with the experimental results illustrated in Fig. 1. The slopes of these calculated curves are also listed in Table III and in general increase with increasing target mass number as shown in Fig. 2. There is thus an inconsistency between the energy dependency predicted by this calculation and the experimental results, as well as with the qualitative interpretation previously suggested for these results. In view of the fact that this calculation does not take into account the refraction of the incident beam, and makes use of a square potential well rather than one with a diffuse edge, the lack of agreement is not too surprising. However, simple nuclear reactions of this type should properly be described by the appropriate quantal calculations.[20] Recently Read and Miller[22] have shown that they can predict the (p,n) cross-section variation with target mass number by making use of a model devised by Benioff.[25] Also, a quantitative theory has recently been worked out by Grover[26] in which the details of the shell-model configurations of the targets of (p,n) reactions are taken into account.

[25] P. A. Benioff, Phys. Rev. **119**, 324 (1960).

ACKNOWLEDGMENTS

We are indebted to Dr. J. P. Shedlovsky, Dr. N. K. Ganguly, Dr. D. J. Reuland, and Dr. G. V. S. Rayudu for helpful discussions and suggestions throughout the course of this work. The authors also wish to express their appreciation for the cooperation of the operating staff of the Carnegie Institute of Technology Nuclear Research Center in carrying out the irradiations with the proton synchrocyclotron.

[26] J. R. Grover, abstract of paper presented at 149th meeting of American Chemical Society Division of Nuclear Chemistry and Technology, 1965 (unpublished).

PHYSICAL REVIEW VOLUME 146, NUMBER 3 17 JUNE 1966

Neutron Total Cross Section of Pu^{242}†

G. F. Auchampaugh, C. D. Bowman, M. S. Coops, and S. C. Fultz
Lawrence Radiation Laboratory, University of California, Livermore, California

(Received 9 December 1965)

The neutron total cross section of Pu^{242} has been studied from 0.02 to 400 eV using the time-of-flight facility at the Livermore linear electron accelerator. Resonance parameters were determined for fourteen resonances, and the s-wave neutron strength function was found to be $(0.95\pm0.40)\times10^{-4}$. The total cross section at 0.025 eV was found to be 38.9 ± 1.6 b.

INTRODUCTION

Strength functions for s-wave neutrons have been measured for a fairly large number of heavy nuclei.[1] A peak in these values is apparent in the neighborhood of $A=239$. However, the position and shape of this peak have not been well determined, and accurate information on the strength function at $A=242$ would be helpful. The neutron cross sections of Pu^{242} are also of interest, since this isotope is a possible target for heavy-element production by multiple neutron capture in a nuclear explosion.[2] We have, therefore, measured the neutron total cross section of Pu^{242} from 0.02 to 400 eV by the time-of-flight method using the 30-MeV electron linear accelerator of the Lawrence Radiation Laboratory as the pulsed neutron source.

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] Summarized by R. E. Coté, R. F. Barnes, and H. Diamond, Phys. Rev. **134**, B1281 (1964).
[2] D. Dorn (private communication).

EXPERIMENTAL DETAILS

The neutron detector for this experiment was situated at the end of an evacuated flight tube 16.7 m long, arranged at 90° with respect to the electron beam direction. The experimental apparatus in the vicinity of the detector is shown in Fig. 1. The dimensions of the neutron beam were reduced from 3 in. in diameter near the neutron source to $\frac{3}{4}$ in. at the sample by two collimators. The primary collimator located at the end of the flight tube consisted of 2 ft of borated polyethylene (about 10% by weight natural boron) lined with a $\frac{3}{8}$-in.-thick iron sleeve. This collimator reduced the beam diameter to $1\frac{1}{2}$ in. The purpose of the sleeve was to prevent the detector from looking directly at any hydrogenous material. The 4-in.-square iron collimator which formed part of the remotely controlled sample changer further reduced the beam diameter to $\frac{3}{4}$ in., about $\frac{1}{8}$ in. less than that of the samples which were placed in the middle of this collimator.

The neutron detector was located 29 in. from the samples. It was shielded by a $\frac{1}{2}$-in.-thick lead sleeve

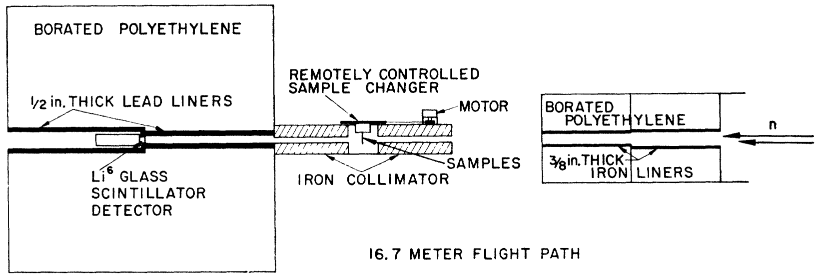

FIG. 1. The experimental arrangement.

which in turn was located inside a cubic box 3 ft on a side, filled with borated polyethylene pellets. The lead sleeve reduced the intensity of the 480-keV capture γ ray from boron in the neighborhood of the detector. With this geometry, the background as measured by the "thick-absorber" technique was less than 4% over the energy interval investigated.

The neutron detector used in these measurements consisted of four 1-in.$\times\frac{1}{4}$-in.-thick circular disks of Li^6 glass scintillator, optically coupled together and mounted on a 6810A PM tube. The Li^6 glass contained 7.3% Li enriched to 96% Li^6. A rather large uncertainty in flight path caused by this "thick" neutron detector and by the finite size of the neutron source limited the energy resolution to about $\frac{1}{2}$% below 400 eV.

A second scintillation detector containing a $\frac{1}{4}$-in.-thick disk of Li^6 glass monitored the flux and formed part of the system which controlled the position of the samples. This detector for most of the experiment was located along a 45° drift tube 25 m from the neutron target. It was removed from this position during the thermal-cross-section measurement and placed beside the hole passing through the 4-in.-square iron collimator. In this position the detector saw the direct beam but did not obstruct passage of neutrons into the $\frac{3}{4}$-in. hole of the iron collimator.

The signals from the neutron detector were routed into either of two time analyzers by automatic sample changing apparatus which was controlled by the signals from the monitor detector. This apparatus was arranged so that data from the neutron detector were accumulated over a time interval which was four times longer for the Pu sample than for the "blank" sample. A complete cycle required about 15 min.

The Pu^{242} samples were prepared by the Radiochemistry Division of the Lawrence Radiation Laboratory from two different batches of PuO_2. Physical properties of the samples are given in Table I. The PuO_2 was mixed with Al powder and pressed into disks 0.936 in. in diameter. Each disk was placed inside a copper cylinder of the same inside diameter and sealed at both ends by 5-mil Ni foils. The samples varied in physical thickness from about 150 to 750 mils, and in Pu content from about 0.1 to 15 g. The results of a radiographic analysis of all thin Pu samples showed that the PuO_2 and Al were uniformly distributed throughout the sample. Samples containing equivalent amounts of Al were made for samples 1a through 2b and used for the sample-out runs.

The experimental conditions under which the measurements were made are given in Table II. For each measurement a standard deviation of 4% or better was obtained on the transmission between resonances.

It was not possible to determine the total cross section between resonances from the first three sets of

TABLE I. Properties of the Pu^{242} samples.

Sample No.	Percent abundance 238	239	240	241	242	244	Pu thickness (atoms/b)
1a	0.036	0.016	0.311	0.155	99.410	0.064	$(4.76\pm0.07)\times10^{-5}$
1b							$(2.65\pm0.04)\times10^{-4}$
1c							$(7.98\pm0.14)\times10^{-4}$
2a	0.426	0.401	1.640	0.472	97.080		$(2.39\pm0.11)\times10^{-3}$
2b							$(7.33\pm0.34)\times10^{-3}$

TABLE II. Experimental conditions for the total-cross-section measurements.

Sets	Energy interval (eV)	Samples	Machine rep. rate (pulses/sec)	Electron pulse width (μsec)	Channel width (μsec)
1	70 –400	1c, 2a	360	0.125	0.0625
2	36 – 75	1c, 2b			
3	0.75– 45	1a	360	0.5	1
4	Thermal region	2b	50	2	4

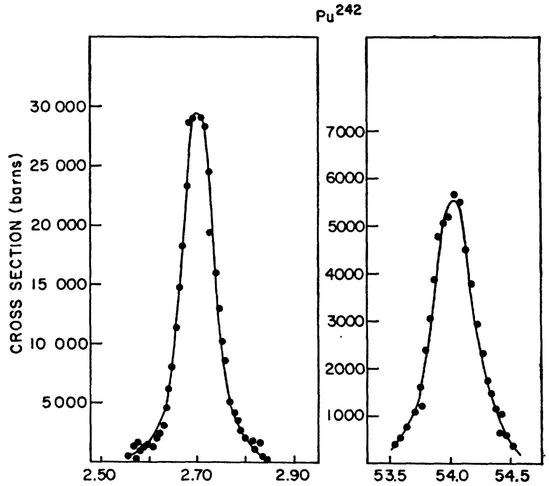

FIG. 2. The resonance cross section below 60 eV. The solid line through the points of the 2.64-eV resonance is a single-level Breit-Wigner fit to the data. The solid line through the 53.5-eV resonance is included to guide the eye.

measurements. The Pu samples were too thin and the intense gamma burst caused saturation effects in the detector and associated electronics which depended upon whether the Pu sample or the "blank" sample was in the beam. The fourth set of measurements on the thickest sample allowed a determination of the total cross section at thermal energy. For this measurement the problem of saturation in the detector system from the gamma burst was greatly reduced by separating the bremsstrahlung target from the neutron-producing target so that the detector looked only at the source of neutrons.

RESULTS

Resonances observed in the Pu^{242} total cross section below 400 eV are shown in Figs. 2 and 3. Where possible, the data from the higher enrichment samples were used to determine these cross sections. The resonance parameters determined from this experiment are given in columns 1, 2, and 6 of Table III. The value of the total width given in column 6 for the 2.64-eV resonance was obtained by shape-fitting the data with a single-level Breit-Wigner curve, taking into account Doppler and resolution broadening. An attempt was made to shape fit the 53.5-eV resonance. However, the shape was too sensitive to the width of the resolution function so that no meaningful value of the total width could be obtained. By applying the area analysis to the thick and thin data for this resonance, a value for Γ of $(71\pm20)\times10^{-3}$ eV was obtained. The large error in Γ for this resonance can be attributed to insufficient sample thickness. The parameter Γ_n for the remaining resonances was obtained from an area analysis of the data. The errors quoted in Γ_n reflect estimates of the standard error in the transmission and uncertainties in the delineation of the area and base line. The resonance energies are given with an error of about 0.5%.

Until recently, the only other measurements on Pu^{242} were those of Egelstaff *et al.*[3] and Coté *et al.*[4] Their values of Γ_n and Γ given in columns 4, 5, and 7 are in satisfactory agreement with ours. Recently, Pattenden[5] has made some measurements on Pu^{242} using a sample about three times as thick as sample 2b and with an isotopic purity of about 91% Pu^{242}. His values of Γ_n are given in column 3. In general, the agreement between corresponding values of Γ_n is good except for the 205-eV resonance and a few of the smaller resonances. The 306-eV resonance appears as two resonances in his data. A slight indication of this splitting is apparent in our data as well, It is possible that one of these resonances belongs to Pu^{240}, since a resonance at 306.5 eV in Pu^{240} has been observed by Moxon *et al.*[6] The additional resonances observed by Pattenden and

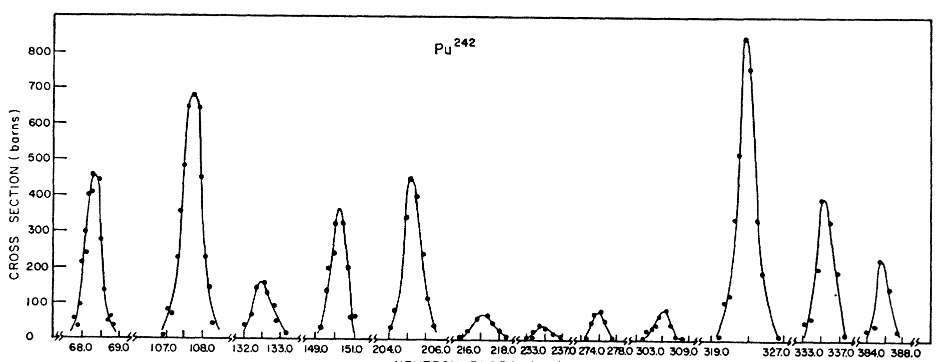

FIG. 3. The resonance cross section from 60 to 400 eV. The solid lines through the points are included to guide the eye. Different abscissa scales are used for each resonance for the convenience of displaying the data.

[3] P. A. Egelstaff, D. B. Gayther, and K. P. Nicholson, J. Nucl. Energy 6, 303 (1958).
[4] R. E. Coté, L. M. Bollinger, R. F. Barnes, and H. Diamond, Phys. Rev. 114, 505 (1959).
[5] N. J. Pattenden, in International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, 1965 (unpublished).
[6] M. C. Moxon, E. R. Rae, and C. M. Mycock, Atomic Energy Research Establishment—Progress Report/Nuclear Physics Division No. AERE-PR/NP-4, p. 16, 1963 (unpublished).

TABLE III. Resonance parameters of Pu^{242}.

E_0 (eV)[a]	Γ_n (10^{-3} eV) LRL	Harwell b	c	ANL[d]	Γ (10^{-3} eV) LRL	ANL
2.64	1.92± 0.10		1.7±0.8	1.9±0.2	27.4± 1.0	27.0±2.7
14.60		0.061± 0.013				
22.48		0.28 ± 0.02				
40.96		0.48 ± 0.04				
54.0	47.5 ± 5.5	56 ± 3		44.9±6.0	71 ±20	
68.3	4.6 ± 0.9	2.7 ± 0.4				
89.1		0.80 ± 0.16				
106		0.6 ± 0.4				
107.7	14.8 ± 1.5	19 ± 4				
132.5	5.1 ± 1.5	6.7 ± 1.7				
150.3	17.9 ± 2.7	17.0 ± 5.6				
166		1.0 ± 0.6				
205	31.0 ± 3.0	100 ±49				
217	6.3 ± 1.8	3.4 ± 1.1				
235	7 ± 3	8.8 ± 2.9				
276	10.1 ± 2.1	19 ± 8				
306	21 ± 5	9.6 ± 3.4				
311		11.0 ± 5.5				
323	229 ±45					
335	94.5 ±18.0					
386	47.3 ± 1.6					

[a] The energies of the resonances not observed in the present measurement are taken from Ref. 5.
[b] Values of Γ_n listed in this column were obtained by Pattenden (Ref. 5).
[c] This value of Γ_n was obtained by Egelstaff *et al.* (Ref. 3).
[d] ANL: refers to Coté *et al.* (Ref. 4).

assigned to Pu^{242} may be attributed to his thicker sample and better resolution.

Assuming that all the resonances observed in the present measurement are due to *s*-wave interactions, the *s*-wave neutron strength function $\langle\Gamma_n^0/D\rangle$ for Pu^{242} has been found to be $(0.95\pm0.40)\times10^{-4}$. The error is based on the number of resonances included in the evaluation of the strength function and results from the assumption of a Porter-Thomas[7] distribution for the neutron width Γ_n^0 and a Wigner[8] distribution for the level spacing D. This value of the neutron strength function is to be compared with the values $(1.3_{-0.5}^{+4.75})\times10^{-4}$ and $(0.72\pm0.25)\times10^{-4}$ obtained by Coté *et al.*[4] and Pattenden,[5] respectively. Our value is larger than Pattenden's because the three resonances above 315 eV which have large values of Γ_n^0 were not included in his calculations. The effect of the additional resonances reported by him on our value of $\langle\Gamma_n^0/D\rangle$ is less than 1%. The present measurement on $\langle\Gamma_n^0/D\rangle$ strengthens the conclusion made by Coté *et al.*[1] that a peak in $\langle\Gamma_n^0/D\rangle$ has been reached near $A=239$ and that Pu^{242} lies on the high-mass side of this peak.

The low-energy measurements on sample 2b yield a total cross-section value of 38.9 ± 1.6 b at. 0.025 eV, after correcting for the other Pu isotopes and oxygen present in the sample. The error quoted represents the statistical uncertainty in the data. A value of the scattering cross section of 8.9 ± 2.6 b at 0.025 eV can be determined by subtracting from our measurement of σ_T (0.025 eV) the reported thermal-absorption cross-section value of 30 ± 2 b.[9]

[7] C. E. Porter and R. G. Thomas, Phys. Rev. **104**, 483 (1956).

[8] E. P. Wigner, in *Proceedings of the Conference on Neutron Physics by Time-of-Flight, Gatlinburg, Tennessee, 1956* [Oak Ridge National Laboratory Report No. ORNL 2309, p. 59 (unpublished)].

[9] *Neutron Cross Sections* (Brookhaven National Laboratory Report No. BNL-325, 1958), 2nd ed.