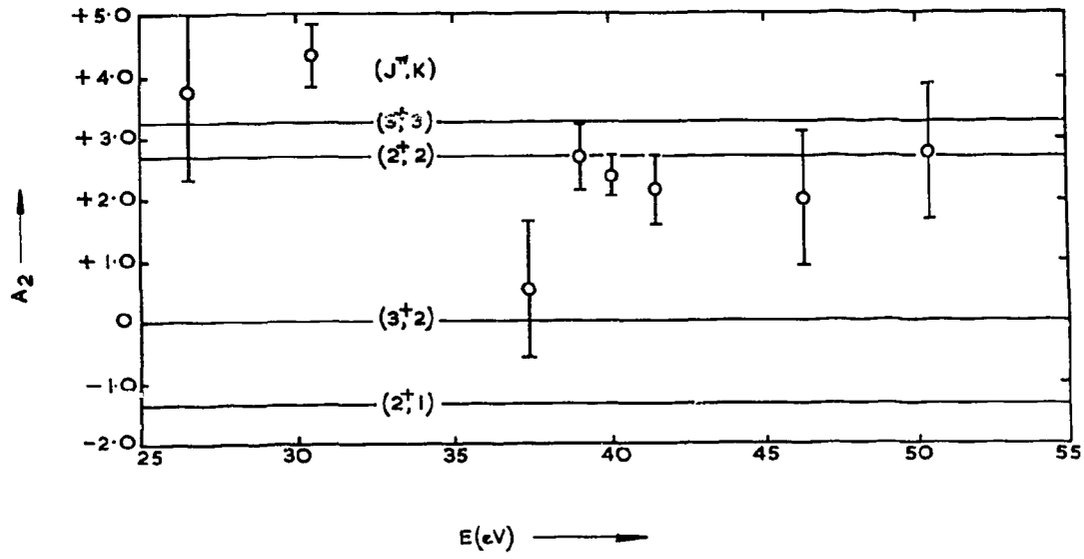


Fig. 3 ^{237}Np: A_2-*values for the resonances in the 40 eV group.*

(1) Pattenden N. J. et al. AERE - PR/NP 16 p. 21 (1969).

(2) Bohr A. Proc. First Conf. on Peaceful Uses of Atomic Energy 2, 151 (1956).

(3) Lynn J. E. Proc. of Second IAEA Symp. on Physics and Chemistry of Fission, Vienna, 249, (1969).

E. Gamma-ray spectra from resonance neutron capture in ^{201}Hg (B. W. Thomas, J. Murray and E. R. Rae)

The experimental details concerning these measurements have previously been described in connection with the resonance spectra from the reaction $^{198}Hg(n,\gamma)$ ^{199}Hg[1]. Resonance spectra were normalised to the integrated spectrum between 1.5 and 2.5 MeV, and absolute intensities were obtained from a comparison of our normalised spectrum for the 34 eV resonance in ^{199}Hg with the data of Rae et al[2].

The capture of s-wave neutrons by ^{201}Hg results in compound states of spin and parity 1^- or 2^-. In the present experiment, data have been obtained for three 1^- and two 2^- resonances up to a neutron energy of 560 eV. Transition strengths for 29 primary gamma-rays above 4.7 MeV are shown Table I for each of the five resonances. Prominent low energy gamma-rays are also considered for the three strongest resonances at 43, 71 and 210 eV.

(1) Thomas B. W., Murray J., Rae E. R. Nuclear Physics Division Progress Report AERE - PR/NP 15, p. 18 (1968).

(2) Rae E. R., Moyer W., Fullwood R. R. and Andrews J. L. Phys. Rev. 155, No. 4 1301 (1967).

TABLE I

Strengths of transitions in reaction $^{201}Hg(n,\gamma)^{202}Hg$

E_γ keV	Energy Final State keV	TRANSITIONS PER HUNDRED CAPTURES ± STANDARD DEVIATIONS									
		43 eV Res. (J = 2)		71 eV Res. (J = 1)		210 eV Res. (J = 1)		445 eV Res. (J = 1)		564 eV Res. (J = 2)	
		I	ΔI	I	ΔI	I	ΔI	I	ΔI	I	ΔI
7756	0	-0.1	0.3	-0.2	0.8	10.3	0.5	6.3	0.9	0.5	0.7
7313	443	1.1	0.2	31.0	1.2	1.6	0.4	5.8	0.9	1.8	0.8
6790	966	0.7	0.3	6.6	0.8	0.1	0.3	0.3	0.9	3.1	1.0
6403	1353	3.8	0.3	0.4	0.9	1.8	0.5	6.9	1.0	6.9	1.4
6352	1404	2.3	0.4	0.4	0.9	1.5	0.5	0.6	1.2	0.8	1.4
6187	1569	0.3	0.5	0.2	0.9	1.5	0.6	2.7	1.3	0.6	1.5
6066	1690	1.3	0.5	1.0	1.0	3.6	0.6	0.4	1.3	0.6	1.5
6005	1751	0.5	0.5	0.1	1.0	0.2	0.6	4.3	1.3	-0.4	1.5
5960	1796	1.6	0.6	2.4	1.0	4.1	0.7	0.7	1.3	3.8	1.7
5925	1831	-0.2	0.5	13.5	1.1	4.2	0.7	0.5	1.4	-0.5	1.5
5895	1861	10.4	0.9	9.0	1.1	1.2	0.7	3.3	1.3	8.0	1.9
5844	1912	0.4	0.6	-0.5	1.1	2.6	0.7	1.6	1.4	-0.9	1.6
5789	1967	0.6	0.6	1.7	0.8	2.6	0.5	2.0	1.4	-0.2	1.7
5671	2085	-0.1	0.6	0.1	1.0	5.4	0.7	0.5	1.4	-1.3	1.8
5619	2137	-0.1	0.6	1.9	1.1	0.5	0.7	4.2	1.4	2.2	2.0
5584	2172	0.0	0.6	1.3	1.1	5.3	0.7	2.6	1.4	1.6	1.9
5433	2323	3.2	0.7	-0.2	1.1	1.5	0.7	1.9	1.4	1.5	1.9
5372	2384	0.2	0.7	0.1	1.1	0.7	0.7	-0.2	1.4	11.1	2.3
5322	2434	1.0	0.7	4.3	1.2	-0.1	0.7	4.5	1.5	-1.3	2.0
5287	2469	0.9	0.7	6.1	1.2	0.9	0.7	-0.2	1.5	0.5	2.0
5201	2555	0.2	0.7	1.6	1.2	2.1	0.7	2.4	1.5	3.2	2.1
5091	2665	-0.1	0.7	0.8	1.2	1.0	0.8	1.5	1.6	7.0	2.3
5066	2690	0.0	0.6	0.4	1.2	3.5	0.8	0.8	1.6	3.0	2.2
5050	2706	5.9	0.7	2.2	1.2	1.2	0.8	-0.5	1.6	3.1	2.2
5000	2756	4.6	0.8	2.3	1.2	2.5	0.8	1.4	1.6	-0.6	2.2
4925	2831	2.0	0.8	2.2	1.2	0.7	0.7	1.4	1.6	5.3	2.3
4910	2846	-0.1	0.8	2.3	1.2	2.1	0.8	1.3	1.6	0.0	2.2
4834	2922	0.6	0.8	-0.4	1.2	5.1	0.8	0.9	1.7	4.5	2.4
4726	3030	1.6	0.8	1.7	1.3	-0.1	0.8	-1.2	1.7	1.3	2.6
1959		2.1	1.9	0.1	3.0	4.3	1.9				
1722		0.2	1.9	2.9	3.0	7.4	1.8				
1632		2.2	1.9	1.2	2.8	7.7	1.8				
1411		8.1	1.8	3.4	2.8	0.2	1.7				
1386		0.8	1.7	8.6	2.7	3.9	1.6				
1351		5.3	1.7	-0.9	2.6	9.7	1.6				
1122		3.9	1.6	2.2	2.2	6.0	1.5				
1102		2.5	1.6	2.1	2.1	2.5	1.4				
961		1.7	1.2	3.0	1.8	1.2	1.0				
951		9.8	1.4	6.9	1.8	0.7	0.9				
906		11.9	1.4	5.3	1.8	6.3	0.9				

E. Resonance capture studies (J. Murray, P. Riehs (Seibersdorf) and B. W. Thomas)

(a) Correlation analysis of partial widths

The use of correlation techniques to search for non-statistical effects in resonance capture has continued[1]. The original motivation for such analysis was to demonstrate the existence of channel capture. Although channel capture, which is due to the long range nature of the electromagnetic interaction, gives a single particle component in the partial width, the statistical description for the resonance wave function is retained. The Brookhaven group observed a significant correlation in ^{170}Tm[2] which cannot be explained by channel capture, between the partial widths and the reduced neutron widths of the resonances when averaged over final states. Lane[3] has suggested an explanation in terms of a doorway state common to the emission of a neutron and of a photon. The basis of the theory lies in the results of a 1p-1h diagonalisation for ^{208}Pb[3]. Such a doorway state for the emission of a photon is invoked to explain the pygmy resonance observed in nuclei between Ta and Pb. The results of the correlation analysis for the partial widths in ^{239}U, ^{199}Hg, ^{187}W, ^{185}W, ^{184}W and ^{183}W are all consistent with no correlation. The Saclay data for ^{196}Pt and the Brookhaven data for ^{182}Ta and ^{167}Er are also consistent with no correlation. It would appear that the explanation of the thulium data on the basis of numerical work on ^{208}Pb requires special pleading.

The ^{183}W data were also tested for the presence of a single particle component in the partial widths. The lack of an observable correlation disagrees with the channel capture prediction.

(b) Direct Capture

The capture spectra for resonances in cobalt have been obtained. The 20% ground state transition in the 4.3 keV resonance required to explain[4] the interference effect observed for this transition near the 132 eV resonance was not found. Although the quality of the data was poor, an upper limit of 6% could be put on the strength for that transition. The interference is usually attributed to direct capture.

(c) Absolute partial widths

The absolute values for the partial widths obtained by averaging over several resonances have been compared with the various estimates given by Lynn[5]. For the tungsten isotopes, ^{199}Hg and ^{239}U, the best estimate is that from the giant dipole resonance model. Using an empirically determined level density law, the total capture width was computed on the basis of these estimates. Even the giant dipole resonance model tends to overestimate the total width while underestimating the strength of the high energy photons.

(d) Low energy γ-rays

A program to study low energy γ-rays in resonance capture is under way. The occupation probabilities for low lying levels are compared with cascade model calculations. Data for ^{167}Er, ^{181}Ta and natural hafnium targets have been obtained. The erbium data agree reasonably with calculation and resonance spins have been assigned on this basis. The tantalum data are not in agreement with calculation. The hafnium data should give spin assignments which can be compared with those determined by the multiplicity method[6]. In addition, consistency with our high energy γ-ray spectra will be sought.

---

(1) Murray J., Thomas B. W. and Riehs P. AERE - PR/NP 16, p. 19.

(2) Beer M., Lone M. A., Chrien R. E., Wasson O. A., Bhat M. R. and Muether H. R. Phys. Rev. Letters 20, 340 (1968).

(3) Lane A. M. Symp. on Neutron Capture Gamma-ray Spectroscopy, Studsvik (1969).

(4) Broomhall G. J. Private communication (1969).

(5) Lynn J. E. Theory of Neutron Resonance Reactions, Oxford University Press (1968).

(6) Coceva C., Corvi F. and Giacobbe P. Nuc. Phys. A117, 586 (1968).

Considerations on a possible isomeric state in ^{241}Pu (J. E. Lynn)

Reactivity measurements carried out on a sample of ^{241}Pu over a period of a few years[1] indicated the existence of an isomer with a half-life of about 0.35 y, this being a component of the reactivity decay of the sample. Possible hypotheses of the nature of this suspected isomer have been examined. None appear to be substantiated by all the known facts, and the existence of such an isomer must still be considered doubtful. One of the most favoured hypotheses was that the apparent 0.35 y decaying "reactivity" was in fact due to a spontaneously fissioning isomer. In a flux of about 10^8 n cm^{-2} sec^{-1} spontaneous fission decay of an isomer formed in the proportion (relative to the ground state of ^{241}Pu) that one would expect in thermal neutron absorption by ^{240}Pu would explain Nisle and Stepan's[1] reactivity measurements. However, Hanna[2] has investigated the history of certain samples of ^{240}Pu containing some fresh ^{241}Pu and found that the neutron emission rate does not show the anomalies that would be expected from the spontaneous fission hypothesis. Simple nuclear structure considerations show that a normal high spin $13/2^+$ isomeric state might possibly be expected in ^{241}Pu, and that this could conceivably have a half-life against electromagnetic decay of up to a few months. Calculations have been made of the likely formation probability of such a state in the gamma-ray cascade following slow neutron absorption by ^{240}Pu. The best estimate of this isomeric ratio is in the range 10^{-3} to 10^{-4} but conceivably could be as high as 10^{-2}. Such a low isomeric ratio (say, 10^{-3}) would imply that the thermal fission cross section of the isomer would have to be in the 10,000 - 100,000 b range, and even then the sample of ^{241}Pu used by Nisle and Stepan in their reactivity measurements would have had to be produced in low burn-up.

(1) Nisle R. S. and Stepan I. E. Nuc. Sci. and Eng. 39, 257 (1970).

(2) Hanna G. C. Private communication.

E. Thermal and low energy fission cross section of ^{241}Pu (G. D. James and D. A. J. Endacott)

Significant differences between reported values of the half-life of ^{241}Pu ranging from 13.0 ± 0.2 y[1] to 14.98 ± 0.33 y[2] have led to a suggestion by Rose[2] that a long lived ^{241}Pu isomer may exist. More recently in a measurement of the time-dependence of the reactivity of a sample of ^{241}Pu, Nisle and Stepan[3] found evidence for a short-lived component (0.34 ± 0.11 y) in the decay of this quantity which they attribute to a short-lived isomeric state. Uncertainty about the history of the ^{241}Pu samples used in various experiments makes an interpretation of all the evidence very difficult. Lynn[4] has considered the possible explanations and concluded that a spontaneously fissioning isomer with a 0.34 y half-life cannot explain the results but that a normal high spin isomer[5] with a high fission cross section may provide an explanation. An experiment to compare the fission cross section of freshly prepared ^{241}Pu with that of ^{241}Pu which is several years old has been carried out. The data extend from 0.005 eV to 20 eV. In this energy range the resonant structure of the two sets of data are identical. By normalising the two sets of data to each other at the 0.24 eV resonance, it is found that the thermal fission cross section of the two samples are equal to to within about 1½% at a time when the fresh sample, prepared by irradiating ^{240}Pu in a flux of 10^{14} neutrons/cm^2 sec for 3 weeks, was 2 months old.

(1) Mackenzie D. R., Lounsbury M. and Boyd A. W. Phys. Rev. 90, 327 (1953).

(2) See Cabell M. J. J. Inorg. Nucl. Chem. 30, 2583 (1968).

(3) Nisle R. G. and Stepan I. E. Idaho Nuc. Corp. Progress Report IN-1317, 149 (1969).

(4) Lynn J. E. Private communication. See previous section.

(5) Nilsson S. G., Ohlen G., Gustafson C. and Moller P. Phys. Lett. 30B, 437 (1969).

H. A search for a long lifetime isomeric state in ^{241}Pu (B. Rose, C. Whitehead and A. C. Sherwood)

A recent measurement of the time-dependence of the reactivity of a sample of ^{241}Pu by Nisle and Stepan[1] indicated the existence of a decay component of half-life 0.34 ± 0.11 y in addition to the principal decay mode with ~15 y half-life. It had earlier been proposed by B. Rose[2] that a long lived isomer could, in principle, explain the discrepancies in measurements of ^{241}Pu half-life. In that the properties of such an isomer may be of importance in the reactor field an experimental investigation has been initiated to examine in detail the build-up of ^{241}Am activity (characterised by the 59.54 keV γ-ray from the decay of ^{241}Am) resulting from the decay of freshly produced ^{241}Pu. In addition to the observation of the 59.54 keV γ-ray, a search is being made for other gamma-rays arising from the decay of the supposed isomeric state.

Thin windowed Ge(Li) detectors (made by ion-implantation techniques) and Si(Li) detectors are being used in this work and so far the decay of chemically separated ^{241}Pu samples from two day and twenty-one day reactor irradiations of ^{240}Pu are being followed.

(1) Nisle R. G. and Stepan I. E. Nuc. Sci. and Eng. (to be published). See references p. 25.

(2) Discussed by Cabell M. J. J. Inorg. Nuc. Chem. 30, 2583 (1968).

E. The distribution of ^{234}U fission widths (G. D. James and D. A. J. Endacott)

It has been shown by James and Slaughter[1] that the fission widths of resonances within the narrow intermediate structure level centred at 638.4 eV in the fission cross section of ^{234}U have a Lorentzian energy dependence superimposed on a Porter-Thomas distribution. The intermediate structure resonance energy was chosen to coincide with the energy of the fine structure level with the largest measured fission width on the assumption that this is a predominantly class II level. The decrease in the fission cross section data of James and Rae[2] beyond this energy indicates that the resonance energy is unlikely to lie much above 638.4 eV. This argument has recently been made more quantitative by an analysis of the average fission cross section[2] to yield an average value of the fission widths over 100 eV intervals from 700 eV to 1100 eV. It will be seen in Fig. 1 that the Lorentzian curve describing the energy dependence of the mean fission width which was deduced from individual fission widths below 700 eV also provides a good fit to average values of the fission width above 700 eV. This confirms the choice of resonance energy.

(1) James G. D. and Slaughter G. G. Nuc. Phys. A139, 471 (1969).

(2) James G. D. and Rae E. R. Nuc. Phys. A118, 313 (1968).

A test for structure in neutron cross section and resonance parameter data (G. D. James)

It is well known that cumulative plots of reduced neutron widths, Γ_n^o, as a function of neutron energy show deviations from the mean value which have the appearance of energy dependent structure. It has been assumed that these deviations arise from the Porter-Thomas distribution of reduced neutron widths. However, it is shown here how a distribution-free statistic developed by Wald and Wolfowitz[1] can be used to test this assumption and thus test for energy dependent structure in the presence of the well known fluctuations of low energy neutron resonance parameter data. The crucial step in the analysis is to recast the data on an ordinal scale[2] (which measures only the property "greater than or less than"). This eliminates the unwanted information appertaining to the Porter-Thomas fluctuation of the data while at the same time presenting the data in a form directly amenable to analysis by the distribution-free

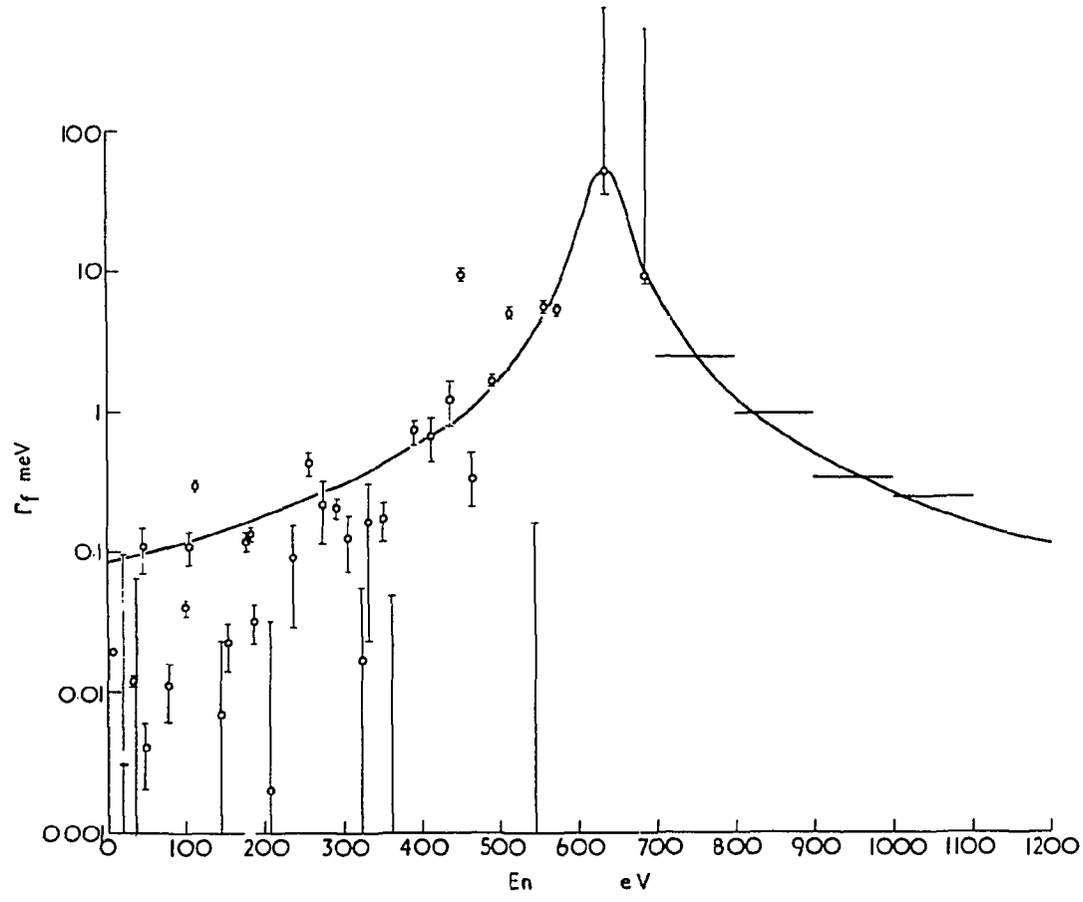


Fig. 1 The energy dependence of the observed fission widths of ^{234}U resonances within the narrow intermediate structure resonance centred at 638.4 eV. The solid line shows a Lorentzian energy dependence of the mean fission width deduced from the individual fission widths below 700 eV. It is seen that average fission widths over 100 eV intervals between 700 eV and 1100 eV are also fitted by this curve thus confirming the choice of resonance energy at 638.4 eV. The individual fission widths fluctuate about the energy dependent mean value with a Porter-Thomas distribution.

method. The method will be illustrated by analysis of the reduced neutron widths of ^{232}Th, shown in Fig. 1. In the energy range below 3.6 keV, 270 values of Γ_n^o are available for analysis (Stehn et al.[3]). They have a χ^2 distribution with a number of degrees of freedom $\nu = 0.94 \pm 0.07$ which is consistent with a Porter-Thomas distribution. For such data, half the values are greater than (approximately) half the mean value and the data can be divided into two roughly equal sets depending on whether they are greater or less than half the mean value. Let one set be marked as zeros and the other as ones. After writing down the sequence of zeros and ones for the reduced neutron widths taken in the order of the resonance energies, the Wald and Wolfowitz statistic U is found by counting the number of runs in the sequence, where a run is an unbroken train of zeros or ones. (A run can be a single zero or one). If m is the total number of zeros and n is the total number of ones, Wald and Wolfowitz have shown that U is normally distributed about an expected value $\Sigma(U)$ with a variance $\sigma^2(U)$ given by the formulae

$$\Sigma(U) = 1 + 2\,mn/(m + n)$$
$$\sigma^2(U) = 2\,mn(2\,mn - m - n)/(m + n)^2(m + n - 1). \qquad \ldots (1)$$

Thus the expression $X = (|U - \Sigma(U)| - 1/2)/\sigma(U)$ is normally distributed with zero mean and unit variance. It includes a half integer to correct for the discrete nature of the distribution. For the sequence obtained from the reduced neutron widths of ^{232}Th, it is found that U = 137, $\Sigma(U) = 136$ and $\sigma = 9.2$ giving a significance level of 52% and showing that despite appearances the data have no energy dependent structure.

This analysis can be applied to any data that should be distributed about a median value with no energy dependence for the distribution and is tantamount to testing whether the correct energy dependence of the median value has been adopted. Thus, for example, the distribution of fission widths for ^{239}U, which are discussed elsewhere in this report[4], about a median value of half the Lorentzian curve shown in the figure, gives a value U = 9 at a significance level of 44.8% showing that the Lorentzian curve adequately represents the data.

A further application of the method is to test for structure in the correlograms obtained from serial correlation analysis of neutron cross section data. Thus Fig. 2(a) shows the correlogram obtained by James and Patrick[5] from an analysis of the fission cross section of ^{239}Pu using an energy independent mean value of $\sigma_f\sqrt{E}$. Fig. 2(b) shows the results obtained by allowing for fairly obvious modulations of the fission cross section with an average spacing of about 500 eV. Fig. 2(b) is clearly more featureless than Fig. 2(a). For data which have no energy dependent structure, the correlation coefficients are equally likely to be positive or negative and this can be tested by the Wald and Wolfowitz statistic which gives U = 15 for Fig. 2(a) (a significance level of <0.003%) and U = 30 for Fig. 2(b) (a significance level of 7.35%). This shows that the structure allowed for by James and Patrick in deducing Fig. 2(b) is a good representation of the data although it could be improved to bring the probability nearer to 50%. In this application to correlograms it must be noted that structure which gives rise to a high value of the correlation coefficient r_k at one value of the spacing k is likely to produce high values of r_{k-1} and r_{k+1}. The values of r_k are therefore not strictly independent of one another and the values of $\Sigma(U)$ and $\sigma(U)$ should not be taken from equation (1) but determined by randomising the fission cross section data. This entails calculating U a large number of times for different permutations of the observed values of $\sigma_f\sqrt{E}$ achieved by exchanging randomly selected pairs of data points. The significance levels quoted above were obtained by randomisation. A direct application of equation (1) to the correlogram of Cao and Migneco[6] derived from the fission cross section of ^{235}U gives U = 12 and a significance level of 10% which is not a strong indication of structure despite the obvious periodic nature of the correlogram.

(1) Wald A. and Wolfowitz A. Annals Math. Stat. XI, No. 2 (1940), see also ref. (2).

(2) Sigel S. Nonparametric statistics for the behavioural sciences (McGraw Hill, New York, 1956).

(3) Stehn J. R. et al. Report BNL 325, 2nd Ed. Suppl. No. 2 (1965).

(4) James G. D. and Endacott D. A. J. This report p. 26.

(5) James G. D. and Patrick B. H. Physics and Chemistry of Fission (IAEA, Vienna 1969) 391.

(6) Cao M. G. and Migneco E. Phys. Lett. 27B, 409 (1968).

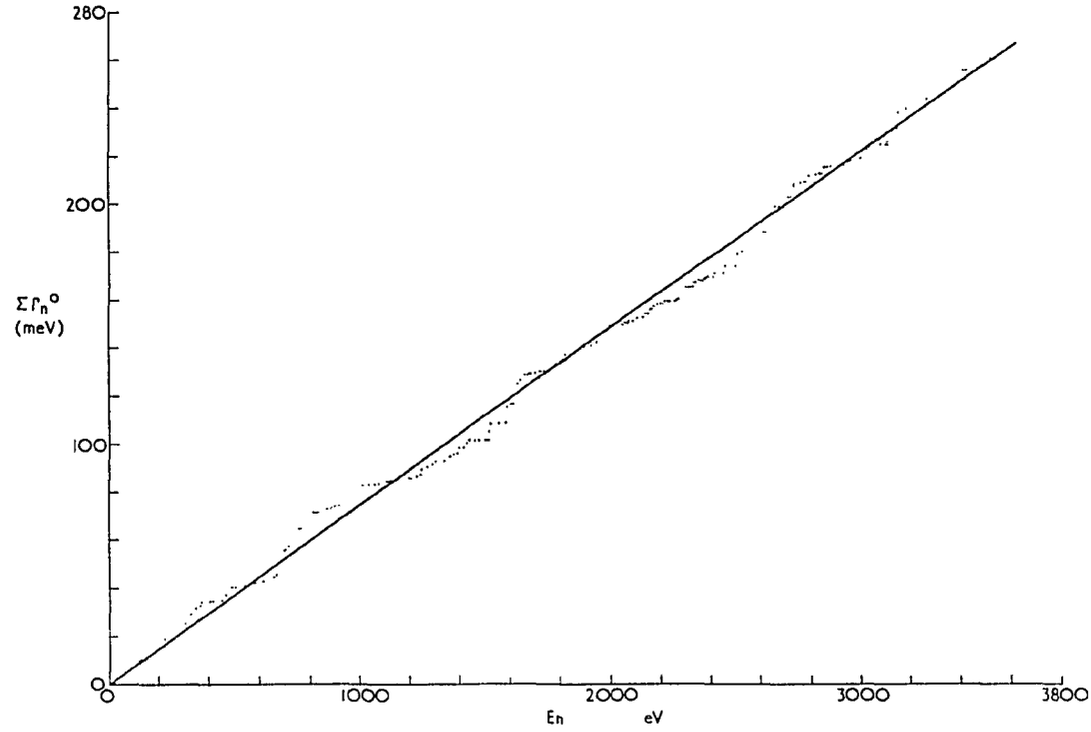


Fig. 1 The cumulative sum of the reduced neutron widths of ^{232}Th as a function of neutron energy. An application of the Wald and Wolfowitz test to these data shows that, despite appearances, they have no energy dependent structure.

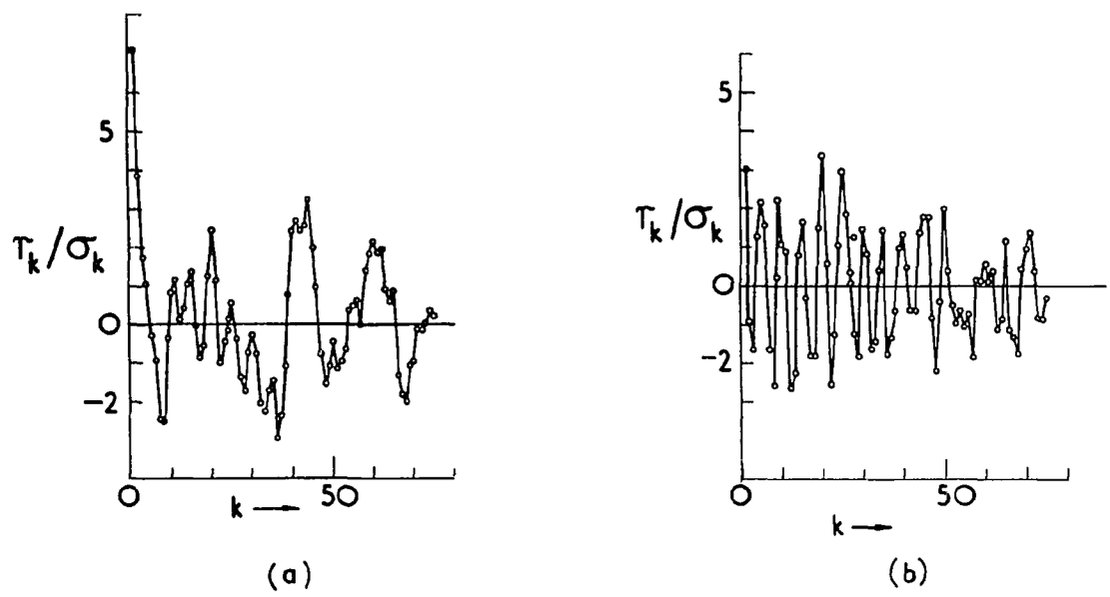


Fig. 2 Correlograms for the fission cross section of ^{239}Pu over the energy range 716 eV to 5683 eV (ref. 5). Here r_k is the serial correlation coefficient, σ_k the standard deviation in r_k and k is the spacing between regions being tested. In calculating (a) the mean fission cross section is assumed to have a $1/\sqrt{E}$ energy dependence whereas in (b) an additional energy dependent structure of the mean fission width is assumed. Correlogram (b) is more featureless than (a) as shown by the Wald and Wolfowitz test thus showing that the assumed structure is reasonably correct.

E. Analysis of the total cross section of carbon below 1.5 MeV (C. A. Uttley and K. M. Diment)

An increasing number of measurements on the total and differential scattering cross sections of carbon are being made largely because carbon is an ideal scattering nucleus for use as a standard in the energy range below 2 MeV. Measurements are usually made on natural carbon since the only resonances below 2 MeV occur at 0.15 and 1.75 MeV in ^{13}C, which is only 1.1% abundant, and produce a negligible effect on the data.

The total cross section measurement from 70 eV to 7 Mev was made using the 300 metre flight path on the 45 MeV electron linear accelerator which also has an intermediate detector station at 120 metres used to study the lower end of the energy range. The present data below 100 keV has been used by Asami and Moxon as a standard relative to which they have measured the neutron scattering cross sections of ^{10}B[1] and ^{6}Li[2].

The smoothly varying cross section below 1.5 MeV can conveniently be expressed by a polynomial in energy which is fitted to the experimental data by minimising χ^2. The fit is shown in Fig. 1 and is given by

$$\sigma_{nT} = 4.744 - 3.707E + 2.389E^2 - 1.114E^3 + 0.242E^4 \qquad \ldots (1)$$

where E is neutron energy in MeV. If the phase shifts due to higher partial waves are small below 1.5 MeV, as differential scattering measurements[3,4] indicate, then an expression of the form of Equation (1) is expected from s-wave effective range theory developed by Bethe[5] and others. The shape dependent effective range approximation expresses the energy dependence of the s-wave phase shift δ_0 as follows

$$k \cot \delta_0 = -1/a + 1/2 \; r_0 k^2 - P r_0^3 k^4 \qquad \ldots (2)$$

where k is the neutron wave number, a is the scattering length, r_0 is the effective range of the nuclear potential and P is a shape factor which represents the effect on scattering of the radial dependence of the potential surface. If expression (2) is substituted into the s-wave scattering cross section $\sigma = 4\pi/k^2 \sin^2 \delta_0$ then σ can be expressed as a polynomial in energy similar to Equation (1) in which the coefficients of E_0 and E_1 are $4\pi a^2$ and $-4\pi a^2 k_0^2 (a^2 - a r_0)$ respectively where k_0 is the wave number at 1 MeV. Thus the scattering length for carbon is a = 6.14 fm and the effective range r_0 = 3.05 fm.

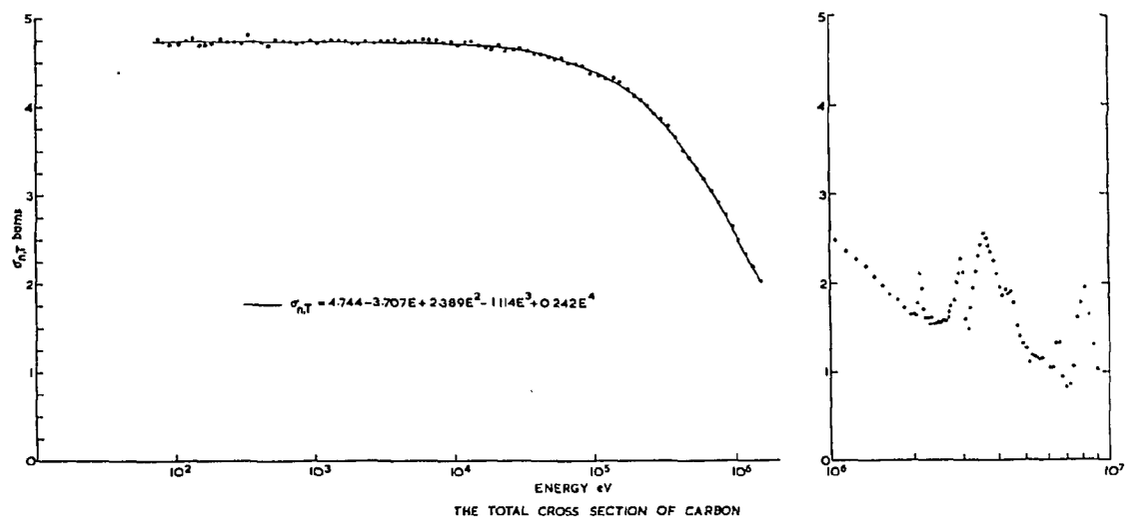


Fig. 1 The total cross section of carbon.

The large value of the scattering length a, relative to the expected hard sphere scattering radius for carbon can only be obtained if the s-wave scattering cross section is determined by a bound $^1/_2{}^+$ state. Such a state is known at -1.86 MeV (C. of M.) and thus the formal R-matrix expression for the s-wave phase shift can be written in terms of a resonance and a background hard sphere component which can be expanded as a series in even powers of k to yield an expression equivalent to Equation (2). Equating coefficients of k^0 and k^2 enables the s-wave scattering radius R = 4.625 fm and the reduced neutron width $\gamma_n{}^2$ = 0.611 MeV (θ^2 = 0.192) of the $^1/_2{}^+$ state at E_λ = -1.86 MeV (C. of M.) to be found from the values of the effective range parameters a and r_o determined above.

The s-wave cross section resulting from these parameters gives a good fit to the total cross section up to ~0.5 MeV but the experimental data diverge increasingly towards 1.5 MeV. A small p-wave scattering cross section can readily account for the remaining cross section. If we assume this to be p-wave potential scattering, which is determined by a radius r, and subtract the p-wave scattering for various values of r, the fits to the remaining cross section in terms of an s-wave potential scattering radius and a reduced neutron width for the bound state shows that χ^2 rapidly diverges from a minimum value as the radius r increases. Thus the data can be fitted by three parameters, the s- and p-wave scattering radii and the reduced width of the bound state. The values found for these quantities are 4.56 fm, 3.07 fm and 0.645 MeV respectively and result in the fit shown in Fig. 2 where the size of the dots represents the statistical errors. The s-wave parameters determined from the fit to the data at higher energies are in agreement with those determined from the effective range parameters which are more concerned with the data below ~0.5 MeV.

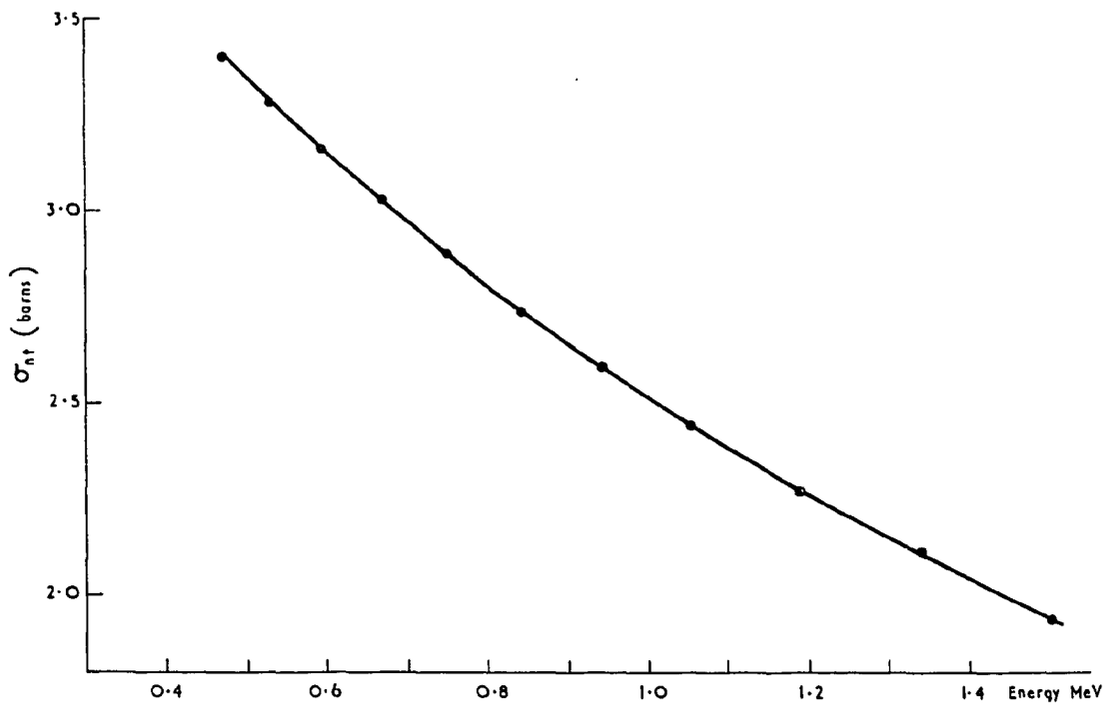


Fig. 2 S-wave fit to the carbon total cross section after subtracting p-wave hard sphere scattering with a radius of 3.07 fm.

Taking into account the small d-wave scattering arising from a phase shift $\delta_2(3/2) = 3^0$ at 1.45 MeV determined by Wells et al.[3], which slightly changes the s- and p-wave parameters to 4.58 fm, 2.97 fm and 0.638 MeV, the p-wave scattering cross section is slightly larger than that arising from the phase shifts of Wells, but is smaller than the one obtained from those of Ahmed et al.[6] in a recent differential scattering measurement on carbon. The work was reported in detail in paper CN-26/24 presented at the IAEA Conference on Nuclear Data for Reactors, Helsinki, June, 1970.

(1) Asami A. and Moxon M. C. AERE - R 5980 (1969).

(2) Asami A. and Moxon M. C. IAEA Conference on Nuclear Data for Reactors, paper CN-26/26, Helsinki, 15-19 June 1970.

(3) Wells J. E., Bair J. K., Cohn H. D. and Willard H. B. Phys. Rev. 109, 891 (1958).

(4) Lane R. O., Langsdorf A. S. Jnr., Monahan J. E. and Elwyn A. J. ANL-6172 (1960).

(5) Bethe H. A. Phys. Rev. 76, 38 (1949).

(6) Ahmed N., Coppola M. and Knitter H. H. IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970.

E. Spin assignments of resonances in ^{165}Ho using a polarized target (H. Marshak (N.S.B., Washington), C. A. Uttley and K. M. Diment)

The transmission measurements on both the 2.5 cm and the 5 cm thick ^{165}Ho samples, mentioned previously, were completed and a provisional analysis was carried out to compare the transmission of each sample as a function of neutron energy, both polarized and unpolarized, and also to compare the cross sections between resonances for both samples in the unpolarized state.

It was found in the latter case that the cross section between resonances for the 5 cm thick sample was ~1.25 barns higher than the corresponding cross section for the 2.5 cm thick sample and this was confirmed by subsequent measurements at room temperature. Furthermore, no significant difference in transmission between the polarized and unpolarized runs on the 5 cm thick sample was observed across the resonances although the provisional data on the 2.5 cm thick sample showed a small effect.

Since it is necessary to know the absolute unpolarized total cross section to determine resonance spins by this method, an analysis of both samples was carried out by Mr. A. Parker of Analytical Sciences Division who found that the material from which the 5 cm thick sample was made contained 0.04% hydrogen by weight and 0.3% oxygen by weight compared with 0.008% and 0.15% by weight respectively for the 2.5 cm thick material. The different hydrogen concentrations, which were confirmed by an analysis of the actual samples at the National Bureau of Standards, account for the observed difference in the potential scattering cross section between the two samples.

If these provisional results are confirmed after a study of the individual runs contained in the transmission data on the 5 cm thick sample, tests will be carried out to determine the effect on the polarization due to a hydrogen concentration of 7 atoms per cent.

B. Neutron fission cross section of ^{230}Th (G. D. James and J. E. Lynn)

A series of measurements on the neutron-induced fission of ^{230}Th have been made in the neutron energy range 680 keV to 1.4 MeV. Over this range the fission cross section has been measured with energy resolution of about 5 keV at fairly close intervals[1]. At a number of selected energies the angular distribution of the fission products with respect to the neutron beam has also been measured, the neutron energy resolution being about 18 keV in this case. For both experiments the neutron source was the ^{7}Li(p,n) reaction, using monoengergetic incident protons from the IBIS accelerator. In the angular distribution measurements, fission product tracks were permanently recorded on a strip of polycarbonate foil surrounding the ^{230}Th target, and were later revealed by an etching and sparking arrangement devised by Lark[2].

The results are of great interest in the light of recent developments in our knowledge of the fission phenomenon. Specifically, they give us spectroscopic information about the excited states (class II states) associated with the quasi-stable highly extended shape of the nucleus (the secondary minimum in the Strutinsky double-humped potential). The fission cross section is shown in Fig. 1. The data points over the prominent peak at 720 keV are very smooth[1]; this tells us that the class II states underlying the peak are not complex in nature. They rule out, for example, the existence of class II states with a spacing of a few hundred eV or so (as in ^{241}Pu), because the Porter-Thomas fluctuations in ten or so such levels averaged in a 5 keV interval would cause rather large statistical fluctuations about a smooth curve. We postulate therefore that the 720 keV peak is caused by a simple class II state that is essentially an excitation of the single-odd neutron of ^{231}Th combined with a β-vibration of the secondary shape. The fact that it seems necessary to postulate this simple type of state already suggests that this β-vibration is just zero point vibration i.e. the secondary minimum is very shallow. We suggest this because the first phonon of β-vibration has never yet been identified in the normal spectroscopy of odd mass nuclei.

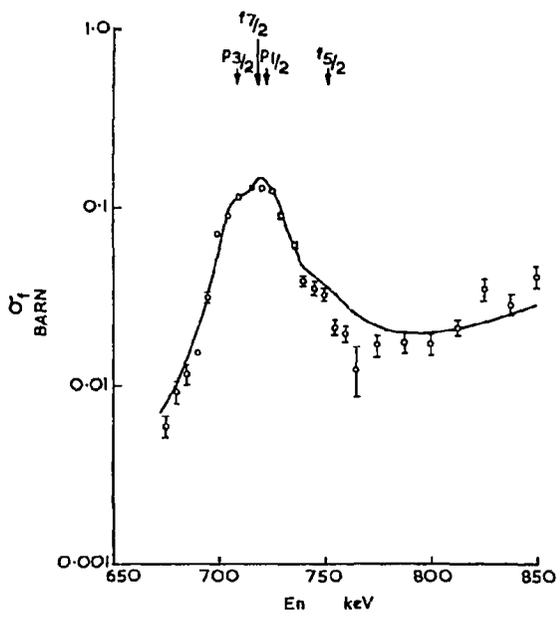


Fig. 1 The fission cross section of ^{230}Th between 600 keV and 850 keV measured with an energy resolution of 5 keV. The resonance at 715 keV is attributed to a vibrational level in the second fission potential barrier minimum and the solid line is a theoretical fit based on the rotational band structure indicated.

We expect a rotational band to be associated with this single neutron excitation, and the data have been analysed under this assumption. To calculate the fission cross section and angular distribution the usual type of compound nucleus average cross section theory, with inelastic scattering competition, has been used, but the fission strength function has been assumed to be the sum of a Lorentzian term and a background term, both having a Hill-Wheeler tunnelling factor included.

The fissioning nucleus is assumed to distort along a cylindrical symmetry axis. The forward-peaked angular distribution of fission products in the 720 keV peak (see Fig. 2) shows the projection K of angular momentum on this symmetry axis is 1/2. The analysis (Fig. 1 and 2: some of the angular distribution are from ref. (3)) indicates that the parity of this class II state is very probably odd, and that the effective moment of inertia of the rotational band is given by $h^2/2g$ = (4 times the normal ground state moment of inertia). This last fact strongly supports the authenticity of the Strutinsky theory.

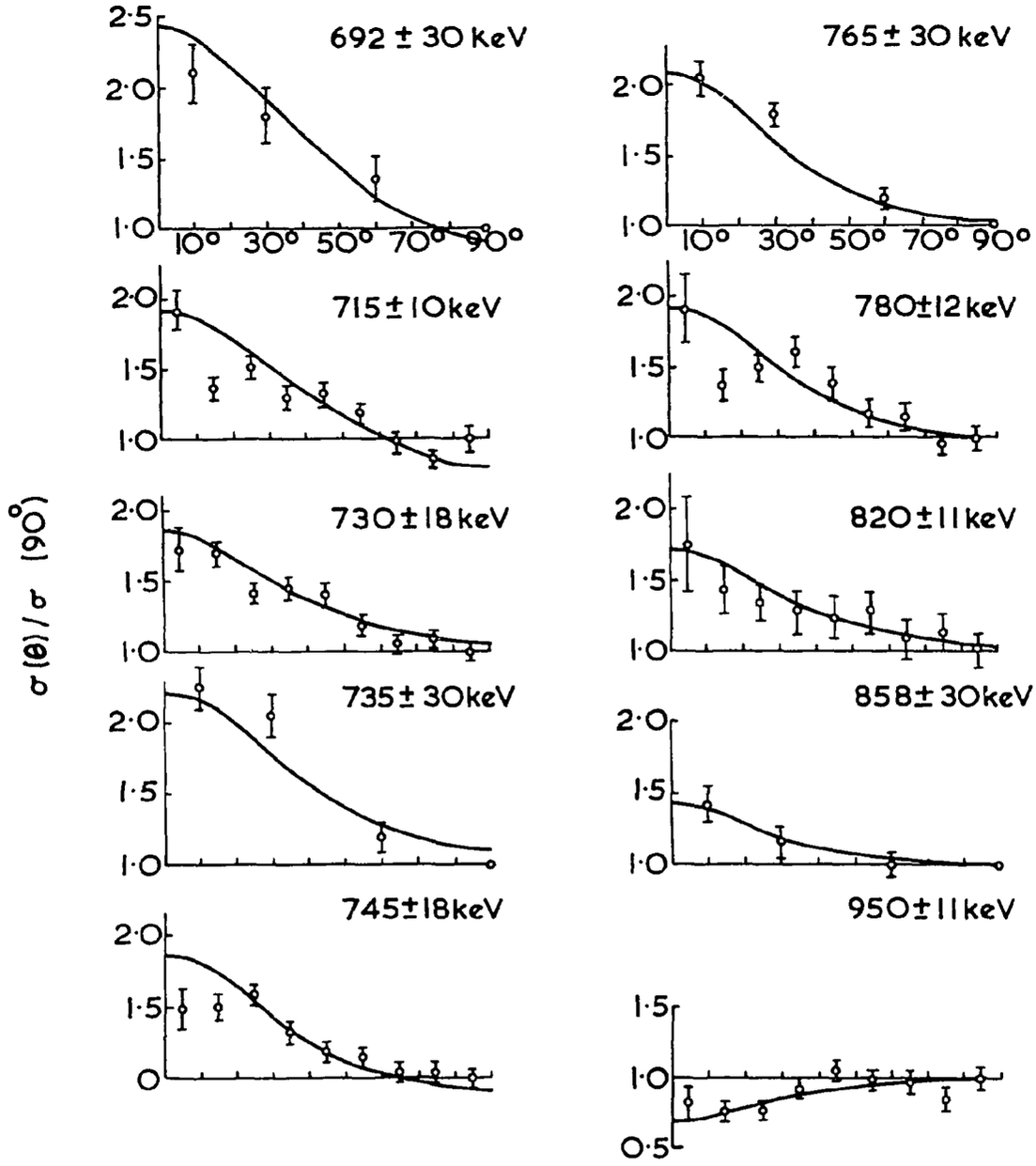


Fig. 2 Fission fragment angular distributions for $^{230}Th(n,f)$ between 692 keV and 950 keV. Distributions with four data points are the measurements of Vorotnikov et al.[3]. The solid line is a theoretical fit for the rotational band structure indicated in Fig. 1. These results provide an estimate of the moment of inertia of the $^{230}Th + n$ nucleus at a deformation corresponding to the second fission potential barrier minimum.

The monotonically rising sequence of data above 800 keV can also be analysed as a sequence of Lorentzian type fission strength functions each being based on a relatively simple class II excitation and its associated rotational band. Thus, there appears to be a $K^{\pi} = {}^{3}/_{2}^{-}$ band at 950 keV and another $K = {}^{1}/_{2}$ band at about 1100 keV.

(1) Earwaker L. G., James G. D. and Endacott D. A. J. Nuclear Physics Division Progress Report AERE - PR/NP 16, p. 6.

(2) Lark N. L. Nuc. Inst. and Methods 67, 137 (1969).

(3) Vorotnikov P. E., Dubrovina S. M., Otroshchenko G. A. and Shigin V. A. Sov. J. N.P. 5, 207 (1967).

H. Sub-threshold fission (G. C. Cox, A. Langsford and Miss A. Khatoon (University of Surrey))

An experiment is in preparation to look for detailed structure, in the fission cross section of heavy elements in the sub-threshold region, as a function of neutron energy. Preliminary work has been concerned to demonstrate the viability of surface barrier detectors, used to detect fission fragments, in the pulsed neutron beam from the synchrocyclotron. By using an array of detectors the experiment will also yield information on the angular distribution of fission fragments from this process.

Nuclear structure information from the study of isomeric states (T. W. Conlon)+

New examples of isomeric states are being produced and the occurrence of isomerism in several distinct regions of nuclei studied using pulsed beams of both light and heavy ions from the Variable Energy Cyclotron. In the region Z = 63-83 information is provided on the systematics of Nilsson states and multi-quasi-particle states (i.e. ^{181m}Re below); identification of Nilsson states in the new region of stable deformation close to ^{126}Ba enables definitive statements to be made concerning the sign of the equilibrium deformation which is predicted to be negative yielding oblate shaped nuclei. The decay scheme of an isomeric state in ^{127}Cs for example, reported below, provides convincing evidence that among the low-lying states of this nucleus some levels correspond to oblate deformation and another to prolate deformation. Finally, the new isomer observed in ^{214}Ra may provide evidence for the recent suggestion that the double-humped potential barrier, important for the understanding of fissioning isomers, also occurs in this nucleus; in this case, however, gamma-decay through the inner barrier would appear to dominate fission through the outer barrier.

I Isomeric states in the region Z = 63-83

A detailed account has now been published(1) of the observed properties of the 11.4 μsec isomeric transition connecting two three-quasi-particle states in ^{181}Re which was discussed briefly in the last report.

Further work is planned on the decay schemes of other new isomeric states observed in this region produced by (p, Xn) and (^{4}He, Xn) reactions.

II Shape Isomers

(1) Isomerism in Ba, Xe and La Isotopes (In collaboration with A. J. Elwyn)++

It is now established(2) that there exists a new region of deformation close to ^{126}Ba (the region Z > 50, N < 82). Many of these nuclei are expected to be oblately deformed in the ground state but may contain low-lying states associated with the opposite sign of the deformation, that is prolate states. Transitions between states of different shape are expected to be hindered and thus cause isomerism. Isomerism moreover should also occur in these nuclei since the expected(3) single particle Nilsson level-diagram for oblate deformed nuclei shows that states should exist with large spin difference but small energy difference. Some of the new isomeric states in Ba, Xe and La nuclei presented in the last report have been shown in our recent publication(4) to be of the latter type and provide evidence in support of the occurrence of oblate nuclear states in the region Z > 50, N < 82. More recent experimental studies of isomerism in Cs isotopes, discussed below, suggest that isomerism of the former type has also been observed.

+On leave at United Nations Development Programme, Santiago, Chile.
++On leave from Argonne National Laboratory, Argonne, Illinois, U.S.A.

(2) The ^{127}Cs Isomer

The work outlined in Section II(1) above has been continued in order to study isomerism in the neutron difficient isotopes of Cs of atomic number 122-129 produced via the reactions $^{115}In(^{12}C, Xn)$ $^{122,123}Cs$ and ^{127}I $(^{4}He, Xn)$ $^{126,127,128,129}Cs$. We have not investigated the $^{124,125}Cs$ isotopes.

In ^{122}Cs we have observed the known isomer[5] which decays by means of a single M2 transition of energy 95.1 keV.

A new isomeric state has been produced in ^{127}Cs which decays with a half-life of 55 μsec. The energy spectrum of gamma-rays observed from the decay of this state is shown in Fig. 1. On the basis of our accurately measured transition energies and transition intensities, shown in Table I, the decay scheme presented in Fig. 2 is believed to be well established. Using the relative intensities and the intensity balance at each level, we have deduced multipolarities for some of the transitions, as shown in Table I, and we are able to conclude that the 133.7 keV transition is M1, E2 or a mixture M1 + E2. The ground state spin-parity of ^{127}Cs, which has been measured to be $\frac{1}{2}^{+}$[6], was the only information available for this nucleus prior to the current work. Using the ground state assignment and our assigned multipolarities, we are able to make unique spin-parity assignments for the isomeric level and the 272.5 keV and 65.9 keV levels shown in Fig. 2. The 138.8 keV level is very probably $3/2^{+}$, but a $5/2^{+}$ assignment cannot be positively excluded. Thus all levels involved in the isomeric decay have been idenfitied and ^{127}Cs becomes one of the very few nuclei in the region $Z > 50$, $N < 82$ for which detailed information on low-lying excited states exists. It is therefore appropriate to compare the experimentally assigned levels with those expected on the basis of calculations of Kumar and Baranger[3] and Arzeniev et al.[7] which are in substantial agreement with each other. In both cases four of the five lowest-lying excitations have spin-parity $11/2^{-}$, $7/2^{+}$, $5/2^{+}$, $3/2^{+}$ corresponding to the Nilsson orbitals [505]↑, [413]↑, [413]↓ and [411]↑ which are available for negative (oblate) values of the deformation, β; the fifth state is predicted in both cases to be $\frac{1}{2}^{+}$ but may be either [411]↓ of reference 3 or [420]↑ as predicted by Arzeniev et al. – the latter being the only state with a prolate deformation (positive β) they expect in the odd Cs isotopes.

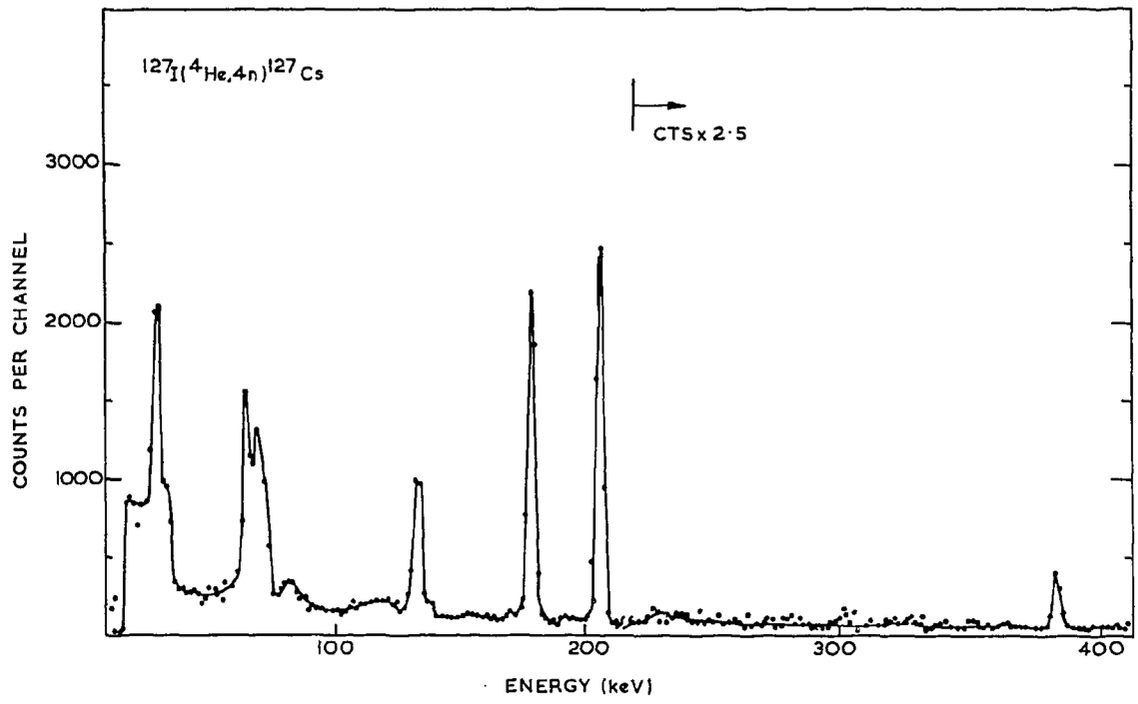


Fig. 1 Energy spectrum of gamma-rays from 55 μsec ^{127m}Cs.

TABLE I

Energies and relative intensities of transitions from ^{127m}Cs

(1) E_x keV	(2) Relative Intensities	(3) Assigned Multipolarity
30.6 ± 0.4		
35.2 ± 0.8		
65.9 ± 0.5	144 ± 15%	E2 (+ M1)
72.9 ± 0.8	71 ± 20%	
133.7 ± 0.3	119 ± 7%	
139 ± 1.0	30 ± 30%	
178.8 ± 0.3	533 ± 4%	M 2
206.0 ± 0.3	740 ± 4%	
385.5 ± 0.5	127 ± 10%	E 3

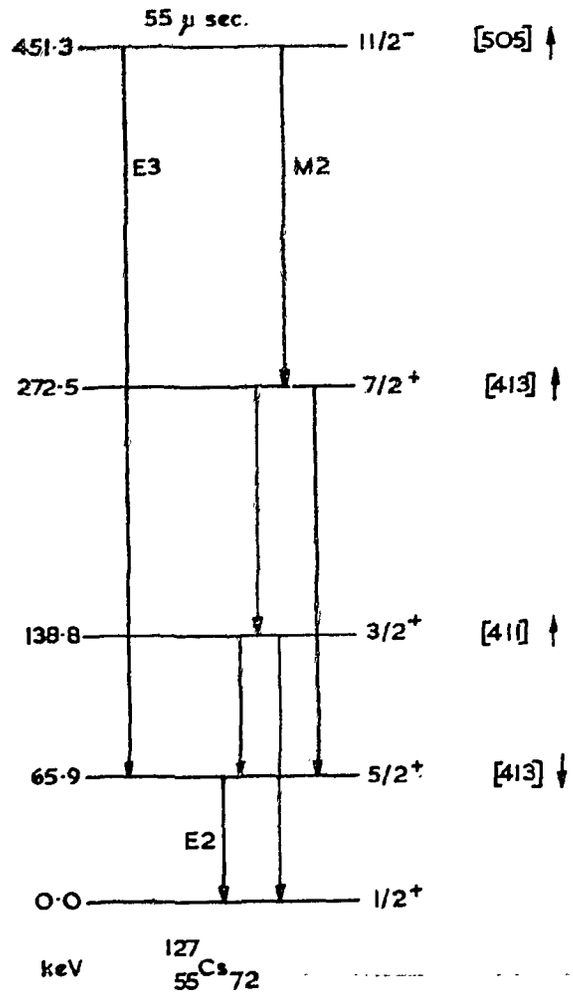


Fig. 2 Partial energy level diagram of ^{127}Cs showing levels involved in the isomeric decay of ^{127m}Cs.

The five lowest-lying states determined from the decay of the 55 μsec isomer (Fig. 2) have the same spin-parity as the five states to which the calculations refer. While the level order observed is not the same as that predicted, (and is not surpising, since the order depends on the actual magnitude of β) the experimental range of excitation energies over which the levels occur is 500 keV compared to their predicted 650 keV. It is felt that the overall agreement is very good and is an effective confirmation not only of the correctness of the theoretical procedures but also of the occurrence of oblate nuclear states in ^{127}Cs.

The two candidates for the $\frac{1}{2}^+$ ground state, which we discussed above, are [411]↓ or [420]↑, and, since reference 7 shows that the latter is expected at much lower excitation energy than the former, we prefer the [420] ↑ assignment. It has been noted above that the [420]↑ state has a prolate equilibrium deformation whereas the other four states correspond to an oblate shape. If our assignment to the ground state is correct then ^{127}Cs is the only known nucleus exhibiting well deformed prolate and oblate states. On this basis both the 65.9 keV and the 138.8 keV transitions *involve shape changes; indeed the branching ratio* from the 138.8 keV level is such that the 138.8 keV

transition appears to be retarded by about a factor of 50 (with respect to the single particle Weisskopf estimate). Unfortunately there is no theorectical estimate of how strongly hindered the transitions involved here should be.

An account of this work is being prepared for publication.

(3) A possible shape isomeric state in ^{214}Ra

A diagram from an earlier progress report showing the expected variation of nuclear binding energy with the deformation β in various regions of nuclei is reproduced in Fig. 3. Here Fig. 3(v) applies, for example, to the region Z > 50, N < 82 discussed in Section 2.

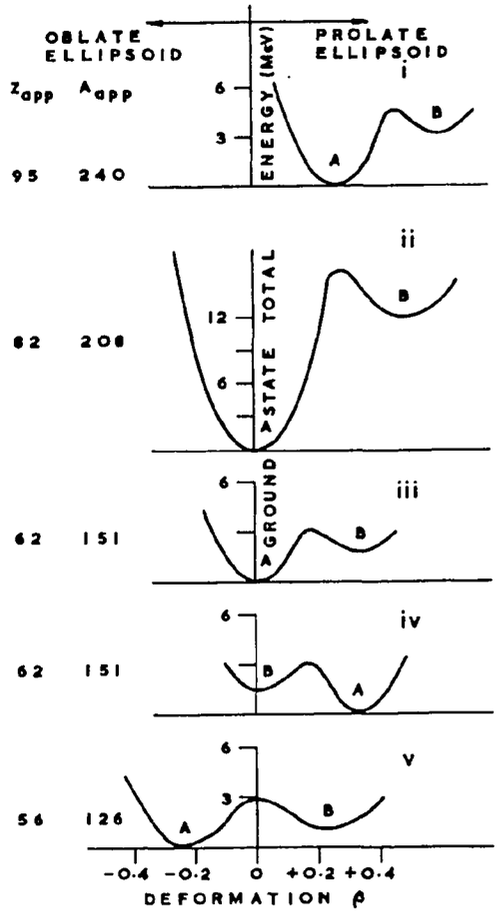


Fig. 3 Characteristic variation of nuclear binding energy with deformation, β, for particular combinations of N and Z

A wide variety of fissioning isomers are now known; these isomers are attributed to the decay of states in the second minium, B, of Figure 3(i) which refers to the actinide region. In this case fission through the outer barrier (to the right of B) is preferred to tunnelling through the inner barrier (between B and A) and consequent gamma-decay. The gamma-ray branch is so weak that it has not yet been observed from any known fissioning isomer. According to recent calculations[8] of barrier shapes, however, the relative heights of the barriers in some neutron deficient isotopes of the elements Z = 80 to 90 is such that the shape isomeric state is predicted to favour tunnelling through the inner barrier rather than fission. For these nuclei the equilibrium deformation is zero (i.e. they are spherical nuclei) and the situation is similar to that shown in Figure 3(ii) and (iii).

We have investigated these predictions, following a suggestion by J. E. Lynn[9], by using reactions of the form (p, Xn), (^{4}He, Xn) and (^{12}C, Xn) on selected targets in the region Z = 63-83 to produce a large number of the neutron deficient isotopes of Z = 80-88 nuclei; the thorium Z = 90 nuclei have not yet been investigated. A search for isomeric activity in the range 10^{-6} second to 1 second has been made, but the only isomer seen very strongly resulted from the 88 MeV ^{12}C pulsed beam bombardments of ^{206}Pb and ^{207}Pb. The final nucleus is identified as ^{214}Ra produced in the ^{206}Pb (^{12}C, 4n) ^{214}Ra and ^{207}(^{12}C, 5n)^{214}Ra reactions. The isomeric state has a half-life of 57 μsec and appears to decay via the emission of two gamma-rays of 180.4 keV and 256.6 keV in cascade. While the possibility of a third highly converted transition cannot be positively excluded, it can be shown by arguments based on the observed half-life and observed upper limit of the intensity of such a transition that it is a most unlikely possibility. An energy spectrum of gamma-rays from the isomeric state is shown in Fig. 4 in which the characterstic Ra x-rays are produced by internal conversion of the two gamma-rays and the Pb x-rays are produced mainly in the process of target alternation of the Ra K_α x-rays.

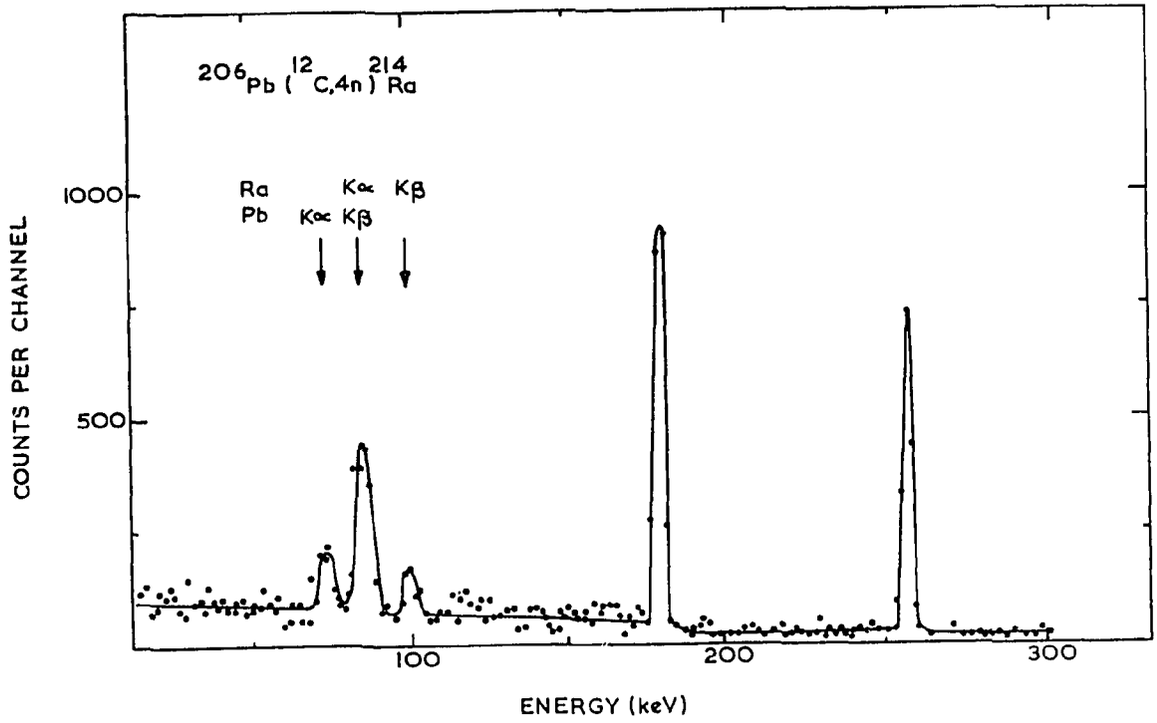


Fig. 4 Energy spectrum of gamma-rays from 57 μsec ^{214m}Ra.

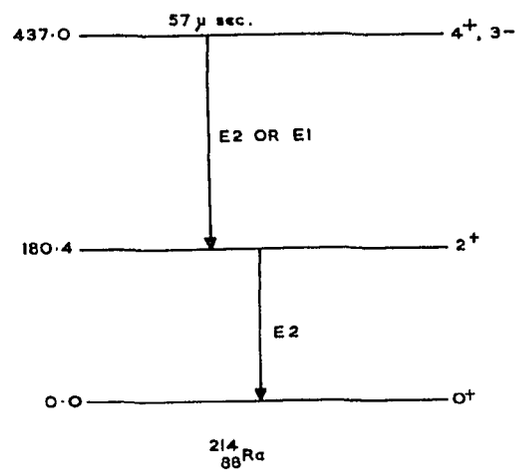


Fig. 5 Probable decay scheme of the ^{214}Ra Isomer.

From the observed relative intensities of the Ra x-rays and the two gamma-rays it is possible to put limits on the values of the K-shell and total conversion coefficients of the gamma-rays; in this way it can be shown that the 180.4 keV transition is E2 and the other transition E2 or E1. One transition presumably must be the first excited state to ground state ($2^+ \rightarrow o^+$) E2 transition in the ^{214}Ra even-even nucleus. On the basis of the systematics[10] of the energies of the known 2^+ states in other even-even Ra isotopes of mass number A = 228 to 220, the 180.4 keV transition is the more likely candiate for the $2^+ \rightarrow o^+$ assignment. In Fig. 5 the most likely decay scheme of the isomeric level is presented. The E2 or E1 nature of the 256.6 keV isomeric transition and the lack of a cross-over transition to the ground state demands a spin-parity assignment of 4^+ or 3^- for the isomeric level. (This assignment and the multipolarity of the isomeric transition is independent of which of the two gamma-rays is in fact the isomeric transition and which the actual $2^+ \rightarrow o^+$ transition).

The single particle estimate for an E2 and E1 transition of energy about 200 keV is 8×10^{-9} sec and 2×10^{-14} sec respectively; the observed half-life of 57 μs shows therefore that the transition is hindered by a factor of 7×10^3 if E2 and 3×10^9 if E1. Such a huge inhibition for an E2 transitions is most unusual and for an E1 transition has no known parallel, apart from the K-forbidden isomers in even nuclei found in well-deformed rare-earth nuclei, which, in any case, can only occur above the pairing

energy gap of 1-2 MeV. It would seem possible to explain the very long lifetime for this E2 or E1 transition if the state responsible corresponded to a state in the second minimum, B, of a potential similar to that shown in Fig. 3(ii) or (iii). However the occurrence of the state at such a low excitation energy, a mere 437.0 keV compared for example to the excitation energy of the known fissioning isomers, which is typically about 3 MeV, may cast some doubt on this interpretation. On the other hand the recent calculations of Tsang and Nilsson[8] not only predict that such gamma-ray shape isomerism should occur but note that the second minimum in certain neutron deficient Ra isotopes should have the smallest values for the energy difference of the two minima of any nuclei in this region.

---

(1) Conlon T. W. Nucl. Phys. A136, 70 (1969).

(2) Ward D., Diamond R. M. and Stephens F. S. Nucl. Phys. A117, 309 (1968) and references therein.

(3) Kumar K. and Baranger M. Phys. Rev. Letters 12, 73 (1964).

(4) Conlon T. W. and Elwyn A. J. Nucl. Phys. A142, 359 (1970).

(5) Alexander K. F. JINR Report No. P7-3185, also Nucl. Sci. Abs. 21, 13481 (1967).

(6) Lindgren I. Table of Nuclear Spins and Moments, Appendix 4, in "Alpha, Beta and Gamma-ray Spectroscopy" (North Holland, Amsterdam, 1965) Ed. K. Siegbahm.

(7) Arzeniev D. A., Sobiczewski A. and Soloviev V. G. Nucl. Phys. A126, 15 (1969).

(8) Tsang C. F. and Nilsson S. G. Nucl. Phys. A140, 275 (1970).

(9) Lynn J. E. Private Communication.

(10) "Table of Isotopes" (6th Ed. 1967) C. M. Lederer, J. M. Hollander and I. Perlman.

REPORTS, PUBLICATIONS AND CONFERENCE PAPERS

REPORTS

AERE - R 6039 — The total cross section of ^{234}U and the parameters of its sub-threshold fission resonances. G. D. James and G. G. Slaughter.

AERE - R 6074 — The neutron capture cross section of ^{238}U in the energy region 0.5 to 100 keV. M. C. Moxon.

AERE - R 6169 — A ^{3}He-^{4}He dilution refrigerator for nuclear orientation experiments at the 45 MeV Harwell Electron Linac. H. Postma.

AERE - R 6195 — The $^{31}P(n,n'\gamma)^{31}P$ reaction. B. H. Armitage, A. T. G. Ferguson, G. C. Neilson and W. D. N. Pritchard.

AERE - R 6316 — The ratio of the $^{6}Li(n,\alpha)$ to $^{10}B(n,\alpha)$ cross section from 10 eV to 80 keV and recommended values of the $^{10}B(n,\alpha)$ cross section. M. G. Sowerby, B. H. Patrick, C. A. Uttley and K. M. Diment.

AERE - R 6350 — *Structure in the fission cross section of* ^{235}U. B. H. Patrick, M. G. Sowerby and M. G. Schomberg.

MEMORANDA

AERE - M 2157 (revised) — Average fission cross sections and resonance integral contributions between 10 eV and 20 keV deduced from SCISRS data tapes. G. D. James and M. G. Schomberg.

PUBLICATIONS

ASAMI A. and MOXON M. C. The low energy scattering cross section of ^{10}B. J. Nuc. Energy 24, 85, (1970).

ARMITAGE B. H., FERGUSON A. T. G., NEILSON G. C. and PRITCHARD W. D. N. Energy levels of ^{56}Fe: the $^{56}Fe(n,n'\gamma)^{56}Fe$ reaction and the γ-spectrum of ^{56}Co. Nuc. Phys. A133, 241 (1969).

CONLON T. W. Three quasi-particle states in the decay of the new isomer ^{181}Re. Nuc. Phys. A136, 70 (1969).

CONLON T. W. and ELWYN A. J. Isomeric states in the region Z>50, N<82 produced in (^{12}C,Xn) reactions. Nuc. Phys. A142, 359 (1970).

ELWYN A. J. and FERGUSON A. T. G. Short lived fission isomers from neutron studies. Nuc. Phys. A148, 337 (1970).

JAMES G. D. and SLAUGHTER G. G. The total cross section of ^{234}U and the parameters of its sub-threshold fission resonances. Nuc. Phys. A139, 471 (1969).

JAMES G. D. Pulsed neutron research - survey. Encyclopaedic dictionary of physics. J. Thewlis (Ed) Supplementary Vol. III p. 326 (Pergamon Press, Oxford, 1969).

STEIN W. E., THOMAS B. W. and RAE E. R. Gamma-ray spectra of ^{64}Cu and ^{66}Cu following resonant neutron capture. Phys. Rev. C, No. 4, 1468 (1970).

IN COURSE OF PUBLICATION

COOKSON J. A. and LOCKE J. G. Elastic and inelastic scattering of 9.72 MeV neutrons by ^{10}B and ^{11}B. Nuclear Physics.

CONLON T. W. Evidence for states of prolate and oblate deformation and for shape isomerism in ^{127}Cs.

CONLON T. W. A possible shape isomeric state in ^{214}Ra.

PATRICK B. H., SOWERBY M. G. and SCHOMBERG M. G. Structure in the fission cross section of ^{235}U. J. Nuc. Energy.

SOWERBY M. G., PATRICK B. H., UTTLEY C. A. and DIMENT K. M. The ratio of the $^{6}Li(n,\alpha)$ to $^{10}B(n,\alpha)$ cross section from 10 eV to 80 keV and recommended values of the $^{10}B(n,\alpha)$ cross section. J. Nuc. Energy.

WINHOLD E. J., BOWEY E. M., GAYTHER D. B. and PATRICK B. H. Structure in the gamma ray strength of ^{119}Sn and ^{117}Sn. Physics Letters.

CONFERENCE PAPERS

Invited Papers

JAMES G. D. Cross sections of the heavy nuclei in the resonance region. Second Int. Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970.

LYNN J. E. Intermediate structure in sub-threshold fission. Amer. Phys. Soc. Meeting New York, February 1969.

LYNN J. E. Structure phenomena in near-barrier fission reactions. IAEA Symp. on Physics and Chemistry on Fission, Vienna, July 1969.

LYNN J. E. Progress in understanding neutron interactions with nuclei. Second Int. Conference on Nuclear Data for Reactors, Helsink, 15-19 June 1970.

RAE E. R. Intermediate structure effects in neutron-induced fission cross sections. Proc. IAEA Panel on Future of Nuclear Structure Studies, Dubna, July 1969.

Contributed Papers

International Conference on Heavy Ion Reactions, Heidelberg, July 1969

CONLON T. W. and ELWYN A. J. Isomeric states in the region $Z>50$, $N<82$ produced in $(^{12}C,Xn)$ reactions.

IAEA Symposium on the Physics and Chemistry of Fission, Vienna, July 1969

ELWYN A. J. and FERGUSON A. T. G. Spontaneous fission in the neutron bombardment of uranium isotopes.

JAMES G. D. and PATRICK B. H. Correlation analyses of the total and fission cross sections of ^{239}Pu.

PATTENDEN N. J. Note on fission of oriented ^{235}U.

International Symposium on Neutron Capture Gamma-ray Spectroscopy, Studsvik, 11-15 August 1969

MURRAY J., THOMAS B. W. and RAE E. R. Some statistical properties of partial radiation widths in tungsten.

IPPS Conference, Guildford, April 1969

THOMAS B. W., MURRAY J. and RAE E. R. Investigation of the low lying levels of ^{239}U by means of the ^{238}U(n,γ)^{239}U reaction.

Second International Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970

ASAMI A. and MOXON M. C. Low energy neutron scattering cross section of ^{6}Li.

COATES M. S., HUNT G. J. and RAE E. R. A neutron detector with a flat energy response for use in time of flight experiments.

MOXON M. C. Neutron capture cross section of structural and cladding materials in the energy range 1-100 keV.

SOWERBY M. G., PATRICK B. H., UTTLEY C. A. and DIMENT K. M. A measurement of the ratio of the ^{6}Li(n,α) and ^{10}B(n,α) cross sections from 10 eV to 80 keV and recommended values of the cross sections up to 200 keV.

SOWERBY M. G. and PATRICK B. H. A simultaneous evaluation of the fission cross sections of ^{235}U, ^{239}Pu and ^{238}U and the capture cross section of ^{238}U in the energy range 100 eV to 20 MeV.

SOWERBY M. G., SCHOMBERG M. G., BOYCE D. A., MURRAY K. J. and SUTTON D. L. (Miss). The ratio of the capture and fission cross section of ^{239}Pu in the energy range 100 eV to 30 keV.

THOMAS B. W., MURRAY J. and RAE E. R. Observation of an isomeric level in ^{239}U by means of the ^{238}U(n,γ)^{239}U reaction.

UTTLEY C. A. and DIMENT K. M. The analysis of the total cross section of carbon from 0.07 to 1500 keV.

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

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

The measurement of half-lives by gamma-ray spectrometry (M. J. Cabell and M. Wilkins)

It has been shown recently (D. C. Robinson, AERE Report R 5911 (November, 1968), M. J. Cabell and M. Wilkins, AERE Report R 6303 (June, 1969)) that the common method of determining radioactive half-lives by fitting a straight line to a plot of the logarithm of the decay rate versus time by the method of least squares yields results which depend on the period of time during which the decay data were accumulated. It has also been shown that this linear transformation may of itself result in biased estimates of the time values. These difficulties are overcome if an exponential fit is made directly to the untransformed decay curve, and if the squares of the residuals are weighted proportionally to the reciprocals of the variances of the fitted data points. The problem then becomes non-linear and the calculations can only proceed by iteration, so that a digital computer may be necessary to obtain the desired accuracy. Absolute results are obtained when the data analysed are taken over three half-lives or more. Additional data points then serve to increase the precision of the result without affecting its absolute value.

These principles have been applied to the determination of the half-lives of ^{198}Au and of the ground state of ^{148}Pm by gamma-ray spectrometry.

Two unbiased estimates gave the half-life of ^{198}Au as 2.6948 ± 0.0014 days and 2.6944 ± 0.0013 days respectively, and corresponding values of 5.369 ± 0.012 days and 5.372 ± 0.014 days were obtained for ^{148}Pm. Taking the weighted means of these pairs it was concluded that the half-lives of ^{198}Au and ^{148}Pm are 2.6946 ± 0.0010 days and 5.370 ± 0.009 days respectively.

The absolute determination of ^{148g}Pm by gamma-ray spectrometry and a measurement of the emission probability of its 1.465 MeV gamma-ray (M. J. Cabell and M. Wilkins)

The cross section of the reaction ^{147}Pm(n,γ)^{148g}Pm is at present uncertain. For example, values as different as 124 ± 13 barns, 105 ± 5 barns and 82 ± 8 barns have been quoted for 2200 m/sec neutrons. In an attempt to improve this situation new activation measurements have been undertaken. The calibration of a γ-counter for the absolute determination of ^{148g}Pm by counting the 1.465 MeV γ-photons emitted in its decay was a necessary preliminary step.

A sample of ^{147}Pm was irradiated for five days in a high-flux position of the PLUTO reactor. After purification by cation exchange chromatography a stock solution was then prepared which consisted of a mixture of ^{147}Pm, ^{148g}Pm, ^{148m}Pm and ^{149}Pm. Aliquots were taken from this stock and their activities were determined as a function of time by (a) counting the β^- particles emitted, using a $4\pi\beta^-$-γ coincidence counter and by (b) counting the 1.465 MeV γ-photons emitted, using a γ-ray spectrometer.

The gross β^- decay curves were analysed by the method of weighted least squares (a Fortran program for the Harwell IBM 360/75 was especially written for this purpose) and the absolute disintegration rates of the ^{148g}Pm in the sources were derived. By combining this data with the results of the γ-spectrometry, the γ-counter was calibrated for determining ^{148g}Pm absolutely with an accuracy of ± 0.8 per cent.

With the same geometry as in the above, the response of the γ-counter to a known number of 1.465 MeV γ-photons was also determined by using a set of IAEA standard sources. From a comparison of the two results it was concluded that the probability that a 1.465 MeV γ-photon is emitted in the β^- decay of ^{148g}Pm was 0.222 ± 0.005 per disintegration. Previous measurements have given this quantity as 0.25, 0.35, 0.27 ± 0.05 and 0.24 ± 0.04.

PUBLICATIONS

CABELL M. J. and WILKINS M. Gamma-ray spectrometric measurements of the capture cross section of gold-198 for reactor neutrons. J. Inorg. and Nucl. Chem., 31, pp. 1229-1240, 1969.

CABELL M. J. and WILKINS M. The half-life of ^{198}Au and the measurement of half-lives by gamma-ray spectrometry. AERE - R 6063 (H.M.S.O. June 1969).

CABELL M. J. and WILKINS M. The half-lives of ^{198}Au and ^{148}Pm and the measurement of half-lives by gamma-ray spectrometry. J. Inorganic & Nuclear Chemistry, 32, pp. 1409-1412, 1970.

CABELL M. J. and WILKINS M. Some recent Harwell measurements of neutron capture cross sections by activation and mass spectrometric methods. AERE - R 6384 (H.M.S.O., May 1970).

CHEMISTRY DIVISION, A. E. R. E.

(Division Head: Dr. W. Wild)

V.E.C. Experiments

Measurements of Coulomb Distortion by Heavy Ion Scattering (J. G. Cuninghame and A. M. Friedman (Argonne National Laboratory))

Various theoretical calculations have indicated that in heavy ion reactions the distortion of the target and projectile nuclei by their coulomb fields may change the effective nuclear radii by as much as 30%. Since a change as large as this has a considerable effect on the cross-section for forming super-heavy nuclei by use of heavy-ion reactions, it would be of great value to test these theoretical calculations. One simple method of determining this change is to study the elastic scattering of heavy ions both by nuclei which are easily deformed and by those that are not. The experiment consists of studying the angular distribution of elastically scattered C and N ions from the V.E.C. by targets of Pb, Nd, Sm and Gd isotopes.

Information on coulomb distortions will be of great value in deciding the minimum beam energy needed for the production of isotopes by any heavy ion reaction, and it will be extremely useful to take the effect into account when deciding on any heavy ion experiment with the V.E.C.

Fission measurements (J. G. Cuninghame and I. F. Croall)

Because of pre-emption of the V.E.C. for metallurgical studies only six runs have been possible during this period. Kinetic energy spectra of pairs of fission fragments in coincidence have been measured for fission of ^{206}Pb and ^{209}Bi by protons and ^{4}He ions of various energies, in continuation of the work on the effects of change in angular momentum on the kinetic energy and mass distributions of fission fragments. This work has opened up the possibility of measuring mass yields in tailored neutron spectra required for the Fast Reactor programme, by means of a low energy neutron source on the V.E.C.

Mass Spectrometry (E. A. C. Crouch, I. C. McKean and M. Brownsword)

Half-Life of ^{241}Pu

Reports from the U.S.A. of the possible existence of a short-lived species of ^{241}Pu has prompted collaboration with Nuclear Physics Division in the pile irradiation of separated ^{240}Pu and the examination of the "young" ^{241}Pu so formed. Previous work (Cabell, J. Inorg. Nucl. Chem. 30 (1968) p. 2583) on the half-life of "old" ^{241}Pu, and on the prolonged irradiation of ^{239}Pu (AERE - R 6041), provided evidence for the existence of two isomers of ^{241}Pu combining to give an apparent half-life depending on the "age" of the ^{241}Pu.

About 5 mgm ^{240}Pu were irradiated at the maximum obtainable flux in PLUTO to give ~40% ^{241}Pu in the product, which was then purified from fission products and other heavy elements for examination of its γ-emission and fission cross-section in Nuclear Physics Division.

The decay of the freshly prepared ^{241}Pu has been watched by regular mass-analysis after chemical removal of ^{241}Am. No obvious short-lived isomers of ^{241}Pu have been observed and on the basis of results to date no more than some 1% or so of such an isomer could exist. The half-life of ^{241}Pu observed so far is 14.2±0.7 yr. which is consistent with the results obtained on the same sample by Nuclear Physics Division by γ-emission methods.

National Isotopic Composition of Natural Molybdenum

Work on the $^{94}Mo/^{98}Mo$ mixtures has continued as machine availability allowed, in an attempt to discover whether it is really necessary to purify the separated isotopes, the constituents of the

synthetic mixtures. Because separated isotopes are expensive and available only in limited amounts, chemical purification and preparation in stoichiometric form presents difficult problems, and if it were possible to calibrate synthetic mixtures knowing only the relative proportions of the components this purification would be unnecessary. Formally the appropriate equations have solutions, and work is continuing.

Delayed Neutron Emission from Fission Product Selenium and Tellurium (L. Tomlinson and M. H. Hurdus)

The experiments on delayed neutron emission from selenium isotopes are now completed. The data obtained are being processed prior to writing up.

In the final series of experiments, the time for separation of fission product selenium was reduced to 1.0 sec. By combining this fast chemistry with an irradiation time of 0.5 sec., it was possible to reduce the contributions of longer-lived selenium isotopes and allow ^{89}Se to be detected. This is another new selenium isotope. It was found to have a half-life of about 0.5 sec. and a neutron branching ratio of approximately 6%.

The fission rate used in these experiments has been measured by separation of ^{140}Ba and by cobalt flux monitors. This should allow the fission yields of $^{87-89}Se$ to be obtained from the experimental data.

Exploratory work is in progress to determine whether fission product tellurium can be separated by isotopic exchange with hydrogen telluride gas.

Delayed Neutrons (Fission Product Emission)

Selenium Fission Products (L. Tomlinson and M. H. Hurdus)

The data processing for this work is almost complete. The work will be written up as soon as time permits. The final results are as follows (errors are 1 standard deviation, where they have been calculated):

	Half-life (sec)	Delayed neutron branching ratio %		Cumulative fission yield %	
		Exp.	Theory	Exp.	Theory
^{87}Se	5.41 ± 0.05	0.16 ± 0.03	1	0.60	0.69
^{88}Se	1.53 ± 0.05	0.75 ± 0.06	2.5	0.37	0.32
^{89}Se	0.41 ± 0.03	5.0 ± 1.5	6	0.11	0.10

For ^{87}Se and ^{88}Se the experimental delayed neutron branching ratios are smaller than predicted - indicating that many levels in the emitter, above the neutron binding energy, are de-exciting by gamma rather than neutron emission. The agreement between the measured fission yields and those calculated from the latest Wahl charge distribution formula (A.C. Wahl et al., 2nd Symposium on the Physics and Chemistry of Fission, I.A.E.A. (1969) page 813) is very good indeed, showing that the Zp's and Gaussian width parameters for these chains are about right.

PUBLICATIONS

Conference Papers

Dependence of fragment total kinetic energy and mass distribution on the excitation energy and angular momentum distribution of the fissioning nucleus ^{210}Po. J. P. Unik, J. G. Cuninghame and I. F. Croall. 2nd Symposium on the Physics and Chemistry of Fission, IAEA Vienna 1969. Paper SM 122/58.

Techniques used in on-line fission experiments with the V.E.C. I. F. Croall and J. G. Cuninghame. Proc. Oxford Cyclotron Conference, 1969.

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

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

Neutron Scattering by Mo (D. Porter and R. E. Coles)

The time of flight method has been used to study fast neutron elastic and inelastic scattering in the energy range 1.0 to 5.0 MeV by natural molybdenum. Differential cross-sections at 10 angles from 30-135° were measured at 0.5 MeV intervals for elastic scattering and inelastic scattering to groups of levels up to 1.6 MeV excitation in the target and inelastic scattering to a continuum above 1.6 MeV excitation. Excitation functions were derived from 125° yields measured at 0.2 MeV intervals between 1.0 and 3.0 MeV.

The continua spectra in the range 2.0 to 5.0 MeV have been analysed in terms of statistical evaporation theory and parameters describing secondary energy distributions of the continua scattered neutrons are extracted.

A report on this work is almost complete.

Neutron Scattering by Na (D. Porter and R. E. Coles)

Analysis of data obtained at 5.0 MeV incident energy is in progress. Differential cross-sections at 10 angles between 30° and 135° of the elastic and inelastic to groups at 0.439 MeV, 2.08, 2.39, 2.68, 2.98, 3.68 and 3.88 MeV will be obtained.

Neutron Scattering by ^{93}Nb (D. Porter and R. E. Coles)

Experimental results similar to those for Mo have been obtained, but the data are awaiting analysis.

(n,n'γ) Reactions in ^{51}V and ^{89}Y (D. Porter, R. E. Coles and W. B. Gilboy*)

A paper with the following abstract will be published as an AWRE report.

"The AWRE 6MV Van de Graaff generator has been used to study (n,n'γ) reactions in ^{51}V and ^{89}Y for incident neutrons in the energy range 0.3 to 4 MeV. A 20 cc Ge(Li) spectrometer was used to detect de-excitation γ-rays following inelastic scattering from samples in ring geometry. In all, 33 transitions in ^{51}V and 15 in ^{89}Y were observed and production cross-sections for these γ-rays, at a mean angle of 100°, were derived as functions of incident neutron energy.

Improved decay schemes, branching ratios and level energies are presented and, where knowledge of these and appropriate γ-ray angular distributions permit, comparisons with the predictions of Hauser-Feshbach theory modified for level width fluctuations are made.

Spin assignments of recent work are confirmed and possible assignments for other levels observed are discussed."

$\bar{\nu}$-measurement of Pu^{239} (D. S. Mather, P. F. Bampton, G. James and P. J. Nind)

This work is now complete and an AWRE report with the following abstract will be issued shortly.

"A large liquid scintillator counter has been used to measure average values of prompt $\bar{\nu}$ for the neutron induced fission of Pu^{239} over 11 energy bands below 1.2 MeV. The energy bands were 40-115, 115-285 and 100 keV wide from 300 keV to 1.2 MeV. The relative accuracy was 1%."

---

*Now at University of Surrey.

Measurement of (n,2n) cross-sections (D. S. Mather, G. James and P. J. Nind)

Using the large liquid scintillator measurements have been made on thulium, rhodium and niobium at 14.1 MeV with a 160 keV energy spread. Preliminary values are 2.1, 1.6 and 1.5 b, respectively, the error being ±10%.

Neutron cross-section measurements using neutrons from nuclear explosions (A. Moat)

The 90^0 Pu 238 (n,f) data measured by the AWRE team have been sent to LASL for detailed comparison with their data. One adjustment may still be required to a routine which removes a small amplitude ringing effect. A joint paper on these results is now at an advanced stage. The 55^0 data have some problem areas which are giving difficulty, although the overall picture is of fair agreement with 90^0 data. Work on the 55^0 problems has been hampered by the lack of a working assessor machine: the Mark II assessor has recently been delivered, but is not yet operational.

Evaluation of the neutron cross-sections of carbon (D. Porter and K. Wyld)

An evaluation of the cross-sections and angular distributions for total, elastic and inelastic scattering of neutrons from natural carbon in the energy region leV to 15 MeV has been made. Data have been produced from semi-automatic fits to edited experimental cross-sections, which for the angular distributions of the elastics, eye-fits were made to the Legendre polynomial coefficients of these distributions as functions of incident energy guided where necessary by theoretical estimates. Compared with the existing UKAEA data file, the present total cross-section is slightly lower below 2 MeV and there are significant changes in the inelastic cross-section to the first excited state in ^{12}C below 9 MeV.

Fission Parameter Evaluations (D. Mather and P. Bampton)

Evaluation of $\bar{\nu}$ (E) values for Pu^{239} up to 14 MeV is presently in progress. Also in progress and in collaboration with Sowerby and Patrick of AERE, Harwell, is a simultaneous evaluation of σ_{nf} for U^{235}, U^{238} and Pu^{239} and $\sigma_{n\gamma}$ for U^{238}, all as functions of incident neutron energy.

The SCORE Programme (J. Cameron)

SCORE has been further developed. In particular output is now available in the format of the UK nuclear data library.

PUBLICATIONS

1. P. H. White: Alpha and Fission Counting of Thin Foils of Fissile Material. Nuclear Instruments and Methods 79 (1970) 1.

2. J. A. Cookson and J. G. Locke: Elastic and Inelastic Scattering of 9.72 MeV neutrons by ^{10}B and ^{11}B. Nuclear Physics A146 (1970) 417.

3. D. Porter, R. E. Coles and K. Wyld: Elastic and Inelastic Scattering of neutrons in the energy range 2-5 MeV by ^{10}B and ^{11}B. AWRE 0 45/70.

DIVISION OF RADIATION SCIENCE, NATIONAL PHYSICAL LABORATORY

(Superintendent: Dr. P. J. Campion)

Thermal Neutron Capture Cross Sections (T. B. Ryves)

The activation measurements were made in the known flux and spectrum of the NPL standard thermal neutron flux. The measured 2200 ms^{-1} cross-sections and reduced resonance integrals (less i/v part) I^1 are given in the Table, and are relative to $Au\sigma_0 = 98.8 \pm 0.3b$ and $I^1 = 1514 \pm 60b$. Random errors have been calculated at a 99% confidence limit from the standard errors on the mean, and are added linearly to the estimated systematic errors to give the overall errors.

Reaction	Half-life	σ_0 barns	I^1 barns
$^{23}Na\ (n,\gamma)^{24}Na$	15.0h	$0.527 \pm 0.004_5$	0.080 ± 0.012
$^{27}Al\ (n,\gamma)^{28}Al$	2.25m	0.230 ± 0.004	0.066 ± 0.009
$^{37}Cl\ (n,\gamma)^{38}Cl$	37.3m	0.433 ± 0.006	0.12 ± 0.06
$^{51}V\ (n,\gamma)^{52}V$	3.77m	4.88 ± 0.04	0.48 ± 0.09
$^{69}Ga\ (n,\gamma)^{70}Ga$	21.1m	1.68 ± 0.07	14.8 ± 1.5
$^{71}Ga\ (n,\gamma)^{72}Ga$	14.1h	4.71 ± 0.23	29.1 ± 2.9
$^{75}As\ (n,\gamma)^{76}As$	26.5h	4.48 ± 0.11	59 ± 6
$^{89}Y\ (n,\gamma)^{90}Y$	64h	1.21 ± 0.05	0.44 ± 0.06
$^{107}Ag\ (n,\gamma)^{108}Ag$	2.39m	37.2 ± 1.2	77 ± 5
$^{109}Ag\ (n,\gamma)^{110m}Ag$	255d	4.72 ± 0.21	-
$^{139}La\ (n,\gamma)^{140}La$	40.2h	9.03 ± 0.33	7.5 ± 0.8
$^{151}Eu\ (n,\gamma)^{152m}Eu$	9.3h	2620 ± 240	-
$^{196}Pt\ (n,\gamma)^{197}Pt$	18h	0.74 ± 0.08	8 ± 2
$^{198}Pt\ (n,\gamma)^{199}Pt$	30m	3.66 ± 0.19	54 ± 6

Measurement of $\bar{\nu}$ for spontaneous fission of ^{252}Cf (E. J. Axton, B. N. Audric and A. G. Bardell)

Measurements have now been made with both old and new samples of ^{252}Cf, the latter containing a higher proportion of ^{252}Cf relative to the other californium isotopes. The results with the new sample appear to lie up to one per cent higher than those with the old sample, giving a value for $\bar{\nu}$ of about 3.72. It is planned to measure one more modern sample and to repeat the measurement of the old sample before issuing a final report.

Attempts to compare fission counting with Argonne National Laboratories, USA failed because no design of source was suitable for the different techniques used at the two laboratories. A similar exercise with the Research Institute of National Defence, Stockholm failed because the gating system employed by this laboratory does not permit absolute measurement of the fission rate of a sample.

The old sample of californium referred to above, is now in the custody of its owners, BCMN Euratom. The sample is in the form of a dilute solution of californium chloride in hydrochloric acid. Comparison of the fission rate per mg of aliquots of this solution are in progress between BCMN and NPL.

Intermediate Energy Neutron flux Measurements and Long Counter Calibration (J. B. Hunt, J. C. Robertson and T. B. Ryves)

The responses of the NPL and the De Pangher long counters have been compared with that of a collimated Vanadium Sulphate bath detector over the energy range 150 keV to 650 keV using the 0° yield of neutrons from the $^{7}Li(p,n)^{7}Be$ reaction. The results indicate that the long counter response is independant of energy to within ± 2% (Standard error) over the indicated energy range. The absolute efficiency of the long counter has been determined by means of calibrated NaBe - Sb-Be neutron sources and this will be compared with the efficiency as measured by absolute counting of the residual ^{7}Be target activity.

Intermediate Energy Neutron Reaction Cross-Sections (J. B. Hunt, J. C. Robertson and T. B. Ryves)

Work is in progress to measure the n,γ capture cross section of In, I and ^{238}U by activation techniques at a number of energy points in the range 150 keV to 650 keV. No results are available at present.

Fast Neutron flux and Cross Section Measurements (J. C. Robertson, B. N. Audric)

A recoil proton monitor is used to measure neutron flux at energies in the neighbourhood of 14 MeV. Subsequently the method will be compared with the associated particle counting technique. Work is in progress to measure the cross section for the $^{56}Fe(n,P)^{56}Mn$, $^{27}Al(n,\gamma)^{24}Na$, and $^{27}Al(n,P)^{27}Mg$ reactions. These cross sections have been selected as standards since the product activities can readily be measured to high accuracy, and both ^{56}Mn and ^{24}Na have been the subject of international intercomparisons. The excitation functions of these reactions are being measured.

GLASGOW UNIVERSITY (KELVIN LABORATORY)

ELECTRON LINEAR ACCELERATOR

(Director: Prof. G. R. Bishop)

The accelerator is powered by three klystrons (TV2011; frequency 2856 MHz; 20 megawatt peak power) and delivers a beam of 250 mA peak current at energies up to 110 MeV. Pulse durations from 3 microseconds to 3.5 nanoseconds are available. At the lower end of this range there is effectively no beam loading and energies up to 135 MeV are available.

The experimental programme is devoted to low energy nuclear structure and includes provision for photoneutron and neutron scattering time of flight studies. Seven flight paths, 20 metres long, radiate from a neutron target cell and cover laboratory angles from 42° to 156° with respect to the incident electron beam. One of these flight paths (72°) extends to 100 metres.

Inelastic Neutron Scattering (G. I. Crawford and J. D. Kellie)

The reaction $Al^{27}(n,n'\gamma)Al^{27}$ has been studied over the neutron energy range from 1 to 9 MeV. The unique feature of this experiment is the measurement with high energy resolution of the inelastic cross sections simultaneously over the whole of this energy range. At those particular energies where comparison with other work is possible the cross sections agree with previous results.

A 3 ns pulse of electrons with p.r.f. of 480 Hz strikes a thick lead target, producing neutrons and photons. To minimise background from the prompt gamma rays, a flight path at 142° to the electron direction was used and the radiation filtered with 5 cm of lead. The Al scatterer was 15 cm in diameter, 5 cm thick and was at 25.9 m from the lead target. A 10 cm diameter by 10 cm high NaI(Tl) detector was placed at 30 cm from the scatterer and a liquid scintillator at 29 m from the lead radiator monitored the neutron flux. The energy of the γ ray and the time of flight of the neutron were obtained for each event and the resulting information was collected, sorted and stored by the two parameter analysis programme developed for the PDP-7.

The production cross sections for the 0.84, 1.01 and 2.21 MeV de-excitation γ rays are shown in Figures 1 to 4. Also included are the measurements of other authors, and in Figure 3 the theoretical determinations of the cross section for exciting the 0.84 and 1.01 MeV levels. Of the three calculations, which are (a) Hauser-Feshbach, (b) width fluctuations with level repulsion, and (c) width fluctuation assuming a Porter-Thomas distribution of reduced widths, it is seen that between 2 and 3 MeV neutron energy (b) is in best agreement with the data.

Estimates of $<\Gamma>$, the average total width of the compound nucleus states in Al^{28*}, have been obtained by calculating auto correlation functions $R(\epsilon)$ for the 0.84 and 1.01 MeV level excitation functions. An average value of $<\Gamma> = 32.5 \pm 5$ keV is found for an incident neutron energy of 2 MeV, which is consistent with Ericson's predictions. The ratio $<\Gamma>/D$, obtained from a Hauser-Feshbach calculation, takes values of 2.1 ± 0.3 at 12.7 MeV, of 2.9 ± 0.1 at 13.7 MeV and 5.7 ± 0.5 at 14.7 MeV in the excited compound nucleus Al^{28*}.

From an examination of the cross section it is apparent that the fine structure, analysed in terms of Ericson fluctuations, is superimposed on a modulated background. The 0.84 and 1.01 MeV excitation functions, energy-averaged with an interval of 150 keV, are given in Figures 5 and 6. It is clear that there is a correspondence in the positions of the modulations between the cross sections for these two inelastic channels. Similar structure found in other partial cross sections has been attributed to Doorway States.

Intermediate Structure in Neutron Scattering (S. J. Hall, J. McKeown and H. R. Siddique)

Data have been taken on the elastic scattering of fast neutrons by Ca^{40} to extend the angular range examined, and analysis of the results made. Monitoring of the incident neutron flux on the scatterer is the principal problem in relating the runs at various angles. Cross checks on background conditions and timing were obtained by intercomparison of four different monitors

(1) The charge in the beam pulse from the linac was measured using a fast non-intercepting toroid

(2) The charge deposited on a Lead neutron radiator was integrated and stored in the PDP-8

(3) A thin sheet of polythene was inserted in the path of the neutrons before they reached the calcium scatterer. Neutrons scattered from the beam were viewed with a plastic scintillator

(4) The final data were obtained in three runs, three of the detectors being moved to different angles after each, one remaining fixed to provide overlap data for each set of angles. These monitors agreed with each other and each showed excellent linearity.

The experiment was performed to study fluctuations and demonstrate the existence of Doorway States in Ca^{40}. Below the first excited state at 3.35 MeV, we expect that the addition of a fast neutron results in a compound nucleus with only elastic and radiative capture exit channels, the latter being small enough to be negligible. Thus the high resolution cross section measurements of this study are averaged over suitable energy ranges to detect the presence of substructures with widths of the order of 100 keV. Two of these appear at 1.2 MeV and 1.8 MeV, and the object of further analysis is to determine the spin and parity of these structures and compare with theoretical expectations of the shell model structure of two particle-one hole states at the excitation energies in question. The early analysis of the raw data into cross sections was made with the advanced software package of the PDP-7 computer. Some time was spent on enabling this system but it did not fulfil all of the expectations. The energy averaging and angular distribution fits are now made on the PDP-10. Comparison with the previously existing data over limited energy ranges is excellent, as shown in Figure 7 for angular distributions of scattered neutrons.

Analysis programmes run on the PDP-10 have allowed for effects of multiple scattering in the calcium sample, and check that the absolute cross section figures obtained are accurate by comparison with neutron scattering from carbon, performed with the same apparatus.

A phase shift analysis of the differential cross sections thus obtained shows that the Doorway State interpretation is of only limited value in the interpretation of the origin of energy averaged ($\simeq$100 keV bin width averaging) cross section fluctuations. While an assignment of spin and parity could be achieved for the lower of the two substructures observed, the upper one proved less susceptible of analysis. A detailed study will appear shortly.

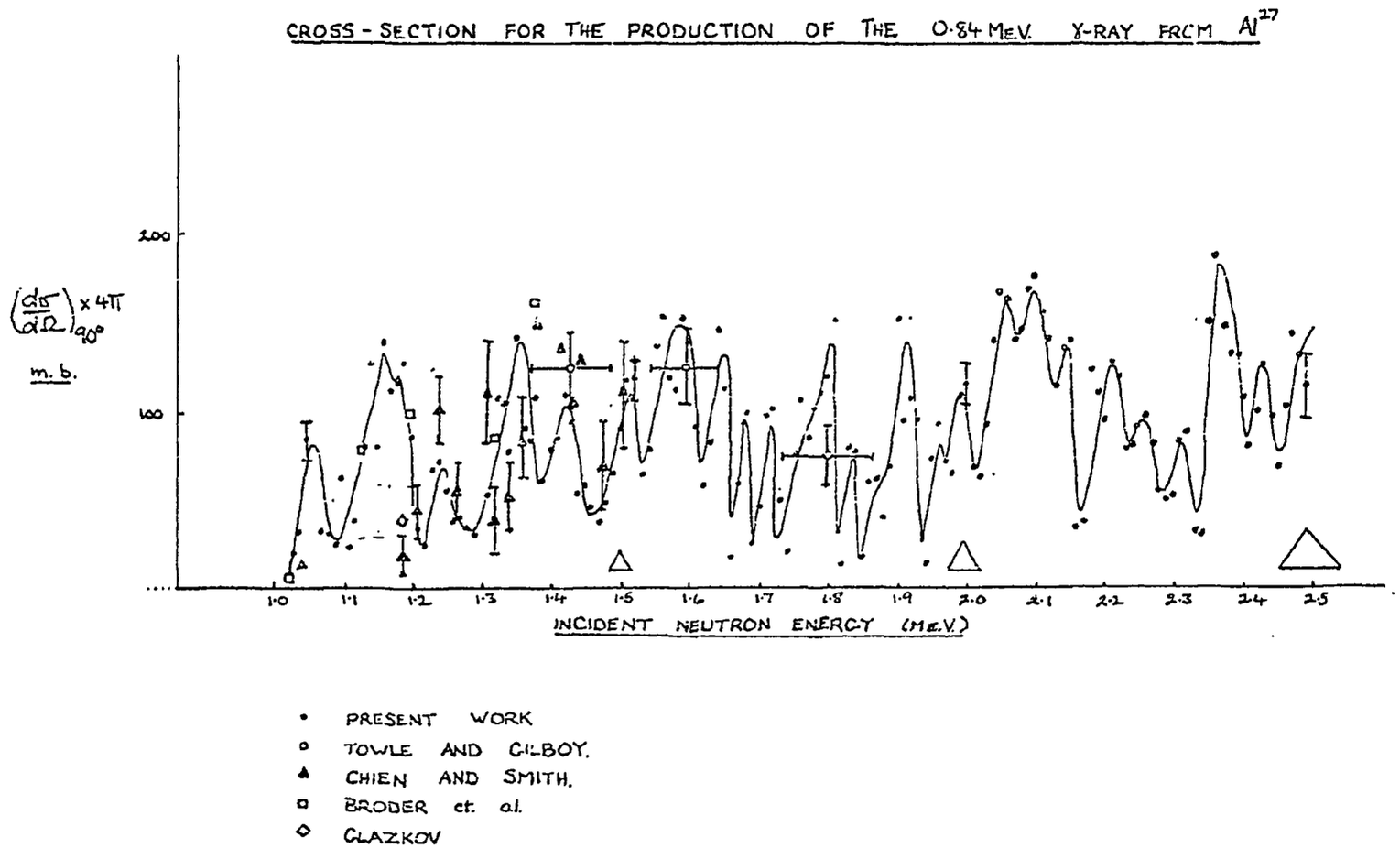
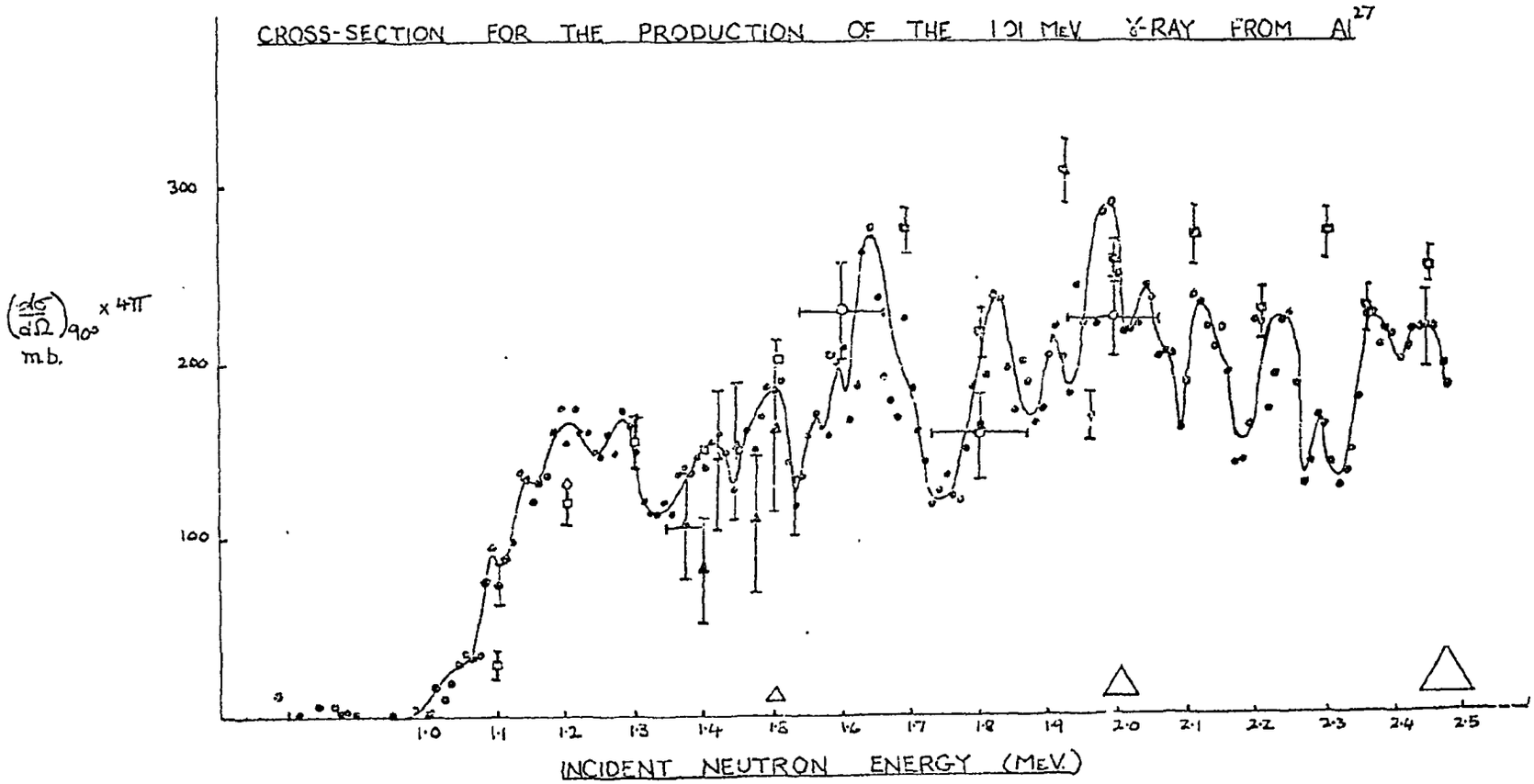

CROSS - SECTION FOR THE PRODUCTION OF THE 0·84 MeV. γ-RAY FROM Al27
(dσ/dΩ)90° x 4π
m. b.
200
100
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
1·8
1·9
2·0
2·1
2·2
2·3
2·4
2·5
INCIDENT NEUTRON ENERGY (MeV.)
PRESENT WORK
TOWLE AND GILBOY.
CHIEN AND SMITH.
BRODER et. al.
GLAZKOV

Fig. 1

DIAG 5·13



- ● PRESENT WORK
- ○ TOWLE AND GILBOY
- △ CHIEN AND SMITH.
- □ BRODER et. al.
- ◇ GLAZKOV.

Fig. 2

CROSS-SECTION FOR THE PRODUCTION OF THE 0·84 AND 1·01 MEV. STATES IN Al^{27}

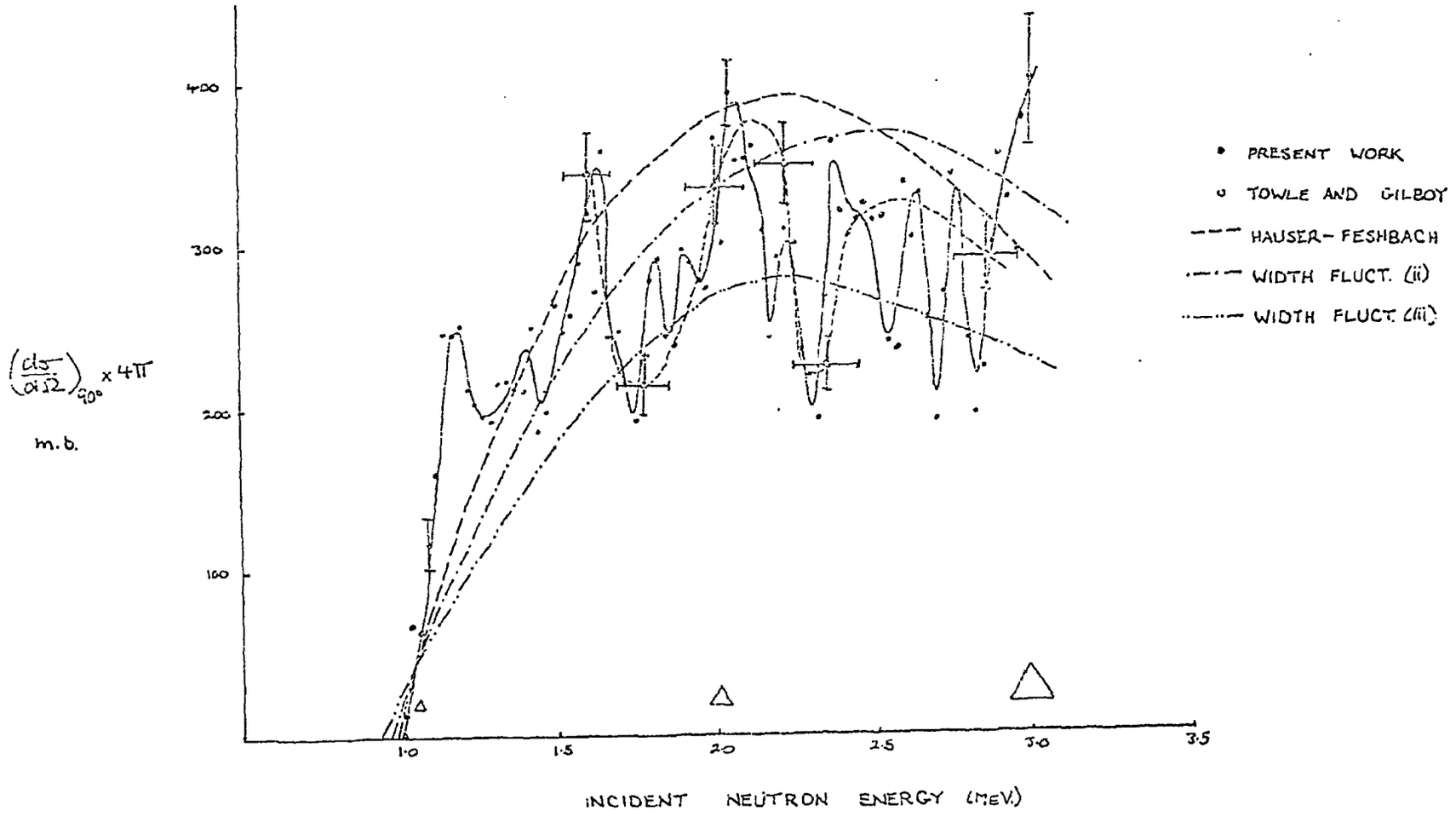
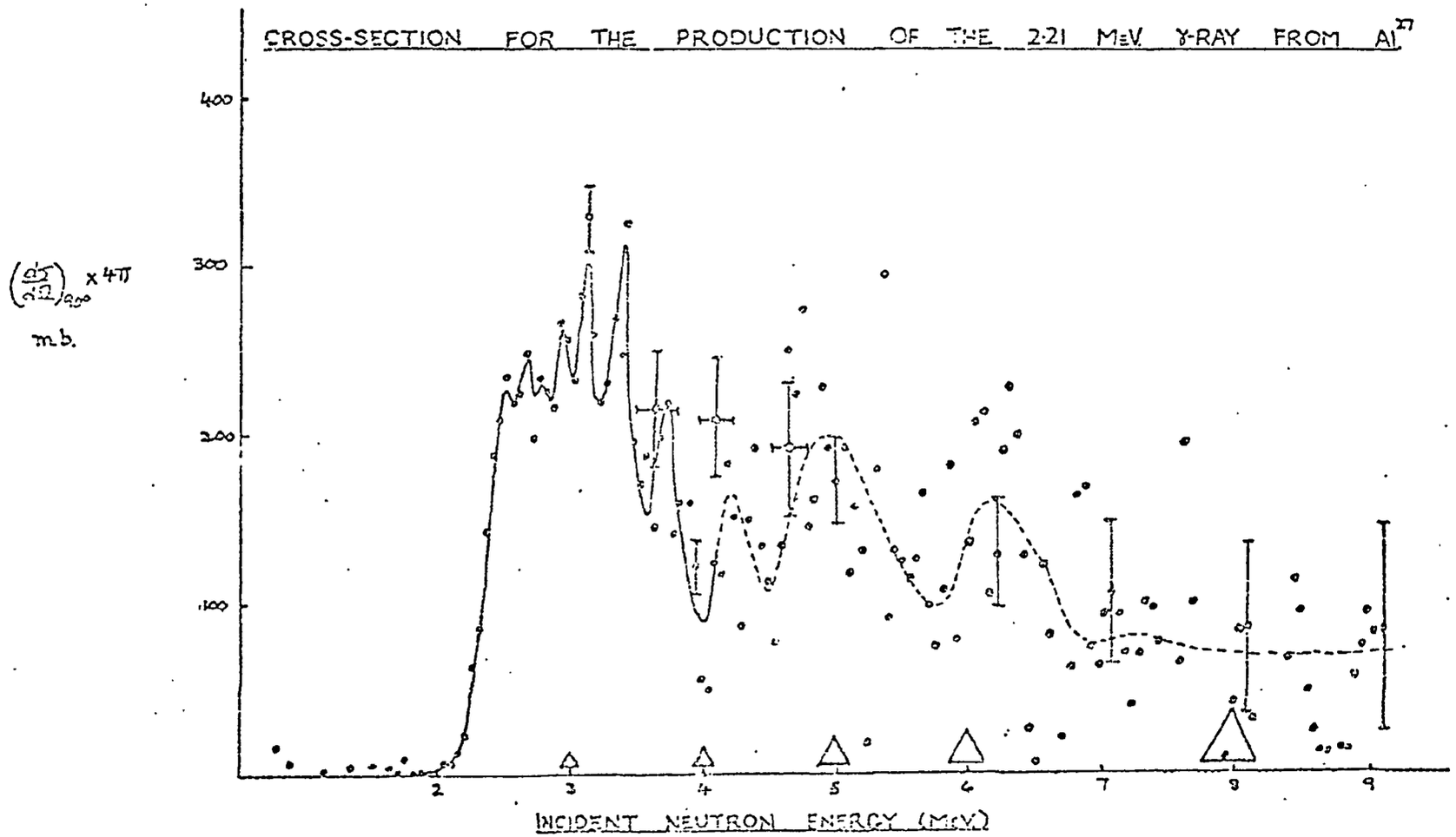


Fig. 3

DIAG. 5·17



• PRESENT WORK

∘ MATHUR et al.

Fig. 4

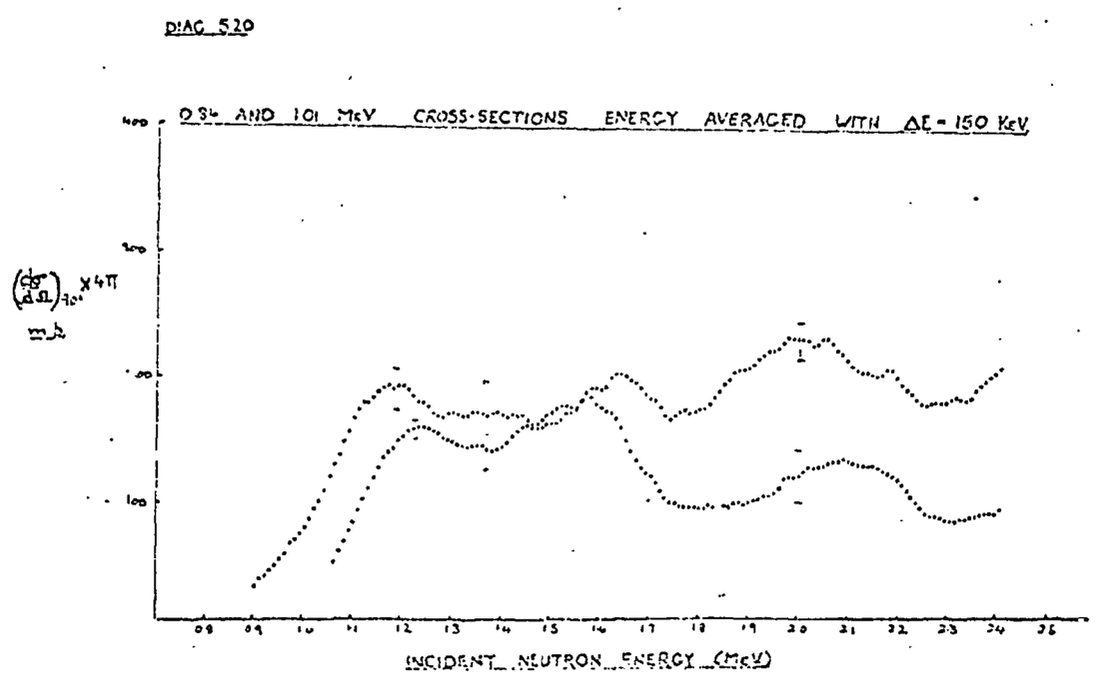

DIAG 520
0.94 AND 1.01 MeV CROSS-SECTIONS ENERGY AVERAGED WITH ΔE = 150 KeV
INCIDENT NEUTRON ENERGY (MeV)

Fig. 5

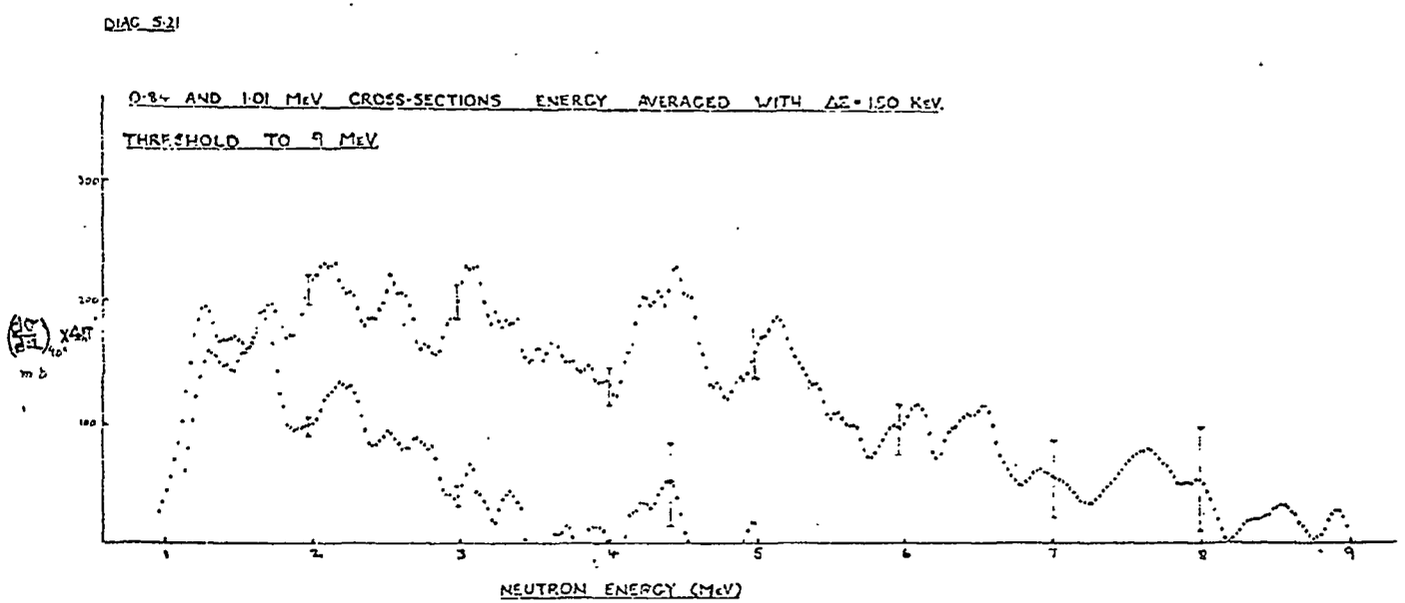

DIAG 5.21
0·84 AND 1·01 MeV CROSS-SECTIONS ENERGY AVERAGED WITH ΔE = 150 KeV.
THRESHOLD TO 9 MeV
300
200
100
mb
1
2
3
4
5
6
7
8
9
NEUTRON ENERGY (MeV)

Fig. 6

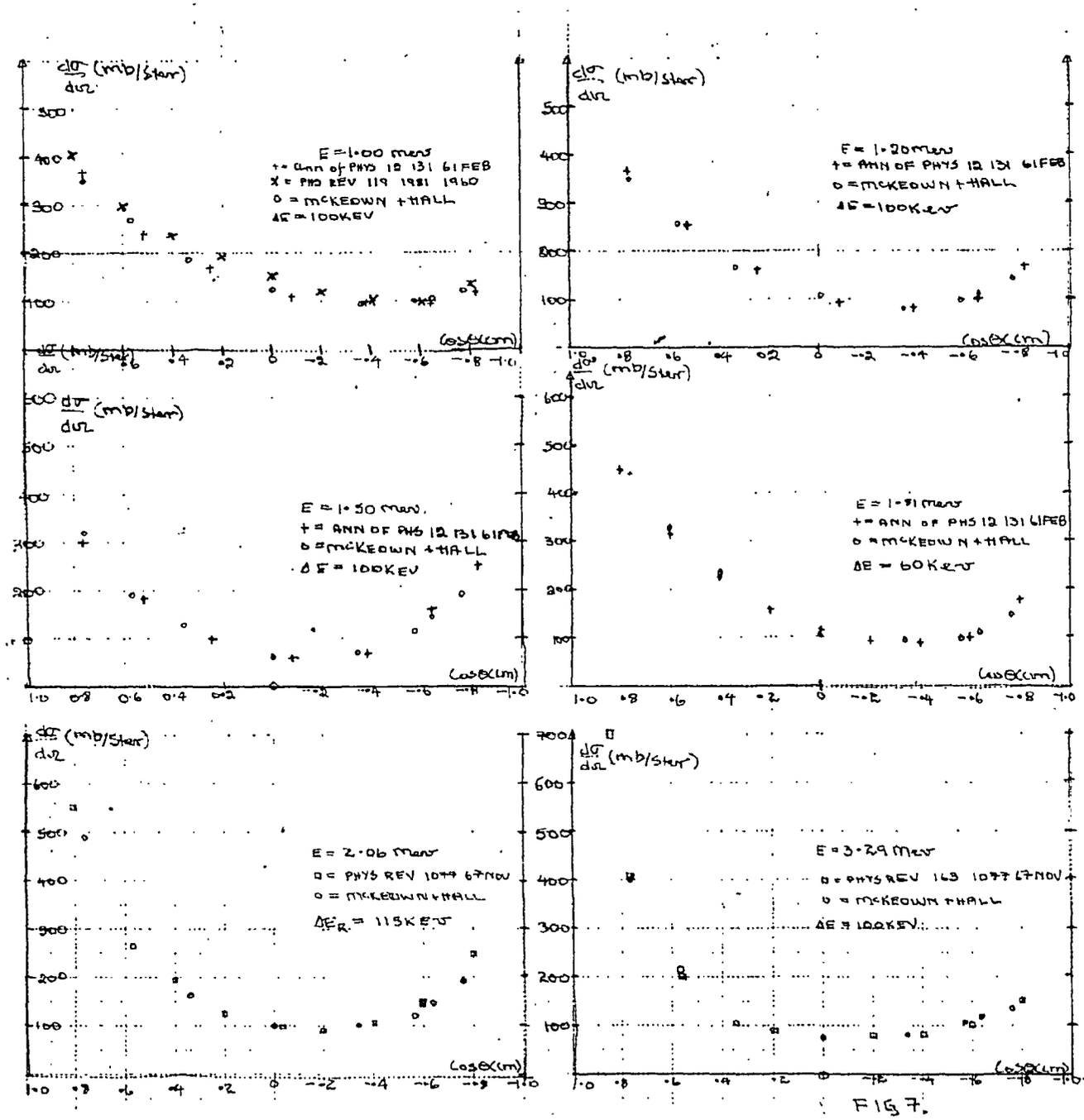

dσ/dΩ (mb/ster)
E = 1·00 mev
+ = Ann of PHYS 12 131 61FEB
X = PHS REV 119 1981 1960
o = McKEOWN + HALL
ΔE = 100KEV
cos θ(cm)
E = 1·20 mev
+ = ANN OF PHYS 12 131 61FEB
o = McKEOWN + HALL
ΔE = 100KEV
E = 1·50 mev.
+ = ANN OF PHS 12 131 61FEB
o = McKEOWN + HALL
ΔE = 100KEV
E = 1·81 mev
+ = ANN OF PHS 12 131 61FEB
o = McKEOWN + HALL
ΔE = 60KEV
E = 2·06 mev
□ = PHYS REV 1077 67NOV
o = McKEOWN + HALL
ΔE_R = 115KEV
E = 3·29 mev
□ = PHYS REV 163 1077 67NOV
o = McKEOWN + HALL
ΔE = 100KEV
FIG 7.

Fig. 7