Neutron Resonance Parameters and Transmission Measurements in U^{235}†

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Transmission measurements have been made for U^{235} with a resolution of 0.05 to 0.07 μsec/meter using the Materials Testing Reactor fast chopper, and resonances have been studied below 60 ev. Breit-Wigner parameters have been obtained for more than 40 resonances. Four new resonances have been found at 12.8, 28.6, 29.9, and 34.7 ev. The 25.7-ev resonance previously reported has been split into two resonances, 25.6 and 25.9 ev. The ratio of $\bar{\Gamma}_n^0/D$ for resonances below 50 ev was found to be $1.0\pm0.2\times10^{-4}$. The level spacing of 1.40 ± 0.15 ev is one of the smallest so far observed. Data on the distributions of Γ_n^0 are presented.

I. INTRODUCTION

TRANSMISSION measurements of U^{235} have been made with the Materials Testing Reactor (MTR) fast chopper[1,2] from 10 to 100 ev. The data were taken with a resolution of 0.05 to 0.07 μsec/meter using a flight path of 45 meters and a BF_3 counter length of 3 in. along the neutron beam. These transmission measurements were analyzed by the area method, and level parameters were obtained by assuming the single level Breit-Wigner formula holds true for closely spaced *s*-wave levels (an average of 0.7 ev between resonances in the case of U^{235}).

The low-energy cross section of U^{235} has been summarized by Sailor.[3] In recent papers[4–6] measurements have been extended, and reasonable agreement was found in the total cross section and resonance parameters. In addition to the very great practical interest of the U^{235} cross section and the resonance parameters, considerable theoretical interest exists. The average $\bar{\Gamma}_n^0/D$ is of interest as a check upon current models,[7,8] and the major objective here was to obtain this quantity. In addition, the existence of many levels affords a possibility that enough Γ_n values could be measured to obtain good statistical information about the distribution of Γ_n in a single isotope.[9–11] The fission process is also of great interest[12] although the measured Γ_f widths are of limited accuracy.

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II. EXPERIMENTAL DATA

A. Transmission Measurements

The transmission measurements for the different sample thicknesses are shown in Fig. 1. The samples used for most of the data had a purity of >90% U^{235}. Since the level spacing of the major contaminant, U^{238}, is large, little effect on the data is expected. In the region of 22 ev where a U^{238} resonance is found, a sample was run having a purity of 99.8% U^{235}. The data have not been corrected for other contaminants or other U^{238} resonances. The 37- and 67-ev resonances are due to U^{238}.

In the region 9 to 24 ev a new, small resonance is observed at 12.8 ev, and it is suspected that a few small resonances are still unresolved. For example, in the interval from 13 to 15 ev only three resonances are quoted, but the data seem to indicate that several resonances may be present. The transmission data show a strong possibility of resonances being at 10.6, 13.8, 17.5, and 20.3 ev. In this region, it is possible that the levels actually overlap each other, although the resolution is not adequate to justify such a conclusion. Three new resonances in the interval from 24 to 35 ev have been found having energies of 28.6, 29.9, and 34.7 ev. The 25.7-ev resonance, previously reported, has been split into two resonances at 25.6 and 25.9 ev. From 18 to 100 ev many resonances are definitely unresolved because of the closely spaced levels. At approximately 40 ev the instrument resolution is equal to the average level spacing between resonances (0.7 ev).

B. Data Analysis

The general procedures used in applying the area method for the determination of parameters have been discussed previously.[13] The particular procedure used is fast and affords a simple means of assigning errors to the parameters.

A list of the resonance parameters is given in Table I. For several resonances it was possible to make "thick-thin" transmission measurements, and therefore, values of Γ could be determined. The values of Γ_f quoted were obtained by subtracting Γ_n and Γ_γ from Γ, assuming that the statistical factor $g=\frac{1}{2}$ and that $\Gamma_\gamma=30$ mv.

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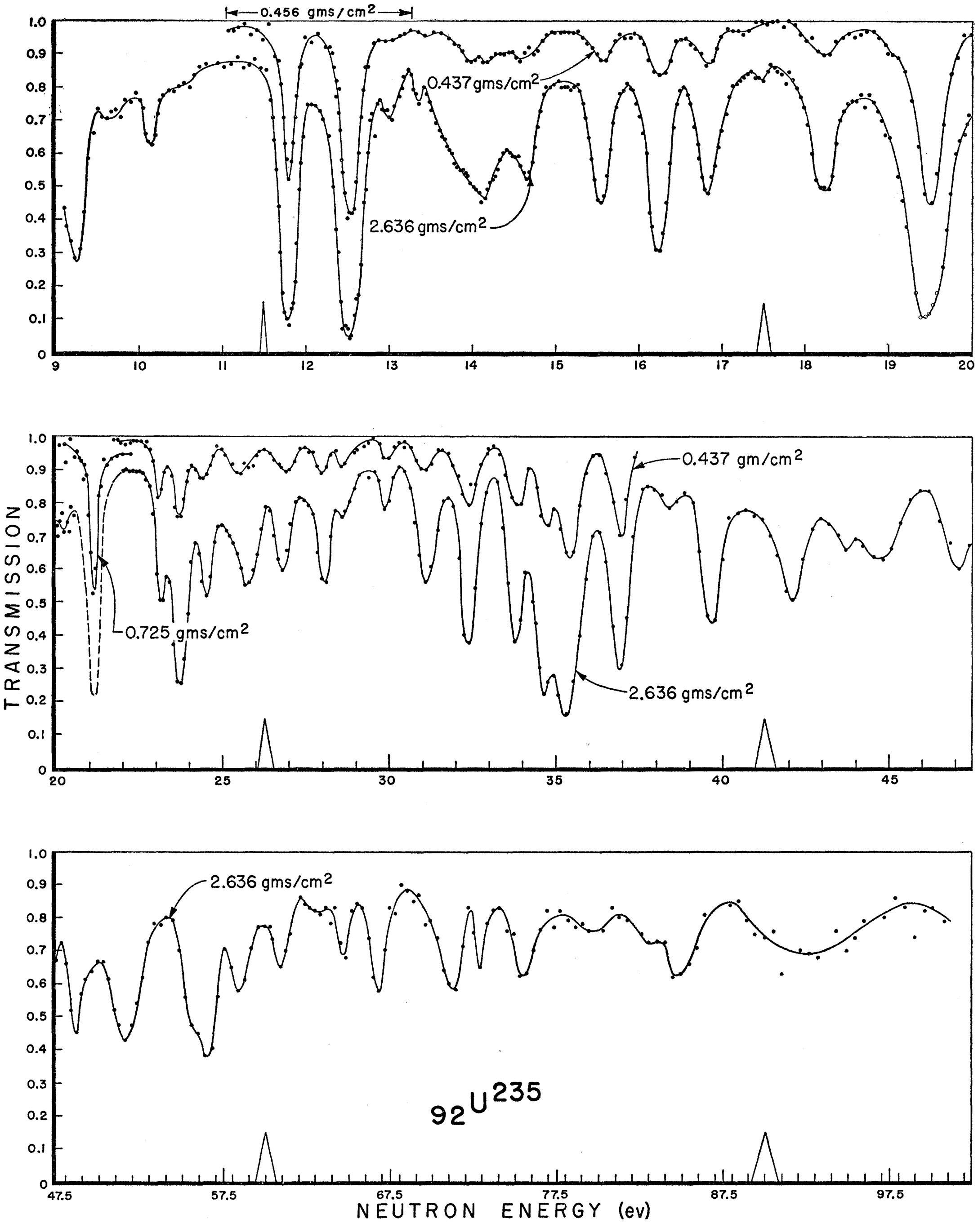

FIG. 1. The neutron transmission of U^{235} as observed with a resolution of 0.05 to 0.07 μsec/meter and a flight path of 45 meters.

Where measurements were limited to thin samples, only values of $\Gamma_n{}^0=\Gamma_n/\sqrt{E_0}$ are quoted. For thin samples, where $\Gamma_n\propto(1/g)\sigma_0\Gamma\propto$ area, Γ_n is reasonably independent of the value of Γ assumed, but an increase in errors is introduced due to the large variation in Γ_f.

A major problem in applying the single-level analysis was caused by the very close spacing of the levels. For a single isolated resonance, the transmission dip is superimposed on a constant background transmission. A good approximation for this background can be obtained by calculating the transmission due to the potential scattering and using this as a base line for the resonance. When parameters for the resonance have been determined, they can be used to calculate the transmission in the wings, where the true transmission is resolved, to see if the original base line is correct. In contrast, many U^{235} levels are found to be on a background of transmission effects due to other resonances. The situation is complicated by the fact that individual resonances are not completely resolved by the spectrometer, and the overlap is increased by the instrument resolution. Under these circumstances the concept

TABLE I. Resonance parameters for U^{235} obtained by an area analysis method. The following assumptions were made: $\Gamma_\gamma=30$ mv, $\Gamma=100$ mv, and $g=\frac{1}{2}$. (1 mv$=10^{-3}$ ev.)

E_0(ev)	$(1/n)\times10^{24}$ (cm²/atom)	Area (ev)	Γ_f(mv)	Γ_n^0(mv)
9.25±0.05	148	0.165±0.040		0.054±0.015
9.70±0.05	148	0.076±0.020		0.022±0.005
10.13±0.05	148	0.067±0.025		0.017±0.005
11.6 ±0.1	148	0.293±0.010	9_{-9}^{+11}	0.171±0.015
	857	0.097±0.005		
12.4 ±0.1	148	0.441±0.010	16±12	0.396±0.025
	857	0.186±0.010		
12.8 ±0.1	148	0.046±0.015		0.014±0.005
13.3 ±0.1	148	0.104±0.015		0.030±0.005
14.1 ±0.1	148	0.236±0.020		0.092±0.010
14.7 ±0.1	148	0.099±0.010		0.032±0.005
15.5 ±0.1	148	0.153±0.005		0.054±0.005
	893	0.030±0.005		
16.2 ±0.1	148	0.200±0.010	12_{-12}^{+17}	0.087±0.005
	893	0.046±0.005		
16.8 ±0.2	148	0.145±0.015		0.055±0.005
	893	0.030±0.005		
18.2 ±0.2	148	0.200±0.040		0.079±0.003
19.5 ±0.2	148	0.703±0.020	79±22	0.63 ±0.04
	893	0.243±0.025		
21.2 ±0.2	893	0.120±0.025		0.28 ±0.06
23.2 ±0.3	148	0.209±0.030		0.13 ±0.02
	893	0.062±0.005		
23.7 ±0.3	148	0.503±0.045	105±81	0.31 ±0.02
	893	0.132±0.010		
24.5 ±0.3	148	0.238±0.035		0.13 ±0.02
	893	0.069±0.010		
25.6 ±0.3	893	0.049±0.010		0.12 ±0.03
25.9 ±0.4	893	0.034±0.010		0.076±0.025
26.8 ±0.4	148	0.248±0.045		0.16 ±0.04
	893	0.082±0.020		
28.0 ±0.4	148	0.245±0.025		0.13 ±0.02
	893	0.054±0.010		
28.6 ±0.4	148	0.093±0.030		0.066±0.020
	893	0.039±0.010		
29.9 ±0.5	148	0.082±0.030		0.048±0.020
	893	0.025±0.010		
31.1 ±0.5	148	0.311±0.045		0.20 ±0.03
	893	0.077±0.010		
32.3 ±0.5	148	0.452±0.045		0.41 ±0.10
	893	0.138±0.035		
33.8 ±0.5	148	0.379±0.045		0.35 ±0.07
	893	0.118±0.010		
34.7 ±0.6	148	0.501±0.040	48±27	0.46 ±0.08
	893	0.150±0.025		
35.3 ±0.6	148	0.757±0.060	82±33	0.90 ±0.15
	893	0.166±0.005		
38.4 ±0.7	148	0.048±0.010		0.026±0.007
39.7 ±0.7	148	0.434±0.040		0.40 ±0.10
42.0 ±0.7	148	0.537±0.070		0.35 ±0.10
43.7 ±0.8	148	0.243±0.065		0.15 ±0.05
44.8 ±0.8	148	0.369±0.065		0.27 ±0.07
47.1 ±0.8	148	0.278±0.045		0.18 ±0.04
48.6 ±0.9	148	0.636±0.070		0.75 ±0.16
51.6 ±0.9	148	1.640±0.020		6.40 ±1.50
55.4 ±1.0	148	0.465±0.065		0.39 ±0.08
56.4 ±1.0	148	0.766±0.080		1.15 ±0.25
58.3 ±1.0	148	0.511±0.045		0.50 ±0.10
61.0 ±1.1	148	0.220±0.090		0.15 ±0.08

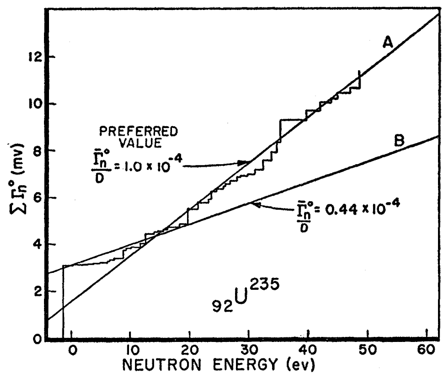

FIG. 2. The sum of the Γ_n^0's observed up to energy E as a function of E for U^{235}. Curve A shows the preferred value of $\bar{\Gamma}_n^0/D$ which is in good agreement with previously reported values. Curve B represents a possible value of $\bar{\Gamma}_n^0/D$ obtained from the positive resonances below 18 ev.

of a base line (implying a straight line) can be misleading.

An analytical procedure used as a check for low-energy area determinations was to estimate the transmission of the individual level by dividing out the transmission caused by other levels and potential scattering. If the adjacent regions are resolved, reiteration procedures were followed until the wings and resonance parameters were self-consistent. Based on the checks outlined above, it has been found that the empirical procedure of drawing a constant-background base line and estimating the size of a level is accurate within the errors assigned to the results determined by the more exact method. The data below 18 ev were checked by the more exact procedure outlined above. For the resonances above 18 ev, a constant base line was used.

III. CONCLUSIONS AND DISCUSSION

The observed average level spacing per spin state for resonances up to 18 ev is 1.40±0.15 ev. This average includes the low-energy data presented by Sailor,[3] and is in good agreement with the value obtained at the lower energies. The error quoted is the standard deviation of the mean level spacing due to variations in the individual level spacings (errors in the energy measurements are considered negligible in comparison). The two spin states have been assumed to have equal numbers of levels uniformly distributed, and the level spacing of a single spin state is assumed to be twice the observed level spacing. Many levels are definitely being missed above 18 ev. Since only 28 spacings are involved (14 per spin state), the small size of the error implies that the spacing distribution is not random.

Figure 2 is the plot from which the preferred value of $\bar{\Gamma}_n^0/D$ has been obtained. When, this value is used, the average reduced neutron width $\bar{\Gamma}_n^0$ can be obtained by multiplying by the level spacing. This gives $\bar{\Gamma}_n^0=0.14$ ±0.03 mv. To obtain values of $\bar{\Gamma}_n^0/D$ and $\bar{\Gamma}_n^0$ by this method, it is necessary to assume that the sum of the

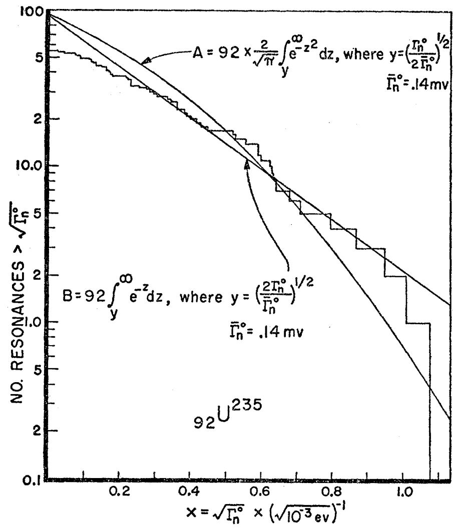

FIG. 3. The experimental integral distribution curve of $\sqrt{\Gamma_n{}^0}$ for resonances from -1.4 to 61 ev. Curve A shows the distribution proposed by Porter and Thomas and curve B that by Bethe. The constants used for both curves are based upon the experimental average $\bar{\Gamma}_n{}^0$ and the number of levels expected for the energy interval used. Thus, it is expected that many levels are unaccounted for. The curvature at small $\sqrt{\Gamma_n{}^0}$ favors the Porter-Thomas distribution. The absolute magnitude of the experimental data at low $\sqrt{\Gamma_n{}^0}$ is known to be low.

$\Gamma_n{}^0$'s for increasing energy as a function of E are independent of whether or not the resonances are resolved. This assumption should be very good where thin-sample measurements are used to determine the $\Gamma_n{}^0$'s for the unresolved resonances. A reasonably straight line is observed up to 50 ev, and the value of $\bar{\Gamma}_n{}^0/D$ of $(1.0\pm0.2)\times10^{-4}$ is in agreement with others quoted previously.[3,5,6] This result agrees well with the predictions of the continuum theory of nuclear reactions for a 42-Mev well depth.[7] The "cloudy crystal ball" model[8] must be modified to agree with this value.

Some ambiguity exists in the selection of values of $\bar{\Gamma}_n{}^0/D$ and $\bar{\Gamma}_n{}^0$. For example, curve B indicates lower averages. This includes only the region where the resonances are resolved, and the negative resonance must be discounted as a contribution if this line were chosen to determine $\bar{\Gamma}_n{}^0/D$, i.e., the negative resonance contributes a large fraction of $\sum\Gamma_n{}^0$. The choice of curve B for the energy region below 18 ev can be supported by the following arguments. The distribution of $\sqrt{\Gamma_n{}^0}$ for the resonances below 18 ev fits the distribution proposed by Bethe[9,10] with the $\bar{\Gamma}_n{}^0$ obtained from curve B. Since the samples used above 18 ev, where the resonances are definitely unresolved, were not always thin; the values obtained for Γ_n depend strongly upon the assumed value of Γ_γ. Multiple-resonance groups considered as single resonances for thick samples may give Γ_n's which are too large.

The above arguments in support of slope B in Fig. 2 are considered to be outweighed by the experimental results quoted by Hughes *et al.*[6] These authors quote a value of $\bar{\Gamma}_n{}^0/D$ in agreement with curve A, which has been obtained by an independent experimental technique. This independent method is an absorption coefficient experiment for which it is difficult to conceive errors which would give values of $\bar{\Gamma}_n{}^0/D$ that are too large. Thus, it appears that the summation method of obtaining $\bar{\Gamma}_n{}^0/D$ is valid over a fairly wide sample thickness range. Since curve B covers such a small energy region, it is considered to be representative only of the region 0 to 18 ev and does not represent $\bar{\Gamma}_n{}^0/D$ for U^{235}. Figure 3 shows the experimental integral distribution curve for resonances from -1.4 to 61 ev. Curve A shows the integral distribution predicted by Porter and Thomas,[9] assuming the 92 levels predicted from the proposed level spacing and energy interval, and assuming the $\bar{\Gamma}_n{}^0$ obtained from the preferred value of $\bar{\Gamma}_n{}^0/D$ and D. Likewise, curve B is a calculated curve for the distribution proposed by Bethe[10] assuming the same experimental average parameters. Curve A represents a Gaussian distribution in $\sqrt{\Gamma_n{}^0}$ and curve B an exponential distribution. Either curve is felt to be in reasonable agreement with the experimental data considering the region of unresolved resonances that is involved. An exponential distribution in the variable $\Gamma_n{}^0$, as proposed by Hughes and Harvey,[9] does not fit the U^{235} data as well, particularly if the proposed $\bar{\Gamma}_n{}^0$ is used to determine the slope. A single exponential of this type fails to account for the large and small resonances. Agreement with the Bethe or Porter-Thomas distributions is added argument for the average $\bar{\Gamma}_n{}^0/D$ value chosen.

The Porter-Thomas distribution is favored here on the basis of general curvature considerations. This becomes more pronounced, and the fit is better if one or two of the large resonances are assumed to be multiple. Thomas[11] has recently given the Hughes-Harvey and Porter-Thomas distributions theoretical foundation. Thus, the Porter-Thomas distribution implies one channel or degree of freedom while the Hughes-Harvey distribution implies two degrees of freedom.

The wide variations in the Γ_f values imply a limited number of exit channels in the fission process. The data given in Table I are an extension of the values presented by Sailor.[3] The size distribution in Γ_f is not presented since the accuracies of the determined values are very limited.