Parameters for the Neutron Resonance in Gold*

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A highly detailed study of the 4.906-ev neutron resonance in Au^{197} has been made for the purpose of establishing preliminary values for a "standard" resonance. Such a standard can serve as a basis for comparing results from various neutron spectrometers and should assist in reducing large discrepancies in resonance parameters which now exist. The new measurements were made on a crystal spectrometer with unusually good resolution. Methods of "shape analysis" were used to fit the data to the one-level formula and the following parameters were obtained: $E_0=4.906\pm0.010$ ev; $\sigma_{t0}\Gamma^2=(725\pm15)\times10^{-24}$ cm^2 ev^2; $\sigma_{t0}=(37\,000\pm500)\times10^{-24}$ cm^2; $\Gamma=0.140\pm0.003$ ev; and $\sigma_p=(11.1\pm0.8)\times10^{-24}$ cm^2. The one-level formula with these parameters gives an accurate fit to the data over the entire energy range from 0.35 to 15 ev. The nuclear radii corresponding to the two possible spin orientations of the incident neutron were found to be the same to within experimental error.

INTRODUCTION

An isolated neutron resonance is expected to have a shape which fits the Breit-Wigner one-level formula. There are many examples[1–3] which demonstrate good agreement between this formula and experimental curves. Of course, satisfactory agreement in such a comparison does not constitute proof of the general validity of the one-level formula; nor does agreement prove that this formula uniquely fits the data. It is noteworthy, however, that no cases have been found up to the present for which reliable experimental data violate the one-level formula when properly applied. As experimental precision improves, more highly detailed comparisons with the theoretical formula are possible.

During the past four or five years, rapid improvements in experimental techniques have made the detailed analysis of neutron resonances more feasible. The most significant advance has come in spectrometer resolution which has been improved by a factor of approximately 20 during this period.

Despite the improvement in technique and despite the apparent "good" agreement between data and Breit-Wigner formula, the measurement of resonance parameters unfortunately is not in a satisfactory state. Sets of parameters for any given resonance derived from two or more independent measurements almost invariably show discrepancies far greater than the experimental errors would indicate. Such discrepancies must be eliminated before resonance data can be accepted with full confidence.

The discrepancies arise from several sources. It has long been recognized[4–8] that two major difficulties are encountered in the analysis of experimental resonance curves; i.e., the finite resolution of the measuring instrument and the Doppler broadening resulting from the thermal motion of the target atoms. Each of these tends to broaden a resonance and to decrease the measured peak cross section. The distortion becomes more serious for resonances at higher energies and for those having smaller total widths. At present, with the most advanced spectrometers, resolution corrections are very minor for resonances lying below 10 ev, except for a few unusual resonances having very small widths.

There is yet another difficulty in data analysis which arises from the mathematical nature of the Breit-Wigner formula. The number of parameters to be obtained from the data gives considerable latitude in fitting the curve. Unless many experimental points are used and proper precautions taken, erroneous parameters can be obtained which give the false appearance of being a unique and valid solution. The question of the uniqueness of any solution cannot lightly be dismissed.

At the present time, considerable effort is devoted to the study of neutron resonances by many research groups. The results of the measurements are in active demand both in the field of nuclear theory and in many elaborate reactor design calculations.

In view of the magnitude of the effort in these many fields, it appears highly desirable to establish as soon as possible one or more "standard" resonances which can serve as a basis for comparing results obtained with various spectrometers. Such standards must be carefully chosen so as to have a minimum of complications; i.e., the resonances should be, as closely as possible, "ideal" Breit-Wigner resonances. Until agreement can be reached on the parameters for the "ideal" resonances,

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[1] J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136 (1946).
[2] Sawyer, Wollan, Bernstein, and Peterson, Phys. Rev. **72**, 109 (1947).
[3] V. L. Sailor, Phys. Rev. **91**, 53 (1953).
[4] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).
[5] B. D. McDaniel, Phys. Rev. **70**, 832 (1946).
[6] W. W. Havens, Jr. and J. Rainwater, Phys. Rev. **70**, 154 (1946).
[7] G. V. Dardel and R. Persson, Nature **170**, 1117 (1952).
[8] Melkonian, Havens and Rainwater, Phys. Rev. **92**, 702 (1953).

little confidence can be placed in parameters obtained for more complicated resonances.

The resonance in the gold cross section at 4.906 ev is in many respects the most ideal case for use as a standard. This is a strong isolated resonance and hence is relatively free of complications introduced by neighboring resonances. It occurs at an energy which is conveniently within the high-resolution region of both crystal and time-of-flight spectrometers and at an energy where the Doppler broadening is not excessive. Furthermore, gold has only a single stable isotope and, of course, is readily available in the form of uniform thin foils of high purity.

A recent report by Landon and Sailor[9] indicated that the measurements on the gold resonance were in an unsatisfactory state; i.e., the parameters which fit the wings of the resonance and gave good agreement with the thermal cross section did not appear to give a satisfactory fit to data in the center of the resonance. Independent results by Seidl *et al.*[10] were not in agreement with the results of Landon and Sailor and neither of these were compatible with the scattering measurements of Tittman and Sheer.[11]

Recently, it has been possible to improve the resolution of the Brookhaven crystal spectrometer by a large factor, thus largely eliminating the uncertainty due to the resolution correction in the analysis. The center of the gold resonance was remeasured with the improved resolution in an effort to reduce the discrepancies. Additional data were also taken in the wings of the resonance with the old resolution so as to improve statistical accuracy.

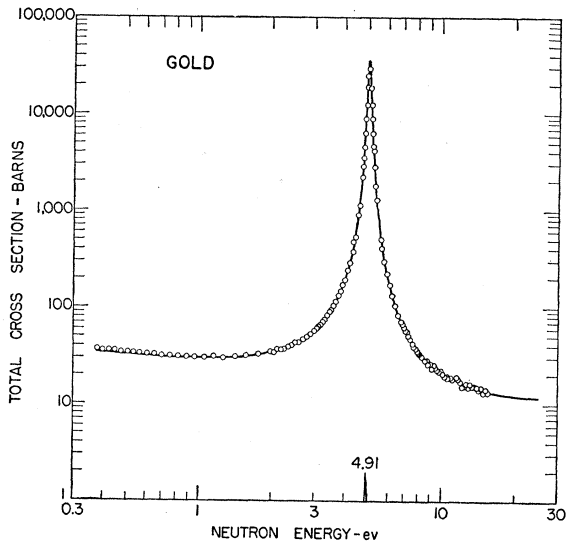

FIG. 1. The total cross section of gold as a function of neutron energy. The curve is the one-level formula calculated from the parameters listed in Tables I and II. The deviation of the experimental points from the theoretical curve at low energies is attributed to contributions from one or more bound states in Au^{198}. Details of the center of the resonance, where corrections for Doppler broadening and instrument resolution are appreciable, are shown in Fig. 2. Uncertainties due to counting statistics are everywhere smaller than the diameter of the plotted points.

[9] H. H. Landon and V. L. Sailor, Phys. Rev. **93**, 1030 (1954).
[10] Seidl, Hughes, Palevsky, Levin, Kato, and Sjöstrand, Phys. Rev. **95**, 476 (1954).
[11] J. Tittman and C. Sheer, Phys. Rev. **83**, 746 (1951).

EXPERIMENTAL DETAILS

The Spectrometer

A general description of the BNL crystal spectrometer has been presented previously.[12] Since this report, a considerable improvement in the resolution of the spectrometer has been achieved by means of a new collimator having an angular divergence of only 1.6 minutes of arc. This collimator is a multiple slit arrangement (Soller slit),[13] each slit being very narrow. The instrument resolution function is approximately Gaussian having a full width at half maximum of $\Delta E=0.00474E^{\frac{3}{2}}$ ev (equivalent to 0.17 μsec/m) when Be $(12\bar{3}1)$ is used as the monochromator. Thus at the resonant energy for gold, $E_0=4.906$ ev, the spread in energy of the monochromatic beam, $\Delta E=0.0515$ ev, and the resolution $R\equiv\Delta E/E=0.0105$. Slightly better resolution can be obtained by using the Be $(22\bar{4}2)$ planes as monochromator. With these planes, $\Delta E=0.00350E^{\frac{3}{2}}$ (0.127 μsec/m) which give $\Delta E=0.038$ ev and $R=0.0078$ at the center of the resonance.

With the aforementioned resolution, counting rates are reasonable and background is not excessive. About one hour is required for measuring the transmission at one energy in the vicinity of 5 ev to a statistical accuracy of one percent. It should be noted that the new system yields data of much superior quality than could be obtained previously[9]; i.e., a more favorable ratio of true counts to background, better statistical accuracy, and significantly higher resolution. The older data of Landon and Sailor[9] were obtained with a resolution, $R=0.025$, with Be $(24\bar{6}1)$ as monochromator.

Samples

Data were obtained through the center of the resonance with two gold samples having thicknesses of 0.0131 and 0.00668 g/cm^2. These gave minimum transmissions of approximately 0.306 and 0.542 respectively. Runs were made with both Be $(12\bar{3}1)$ and Be $(22\bar{4}2)$.

Great care was used in the preparation of the samples so that accurate values of the sample thickness could be obtained. The two samples were independently prepared by different people so as to reduce the possibility of systematic errors in the sample thickness. The results with the two samples were consistent to better than one percent.

Statistical Accuracy of Data

The present data include many new measurements in the wings of the resonance, thus providing a more

[12] L. B. Borst and V. L. Sailor, Rev. Sci. Instr. **24**, 141 (1953).
[13] W. Soller, Phys. Rev. **24**, 158 (1924).

complete and detailed curve for analysis. These data were taken with the old resolution, 0.86 μsec/m, which is adequate in the wings because the effect of resolution is negligible.

Enough time was spent on each measurement, both in the center and in the wings, so that the uncertainty in cross section due to counting statistics was in the range from one to three percent. The measured cross sections are plotted in Figs. 1 and 2. Statistical uncertainties are everywhere smaller than the diameter of the plotted points.

ANALYSIS OF DATA

One-Level Formula

The application of the one-level formula to experimental data has been discussed in considerable detail in the past.[3,8–11] The analysis, which follows, differs in that the interference term in the scattering cross section is taken into account explicitly. For a single isolated resonance the total cross section, σ_t, as a function of neutron energy is given by:

$$\sigma_t(E)=\sigma_c(E)+\sigma_s(E), \tag{1}$$

where σ_c is the capture and σ_s the scattering cross section. These may be expressed as follows:

$$\sigma_c=4\pi\lambda\lambda_0\frac{g\Gamma_n\Gamma_\gamma}{4(E-E_0)^2+\Gamma^2}=\left(\frac{E_0}{E}\right)^{\frac{1}{2}}\frac{\sigma_{c0}\Gamma^2}{4(E-E_0)^2+\Gamma^2}, \tag{1a}$$

and

$$\sigma_s=4\pi\lambda_0^2\frac{g\Gamma_n^2}{4(E-E_0)^2+\Gamma^2}+16\pi\lambda_0 g\Gamma_n R_g\frac{(E-E_0)}{4(E-E_0)^2+\Gamma^2}+\sigma_{p'}$$

$$=\frac{\sigma_{s0}\Gamma^2}{4(E-E_0)^2+\Gamma^2}+\vartheta\frac{E-E_0}{4(E-E_0)^2+\Gamma^2}+\sigma_{p'}. \tag{1b}$$

The second term in (1b) results from interference between the resonant scattering and potential scattering. In the equations, the subscript zero refers to values at exact resonance, $2\pi\lambda$ is the neutron DeBroglie wavelength, E the neutron energy, Γ_n and Γ_γ the partial widths for scattering and radiative capture respectively, $\Gamma=\Gamma_n+\Gamma_\gamma$ the total width, g the statistical weight factor, ϑ the coefficient of the interference term, and R_g is the effective nuclear radius for neutrons of the same spin alignment as for the resonant state. We have used the symbol σ_p' to designate the "constant" portion of the scattering cross section. This, in general, would differ slightly from the true potential scattering because of contributions from neighboring resonances. If only one isotope were present in the target and if only one resonance were affecting the cross section the potential scattering, σ_p, would be given by

$$\sigma_p=4\pi[gR_g^2+(1-g)R_{1-g}^2]\equiv 4\pi R_{\text{eff}}^2. \tag{1c}$$

In the equation, R_{1-g} is the nuclear radius presented to a neutron of spin opposite to the resonant state. As far as is presently known, R_g and R_{1-g} are not necessarily identical.

The parameters which fully describe the resonance are E_0, Γ_n, Γ_γ, g, R_g, and R_{1-g}. With so many parameters available for adjustment, considerable care must be exercised in interpreting the data so as to obtain a unique fit. Fortunately, certain regions of the resonant curve are primarily dependent on certain combinations of the parameters while other regions are sensitive to different combinations. For example, the center region is dependent primarily on E_0 and $\sigma_{t0}\Gamma$, the "near" wings on E_0 and $\sigma_{t0}\Gamma^2$, and the "far" wings on σ_p'. The interference coefficient ϑ is manifested primarily in the asymmetry of the resonance in the "near" wings. The above combinations taken together yield all of the one-level parameters with one exception; namely, g and Γ_n. These cannot be obtained individually with any degree of accuracy from total cross-section data but are obtained only as the product $g\Gamma_n$. An additional measurement, e.g., the resonant scattering cross section as a function of energy, is required to obtain g and Γ_n separately.[11]

Treatment of Data

In fitting the data, we have assumed that the effects of other resonances are negligible between 1 and 15 ev.

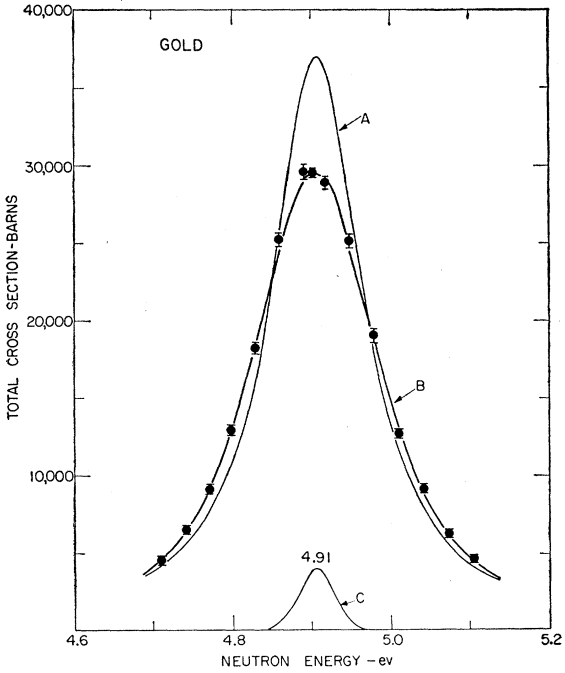

FIG. 2. Detailed plot of the center of the gold resonance. Curve A is the theoretical Breit-Wigner curve giving the best fit. Curve B results from operating on curve A with the Doppler and resolution functions. Curve C is the instrument resolution function plotted on an arbitrary vertical scale. Resolution corrections turn out to be less than 1 percent except for the five points lying nearest the peak. The maximum resolution correction was 4 percent.

The contribution from higher energy resonances can be estimated and are found to be of the order of one barn or less. Calculations indicate that the derived parameters were not affected by these small contributions except that the uncertainty in $\mathcal{J}$ is slightly increased and one obtains the quantity σ_p' which might be slightly different from σ_p. As will be seen, however, the extreme low-energy wing of the curve shows an appreciable effect from neighboring levels.

Determination of E_0

The resonant energy E_0 was obtained graphically from transmission curves with thin samples; and is the average of several sets of data. To eliminate the possible uncertainty of the zero angle of the crystal spectrometer, the resonance was measured on both sides of zero. In addition, the independent measurements with Be $(12\bar{3}1)$ and Be $(22\bar{4}2)$ combine to give a value for E_0 which is independent of the spectrometer zero. The internal consistency of the various determinations of E_0 was better than the final error assigned to this parameter (see Table I).

Analysis of Wings of Resonance

The data in the wings were fitted directly to the one-level formula using the method of least squares. Equation (1) can be written in the following form:

$$\sigma_t=\left[\left(\frac{E_0}{E}\right)^{\frac{1}{2}}(1-K)+K\right]\frac{\sigma_{t0}\Gamma^2}{4(E-E_0)^2+\Gamma^2}+\mathcal{J}\frac{(E-E_0)}{4(E-E_0)^2+\Gamma^2}+\sigma_{p'}, \quad (2)$$

where $K\equiv\Gamma_n/\Gamma$.

By the "wings" of the resonance, we mean those regions for which $4(E-E_0)^2\gg\Gamma^2$. For the purpose of this analysis, only those points were used for which $4(E-E_0)^2\geqslant 160\Gamma^2$. In Eq. (2) we seek to solve for the best $\sigma_{t0}\Gamma^2$, $\mathcal{J}$, and σ_p'. One must assume a value for K and for the Γ^2 which appears in the denominator; however, the solution is quite insensitive to these assumed quantities so only order of magnitude values need be known. A careful examination of Eqs. (1a) and (1b) will show that it is valid to use the wings for obtaining only three parameters. If one attempts to solve for more than three (e.g., $\sigma_{c0}\Gamma^2$ and $\sigma_{s0}\Gamma^2$ in place of $\sigma_{t0}\Gamma^2$) the results are not valid.

TABLE I. One-level parameters obtained from analysis of the data. The methods used for obtaining these quantities are described in the text. The errors are based partly on the internal consistency of various runs, and partly on the sensitivity of the results to uncertainties in the choice of E_0, Γ_n/Γ (i.e., K) and Γ^2 required for the analysis.

E_0	$=$ 4.906±0.010 ev
$\sigma_{t0}\Gamma^2$	$=$ 725±15 barn ev^2
$\mathcal{J}$	$=$ 96±8 barn ev
σ_p'	$=$ 11.1±0.3 barns
$\sigma_{t0}\Gamma$	$=$ 5180±130 barn ev
σ_{t0}	$=$ 37 000±500 barns
Γ	$=$ 0.140±0.003 ev

One hundred and two experimental points in the wings of the gold resonance were fitted to Eq. (2) by the method of least squares. All experimental points were given equal weight in the solution. The computations were performed on a Remington-Rand, model 409.2R, punched card electronic counter. The values of $\sigma_{t0}\Gamma^2$, $\mathcal{J}$, and σ_p' obtained from this analysis are listed in Table I.

It is difficult to estimate the errors in the derived constants which arise from uncertainties in the input quantities E_0, K, and Γ^2. Therefore, the computations were repeated many times using different combinations of these three inputs, the range of input values in each case extending well beyond the uncertainties involved. In general, it was found that the values of $\sigma_{t0}\Gamma^2$ and σ_p' were quite insensitive to all the variations which were tested. The extreme deviations in $\sigma_{t0}\Gamma^2$ amounted to less than one percent and in σ_p' to about four percent (i.e., ±0.4 barn). However, the interference coefficient $\mathcal{J}$ showed larger deviations, the maximum being approximately twenty percent. $\mathcal{J}$ was found to be particularly sensitive to E_0, a change of 0.4 percent in E_0 producing a change in $\mathcal{J}$ of 10 percent. This is understandable because $\mathcal{J}$ is derived essentially from the asymmetry in the resonance. The errors listed in Table I are based on these many computations.

Additional fitting was done on various individual sections of the curve to see if any region yielded constants appreciably different from the over-all solution. No discrepancies were found which were larger in magnitude than the aforementioned fluctuations. However, at the extreme low-energy end of the curve, a small but systematic departure between the observed cross sections and the derived Breit-Wigner curve was noted. It can be readily seen in Fig. 1 that between 0.3 ev and 0.8 ev, the points all lie slightly above the curve. This discrepancy is greatest on the low-energy side and disappears at higher energies. The average deviation below 0.8 ev is ~1.7 barns or ~6 percent of the total cross section.

Analysis of Center of Resonance

The purpose in analyzing the data at the center of the resonance is to obtain values for σ_{t0} and Γ which combined with the wing analysis permit a solution for the complete set of one-level parameters (except for separating g and Γ_n). In general, it may be stated that the analysis yields the product $\sigma_{t0}\Gamma$ to better precision than individual values of σ_{t0} and Γ, although where Doppler and resolution corrections are small (as is the case) the difference in precision is minor. Note that the central region can yield only two constants (aside from E_0). This is true because only two terms in Eqs.

(1a) and (1b) are appreciable, σ_c and the first term of σ_s. These terms contain only the two adjustable parameters $g\Gamma_n$ and Γ. The third parameter, R, which appeared in the wing analysis, is missing here because potential and interference scattering are negligible close to the center.

Two methods have been used to analyze the center of the gold resonance. The first is the exceedingly laborious but accurate "trial and error" method described previously.[3] This method takes account of instrument resolution as well as Doppler broadening. The results are shown in Fig. 2. The resolution corrections for the worst case amounted to less than 4 percent and only a few points had corrections as large as 1 percent.

The second method used is somewhat novel, and since it promises to be highly useful, is worth describing in detail. Since the central region of a resonance is appreciably distorted by Doppler broadening, the one-level formula cannot be applied. The Doppler-broadened formula is awkward to use in computations; however, tables of this function are now available.[14] These can be used to construct accurate curves which give useful relationships between corresponding properties of the Breit-Wigner and the Doppler curves. For example, it is possible to obtain the "true" width from the observed width with the aid of such curves, even though the relationship between these two quantities cannot be expressed analytically. In particular, a curve of $\Gamma_{\rm obs}/\Delta$ *vs* Δ/Γ has proved very useful. Of course, the accuracy with which such conversions can be made depends upon the seriousness of the Doppler broadening; i.e., on the ratio of the Doppler width Δ to the true width Γ. In the case of gold, the Doppler width is small compared to the true width of the 4.906-ev resonance, and it turns out that the loss in precision in converting from "observed" values to "true" values is negligible.

The "observed" width $\Gamma_{\rm obs}$ and the "observed" maximum cross section $\sigma_{\rm obs}$ were determined from the data by using the method of least squares. It is not practical to fit the data directly to the Doppler-broadened formula, so an arbitrary function must be devised which adequately approximates the shape of the Doppler-broadened resonance. The arbitrary function chosen to serve this purpose was the capture term of the Breit-Wigner formula, Eq. (1a). To avoid the need for a resolution correction, the points having corrections greater than 1 percent were discarded in making the fit. The observed parameters, $\Gamma_{\rm obs}$ and $\sigma_{\rm obs}$ derived from this analysis, were converted to Γ and σ_0 by means of the curves described above. The values of Γ and σ_0 obtained in this way agreed with the values obtained from the "trial and error" method to better than 1 percent.

[14] Rose, Miranker, Leak, and Rabinowitz, Brookhaven National Laboratory Report BNL-257, 1953 (unpublished); and Rose, Miranker, Leak, Rosenthal, and Hendrickson, Westinghouse Electric Corporation Atomic Power Division WAPD-SR-506, 1954 (unpublished).

TABLE II. One-level formula parameters for the 4.906-ev resonance in gold. These parameters are computed from the various combinations listed in Table I. Values of the individual widths are based on the g assignment of Wood.[a]

E_0	$= 4.906\pm0.010$ ev
Γ	$= 0.140\pm0.003$ ev
$g\Gamma_n$	$= 0.00976\pm0.0002$ ev
$(g$	$= 5/8)$[a]
Γ_n	$= 0.0156\ \pm0.0004$ ev
$\Gamma_n{}^0\equiv\Gamma_n/E_0^{\frac{1}{2}}$	$= 0.00705\pm0.0002$ ev
Γ_γ	$= 0.124\pm0.003$ ev
σ_p	$= (11.1\pm0.8)\times10^{-24}$ cm^2
R_g	$= (0.95\pm0.12)\times10^{-12}$ cm
R_{1-g}	$= (0.92\pm0.15)\times10^{-12}$ cm

[a] See reference 15.

DISCUSSION

Agreement Between Data and Breit-Wigner Formula

The quantities obtained from analysis of the data are listed in Table I. The parameters of the one-level formula derived from combinations of these are presented in Table II. The agreement between the experimental points and the derived Breit-Wigner curve is reasonably good over the entire range and to very fine detail (Figs. 1 and 2).

As previously noted, in the region 0.3 to 0.8 ev, the observed cross sections all lie one or two barns above the curve. Contributions from resonances at higher energies can be estimated from parameters listed by Seidl *et al.*[10] These contributions are of the magnitude of -0.4 barn in the range 0.3 to 0.8 ev. They are negative because the scattering interference term dominates. The fact that the observed points lie *above* rather than *below* the curve must be attributed to the effects of levels in Au^{198} lying below the binding energy. The presence of such levels and the magnitude of their contribution at 0.3 ev is compatible with the observed density and strength of states just above the binding energy. (For example, a level lying at $E_0=-15$ ev and having approximately the same parameters as the 4.906-ev resonance would account for this effect. Such a resonance would not cause the thermal cross section[15] to be measurably distorted from $1/v$.)

The results reported here do not by themselves provide all the necessary information for calculating g for the resonance. However, resonance scattering measurements by Wood[16] indicate that $g=\frac{5}{8}$ $(J=2)$. (It is of interest to note that the detailed shape of the scattering curve obtained by Wood[17] gives excellent agreement with the parameters in Table II.) Wood's assignment of $g=\frac{5}{8}$ can be verified by combining the

[15] Carter, Palevsky, Myers, and Hughes, Phys. Rev. **92**, 716 (1953).
[16] R. E. Wood, Phys. Rev. **95**, 644 (1954).
[17] R. E. Wood (to be published).

value of σ_{t0} in Table II with the ratio Γ_n/Γ reported by Tittman and Sheer.[11]

Comparison with Other Results

Comparisons between the parameters in Table II and older measurements[9–11] disclose large discrepancies. Agreement is within experimental error on the value of $\sigma_{t0}\Gamma^2$, but values of σ_{t0} and Γ are widely divergent. The discrepancies undoubtedly arise from analysis techniques. In the case of the work by Landon and Sailor,[9] the data compared to that presently available were of inferior quality and required large resolution corrections. It is interesting to note that the product $\sigma_{t0}\Gamma$ which they obtained is substantially the same as reported here; so the error apparently lay in trying to extract σ_{t0} and Γ individually from inadequately resolved data.

Thermal Cross Sections

Thermal Capture Cross Section

The contribution to the gold thermal capture cross section from the 4.906-ev resonance (computed from the parameters in Tables I and II) is 93.7±2.3 barns. Direct measurements of the thermal cross section by Carter *et al.*[15] gave $(\sigma_c)_{\rm th}=98.7\pm0.6$ while those by Allen *et al.*[18] gave 96.5±0.7. It would appear that between 3 and 5 barns of the thermal capture cross section must be attributed to resonances other than the one at 4.906 ev. The parameters of Seidl *et al.*[10] indicate that the resonance at 61.5 ev would account for approximately 0.8 barn, while all other known resonances combined would contribute less than 0.5 barn. The balance still to be accounted for must be attributed to the bound states of Au^{198}; i.e., resonances at negative energy.

Coherent and Incoherent Scattering

If only the 4.906-ev resonance were affecting the thermal scattering cross section, the values may be computed[19] as follows (assuming $R_g\approx R_{1-g}$):

$$(\sigma_s)_{\rm th}=\sigma_p-\frac{g}{4E_0}+\frac{\sigma_{s0}\Gamma^2}{4E_0^2}=7.04 \text{ barns},$$

$$\sigma_{\rm coh}=\sigma_p-\frac{g}{4E_0}+g\frac{\sigma_{s0}\Gamma^2}{4E_0^2}=6.72 \text{ barns}$$

$$\sigma_{\rm inc}=(1-g)\sigma_{s0}\Gamma^2/4E_0^2=0.32 \text{ barn}.$$

A small difference between R_g and R_{1-g} would cause only a very small change in $\sigma_{\rm coh}$ and $\sigma_{\rm inc}$. The values observed directly are: $(\sigma_s)_{\rm th}=8.7\pm0.9$,[18] $\sigma_{\rm coh}=7.5\pm0.5$[20] and $\sigma_{\rm inc}=0.50\pm0.26$[21] barn. Thus it is seen that the 4.906-ev resonance alone fails to account for the thermal scattering cross sections, particularly $(\sigma_s)_{\rm th}$ and $\sigma_{\rm coh}$.

The effect of the other known resonances[10] can be roughly estimated, although an accurate calculation would require more exact data. Strictly speaking, one should use the many-level formula which would require that the spin of each level be known. In general, however, the resonances at higher energy tend to *decrease* both $(\sigma_s)_{\rm th}$ and $\sigma_{\rm coh}$ because the interference scattering term (of negative sign) is the dominating contribution. The cross terms in the many-level formula, i.e., the interference between resonances, would be of smaller magnitude. For example, the interference scattering of the 61.5-ev resonance would contribute approximately −0.6 barn to both $(\sigma_s)_{\rm th}$ and $\sigma_{\rm coh}$ and less than 0.01 barn to $\sigma_{\rm inc}$. Cross terms in the many-level formula arising from the 4.906- and 61.5-ev resonances (if of the same spin) would contribute only 0.1 barn to $(\sigma_s)_{\rm th}$ and $\sigma_{\rm coh}$.

On the basis of these estimates, one must assume that bound levels are having an appreciable effect on $(\sigma_s)_{\rm th}$ and $\sigma_{\rm coh}$. A level located at $E_0=-15$ ev having parameters similar to those of the 4.906-ev resonance would contribute approximately +1.5 barns to both $(\sigma_s)_{\rm th}$ and $\sigma_{\rm coh}$ and +0.05 barn to $\sigma_{\rm inc}$.

Effect of Neighboring Levels on the Derived Parameters

The foregoing discussion makes it evident that even in an "ideal" case, such as gold, where the levels are widely spaced (i.e., $D\gg\Gamma$) and where the resonance under study is unusually strong, the effects of nearby levels cannot be completely ignored. Of the parameters listed in Table I, E_0, $\sigma_{t0}\Gamma^2$, $\sigma_{t0}\Gamma$, σ_{t0}, and Γ are not affected by the other levels because the perturbations are negligible in the region of the curve where they are determined. The effects on g and σ_p could be appreciable; unfortunately, however, they cannot be accurately computed due to insufficient knowledge of the parameters of the important neighbors. The value of g could be increased by as much as 5 percent if the level at 61.5 ev is of the same spin as the 4.906-ev resonance; if they are of opposite spin, however, g would be unaffected. Similarly, the true potential scattering, σ_p, could be as much as 0.7 barn smaller than the derived quantity, σ_p', depending upon how the terms from the bound levels and the 61.5-ev resonance combine with the 4.906-ev level. In view of these uncertainties, the errors listed for g in Table I and σ_p in Table II have been correspondingly increased.

Nuclear Radii

The nuclear radii corresponding to each of the two possible spin states of the incident neutron can be derived by combining the values of g and σ_p. The results give $R_g=(0.95\pm0.12)\times10^{-12}$ and $R_{1-g}=(0.92\pm0.15)$

[18] Allen, Stephenson, Stanford, and Bernstein, Phys. Rev. **92**, 1297 (1954).
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$\times 10^{-12}$ cm. It is thus indicated that the radii are the same to within the experimental errors. These are somewhat larger than the radius calculated from the formula $R=1.47A^{\frac{1}{3}}\times 10^{-13}$ cm which gives $R=0.856 \times 10^{-12}$ cm.

CONCLUSION

An intensive study of the 4.906-ev gold resonance has yielded the Breit-Wigner parameters listed in Table II. It is hoped that these results might serve to stimulate comparison between various neutron spectrometers and assist in reducing the large discrepancies which now are common in resonance analysis. The one-level formula affords an accurate representation of the experimental data over the entire energy range and to very fine detail. This, of course, does not constitute an experimental verification of the validity of this formula, nor does it eliminate the possibility that other interpretations might succeed in giving equally successful agreement with the data. On the other hand, the excellent agreement indicates that the one-level formula can be applied with full confidence and at large distances from the center of the resonance to cross sections having widely separated resonances.

As must be expected, if the cross section is examined in sufficiently fine detail, the effects of neighboring resonances can be observed. In the case of gold, the effects are negligible on the parameters which pertain strictly to the resonance; however, terms which involve the nuclear radius (i.e., ϑ and σ_p) have increased uncertainty due to lack of knowledge about the spins of the nearest neighbors. The data indicate that one or more bound levels in Au^{198} have appreciable influence on the thermal cross sections.

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Radioactive Decay of 65-Hour Sb^{122}†

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65-hour Sb^{122} was investigated by using Sb^{121} (97.7 percent–99.4 percent) that had been bombarded with thermal neutrons for 70 hours. Spectrometer measurements show three beta groups with end-point energies: 1.987, 1.423, and 0.734 Mev; and logft values: 8.6 [log$ft(w^2-mc^2)=10.0$, p^2+q^2 shape], 7.6 (allowed shape), and 7.7; and four gamma rays with energies: 0.563, 0.693, 1.152, and 1.256 Mev; and intensities: 73 percent, 3.6 percent, 0.75 percent and 0.8 percent. From gamma-gamma and beta-gamma coincidences the excited states of Te^{122} were found at 0.563 and 1.256 Mev. X-gamma coincidences and x-ray critical absorption showed 2.2 percent and 0.8 percent K-capture transitions to the ground state and to a 1.152-Mev level in Sn^{122}. The ft values for the transitions to Sn^{122} are 13 times smaller than the corresponding transitions to Te^{122}. Annihilation radiation was not observed setting an upper limit of 0.005 percent for positrons. The directional correlation of the 0.693- and the 0.563-Mev gamma rays indicated a 2−2−0 cascade, with the 2−2 transition 91+5 percent quadrupole. The first excited state in Te^{122} was also shown to be 2+ from a measurement of the K conversion coefficient of the 0.563-Mev gamma ray. We conclude therefore that the ground state of Sb^{122} is 2− $(g_{7/2}, h_{11/2})$, the first two excited states of Te^{122} are 2+, and the first excited state of Sn^{122} may also be 2+.

I. INTRODUCTION

AT the time this work was started, the decay scheme of Sb^{122} was thought to be simple[1]: Sb^{122} decayed by beta emission to the ground state, and to the first excited state, of Te^{122}; the beta transition to the first excited state being followed by a gamma transition to the ground state. The first part of this work was carried out at the University of Illinois and reported at the May, 1952 meeting of the American Physical Society.[2] At that time we had found that there were at least three beta groups and four gamma rays in the decay, and on the basis of ft values and the beta spectra shapes, K conversion, and gamma-gamma directional correlation, we assigned spins and parities to the ground state of Sb^{122} and to the first two excited states of Te^{122}. The decay scheme we suggested and which is quoted in the literature,[3] is correct as far as it goes, but no allowance was made in it for a 1.152-Mev gamma ray we knew to be present to the extent of 0.75 percent of all Sb^{122} decays. Further work at the University of Illinois[4] revealed high-energy coincidences which would indicate that the 1.152-Mev gamma ray leads to the first excited state of Te^{122} (at 0.563 Mev), and that there exists a 1.7-Mev level in Te^{122}. However, the second part of this work, carried out at the Palmer

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