to the fact now known[10] that the thin-target bremsstrahlung cross section comes to a finite value at the upper limit and not to zero as suggested by the Bethe-Heitler formula; this affects the thick-target formulas. It is clear, however, that these absorption coefficient measurements should be repeated and extended.

[10] Handel Davies (private communication).

It is noteworthy that the parameter determined by this experiment—$\int \sigma^2 dE / \int \sigma dE$—is similar to that—$\int \sigma^2 dE$—determined by γ-ray scattering.[4]

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I am grateful to Professor W. K. H. Panofsky for reminding me of the work of Dr. Berman.

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Slow-Neutron Resonance Scattering in Ag, Au, and Ta†*

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Slow-neutron resonance scattering measurements by the "bright-line" technique have been used as a supplement to and a check on total cross section measurements. It has thus been possible to obtain a complete and consistent set of resonance parameters for the lowest energy resonances in Ag, Au, and Ta. It was determined that the one-level formula is very well obeyed over wide energy ranges for both the scattering and total cross section data. These resonance parameters are reported in the text with the values for the statistical weight factor, g, of 3/4, 5/8, and 9/16 for Ag^{109}, Au^{197}, and Ta^{181}, respectively.

In addition it was determined that the nuclear radii are the same within experimental errors for the nonresonant and resonant spin states for Au and Ta. The results indicate that either the nuclear radii differ by 45% for the two spin states of Ag^{109} or the potential scattering of Ag^{107} is 55% larger than for Ag^{109}.

INTRODUCTION

DETERMINATION of resonance parameters that fit the Breit-Wigner single-level formulism has been of prime interest both from a theoretical and a practical point of view. Among other things, it is of theoretical interest to determine the region over which the Breit-Wigner single-level formula is valid, and to compare level spacings and parameters with specific nuclear models. It is of practical interest to know the nuclear properties (cross sections in particular) of all elements for the design of reactors and other nuclear devices.

The main emphasis of cross-section measurements in the past has been to determine the total cross section of an element by means of a transmission measurement. This gives the combined effects of radiative capture plus elastic scattering, but does not allow one to separate the two components of the total cross section. The parameters obtained from transmission measurements are therefore composite parameters and not the complete parameters. In order to determine a complete set of resonance parameters, it is necessary to make a measurement, such as scattering, in addition to the total cross section measurements.

Few scattering measurements have been made for slow neutrons because the scattered intensity is very low, since scattering is only a small fraction of the slow-neutron resonance cross section. The first scattering measurements were determinations of the scattering integral by methods such as resonance scattering detectors.[1] Subsequently, the ratios of the scattering to the total cross section,[2] σ_s/σ_t, and the ratios of the scattering to the capture cross section,[3] σ_s/σ_c, have been observed as a function of energy for a few cases.

Early in 1951, Borst devised a new method for direct observation of the scattering cross section as a function of energy.[4] It is felt that this experimental method and method of analysis have now been developed to the point where reliable results can be obtained.[5,6] It is therefore of interest to compare results obtained by this method with results obtained by other methods, and also to see if scattering results can be obtained that are consistent with total cross-section data.

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[1] Harris, Langsdorf, and Seidl, Phys. Rev. **72**, 866 (1947); F. G. P. Seidl, Phys. Rev. **75**, 1508 (1949); C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949); Hibdon, Muehlhause, Selove, and Woolf, Phys. Rev. **77**, 730 (1950); M. Hammermesh and C. O. Muehlhause, Phys. Rev. **78**, 175 (1950); Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950).
[2] Tittman, Sheer, Rainwater, and Havens, Phys. Rev. **77**, 748 (A) (1950); **80**, 903 (1950); **82**, 344 (A) (1951), J. Tittman and C. Sheer, Phys. Rev. **83**, 747 (1950); Sheer, Moore, and Heindl, Phys. Rev. **91**, 449 (A) (1953); C. Sheer and J. Moore, Phys. Rev. **98**, 565 (1955).
[3] B. N. Brockhouse, Can. J. Phys. **31**, 432 (1953); B. N. Brockhouse and D. G. Hurst, Phys. Rev. **83**, 841 (1951); **88**, 542 (1952); Brockhouse, Hurst, and Bloom, Phys. Rev. **83**, 840 (1951).
[4] L. B. Borst, Phys. Rev. **90**, 354 (A) (1953); **90**, 859 (1953).
[5] H. L. Foote, Jr. (to be published).
[6] R. E. Wood, Phys. Rev. **95**, 644 (A) (1954).

The purpose of this study was, therefore, to check further the accuracy and reliability of the method and the analysis, to see if consistency could be obtained with total cross-section data (i.e., that the Breit-Wigner formulism is obeyed), to obtain accurate parameters for gold since it is often used as a standard, and to explore the useful range of this method. The primary purpose of any resonance scattering experiment is to determine the spin of the compound nucleus (total angular momentum for the excited state of the compound nucleus). If the experiment is not sensitive enough to determine the spin of the compound nucleus (or the statistical weight factor g), it can add virtually nothing to the total cross-section data.

The elements studied for this report were chosen for various reasons. Thin foils of a very high purity were readily available for each element, which simplified the problem of sample preparation. Two elements (silver and gold) had been studied previously by a different method,[2] but consistency with total cross-section data was not obtained in this earlier work. It is therefore possible to compare these results with other scattering observations as well as with total cross-section data. Two of the elements (gold and tantalum) are monoisotopic, which makes it possible to determine nuclear radii for the nonresonant spin state as well as for the resonant spin state. The spins of the target nuclei (total angular momentum for the ground state of the target nuclei) for Ag, Au, and Ta are, respectively, 1/2, 3/2, and 7/2. The difficulty in determining the spin of the compound nucleus increases as the spin of the target nucleus increases; thus, tantalum allows a possibility of testing the sensitivity of the experiment with respect to the spin (or the statistical weight factor, g).

DESCRIPTION OF APPARATUS AND EXPERIMENT

Total Cross Section

Total neutron cross sections were determined by means of transmission measurements using the BNL crystal spectrometer.[7] Collimators of very small angular divergence were installed before and after the crystal monochromator giving the spectrometer a very high resolution.[8] The $12\bar{3}1$ planes of Be were used as the neutron monochromator for all measurements of this report. These crystal planes gave a resolution width of $\Delta E=0.00474E^{\frac{3}{2}}$ ev or 0.17 μsec/m.

Scattering Cross Section

The scattering measurements were made by using the "bright line" technique of Borst.[4,5] A sample under study was placed in the center of the Brookhaven reactor in an evacuated pipe which passed completely through the reactor. A collimating system was installed such that the only neutrons incident on the crystal monochromator were those that were scattered from the sample. This was checked experimentally and it was found that the neutron intensity at 1.2 ev was 0.03 ± 0.08 count per minute when the scattering pipe was empty.

A crystal spectrometer of special design was used to determine the energy distribution of the scattered neutrons.[5] With special shielding it was possible to reduce the background intensity to the order of 2 counts per minute. The $12\bar{3}1$ planes of Be were used as the neutron monochromator for all scattering measurements giving a resolution width of $\Delta E=0.0273E^{\frac{3}{2}}$ ev.

Since the scattered neutron intensity was assumed to be proportional to the scattering cross section, it was necessary to determine the proportionality constant for the experiment. The proportionality constant was determined by observing the neutron intensity scattered from a thin graphite sample whose scattering cross section was well known.[9] The calibration was also checked with lead as a standard and was found to agree very well with the graphite calibration.

ANALYSIS OF DATA

Total Cross-Section Analysis

The methods used in analyzing the transmission data have been described in detail elsewhere.[10,11] The notation used in the following equations has been defined in reference 11. The assumption is made throughout the analysis that the resonances under study obey the Breit-Wigner single-level formulism. The transmission data in the wings of a resonance were fitted to the Breit-Wigner single-level formula by the method of least squares. From this analysis it is possible to obtain the resonance strength, $\sigma_0\Gamma^2$, the potential scattering, σ_p, and the coefficient of the interference term, $\mathcal{I}$. The transmission data in the region of the resonant peak were analyzed by the method developed by Sailor.[10] A modification to this method was made in that a trial and error approach was used instead of a least-squares solution. This method gives an accurate inclusion of the resolution and Doppler corrections and allows a determination of σ_0 and Γ. In the analysis of the resonant peak the value of $\sigma_0\Gamma^2$ obtained from the resonance wings was imposed on the trial parameters for σ_0 and Γ. This guarantees that the parameters thus obtained will fit both the wings and peak of the resonance under study.

Scattering Cross-Section Analysis

The principle of the scattering experiment can be illustrated as follows:

$$\frac{I_x(E_2)}{I_y(E_2)}=\frac{N_x\sigma s_x(E_2)K_x(E_2)}{N_y\sigma s_y(E_2)K_y(E_2)}. \qquad (1)$$

[7] L. B. Borst and V. L. Sailor, Rev. Sci. Instr. **24**, 141 (1953).
[8] Sailor, Foote, Landon, and Wood, Rev. Sci. Instr. **27**, 26 (1956).
[9] V. L. Sailor (unpublished).
[10] V. L. Sailor, Phys. Rev. **91**, 53 (1953).
[11] Wood, Sailor, and Landon, Phys. Rev. **98**, 639 (1955).

The neutron intensity, I, scattered from a sample, x, of unknown scattering cross section, σ_s, was compared with the intensity from a sample, y, whose scattering cross section *vs* energy was known; where N represents the sample thickness and K a correction for the effect of self-absorption and energy loss on collision.

The correction, K, is a very important part of the scattering analysis. The derivation of K is not given but follows the method of Tittman and Sheer,[2] with the following result:

$$K(E_2)=\frac{\int_0^{\pi/2} E_1^{-1}[\sigma_s(E_1)/\sigma_s(E_2)]e^{-N\sigma_t(E_2)}[(1-e^{-\alpha})/\alpha]\sin\varphi d\varphi}{\int_0^{\pi/2} E_1^{-1}\sin\varphi d\varphi}+\frac{\int_{\pi/2}^{\pi} E_1^{-1}[\sigma_s(E_1)/\sigma_s(E_2)][(1-e^{-\beta})/\beta]\sin\varphi d\varphi,}{\int_{\pi/2}^{\pi} E_1^{-1}\sin\varphi d\varphi}, \quad (2)$$

where

$$\begin{aligned}\alpha&=N\sigma_c(E_1)\,|\sec\varphi|-N\sigma_t(E_2),\\ \beta&=N\sigma_c(E_1)\,|\sec\varphi|+N\sigma_t(E_2).\end{aligned} \quad (3)$$

All cross sections are modified by Doppler broadening calculated for the temperature of the sample (185°C). The energy, E_1, before collision was determined from the conservation of energy and momentum and φ is the scattering angle. An approximation was made in computing E_1 in that the energy loss was computed for a neutron striking a stationary nucleus; whereas the nuclei were actually moving with a Maxwellian energy distribution due to their thermal motion. The inclusion of the thermal motion of the nuclei in the derivation of the sample thickness correction, K, was investigated and found to be a negligible effect.

Equation (1) was correct where the resolution correction was negligible, which was true for the wings of a scattering resonance. It was therefore possible to apply the sample thickness correction to the intensity observed at each energy in the wings of a resonance and compute a true cross section. The cross section in the wings could then be fitted by the method of least squares to the following equation,

$$\sigma_s=\sigma_p+\frac{\sigma_{s0}\Gamma^2}{4(E-E_0)^2+\Gamma^2}+\frac{\mathcal{I}(E-E_0)}{4(E-E_0)^2+\Gamma^2}. \quad (4)$$

It was thus possible to obtain a comparison between total cross section and scattering cross section measurements, since $\mathcal{I}$ and σ_p were determined by both measurements. Furthermore, it was possible to determine g if σ_0 were known, since $\sigma_0 \propto g\Gamma_n/\Gamma$ and $\sigma_s\Gamma^2/\sigma_0\Gamma^2=\Gamma_n/\Gamma$.

The scattering analysis near exact resonance must include the effect of instrument resolution which is not included in Eq. (1). Thus the intensity from a sample, x, should be computed as follows:

$$I_x(E_i)\propto\frac{\int_0^\infty R(E_2-E_i)N_x\sigma_{sx}(E_2)K_x(E_2)dE_2}{\int_0^\infty R(E_2-E_i)dE_2}. \quad (5)$$

Once again trial parameters must be chosen and the experimental points compared with the theoretical cross section operated upon by Doppler broadening, sample thickness correction, and resolution. Fortunately all parameters should be known at this point and Eq. (5) need be computed only as a final check on the analysis and choice of spin, since the scattering peak should be most sensitive to the choice of spin. The complete solution of Eq. (5) requires a triple numerical integration when the effect of the energy distribution of the target nuclei is included.

There is also the possibility of using an area analysis on the resonant scattering peak.[5] This method is applicable only if the resolution-correction is small, or if a method is found for applying the sample thickness correction directly to the observed intensity. Since the resolution correction was not small for the cases considered, no analysis was performed using this technique.

RESULTS AND DISCUSSION

Standard Scatterers

Graphite was used as the standard scatterer for the calibration of the experiment. The calibration and analysis were also checked by measuring the scattering from lead. The agreement with the graphite calibration was excellent. Since these two elements were to be used as standards, it was necessary to determine their scattering cross sections from total cross section measurements. The absorption cross sections for both lead and graphite are very small; therefore, it was assumed that the total cross section is the same as the scattering cross section. This assumption is certainly valid in the region of interest. The total cross section of graphite had been determined previously as 4.74±0.03 barns.[9] A determination of the total cross section of lead in the region, 1 to 10 ev, was 11.3±0.3 barns.

The observed intensities for graphite and lead are shown in Fig. 1. The curves are the least-squares fit of the equation $I=AE^{-b}$, where A and b are constants. The resulting energy dependency for the two curves was the same within experimental error and agreed very well with the results of Borst and Sailor[7] for an infinitely thick graphite scatterer.

Some very useful and interesting information can be obtained from these results. Substituting the cross sections intensities, and sample thicknesses into Eq.

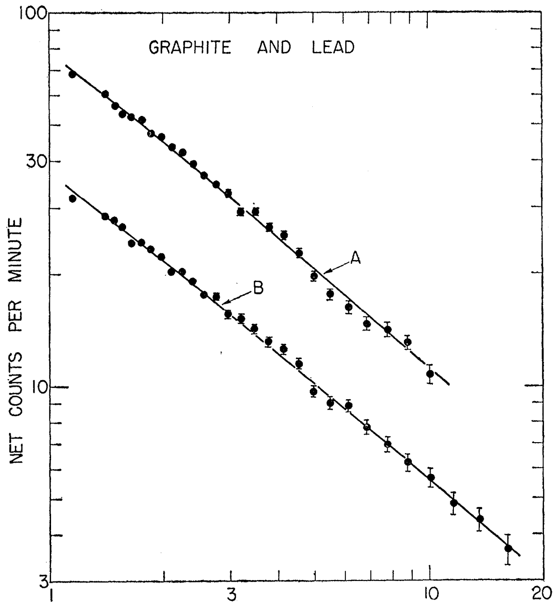

FIG. 1. The observed intensities for the two standard scatterers, lead and graphite. Curve A is the least-squares fit of the experimental points for the lead sample ($N=94.8\times10^{20}$ atoms/cm²). Curve B is the least-squares fit of the experimental points for the graphite sample ($N=103.9\times10^{20}$ atoms/cm²). The counting statistics were smaller than the plotted points except in the regions indicated.

(1) gave the result $K_{\mathrm{C}}/K_{\mathrm{Pb}}=1.031$. The calculated sample thickness correction gave the result $K_{\mathrm{C}}/K_{\mathrm{Pb}}=1.028$, which is in excellent agreement with the observed results and indicates the reliability of the experiment. If, however, the total cross section was used instead of the absorption cross section in computing the neutron attenuation before scattering, the ratio $K_{\mathrm{C}}/K_{\mathrm{Pb}}$ would be 1.097, which clearly does not agree with the observed result. The use of the absorption cross section rather than the total cross section is a correct treatment of multiple scattering for a pure scatterer and is felt to be a good approximation for the effect of multiple scattering from a scattering sample with absorption. This is certainly true in the limit as $\sigma_c\rightarrow\sigma_t(\sigma_s\rightarrow0)$.

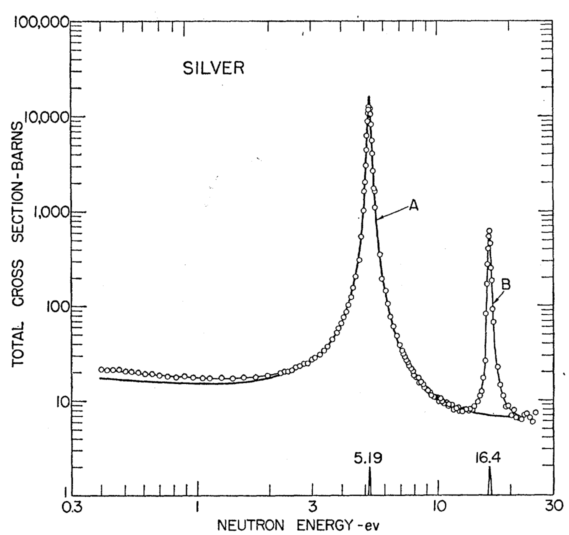

FIG. 2. The observed total cross section of silver as a function of energy. Curve A is the theoretical curve calculated from the Breit-Wigner single-level parameters for the 5.19-ev resonance plus potential scattering. Curve B is a smooth curve drawn through the experimental points. The deviation of the observed points from the theoretical curve at low energies is due to the contributions of all other resonances (primarily a negative-energy resonance). The counting statistics were smaller than the plotted points.

Silver

The total cross section of Ag as observed by the improved BNL crystal spectrometer is shown in Fig. 2. The heavy curve, A, is the theoretical curve for the 5.19-ev resonance in Ag^{109} plus the potential scattering cross section. The light curve, B, is a smooth curve drawn through the observed points. The agreement between the theoretical curve and the observed points is excellent, except at the peak of the resonance where Doppler broadening and resolution are important, and in the low-energy region.

The reason for the discrepancy in the low-energy region is the resulting slope from all other resonances. It can be shown that the contribution to this residual slope from the know high-energy resonances is small (about 12%). Furthermore, it is known that Ag^{107} has a large thermal capture cross section, 30 barns,[12] which cannot be accouted for by known positive energy resonances. A negative energy resonance was therefore postulated and attempts made to prove its existence. These attempts were unsuccessful because the sample of enriched Ag^{107} was too thin.[13]

In the process of analyzing the total cross-section data and the scattering cross-section data the effects of the 16-ev resonance and the negative energy resonance were taken into account. In order to obtain the same potential scattering from both sets of data it was necessary to postulate a resonance at a negative energy of 1.0 to 10 ev. The strength of this resonance was determined from the thermal capture cross section. The effect of this resonance was negligible in the determination of $\sigma_0\Gamma^2$.

The result of the total cross-section peak analysis is shown in Fig. 3. Various combinations of parameters were tried until a best fit was obtained at the peak with the condition that $\sigma_0\Gamma^2=366$ barns-ev², which was necessary to fit the wings. The following parameters were obtained, $\sigma_0=16\,500\pm500$ barns, $\Gamma=0.149\pm0.005$ ev. The resolution correction was only 3.6% at the resonance peak and any error in the resolution would cause a negligible error in the result.

[12] H. Pomerance, Phys. Rev. **83**, 641 (1951); **88**, 412 (1952).

[13] The sample of enriched Ag^{107} was obtained from the Stable Isotope Division of the Oak Ridge National Laboratory.

The scattered intensity observed for one Ag sample is shown in Fig. 4. The sample is "thin" in the wings and "thick" at the peak of the 5.19-ev resonance. It is interesting to notice the "line reversal" common to optical spectroscopy. It can be shown by means of the sample thickness correction that such a line reversal is expected. This reversal is due to the competition between scattering and absorption and the extent of the line reversal is a function of the sample thickness. The asymmetry of the line reversal is due to the loss of energy by the neutron during the scattering process.

It is also worthy of note that there is no observable resonance at 16.4 ev. This indicates that the resolution and counting statistics were too poor at that energy to observe the resonance. This is therefore one indication of the limitations of this particular scattering experiment.

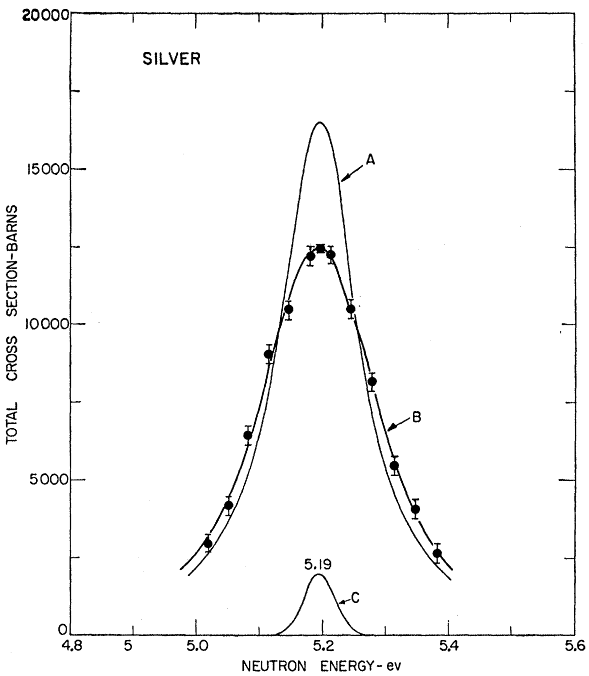

FIG. 3. The total cross section of silver in the region of the resonant peak. Curve A is the theoretical Breit-Wigner curve. Curve B was obtained by operating upon the theoretical curve with instrument resolution and Doppler broadening. Curve C is the resolution function plotted on an arbitrary vertical scale. The counting statistics were as shown.

The points in the wings of the 5.19-ev resonance shown in Fig. 4 were corrected for sample thickness and fitted by the method of least squares to Eq. (4). The results obtained were $\sigma_{s0}\Gamma^2=30.8$ barns-ev^2, $\mathcal{G}=30.0$ barns-ev, $\sigma_p=6.31$ barns. These parameters agree well with those obtained from the total cross section-analysis. The spin of the compound nucleus is obvious from these measurements since $\sigma_{s0}\Gamma^2/\sigma_0\Gamma^2=\Gamma_n/\Gamma=0.0842$, and for each choice of g there is a value for σ_0 that will fit both the scattering and total cross-section wings; thus, $\sigma_0=5170$ barns for $g=1/4$, $\sigma_0=15\,500$ barns for $g=3/4$. The directly observed peak cross section was 12 500 barns, which when corrected for Doppler broadening and resolution is in excellent agreement with the value for $g=3/4$.

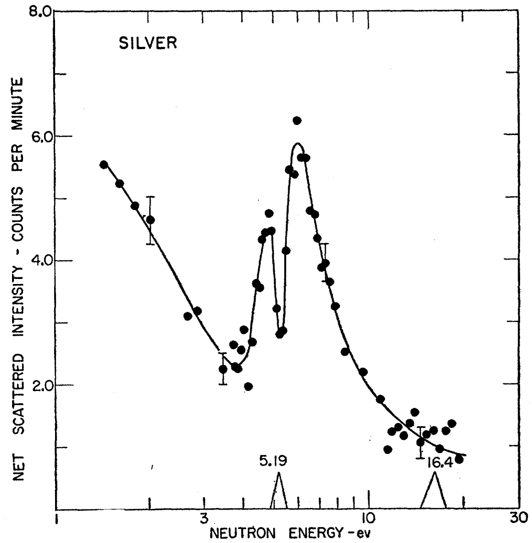

FIG. 4. The net scattered intensity for one silver sample ($N=23.7\times10^{20}$ atoms/cm^2). Note the strong line reversal for the 5.19-ev resonance. It can be shown that such a line reversal is predicted by the theory. The 16.4-ev resonance does not appear at all. Typical counting statistics are shown.

The complete theoretical scattering curve for $\sigma_0=15\,500$ barns is shown in Fig. 5. The points shown are those used for the scattering wing analysis and have been corrected for the effect of sample thickness. The errors shown are those due to counting statistics only.

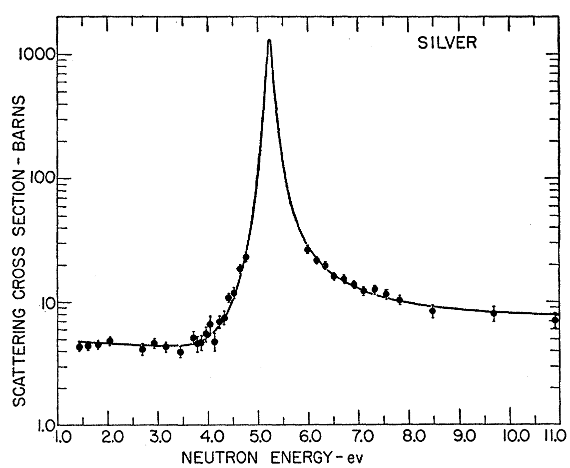

FIG. 5. The theoretical scattering cross section of the 5.19-ev silver resonance. The points shown have been corrected for the effect of sample thickness, and these corrected points were used for the scattering wing analysis. The complete theoretical scattering cross section was obtained by supplementing the results from the scattering wing analysis with $\sigma_0\Gamma^2$ and σ_0 from total cross-section analyses. The counting statistics were as shown.

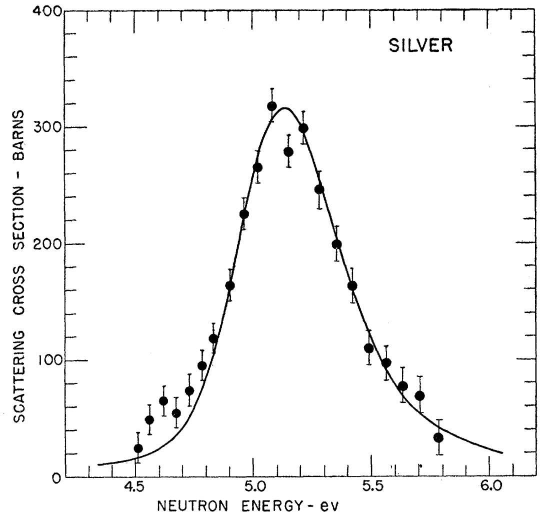

FIG. 6. The comparison of the observed silver scattering cross section with the computed curve for $\sigma_0 = 15\,500$ barns and $g = 3/4$. The spin assignment ($J=1$) is verified by this curve since the other spin ($J=0$) would give an expected cross section approximately three times as large as that shown. The counting statistics were as indicated.

Scattering data was taken with two samples in the region of the resonant peak. The results of one sample are shown in Fig. 6. The solid curve is the theoretical curve operated upon for Doppler broadening, instrument resolution, and sample thickness ($\sigma_0 = 15\,500$ barns, $g = 3/4$). The agreement with the data and the derived curve was just as good for the other sample which was only 1/3 as thick as the sample used for the data of Fig. 6.

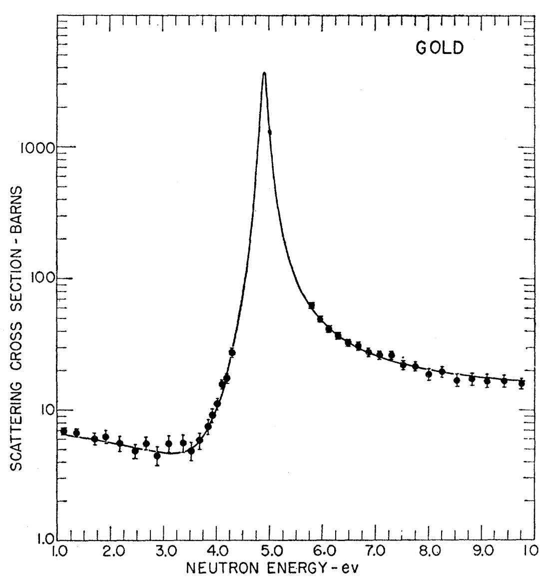

FIG. 7. The theoretical scattering cross section for the 4.91-ev gold resonance. The points shown have been corrected for the effect of sample thickness and were used in the scattering wing analysis. The complete theoretical scattering cross section was obtained by supplementing the results from the scattering wing analysis with $\sigma_0\Gamma^2$ and σ_0 from total cross-section analyses. The counting statistics were as indicated.

If it is assumed that the nuclear radius is the same for the nonresonant spin state as for the resonant spin state, the potential scattering cross section for Ag^{109} is 4.7 barns. This requires a potential scattering cross section for Ag^{107} of 7.3 barns to give a total potential scattering cross section for Ag of 6.0 barns. These results are essentially in agreement with the results of Hibdon and Muehlhause[14] who determined σ_p for both isotopes by observing scattering from samples of enriched isotopes. They obtained the results: $\sigma_p(107) = 7.91$ barns, $\sigma_p(109) = 4.64$ barns. The measurements of Sheer *et al.* also indicate a similar result. They obtained the results: $\sigma_p(107) = 7.80$ barns, $\sigma_p(109) = 4.53$ barns. All of these measurements are within experimental errors and indicate that the potential scattering cross section can differ by as much as 50% between two isotopes.

The final parameters as quoted in Table I do not agree well with the results of Sheer *et al.*[2] who obtained a value for σ_0 of 20 200 barns, but the spin assignment is the same ($g = 3/4$). The value of $\sigma_0\Gamma^2$ is the same as that obtained by Seidl *et al.*,[15] although they obtained a value for σ_0(isotopic) of 27 300±1000 barns and a value for Γ of 0.168±0.008 ev. The value of σ_0 as reported by Draper and Baker[16] is identical with that reported in Table I.

Gold

The results of the total cross-section analysis of Au have been presented elsewhere.[11] These results are included in Table II and will be used throughout the analyses of this section.

The scattering wing data were corrected for sample thickness and analyzed by the method of least squares. The results were as follows: $\sigma_{s0}\Gamma^2 = 78.1$ barns-ev^2, $\mathcal{G} = 91$ barns-ev, $\sigma_p = 11.2$ barns. The agreement with the total cross-section parameters is certainly within experimental error. The value of Γ_n/Γ from the wing analyses was 0.106. This required the following peak cross sections to fit both the scattering and total cross-section wings: $\sigma_0 = 21\,000$ barns for $g = 3/8$, and $\sigma_0 = 35\,000$ barns for $g = 5/8$. The peak cross section directly observed was 30 000 barns and the corrected peak cross section was 37 000 barns. The agreement with the choice of spin $J = 2$ ($g = 5/8$) is extremely good.

The theoretical scattering cross section is shown in Fig. 7 for $g = 5/8$, $\sigma_0 = 35\,000$ barns, and $\mathcal{G} = 91$ barns-ev. The points shown are those used in the scattering wing analysis and are the observed points corrected for the effect of sample thickness. The large asymmetry due

[14] C. T. Hibdon and C. O. Muehlhause [see note in Columbia Nuclear Physics Laboratory Report CU-116, 1952 (unpublished), p. 15].
[15] Seidl, Hughes, Palevsky, Levin, Kato, and Sjöstrand, Phys. Rev. **95**, 476 (1954).
[16] J. E. Draper and C. P. Baker, Phys. Rev. **95**, 644 (A) (1954).

to the interference between the resonant and potential scattering is clearly shown in Fig. 7.

The scattering peak was analyzed for two different sets of parameters and the results are shown in Fig. 8. Both curves are for $g=5/8$ and $\sigma_0\Gamma^2=725$. Curve A was computed for $\sigma_0=35\,000$ barns and curve B for $\sigma_0=31\,000$ barns, which, at the time of analysis, was the most recent value reported in the literature.[17,15] Since these curves required a trial and error process of computation no further variations were tried. The choice of spin $J=2$ is confirmed since the other choice of spin would give a scattering cross section 67% larger than that shown. The peak cross section necessary to fit the scattering is about 10% smaller than that obtained from the total cross section analysis. This discrepancy is small compared with the total corrections of 3.5. Taking account of the thermal motion of the

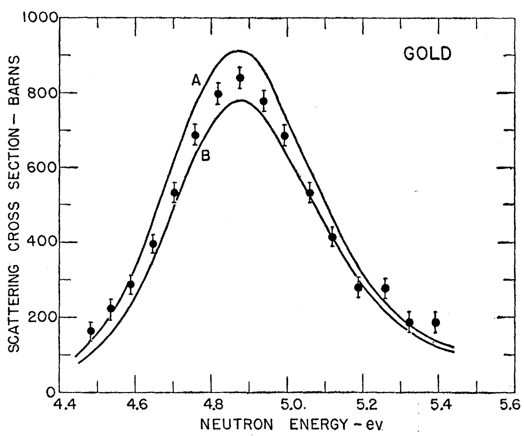

FIG. 8. Comparison of the observed scattering cross section with derived curves for the 4.91-ev gold resonance. Curve A is the derived curve for the parameters obtained from the wing analysis ($\sigma_0=35\,000$ barns, $g=5/8$). Curve B was computed for $\sigma_0=31\,000$ barns, $g=5/8$. The choice of spin ($J=2$) is confirmed because the experimental points agree with the final parameters within 10% for $g=5/8$, and the other choice of spin would give about a 75% discrepancy. The counting statistics were as shown.

traget nucleus accounts for about 1/4 of this discrepancy.

The final parameters for Au are listed in Table II. The nuclear radii for the two spin states are equal within experimental error. This was expected and any true difference between the radii would be expected to be small. The value of the incoherent scattering cross section at thermal energy was measured by Brockhouse[18] as 0.50 ± 0.26 barn. The incoherent scattering cross section from the parameters in Table II is 0.33 barn if the nuclear radii for the two spin states are equal or 0.50 barn if the nuclear radii for the non-resonant spin state is 10% larger than that for the

TABLE I. Final parameters for the 5.19-ev resonance in Ag^{109} (elemental parameters unless indicated otherwise).

E_0	$= 5.194\pm0.010$ ev
$\sigma_0\Gamma^2$	$= 366\pm10$ barns-ev^2
$\mathcal{g}$	$= 30\pm3$ barns-ev
σ_p	$= 6.0\pm0.5$ barns
σ_0	$= 16\,500\pm500$ barns
σ_0(isotope)	$= 34\,000\pm1000$ barns
Γ	$= 0.149\pm0.005$ ev
g	$= 3/4(J=1)$
Γ_n	$= 0.0134\pm0.0006$ ev
Γ_γ	$= 0.136\pm0.006$ ev
R_g	$= (0.61\pm0.07)\times10^{-12}$ cm
$\sigma_p(109)$	$= 4.7\pm0.8$ barns
$\sigma_p(107)$	$= 7.3\pm1.0$ barns

resonant spin state. These results still indicate that the radii are equal within experimental error.

The value of $\sigma_0\Gamma^2$ is consistent with the values obtained by other experimenters, but the value of σ_0 and Γ do not agree with those of Seidl *et al.*[15] who quote σ_0 as $30\,600\pm1500$ barns and Γ as 0.163 ± 0.015 ev. The scattering results of Tittman and Sheer[2] indicated that $g=3/8$ for the total cross section parameters available at that time; however, with the improved total cross-section measurements, their results agree with the choice of spin $J=2$ ($g=5/8$).

Tantalum

The total cross section of Ta as observed by the improved BNL crystal spectrometer[19] is shown in Fig. 9. The heavy curve A is the theoretical cross section for the 4.28-ev resonance plus potential scattering. The light curve B is a smooth curve drawn through the experimental points. The residual slope in the low-energy region is approximately equal to that predicted by the parameters of Melkonian *et al.*[20] for the high-energy resonances. The observed resonance peak cross sections are higher than those measured by previous investigators. This is indicative of the high resolution of the spectrometer.

The total cross-section wing analysis gave the following results: $\sigma_0\Gamma^2=72\pm5$ barns-ev^2, $\mathcal{g}=18\pm4$ barns-ev,

TABLE II. Final parameters for the 4.91-ev resonance in Au^{197}.

E_0	$= 4.906\pm0.010$ ev
$\sigma_0\Gamma^2$	$= 725\pm15$ barns-ev^2
$\mathcal{g}$	$= 96\pm12$ barns-ev
σ_p	$= 11.1\pm0.8$ barns
σ_0	$= 37\,000\pm500$ barns
Γ	$= 0.140\pm0.003$ ev
g	$= 5/8(J=2)$
Γ_n	$= 0.0156\pm0.0004$ ev
Γ_γ	$= 0.124\pm0.003$ ev
R_g	$= (0.95\pm0.12)\times10^{-12}$ cm
$R_{(1-g)}$	$= (0.92\pm0.15)\times10^{-12}$ cm

[17] H. H. Landon and V. L. Sailor, Phys. Rev. **93**, 1030 (1954).
[18] B. N. Brockhouse [see note in Carter, Palevsky, Myers, and Hughes, Phys. Rev. **92**, 716 (1954)].
[19] The data in the Ta total cross section wings were from R. L. Christensen, Phys. Rev. **92**, 1509 (1953).
[20] Melkonian, Havens, and Rainwater, Phys. Rev. **92**, 702 (1953).

$\sigma_p = 7.3 \pm 1.0$ barns. The results of the total cross-section peak analysis are shown in Fig. 10. The following parameters were obtained: $\sigma_0 = 25\,000 \pm 3000$ barns, $\Gamma = 0.053 \pm 0.005$ ev. The resolution correction is again quite small (about 7%) but the Doppler correction is very large due to the small line width. The Doppler modified cross section at the peak is 54% of the theoretical peak cross section. Large Doppler corrections impose large errors on any results obtained by shape analysis. It is thus questionable if shape analysis can be used at higher energies. The elevated temperature of the scattering sample also aggravates the situation for the scattering determinations.

The scattering cross sections observed for four different Ta samples are shown in Fig. 11. The effect of sample thickness is clearly shown. The observed cross section for the 4.28-ev resonance is only about 1/10 of the theoretical cross section, but it is doubtful if anything of significance is observed for the 13.9-ev resonance.

Preliminary sample thickness corrections were made on the 4.28-ev scattering wing data. The analysis of this corrected data gave the following results: $\sigma_{s0}\Gamma^2 = 5.4$ barns-ev^2, $\mathcal{G} = 15$ barns-ev, $\sigma_p = 6.3$ barns. These results tentatively indicated that $g = 9/16$, but more comprehensive data are needed to make this assignment conclusive.

The final parameters from this study are shown in Table III. All derived parameters are tentative upon the correct choice of the spin.

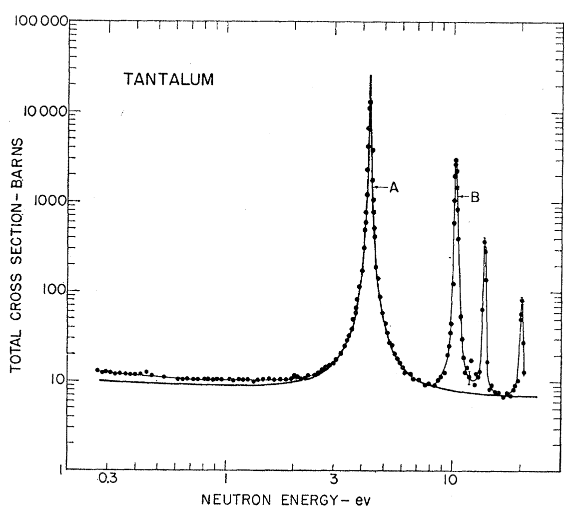

Fig. 9. The observed total cross section for Ta as a function of energy.[20] Curve A is the theoretical curve for the 4.28-ev resonance plus potential scattering. Curve B is a smooth curve drawn through the experimental points. The agreement of the experimental points with the theoretical curve is excellent where the corrections for Doppler broadening, resolution, and other resonances are small. The counting statistics were smaller than the plotted points except in the regions specifically indicated.

CONCLUSIONS

The accuracy and reliability of the method and the analysis have been checked to a high degree of accuracy by using two standard scatterers. The method and the analysis have also been checked for a resonance scatterer by means of two silver samples. All parameters obtained from scattering measurements were within 10% of the parameters obtained from total cross-section measurements when a complete analysis of the scattering data was made. It was therefore concluded that reliable results can be obtained from this type of scattering measurement to an accuracy of 10%.

One set of resonance parameters was found to agree with both the total cross-section data and the scattering cross-section data over wide energy limits. The agreement was within the estimated errors of the experiments. It is thus possible to say that the Breit-Wigner formula has been checked to an accuracy of approximately 3% for total cross-section measurements and 10% for scattering cross-section measurements.

The results on resonances in general cannot be trusted until several independent experimenters derive consistent parameters for the same resonances. It was for this purpose that the gold parameters were determined since it is an ideal standard. It is felt that the consistency between the various measurements of this study indicates the accuracy of the results. If consistent parameters are obtained for some standard resonance, it would be very useful in checking resolution, new experiments, etc.

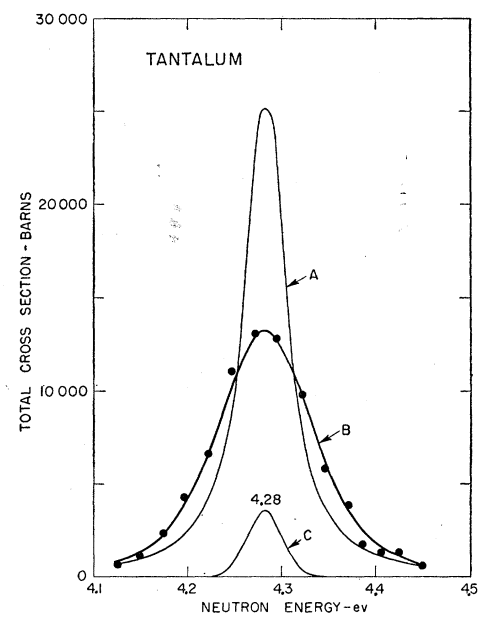

Fig. 10. The Ta total cross section in the region of the 4.28-ev resonant peak. Curve A is the theoretical Breit-Wigner curve. Curve B is the derived curve after correcting for the Doppler broadening and resolution. Curve C is the resolution function plotted on an arbitrary vertical scale. The counting statistics were smaller than the plotted points.

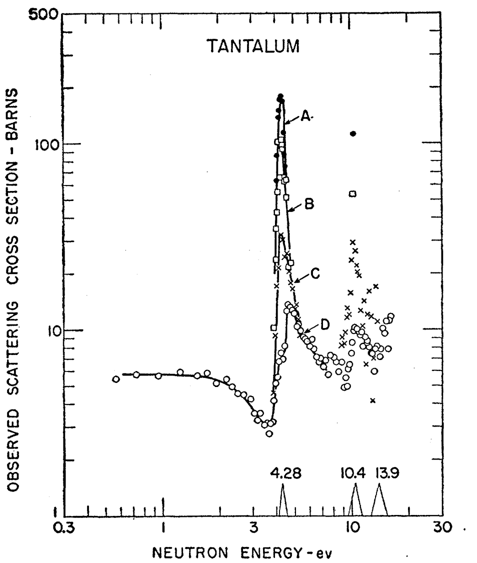

FIG. 11. The observed scattering cross section for four different Ta samples. The following samples were used: Curve A, $N=0.684\times10^{20}$ atoms/cm^2; Curve B, $N=1.670\times10^{20}$ atoms/cm^2; Curve C, $N=4.67\times10^{20}$ atoms/cm^2; Curve D, $N=19.88\times10^{20}$ atoms/cm^2: the effect of sample thickness is clearly shown. The observed peak scattering cross section is about 1/10 of the theoretical value.

The scattering measurements as made for this study suffered from three disadvantages. First, the neutron flux had to be normalized to the pile power and this gave all scattering measurements an uncertainty of about 5% which would be a consistent error for any one sample. Second, the resolution and intensity were too poor to use this particular arrangement above 10 ev. Third, a great deal of computing is necessary and all results are dependent upon the accuracy of large corrections. The primary advantages of this method are: first, low background intensity; second, perfect scattering geometry; third, excellent detector geometry. With everything considered, it was concluded that a more practical method for observing scattering should be developed. One such method is the measurement of σ_s/σ_t by thin samples placed on the spectrometer arm at a very small angle with respect to the neutron beam.

TABLE III. Final parameters for the 4.28-ev resonance in Ta^{181}.

E_0	$=4.282\pm0.008$ ev
$\sigma_0\Gamma^2$	$=72\pm5$ barns-ev^2
$\mathcal{G}$	$=18\pm4$ barns-ev
σ_p	$=7.0\pm1.0$ barns
σ_0	$=25\,000\pm3000$ barns
Γ	$=0.053\pm0.005$ ev
g	$=9/16(J=4)$
Γ_n	$=0.0039\pm0.0006$ ev
Γ_γ	$=0.049\pm0.006$ ev
R_g	$=(0.74\pm0.20)\times10^{-12}$ cm
$R_{(1-g)}$	$=(0.75\pm0.20)\times10^{-12}$ cm

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