TABLE I. Total cross sections for ground and first excited state neutrons as a function of the average deuteron interaction energy in the target.

E_d (kev)[a]	σ_T[b] (ground state) (mb)	σ_T[b] (1st excited state) (mb)
1090	31	...
940	18	...
920	...	30
735	7.2	...
725	...	16
537	1.5	...
525	...	4.6
437	0.49	...

[a] ±15 kev.
[b] To within ±10%.

possibility of stripping from the target nucleus is included.[3] The differential cross section is

$$\frac{d\sigma}{d\Omega}=C(E)\left|(i)^{l(p)}G_D(K_1)j_{l(p)}(k_1R_1)-\frac{\Lambda_2}{\Lambda_1}(-i)^{l(n)}(i)^{l(C)}G_H(K_2)j_{l(C)}(k_2R_2)\right|^2,$$

TABLE II. Parameters used in obtaining the fits shown in Fig. 3, as a function of deuteron bombarding energy.

E_d	0.6 Mev	1.0 Mev
R_1	7.2×10^{-13} cm	6.8×10^{-13} cm
R_2	4.0×10^{-13} cm	4.0×10^{-13} cm
Λ_2/Λ_1	0.69	0.66

where the notation is that of reference 3. The theoretical curves are shown in Fig. 3. The assignment of 2^+ to the first excited state of C^{12} requires that $l(p)=1$, where $l(C)$ must be 0 or 2. Attempts to fit the data with $l(C)=2$ were unsuccessful, as might be expected at low bombarding energies. The values of R_1, R_2, and used to obtain the theoretical fits are shown in Table II.

We have attempted theoretical fits to the angular distributions obtained in the vicinity of 4 Mev[2] and good agreement has been found. The values of R_1 needed to fit the data at these energies are of the order of 5×10^{-13} cm.

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Neutron Scattering Cross Section of U^{235}†

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The neutron elastic scattering cross section for U^{235} has been measured by the "thick-thin" method over the range of neutron energies from 0.27 to 7.7 ev. The cross section rises at lower energies, the rise being qualitatively that expected if an unusually strong level were present just below the binding energy. Analysis of the data in terms of a Breit-Wigner single-level formula gives a resonant and a constant component. The solution yields a value of 10±1 barns for the constant component, which may be identified as the "potential scattering" cross section. This result is relatively insensitive to the location of the bound level and to the exact analytical form of the resonant component. The magnitude of the resonant component is not in perfect quantitative agreement with the parameters commonly quoted for the "negative energy" resonance at $E_0=-1.4$ ev. This disagreement is probably not significant because of the uncertainties in the analysis of both the total and the scattering cross section.

I. RESONANCES IN U^{235}

TOTAL and fission cross-section measurements[1–3] have yielded a detailed knowledge about the Breit-Wigner parameters for the resonances in U^{235} lying in the energy range from 0 to ~50 ev. These parameters may be used to estimate the scattering cross section contributed by each resonance, by substituting in the single-level formula,

$$\sigma_s(E)=\sigma_{sr}(E)+\sigma_{si}(E)+\sigma_p. \quad (1)$$

The individual terms in Eq. (1) are as follows: the resonant scattering cross section,

$$\sigma_{sr}(E)=4\pi\lambda\!\!\!^{-}{}_0^2\frac{g\Gamma_n^2}{4(E-E_0)^2+\Gamma^2}. \quad (1a)$$

† Work performed under contract with the U. S. Atomic Energy Commission.
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[1] Available results have been reviewed in the following papers: V. L. Sailor, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 199; J. A. Harvey and J. E. Sanders, *Progress in Nuclear Energy, Ser. I, Physics and Mathematics* (Pergamon Press, London, 1956), Vol. 1, p. 46.
[2] Simpson, Fluharty, and Simpson, Phys. Rev. **103**, 971 (1956).
[3] Pilcher, Harvey, and Hughes, Phys. Rev. **103**, 1342 (1956); J. A. Harvey and J. E. Sanders, *Progress in Nuclear Energy, Ser. I, Physics and Mathematics* (Pergamon Press, London, 1956), Vol. 1, p. 1; P. A. Egelstaff and D. J. Hughes, *Progress in Nuclear Energy, Ser. I, Physics and Mathematics* (Pergamon Press, London, 1956), Vol. 1, p. 55.

The potential scattering cross section,

$$\sigma_p = 4\pi[gR_g^2 + (1-g)R_{1-g}^2] \equiv 4\pi R_{\text{eff}}^2, \qquad (1\text{b})$$

and $\sigma_{si}(E)$, an interference term resulting from coherence between the resonant and potential scattering, is given by

$$\sigma_{si}(E) = 16\pi \lambda\!\!\!^{-}_0 g \Gamma_n R_g \frac{(E-E_0)}{4(E-E_0)^2+\Gamma^2}. \qquad (1\text{c})$$

The subscripts used here[4] have the following meaning: *s*—scattering; *sr*—the resonant component of the scattering; *si*—the interference component of the scattering; 0—a value at exact resonance; and *p*—the potential scattering. In most of the U^{235} resonances σ_{sr} (and hence σ_{si}) is unobservably small; e.g., for the resonance at $E_0 = 0.29$ ev, $\sigma_{sr} \approx 12\times10^{-3}$ barn; at $E_0 = 1.142$ ev, $\sigma_{sr} \approx 12\times10^{-3}$ barn; and at $E_0 = 2.035$ ev, $\sigma_{sr} \approx 20\times10^{-3}$ barn.

An important exception which might yield measurable resonant scattering is the so-called "negative-energy" resonance[5] having $E_0 = -1.4$ ev. Such a resonance has been postulated[1] to account for the thermal cross section of U^{235} which is about ten times larger than can be explained by the known resonances. The value of E_0 and Γ_n^0 for this resonance can be obtained from the total cross-section data by fitting the region with a Breit-Wigner single-level formula from 0 to 5 ev after first correcting for the known resonances. Such an analysis, of course, is not sufficiently sensitive to determine whether it is a *single* resonance or *several* resonances at negative energy which are responsible for the large thermal cross section, although it is clear that the cross section between 0 and 5 ev behaves as though a strong resonance exists at -1.4 ev. It is disturbing, however, that the value of Γ_n^0 obtained for this level is unusually large. In fact, it is much larger than that obtained for any resonance observed in the positive-energy region and is approximately thirty times as large as the average Γ_n^0. There is, of course, no reason to prevent a level just below the binding energy from being by chance an unusually strong level; however, one must view the "negative-energy" resonance interpretation for U^{235} with suspicion.

The scattering cross section in the region 0 to 10 ev provides direct evidence about the existence or nonexistence of a strong "negative-energy" resonance. If such a level is present, it should produce a scattering cross section of several barns through this region.

The potential scattering cross section of the heavy elements is given approximately by Eq. (1b), where $R_{\text{eff}} \approx 1.47\times10^{-13}A^{\frac{1}{3}}$ cm. Using this equation, one estimates that for U^{235}, $\sigma_p = 10.3$ barns.

In order to test the interpretations of the -1.4-ev resonance, a scattering measurement was undertaken in the region 0 to 10 ev. If it should be present, the resonant contribution, largely that of the interference phenomenon, Eq. (1c), should be readily observable. That is, we would expect to see a decreasing cross-section curve with increase of energy which would be composed of the potential scattering cross section plus a resonance contribution. In addition, it was desired to measure the potential scattering cross section, if possible, no measurement having been reported previously. These data would be of use in reactor design calculations and would aid greatly the interpretation of the resonance structure in the neutron cross section.

II. THE EXPERIMENT

The scattering measurement was made on a BNL crystal spectrometer using the "thick-thin" technique previously reported.[6] The general arrangement of the experiment is shown in Fig. 1, the source of neutrons in the BNL reactor being approximately sixty feet to the right of the monochromator and off the diagram. The $12\bar{3}1$ planes of a beryllium single crystal were used for the neutron monochromator. Use of these planes, together with the collimation afforded by the slit system, gave an over-all resolution of about 7 minutes of arc ($\sim$0.024 ev for 1-ev neutrons). Details of the scattering chamber are shown in Fig. 2. The thick-thin technique requires that the sample present as thick a section as possible to the incident monochromatic neutron beam while presenting as thin a section as practicable to the detector for the scattered neutrons. This arrangement provides an optimum counting rate with a minimum of

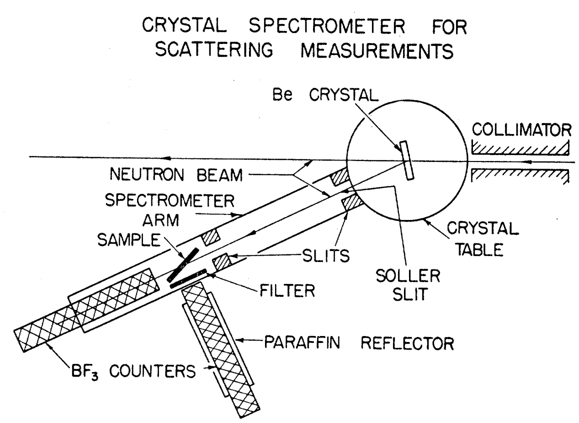

FIG. 1. General arrangement of the scattering experiment—plan view. The source of neutrons in the Brookhaven reactor is approximately sixty feet to the right of the crystal table. The horizontal Soller slit serves to reduce the background from the crystal without appreciably reducing the monochromatic beam. Both the scattered intensity and the transmission of the sample are measured simultaneously with the two BF_3 detectors.

[4] For definition of symbols, see Wood, Landon, and Sailor, Phys. Rev. **98**, 639 (1955).

[5] The term "negative-energy" resonance refers to a level in the compound nucleus lying just below the neutron binding energy. Such a level cannot be observed directly with slow neutrons since neutrons cannot have negative kinetic energy. However, the level does affect the cross section in the positive kinetic energy region and the effect may be calculated by proper application of the single-level formula.

[6] H. L. Foote, Jr. and J. Moore, Phys. Rev. **98**, 1161 (1955).

difficulty in interpretation of results. For this experiment a practical compromise of the various criteria resulted in a sample approximately 4 in.×5 in. in area and approximately 0.030 in. thick, placed at an angle of 6 degrees and 7 minutes to the monochromatic beam axis (angle θ of Fig. 2).

In order to measure the scattered neutron intensity, it is necessary to measure both the background counting rate for the environment and the crystal monochromator as well as the fast-neutron intensity that results from fissions caused by the incident monochromatic beam. The B^{10} filter, shown in Fig. 2, was utilized to obtain the fast-neutron counting rate, by observing counting rates with and without the filter in place. The detector for the scattered neutrons was also sensitive to the β particles given off by the radioactivity in the sample. An aluminum filter reduced this radiation to a negligible level.

The sample was a very pure specimen of uranium enriched to approximately 93% in U^{235}. A difficulty experienced with the sample was in making it flat enough so that the light aluminum sample mount could hold it in proper geometrical relationship to the neutron beam. The sample was very hard, springy, and stiff and rolling did not flatten it sufficiently. This problem was resolved by working the metal with a light ballpein hammer on an anvil. This procedure, with frequent checking against a straight edge and a surface plate, produced a sample flat within several thousandths of an inch.

The principle of the experiment is to observe the scattered neutron counting rate of the uranium sample at a given energy and then to compare it with the counting rate obtained from a lead sample[7] for which σ_s/σ_t is known. The comparison sample is prepared so as to have approximately the same scattering power

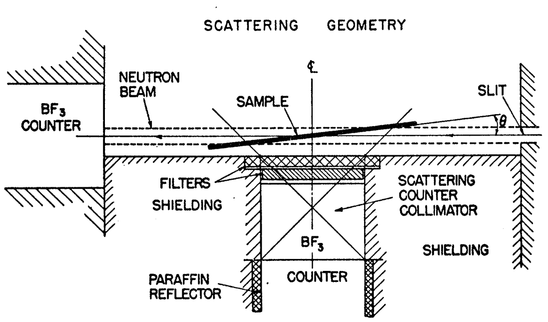

FIG. 2. Top view of the scattering chamber. The B^{10} filter is nearest the sample. When making "filter-out" measurements, the B^{10} filter is replaced by a dummy, identical except for the B^{10}. The short collimator before the scattered neutron detector limits the acceptance angle to ±45 degrees. The paraffin reflector, about $\frac{1}{8}$ inch thick, increases the counting rate of the scattering detector about $2\frac{1}{2}$ times. The beam at the slit is $\frac{3}{8}$ inch wide by 2 inches high. Additional shielding of boron carbide and paraffin not shown in the figure encloses the sample on the side away from the counter.

[7] The high-purity lead used as a standard was obtained from the American Smelting and Refining Corporation.

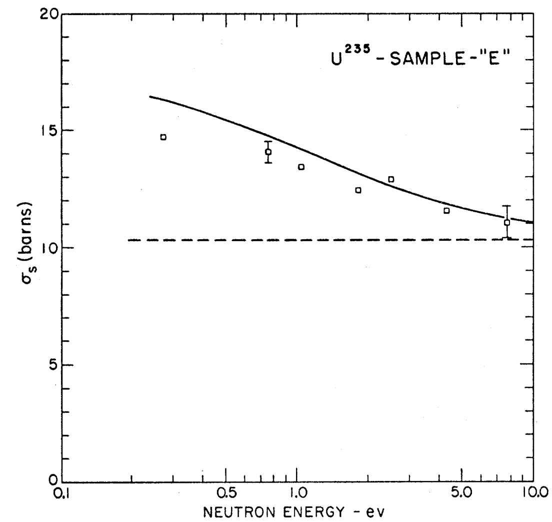

FIG. 3. The scattering cross section for U^{235}. The observed data are the plotted points. Standard deviations are representative and are for counting statistics only. The scattering cross section obtained from Sailor's total cross-section analysis is plotted as the solid curve. The dashed line is the calculated value of the potential-scattering cross section obtained from the relation: $R=1.47\times10^{-13}A^{\frac{1}{3}}$ cm. The analysis of the data points yields a value of 10 ± 1 barns for the constant cross section, i.e., σ_p plus a resonant component.

($N\sigma_s$). The counting rate is measured in the same geometry as for the other sample. The singly scattered counting rate observed for thin samples in the geometry of the experiment is proportional to σ_s/σ_t and may be expressed as follows[6]:

$$\text{Scattered intensity} \equiv I_s = \Phi\epsilon G\frac{\sigma_s}{\sigma_t}(1-T^{\alpha}). \qquad (2)$$

Here, Φ, is the incident neutron flux; G, a term involving geometrical aspects of the experiment; ϵ the counter efficiency; σ_s/σ_t the ratio of the scattering cross section to the total cross section; and $(1-T^{\alpha})$ a correction term, whose value depends upon the transmission of the sample, T, and α, a constant determined from the scattering geometry. Thus, σ_s/σ_t for the scattering sample is determined from the scattered counting rates of the two samples and calculated corrections. Terms of formula (2), such as Φ, G, and ϵ cancel out in making the comparison with the lead sample. The scattering cross section is obtained by multiplying each value of σ_s/σ_t by the corresponding value of σ_t.

III. RESULTS AND CONCLUSIONS

The data obtained are shown in Fig. 3 and are listed in Table I. The observed scattering cross section decreased with increased energy. It is assumed that the scattering cross section consists of a component which is a function of energy and a component which is constant; i.e., that its energy dependence is given by Eq. (1). The data were fitted by the method of least squares to Eqs. (1a) to (1c), assuming that the reso-

TABLE I. Observed and computed values for the scattering cross section of U^{235}.

E (ev)	Observed σ_s (barns)[a]	Computed σ_s (barns) Sailor[b]	Computed σ_s (barns) Harvey and Sanders[c]
0.271	14.7	16.3	14.7
0.756	14.1±0.4	14.8	13.6
1.044	13.4	14.2	13.1
1.81	12.4	13.2	12.4
2.51	12.9	12.6	12.0
4.31	11.5	11.8	11.4
7.74	11.0±0.7	11.2	11.0

[a] Standard deviations indicated are representative values and are for counting statistics only.
[b] These computed values are based on parameters listed in the review paper: V. L. Sailor, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 199. The parameters used were $\sigma_{s0}\Gamma^2=12.7$ barn ev², $\mathcal{I}=32.5$ barn ev, $\sigma_p=10.3$ barns, and $E_0=-1.39$ ev.
[c] These computed values are based on parameters listed in the summary article: J. A. Harvey and J. E. Sanders, *Progress in Nuclear Energy, Ser. I, Physics and Mathematics* (Pergamon Press, London, 1956), Vol. 1, p. 46. Contribution from the −0.02-ev resonance is negligible and has been neglected. The parameters used were $\sigma_{s0}\Gamma^2=7.36$ barn ev², $\mathcal{I}=24.7$ barn ev, $\sigma_p=10.3$ barns, and $E_0=-1.39$ ev.

nance contribution comes entirely from a single bound level (negative-energy resonance) located in the region between 0 and −10 ev. Solutions were obtained for various trial values of E_0. As was already pointed out, the scattering contribution from positive-energy resonances is negligible.

Each solution yielded a constant and a resonant component which correspond respectively to the parameters of Eqs. (1b) and (1c). In all trials, a value of 10 barns (with an estimated over-all error of ±1 barn) was obtained for the constant component, this result being relatively insensitive to the method of fitting and to E_0. These resonance parameters varied more widely for the various trials. This behavior would be expected because of the scatter of the data. The most reasonable fit gives $\mathcal{I}=30$ barn ev $(\sigma_{s0}\Gamma^2=0)$ and $\sigma_p=9.8$ barns. (It is recognized that this solution is not internally consistent, but is the most realistic interpretation in view of the limitations of the data.) The resonance parameters of interest here are $\sigma_{s0}\Gamma^2$ where σ_{s0} is the value of the scattering cross section at resonance, and $\mathcal{I}$, the value of the interference component parameter, i.e., $\mathcal{I}\equiv 16\pi\lambda\!\!\!^{-}_0 g\Gamma_n R_g$.

The constant cross section of 10±1 barns, which is identified as the "potential" scattering cross section, agrees very closely with the value, 10.3 barns, computed from the formula

$$\sigma_p=4\pi R^2, \quad \text{where} \quad R=(1.47\times10^{-13})A^{\frac{1}{3}}\ \text{cm}.$$

The resonant component, $\mathcal{I}=30$ barn ev, agrees qualitatively with the derived parameters of Sailor[1] and Harvey and Sanders.[1] Computed values of the scattering cross section derived from these parameters are listed in Table I. The computed values for Sailor's data are plotted in Fig. 3 as the solid curve. A curve for Harvey's and Sanders' data would pass very nearly through the data points. The horizontal dotted line in Fig. 3 at 10.3 barns represents the potential scattering cross section computed from the formula. While it appears that particularly good agreement with the Harvey and Sanders parameters is obtained, it is, nevertheless, considered that the quality of the scattering data does not warrant undue emphasis of this agreement. Quantitatively, the scattering data tend to verify the presence of a strong bound level. Measurements of better precision extended through lower energies are badly needed since they could provide better information about the presence and parameters of such a level and thus help resolve one of the most difficult problems in the interpretation of the U^{235} cross section.

IV. ACKNOWLEDGMENTS

I wish to thank Dr. V. L. Sailor for suggesting this problem and for valuable discussions. I also wish to acknowledge the assistance of Dr. Sophie Oleksa in the study of the β-radiation background.