Thermal Neutron Absorption Cross Sections of Boron and Gold*

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The cross sections of boron and gold, which are widely used as standards for slow neutron measurements, have been determined as functions of wavelength. Total cross sections were measured in the wavelength range 1.5–10A with the Brookhaven slow chopper, the long wavelengths being used to minimize the effects of scattering. The absorption cross section of boron of "normal" isotopic constitution is 749±4 barns at 2200 m/sec (1.80A); the variation of cross section with boron source is expected to be only about 1 percent. The measurement of the gold cross section is complicated by the deviation from $1/v$ resulting from a nearby resonance and by grain orientation effects in the scattering. The 2200-m/sec value, resulting from measurements at long wavelength together with a small correction for the 4.9-ev resonance, is 98.7±0.6 barns.

I. INTRODUCTION

FOR many applications of slow neutrons involving cross sections of various materials, the use of certain *standard* cross sections is of great value. The standard materials, of accurately known cross sections, can be used to determine other cross sections by relative measurements, which can be performed with much greater accuracy than absolute determinations. The cross-section standards are also applied to measurement of neutron flux and, by means of flux standardization, to calibration of neutron source strength. In these applications it is usually the absorption cross section σ_{abs} that is of interest, which is the cross section for all processes in which the neutron "disappears," consisting mainly, for slow neutrons, of the (n,p), (n,α), and (n,γ) reactions.

Whereas absorption cross sections are difficult to measure directly with precision, for example by the pile oscillator technique, they can for some materials be inferred from the total cross section with much greater accuracy. The latter approach is possible if the absorption is much larger than the scattering, which must be subtracted from the total to obtain the absorption cross section. Although the total cross section can be measured with great precision by transmission measurements, the subtraction of the calculated scattering, even when relatively small, introduces uncertainties of 1–3 barns because of neutron interference effects. It is possible, however, to obtain the absorption cross section from transmission experiments without subtraction of scattering because of the practical disappearance of the latter at long wavelength. This technique has been used only recently, and in the present paper its application to the important cases of boron and gold will be described.

The standard materials for slow neutron absorption are usually boron of normal isotopic constitution or gold; for both of these the absorption cross section at thermal energy (2200 m/sec) is much larger than the scattering. The values of the thermal absorption cross sections for these standards have been determined most accurately from transmission measurements of total cross sections and subtraction of scattering. As the direct absorption measurements, such as the pile oscillator, are used only to measure other materials relative to these standards, they are not applicable to the fundamental standards themselves. For some years the thermal absorption of boron in general use was about 705 barns, a value based on transmission measurements made by Fermi at Argonne Laboratory using neutrons whose velocity was selected by the slow chopper. The gold cross section measured with the same equipment[1] resulted in a value of 93 barns, which was used for several years. The scattering correction uncertainty is negligible in boron relative to the absorption but it amounts to 1–2 percent for gold.

In the last few years the boron cross section has risen by surprisingly large amounts, the most recent values lying in the range 750–760 barns.[2] During this period the gold cross section had risen slightly, to 95 barns, and several measurements[3] of its total cross section were in good agreement. In view of the importance of boron and gold as standards and the recent sharp rise in the boron value, it was thought advisable to make careful measurements of the absorption of these materials with the slow neutrons available with the Brookhaven slow chopper. The availability of long wavelengths makes it possible to avoid uncertainties involved in the subtraction of scattering by measuring the cross section at wavelength beyond the cutoff, where most of the scattering disappears.

II. EXPERIMENTAL METHOD

The method of obtaining absorption cross sections by subtraction of scattering from the total (measured by transmission at 2200 m/sec) involves some uncertainty in the scattering to be subtracted. This uncertainty arises because the scattering in the thermal energy region varies abruptly with wavelength in a manner typical of the Bragg scattering in the poly-

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[1] T. Brill and H. V. Lichtenberger, Phys. Rev. **72**, 585 (1947).
[2] Unpublished results of Argonne (R. Ringo *et al.*) and Columbia (W. Havens *et al.*) transmission measurements.
[3] Listed by H. Pomerance, Phys. Rev. **83**, 641 (1951).

crystalline samples usually used. The scattering is extremely difficult to measure in a separate experiment with monenergetic neutrons, and its calculation is uncertain because the coherent Bragg scattering is reduced by extinction effects in the microcrystals, and is modified by preferred orientation of the crystal grains. In the case of boron the scattering is so small that the uncertainty is negligible, but for gold it is sufficiently large as to affect the final accuracy seriously.

The effect of scattering can be avoided, however, by measuring the cross section at wavelengths longer than the crystal cutoff (twice the largest lattice spacing) because the coherent scattering is not observable beyond this wavelength. For most materials, the scattering is predominantly coherent, and the remaining incoherent scattering beyond the cutoff is usually negligible compared to absorption. The cutoff wavelength is of the order of 4–7A and sufficient neutron intensity is available with the slow chopper at longer wavelengths to make possible accurate transmission measurements.

At long wavelength the cross section is made up of capture and incoherent scattering only, the latter consisting of isotopic incoherence, spin-dependent incoherence, and thermal diffuse scattering.[4] The absorption, which is almost always $1/v$ in the long-wavelength region, can be separated from the various types of incoherent scattering because of its velocity dependence and independence of sample temperature. As the isotopic and spin-dependent incoherent cross sections are constant with wavelength, whereas the temperature-diffuse scattering varies rapidly with temperature, these components can be identified. The method of measuring absorption cross sections with long-wavelength neutrons has a great advantage when the scattering is not negligible relative to absorption because of the practical disappearance of the scattering (for the usual case of predominantly coherent scattering) beyond the cutoff. Some uncertainty exists, however, in the extrapolation of the absorption from the long-wavelength region, where it is measured, to the thermal value at 2200 m/sec. There is no uncertainty in the case of boron, but in gold the departure from $1/v$ is of the order of 1 percent. The smallness of this departure from $1/v$ in the case of gold, which has a prominent resonance near thermal energy, indicates that the effect is negligible for most other materials.

The source of velocity-selected neutrons for the present measurements is the Brookhaven slow chopper,[5] which has been used for "cold" neutron measurements, in the range 1–20A, extensively in the past two years. The chopper allows a burst of pile neutrons to pass periodically to a detector several meters distant and the velocity is selected by the time of flight to the detector (an enriched BF_3 proportional counter). The shutter action is obtained by means of cadmium slits in a rotating cylinder that passes one burst of neutrons per revolution. The distance between the detector and chopper is determined by the wavelength region being investigated and the resolution required for the measurement. The detector can be placed as far as 10 meters from the chopper without causing successive neutron bursts to overlap; at this distance and the normal chopper speeds the energy resolution is approximately 1 percent (full width at half-maximum) for the entire available energy range of 10^{-1} to 10^{-4} ev. For the present measurements, flight paths of about two meters were used hence 5 percent resolution.

The flight time of the neutrons is determined electronically, the timing sequence being initiated by light reflected from a mirror mounted on the shaft of the chopper. At the end of a pre-set time delay, the circuit allows the neutron pulses from the BF_3 counter to pass into twelve scaling and recording channels, spaced consecutively and of equal, variable, time duration. The electronic timing sequence is calibrated with a one-megacycle quartz crystal, with the frequency known to ± 0.1 percent. Although the electronic calibration allows the determination of elapsed time to one part in a thousand, the absolute wavelength scale would be affected by the possible time interval between the moment the neutrons pass the center of the chopper and the instant the zero-time pulse is generated. The proper adjustment of the zero-time pulse to make the two events simultaneous is determined by measuring the flight time corresponding to the Bragg cutoff in graphite. Graphite is used because of the large discontinuity in cross section (9 to 1.3 b) at the cutoff, and the long-cutoff wavelength, 6.70A, which gives a calibration point in the region of interest in the present work.

Because of finite resolution the discontinuity in cross section appears as a line of finite slope in the transmission curve. Figure 1 shows the transmission of neutrons through 1 in. of graphite, for which measurement the resolution function can be represented by a triangle with a full width at half-maximum of 0.15A. The solid line in Fig. 1 is the calculated transmission expected from the graphite crystal structure for infinite resolution, and the dotted line includes resolution. The position of the graphite cutoff is determined by graphical analysis to ± 0.02A, hence the wavelength scale is known to approximately the same accuracy.

The sample is placed between the chopper and the detector, usually about 18 in. from the latter to avoid the small-angle scattering[6] that takes place in fine grain materials, especially at long wavelength. The total cross section is determined by a transmission measurement, i.e., the neutron intensity is measured for the open beam and again for the sample in the beam. The effect of epi-cadmium neutrons that penetrate

[4] D. J. Hughes, *Pile Neutron Research* (Addison-Wesley Press, Cambridge, 1953), pp. 249–254, 270–272.

[5] Seidl, Palevsky, Randall, and Thorne, Phys. Rev. **82**, 345 (1951).

[6] R. J. Weiss, Phys. Rev. **83**, 379 (1951).

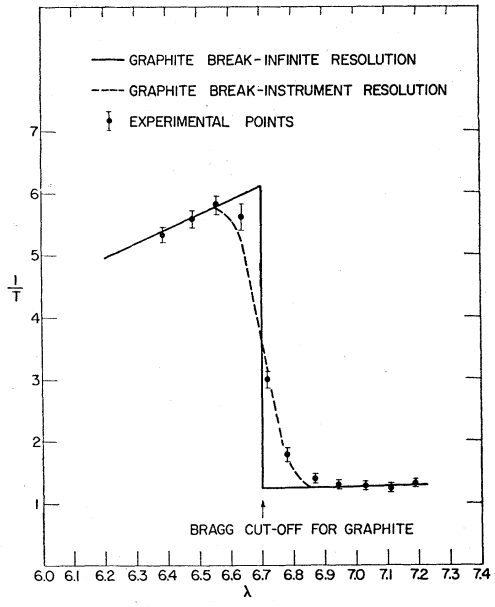

FIG. 1. The discontinuity in neutron transmission of a 1 in. graphite sample, which is used as a wavelength calibration of the slow chopper. The solid curve is calculated from the crystal structure of graphite and the dotted curve includes the instrumental resolution (0.15A).

the chopper as well as all other background neutrons can be accurately determined by placing a thin (0.010-in.) sheet of cadmium at the exit of the chopper. As this sheet removes more than 99 percent of the timed neutrons but does not affect the epi-cadmium background neutrons, the difference between a measurement without and with cadmium gives the correct intensity of the timed neutrons. The epi-cadmium neutron background is reduced as much as possible by adjusting the opening of the beam hole into the pile so that the cadmium ratio is a maximum. In addition, the ratio of timed to background neutrons (of wavelength greater than 3.9A) is improved by the use of a Be filter, which attenuates the epi-cadmium neutrons greatly with only a slight decrease in the intensity of timed neutrons. In the transmission measurements, a second BF_3 counter, mounted in a pile hole adjacent to the slow-chopper hole, serves as an incident intensity monitor. The open-beam counting rates for the present measurements were of the order of 1000 counts per minute per channel at 4A and 100 at 8A.

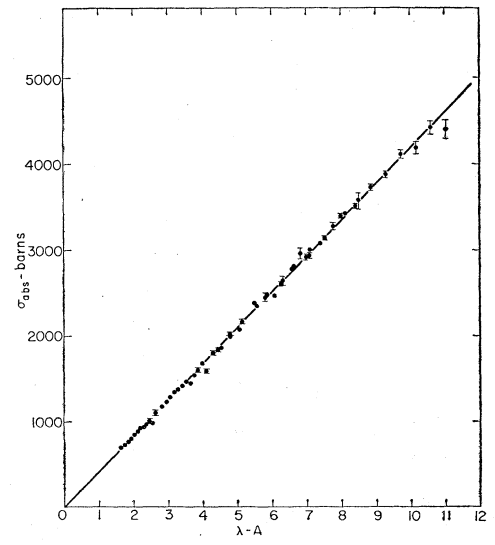

FIG. 2. The absorption cross section of boron as a function of neutron wavelength, obtained by subtraction of scattering from the measured total cross section of the boron solution.

III. BORON

The scattering correction is small for boron and cannot explain the much larger discrepancy among previous measured absorption cross sections (700–760 b) for normal boron. Neither can the discrepancy be ascribed to variations in B^{10} content (which isotope accounts for essentially the entire absorption), for this varies[7] by a *maximum* of ± 2 percent. The most likely explanation of the previous variation in results involves the boron content of the samples used, for instance, the presence of water in boric oxide.

The boron used in the present work was obtained in the form of boric acid powder from R. Ringo at Argonne National Laboratory. This particular born (mined in California) was used because its cross section had been measured at Argonne and its isotopic ratio determined at Oak Ridge. The question of the B^{10} content of this and other samples will be considered in more detail later.

The boric acid was converted into fused B_2O_3 by R. Stoenner of the Brookhaven chemistry department. The boric acid was heated to drive off the water and when the material had reached a point where its weight no longer changed it was checked by chemical analysis to see if it still contained any water. Several attempts were necessary before B_2O_3 was obtained that had less than 0.2 percent (by weight) water. The fused B_2O_3 was then weighed carefully and dissolved in a known amount of D_2O. The boron content was determined by chemical analysis before and after every slow chopper measurement made with each sample in order to detect any change in concentration. The chemical analysis was performed by saturating a given weight of solution with mannitol to increase its acidity, then titrating it with a standard alkali until it was neutralized. The amount of alkali used was thus an accurate measurement of the amount of B_2O_3 present. The boron content as determined by chemical analysis agreed to better than 0.2 percent with the weight determination in each case.

The B_2O_3 was dissolved in D_2O rather than H_2O in order to avoid the large scattering cross section of the

[7] Thode, Macnamara, Lossing, and Collins, J. Am. Chem. Soc. **70**, 3008 (1948).

latter. To increase further the contribution of the boron to the total cross section, the solution was heated to 40°C to increase the B_2O_3 concentration. For the concentrations used, about 30 mg/g of solution, the boron absorption constitutes about 60 percent of the total cross section at 4A. The solutions were used in thin-walled aluminum holders, which allowed the thickness of the sample to be accurately determined. The amount, in grams/cm², of B_2O_3 in the beam was obtained from the product of the concentration, density, and thickness of sample.

The boron transmission was measured by comparing the neutron intensity for the $B_2O_3+D_2O$ sample with a "blank" consisting of D_2O. Since the density of the D_2O is slightly decreased when the B_2O_3 is added, the D_2O blank was made slightly thicker to compensate for this small effect. The D_2O and the $B_2O_3+D_2O$ solution were run alternately in the slow-chopper beam, contained in a temperature-regulated furnace at 40°C.

Transmissions were measured in the range 1.7A to 9.5A, each cycle of measurements consisting of a D_2O blank run, a D_2O background (0.01-in. cadmium), a $B_2O_3+D_2O$ solution run, and a solution background run. Several cycles were completed for each wavelength range and the transmission determined from the ratio of the counting rates after subtraction of background. The total cross section of B_2O_3 per atom of boron determined from the transmission includes that of 1.5 atoms of oxygen as well as a slight contribution from the D_2O, because it was not practical to make the blank contain exactly the same number of D_2O molecules as the sample. The measured cross section was corrected for the D_2O contribution (an effect of approximately $\frac{1}{3}$ percent, determined from a separate cross section measurement of D_2O), as well as for the scattering of boron and oxygen (calculated) to obtain the absorption cross section. Because of the use of a liquid sample, the "cutoff" is not complete and some scattering from the boron and oxygen is present in the wavelength region used—(about $\frac{1}{2}$–1 percent of the total cross section).

In Fig. 2 is plotted the absorption cross section of boron as a function of wavelength, obtained by subtraction of the scattering and D_2O contribution from the measured cross section. A line drawn through zero cross section at zero wavelength fits the points very well, thus verifying the $1/v$ nature of the absorption cross section. The linearity of the curve and the statistical accuracy of the points is better demonstrated in Fig. 3 where σ/λ is plotted against λ. The points are well fitted by a horizontal line at $\sigma/\lambda=416.7$ b/A. Thus we obtain for the cross section of boron at 1.80A (2200 m/sec) the value;

$$\sigma_{abs}=749\pm4 \text{ b},$$

where the principal contributions to the standard error are statistics and uncertainty in wavelength calibration. This value is in good agreement with the unpublished result[8] of Ringo *et al.* at Argonne using the same boron source, but is much higher than older values in the 700–730 b range.

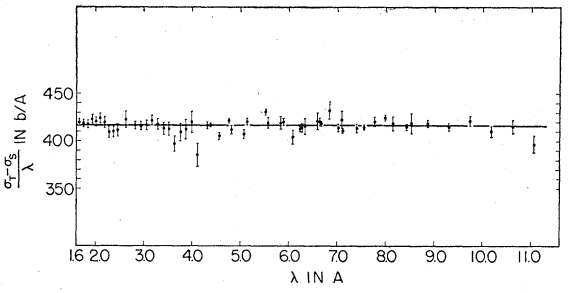

FIG. 3. The boron absorption cross section divided by wavelength as a function of the latter.

In addition to the above data a sample of boron glass was measured in the region 1.5 to 9A. Its transmission had previously been determined at Columbia University and it had been analyzed quantitatively by the Corning Glass Company. It consisted of 13.4 ±0.1 percent B_2O_3 by weight, 80.1 percent SiO_2, 4.5 percent Na_2O, and 2 percent Al_2O_3, these constituents giving rise to a scattering cross section of 4.6 b per atom of boron, assuming that the scattering adds algebraically. The observed cross section, after correction for this scattering, is plotted against wavelength in Fig. 4, where again a straight line through zero fits the points well. The value for the total cross section at 1.80A obtained from the "best" line through zero is 753 b. When this $1/v$ cross section is corrected for the 0.5 b contributed by the absorption cross section of the constituents other than boron, the value for the boron

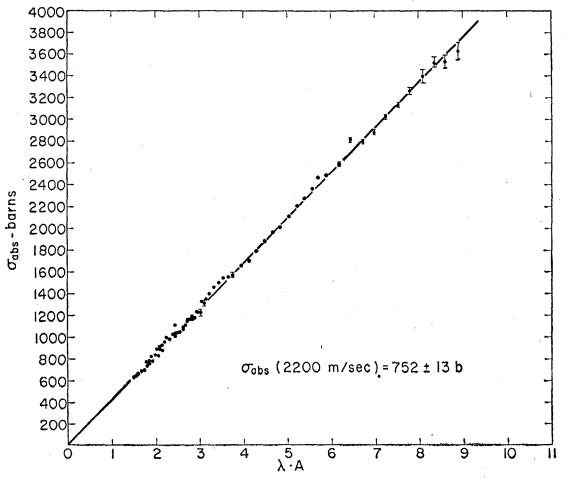

FIG. 4. The boron absorption cross section obtained by subtraction of scattering from the measured total cross section of the boron glass sample.

[8] Quoted by Kaplan, Ringo, and Wilzbach, Phys. Rev. **87**, 785 (1952), as 755±5 b; and by Hamermesh, Ringo, and Wexler, Phys. Rev. **90**, 603 (1953) as 755±3 b.

absorption cross section determined from the glass is 752±13 b. The 13-barn error is based entirely on statistical fluctuations, the error in the corrections being negligible compared to this amount. Although the boron glass was not measured as carefully as the fused B_2O_3, it furnishes a valuable check on the value given above as it was obtained from a different form of sample.

The isotopic content of the boron used in the Argonne and the present measurement has been analyzed by mass spectrograph at Oak Ridge. Although there exists some question concerning the absolute accuracy of isotopic ratios thus determined, the relative values from sample to sample are reliable. Thus the B^{10} content of our sample was measured as 0.185 (systematic error

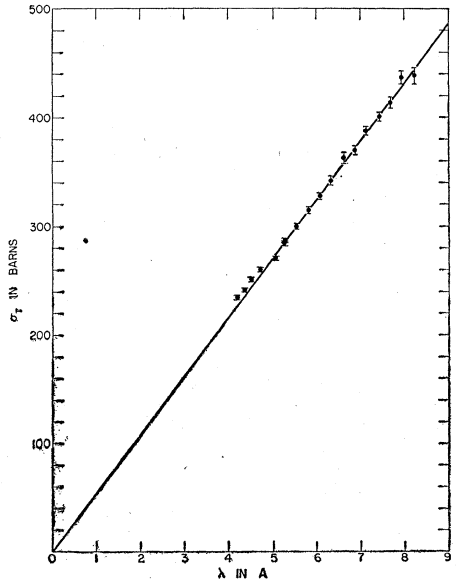

FIG. 5. Measured total cross section of rolled gold foil as a function of wavelength, showing the $1/v$ region beyond the crystal cutoff (4.71A) and the appearance of coherent scattering at shorter wavelengths. Measured points in the thermal region are not shown because the effects of grain orientation prevent calculation of the scattering corrections.

not estimated) but it was found to be the same within instrumental sensitivity ($\frac{1}{2}$ percent) as routine California boron measured at Oak Ridge. Thode *et al.*[7] have found 0.1871 for the B^{10} content of California boron in a careful absolute measurement, a range of $\pm\frac{1}{2}$ percent in California boron, and an extreme range of ±1.8 percent for world wide samples. The isotopic variation in "California" boron (any boron from western United States sources) thus seems to be so small that the cross section of different samples can be taken as equal.

IV. GOLD

The total cross section of gold was measured in the range 1.7 to 8.5A, using foils of purity greater than 99.9 percent, whose thickness varied from 0.010 in. to 0.040 in. Transmissions were obtained in the same manner as described for boron although no "blank" was needed in the open beam measurements.

The observed total cross section is plotted as a function of wavelength in Fig. 5, where the coherent scattering contribution to the cross section is evident at wavelengths less than the 4.7A cutoff. Beyond the cutoff wavelength, the cross section is almost entirely absorption, the calculated inelastic scattering amounting to only 0.3 b and the calculated incoherent (spin-dependent) scattering to 0.4 b,† both negligible compared to absorption.

The straight line drawn through zero cross section at zero wavelength in Fig. 5 fits the points very well, verifying the $1/v$ nature of the absorption cross section in the 5–9A range. The slope of the line is 54.4 ±0.25 b/A, giving the extrapolated $1/v$ absorption cross section at 1.80A (2200 m/sec) as:

$$\sigma_{abs}=97.8\pm0.5 \text{ b}.$$

As for boron, the principle sources of the error are statistics and wavelength calibration.

The 97.8-b result is based on an extrapolation of the $1/v$ cross section to thermal energy (1.80A), an extrapolation that requires some investigation, especially in view of the fact that the present value is higher than earlier results[3] (about 95 barns). The resonance at 4.9 volts should cause the absorption cross section to increase above the $1/v$ line by 1 percent at 1.80A (2200 m/sec) as this level is primarily responsible for the thermal cross section.[9,10] In order to study the variation of absorption for wavelengths less than 4.7A it is necessary to subtract the scattering from the observed total cross section. The scattering can be calculated[11] from the crystal structure of gold, but the result is uncertain because of the unknown effects of crystal orientation and extinction. The observed total cross section at thermal energy, if corrected for scattering by a calculation omitting crystal orientation and extinction effects, gives an absorption 3 percent *less* than the $1/v$ line. Actually a detailed examination of the total cross section reveals that the full value of the last coherent peak (at the crystal cutoff) is not observed. In addition, a total cross section measured with the sample at an angle to the beam revealed crystal orientation effects by changes in the observed peaks. Thus considerable doubt is thrown on the scattering correction in the thermal region for the rolled gold sample.

In order to investigate the cross section in the thermal region with less uncertainty in the scattering cross section, samples of powdered gold were measured,

† *Note added in proof:* Direct measurement of incoherent scattering by B. N. Brockhouse (private communication) gives 0.5±0.26.

[9] Unpublished Brookhaven fast chopper results.

[10] J. Tittman and C. Sheer, Phys. Rev. **83**, 746 (1951).

[11] See reference 4, pp. 270–272.

for which no effects of orientation and extinction should change the calculated scattering. The results of measurements in the wavelength region of interest are given in Fig. 6. Because the sample thickness is difficult to determine accurately for powdered gold, the total cross section is normalized at wavelengths just beyond the cutoff to the $1/v$ line of Fig. 5. The magnitude of the abrupt change in cross section at the cutoff, as well as the location of this change (4.7A), corresponds well with the theoretical scattering, given by the upper curved line.

The agreement of the observed behavior of the cross section at cutoff with the theoretical scattering justifies the use of the latter to the accuracy of the measurements, about one barn. Subtraction of the theoretical scattering for the entire energy range of Fig. 6 gives a result in agreement with the $1/v$ line, because the observed points agree well with the theoretical scattering. With the accuracy shown in Fig. 6, it is not possible to detect the 1 percent increase at thermal energy that should result from the resonance at 4.9 ev.

The value of the $1/v$ line at thermal energy, 97.8 $\pm$0.5 b, is known more accurately than the thermal cross section in Fig. 6 because no scattering cross section is involved. The most accurate value of the actual absorption cross section at thermal energy (2200 m/sec) is obtained by adding the effect of the resonance to the $1/v$ value, with the result:

$$\sigma_{\text{abs}}(2200 \text{ m/sec}) = 98.7 \pm 0.6 \text{ b}.$$

The slight increase in the error arises from uncertainty in the properties of the resonance level.[9,10] The fact that values of this cross section reported in the past have been somewhat lower is probably a result, at least partly, of the uncertainties in scattering. These uncertainties, together with the slight departure from $1/v$ in the thermal region and the prominent resonance absorption, tend to decrease the value of gold as a thermal neutron cross-section standard.

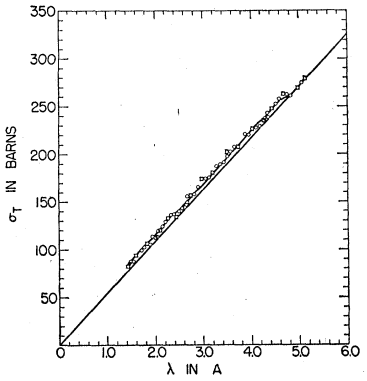

FIG. 6. Total cross section of powdered gold, normalized beyond the cutoff to the rolled gold results of Fig. 5 (straight line). The upper line represents the addition of the calculated scattering.