Neutron Resonance Parameters of Ag^{109}†

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The transmission of a thick sample of 99.2% Ag^{109} has been measured for incident neutron energies from 20 keV to 30 eV. The total cross section from 320 to 30 eV has been fitted in detail with the Breit-Wigner single-level parameters for 15 resonances in this energy region. An acceptable fit was obtained for a common radiation width of 120 ± 10 meV and a radius parameter R' of $(0.63\pm0.01)\times10^{-12}$ cm. From the average cross section in the keV region a neutron strength function of $(0.54\pm0.10)\times10^{-4}$ was obtained.

I. INTRODUCTION

UTILIZATION of automated data-handling techniques coupled with computer-programmed resonance-parameter analysis has made practical a more detailed study of neutron transmission data over a wide energy range. These techniques permit greater accuracy in the determination of the Breit-Wigner resonance parameters. The present paper illustrates the application of these methods in a study of the neutron total cross section of Ag^{109}.

A small computer, continuously time-shared between fast- and slow-chopper experiments at the Brookhaven Graphite Reactor, recorded detected neutron events for the sample in and out of the beam. The same computer was used to reduce the raw data to transmission form by performing the necessary normalization and background subtraction. The main analysis was subsequently performed using the IBM 7094 computer from which were obtained plots comparing measured transmission with the transmissions computed from the sum of Breit-Wigner single-level resonance terms.

The desirability of obtaining more accurate parameters for this particular nuclide derives principally from the interest in the S-wave neutron strength function and in the radius parameter, R', for Ag^{109}. As pointed out by Jain *et al.*,[1] a more accurate knowledge of the S-wave compound-nucleus cross sections in this A region would aid in the determination of P-wave strength functions from kV neutron transmission and capture measurements. Furthermore, the low $l=0$ strength functions generally found in neighboring nuclides have been difficult to fit with an optical model, even when neutron absorption is considered to be peaked at the nuclear surface.[2] Ag^{109} lies in the A region where $K_0R\cong3\pi$ and, as has been noted by Seth, this implies that the R' parameter derived from resonance analysis can be closely identified to the radius R of the optical model. Sheer and Moore[4] have made detailed fits to the lowest lying resonances of Ag^{109} and Ag^{107} and have obtained a substantial difference in the R' for these two isotopes. In the present experiment detailed curve fitting over many resonances in a wide energy region is performed to ensure an R' determination free from the effects of resonance wings.

II. DESCRIPTION OF EXPERIMENT

The Ag^{109} was in the form of two metallic foils, of nominal dimensions $1.07\times0.82\times0.040$ in., with the narrow (0.024 in.) neutron beam passing through the 0.82-in. dimension. The BNL fast chopper contains two slits per arm, and both slits were simultaneously utilized. The actual sample thickness, averaged over the two samples, was 0.121 atoms/b.

A resolution of 50 nsec/meter is obtained with the BNL chopper operating with a flight path of 30 m. The 10 cm thickness of the BF_3 bank introduces an additional resolution spread of 0.0092 μsec per μsec of flight time.

The data accumulation, centered in an SDS-910 computer system, has been previously described.[5] Events were accumulated into 1024 channels, each 0.5 μsec wide. The raw data were reduced to transmission form by performing normalization and background subtraction before final output; however, the raw data are permanently stored on magnetic tape for subsequent examination, if this should prove necessary. Backgrounds were recorded at 25-min intervals throughout the entire run by cycling a 3-in. Lucite plug in the beam. Normalization of sample-in to sample-out runs was checked in a separate experiment by running the samples separately in each of the pair of the chopper slits. The average transmission of the sample over the spectrum of neutrons passed by the chopper (roughly $1/E$ down to 30 eV) was 0.440.

III. ANALYSIS

The method of analysis employed uses a modified version of the Atta and Harvey area analysis code.[6] In brief, this method uses the area above a transmission dip to deduce a value for the resonance neutron width, provided the other Breit-Wigner parameters (E_0, R', g,Γ) are known. Initial guesses can be made for these

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[4] C. Sheer and J. Moore, Phys. Rev. **98**, 565 (1955).
[5] R. E. Chrien, S. Rankowitz, and R. J. Spinrad, Rev. Sci. Instr. **35**, 1150 (1964).
[6] S. E. Atta and J. A. Harvey, Oak Ridge National Laboratory Report No. ORNL 3205 (unpublished).

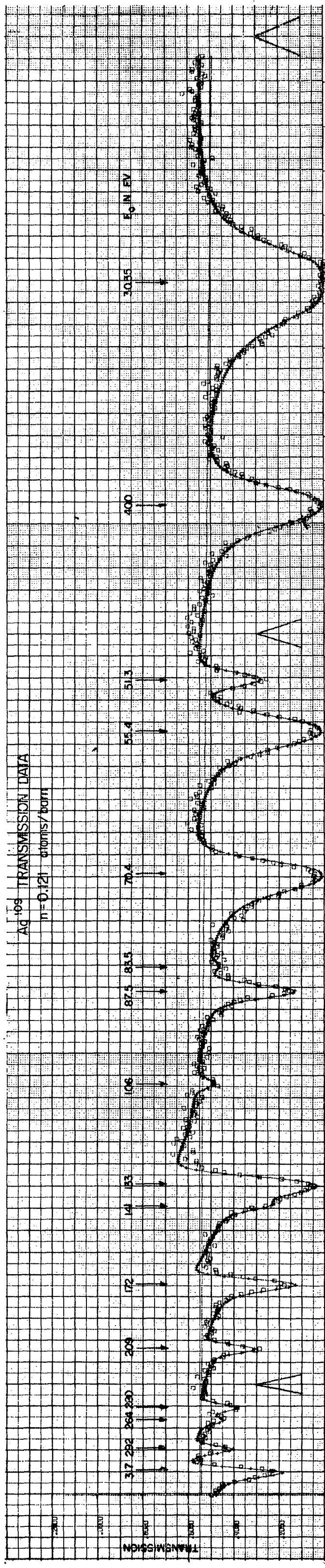

FIG. 1. The transmission of Ag^{109} from 320 to 30 eV. Experimental transmissions (squares) are compared to the predictions of the Breit-Wigner single-level formula (crosses) for 16 resonances in this region. The resonance at 51.3 eV is due to 0.8% Ag^{107} impurity in the sample. A common radiation width of 120 meV was assumed for all resonances, and an R' value of 0.63×10^{-12} cm was necessary to fit the data. The resolution is shown by the triangles, whose full width at half-maximum (FWHM) is the FWHM of the approximately Gaussian resolution function. This plot is produced by a Calcomp plotter from a computer-generated magnetic tape.

parameters or they may be available from other experiments and the corresponding neutron widths obtained. The region between resonances may be used to obtain R' and possibly Γ. The process is reiterated, being terminated with an acceptable X^2 is obtained for the fitted curve obtained from the parameters over the entire energy range being investigated.

A report describing the details of the version of the Atta-Harvey code used in the present analysis will be made available shortly.[7] The principal modifications which have been made are as follows:

(1) A value of the neutron width is calculated from a resonance area for an assumed value of the radiation width. In the original code, the total width is assumed. The values of the radiation width usually vary little among resonances of a nuclide owing to the large number of exit channels available for the (n,γ) process. The radiation width may be known fairly well from capture or scattering data. Furthermore, consistency among the derived neutron width, the assumed radiation width, the statistical weight factor, g, and the total width are assured in the present program.

(2) A program due to Bhat[7] replaces the PFCN routine of the Atta-Harvey code for the calculation of Doppler-broadened cross sections. This new program has, among other advantages, provisions for increasing the speed of calculation at the expense of accuracy.

(3) A more accurate convolution of the various experimental resolution factors is performed.

From scattering and capture data taken at Harwell,[8] a mean radiation width of 120 meV for the resonances in Ag^{109} has been deduced. This mean value was used for all the resonances analyzed in the present experiment. Acceptable fits were obtained with this procedure. In all cases where the spin, and therefore the statistical weight factor, g, is known, that value is employed here, otherwise a g of 0.5 is assumed.

In the kilovolt region where the resonances are not resolved the size and energy dependence of the total cross section are used to calculate the S-wave neutron strength function. A FORTRAN program[9] is available which calculates $\langle\Gamma_n^\circ\rangle/D$ from the total-cross-section data, providing the necessary corrections in relating average neutron transmission to the average over a Porter-Thomas distribution of neutron resonances. The expression for the compound-nucleus cross section for $l=0$ neutrons has been given by Feshbach, Porter, and Weisskopf,[10]

$$\sigma_{l=0}=2\pi^2\lambda\!\!\!^{-2}g\langle\Gamma_n\rangle/D\,,$$

and $\sigma_{l=0}$ has thus a $1/v$ energy dependence. A least-squares fit is made to the average cross section after

[7] M. R. Bhat (private communication).

[8] Atomic Energy Research Establishment, Nuclear Physics Division Progress Report AERE-PR/NP8, 1965 (unpublished).

[9] R. E. Chrien, Brookhaven National Laboratory Report No. BNL 8711, 1965 (unpublished).

[10] H. Feshbach, C. E. Porter, and V. F. Weisskopf, Phys. Rev. **96**, 448 (1954).

TABLE I. The reduced neutron widths of Ag^{109} obtained in the present experiment. ($\Gamma_\gamma = 120$ meV; $R = 0.63 \times 10^{-12}$ cm.) The double errors shown are, in order, a statistical estimate of the width uncertainty, followed by a bracketed error which is derived from a 10-meV uncertainty in the assumed Γ_γ, 120 meV. The isotopic assignments of the 83.5- and 264-eV resonances are considered less certain than for the other resonances. The question marks indicate lack of knowledge of the level spin, and for these levels $g = 0.5$ was assumed in the analysis. For the balance of the levels, the spins were obtained from the work of Asghar (Ref. 11) and Desjardins *et al.*, (Ref. 12) except for the level at 317 eV. For the latter a $J = 1$ was indicated from a comparison of the reduced neutron width of the present experiment with the reduced widths reported by the Columbia[13] and Harwell[14] groups.

E_0 (eV)	$g\Gamma_n^0$ (meV)	J	$g\Gamma_n^0$ (meV) (Columbia)
30.35±0.08	1.02 ±0.01 ±(0.1)	1	1.02
40.04±0.12	0.59 ±0.01 ±(0.04)	1	0.69
55.4 ±0.2	1.04 ±0.02 ±(0.08)	0	1.30
70.4 ±0.2	2.44 ±0.05 ±(0.15)	1	2.43
(83.5 ±0.4)	0.004±0.001±(0.002)	?	0.002
87.6 ±0.4	0.51 ±0.02 ±(0.02)	1	0.51
106.0±0.6	0.010±0.002±(0.004)	?	0.006
133.2±0.7	5.4 ±1.5 ±(0.2)	1	5.30
141±1	0.081±0.014±(0.04)	?	0.09
172±1	3.20 ±0.27 ±(0.10)	1	2.55
209±1.5	0.73 ±0.10 ±(0.02)	1	1.26
252±2	0.48 ±0.11 ±(0.02)	1	1.12
(264±2)	0.10 ±0.02	?	0.12
291±3	0.51 ±0.07 ±(0.02)	0	0.39
317±3	7.2 ±0.5 ±(0.1)	1	7.14

corrections for level fluctuations and isotopic impurities It is appropriate to emphasize here that for thick samples ($n\sigma_T \approx 1$), an accurate knowledge of R' is needed in this analysis so that the total cross section may be decomposed into compound nucleus and potential-scattering cross sections. Hence the value of R' deduced from the lower energy resonance analysis is necessary for the strength-function analysis of the thick sample of the present analysis.

The fluctuation corrections applied to the difference between total cross section and potential-scattering cross sections are dependent on the neutron widths of the resonances, and, therefore, on the neutron strength function and the average level spacing D. The latter is adequately known from the low-energy data, but the former is just the quantity to be measured. However, the total cross section extrapolated to zero time of flight must be $4\pi R'^2$, and the imposing of this restriction permits the extraction of a unique strength function from the analysis.

IV. RESULTS AND DISCUSSION

The procedure outlined above has been carried out to produce the results of Table I and the calculated transmissions of Fig. 1. Acceptable fits were obtained for $R' = 6.3 \pm 0.1$ F, for an assumed radiation width of 120 meV. The corresponding χ^2 value over the 653 data channels from 320 to 30 eV was 1.6 per degree of freedom. The principal deficiencies in the fit are to be found near the peaks of the resonances. Spin assignments

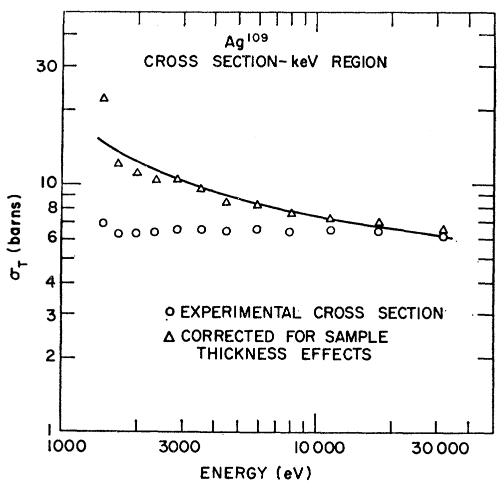

FIG. 2. The keV cross section of Ag^{109}. The experimental points are the "apparent" cross sections derived from $\sigma = -1/n \ln T_{av}$ where T_{av} represents the average transmission over a 4.0-μsec interval. The corrected cross sections are the "true" average cross sections derived from the average transmissions, after evaluating the effects of averaging over the Breit-Wigner resonance shape and over the Porter-Thomas distribution of resonance widths. The curve is shown for the least-squares fit to a $(\langle\Gamma_n^0\rangle/D)_{l=0}$ value of 0.54×10^{-4}.

in Table I are taken from the report of Asghar[11] and the paper of Desjardins *et al.*,[12] except in the previously unassigned level at 317 eV. For this level a $J = 1$ assignment is indicated from a comparison of the present data with the results of Garg *et al.*[13] and Pattenden.[14] [*Note added in proof.* In a private communication M. Asghar indicates that he assigned $J = 1$ to the 317-eV resonance from scattering, capture and transmission work—M. Asghar, thesis, Oxford University, 1964 (unpublished).] The sizable level ascribed to Ag^{109} at 144 eV by Asghar is not seen in the present experiment and must be presumed to be in Ag^{107}. The $g\Gamma_n^0$ values of the present experiment are compared to values obtained by Garg *et al.*[13] Values obtained at Harwell by Pattenden have been quoted in report from.[14] Results of Garg *et al.* are for normal silver and have been recalculated for Ag^{109}.

Two kinds of errors have been attached to the results in Table I. The first error is a statistical estimate, the second, bracketed error is calculated from a presumed 10-meV uncertainty in the radiation width and indicates the dependence of the results on radiation width.

Many additional levels have been observed by Garg *et al.*[13] in natural Ag, but are too small to be observable with the available resolution. Many of these are undoubtedly P-wave levels. The 51-eV level of Ag^{107} shows up in the present experiment because of 0.8% Ag^{107} impurity in the sample used. Analysis of this level

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[12] J. S. Desjardins, J. L. Rosen, W. W. Havens, Jr., and J. Rainwater, Phys. Rev. **120**, 2214 (1960).
[13] J. B. Garg, J. Rainwater, and W. W. Havens, Jr., Phys. Rev. **137**, B547 (1965).
[14] N. J. Pattenden (unpublished); see Ref. 8.

yielded the following parameters for $(J=1)$: $E_0=51.3 \pm 0.2$ eV, $\Gamma_n^0=3.28\pm0.16\pm(0.16)$ meV.

Figure 2 shows the cross section measured in the keV region and the true average cross section as computed taking into account the sample thickness corrections. The value of the spin-averaged strength function is $(0.54\pm0.10)\times10^{-4}$. The principal source of uncertainty stems from the error in R', and is included in the error estimate of 0.10×10^{-4}. The value of $\langle\Gamma_n^0\rangle/D$ calculated from the resonance parameters from the relation $\langle\Gamma_n^0\rangle/D=\sum g\Gamma_n^0/(E_f-E_i)$ is $(0.76\pm0.27)\times10^{-4}$. Garg *et al.*[13] have reported a value of $(0.46\pm0.05)\times10^{-4}$ for natural Ag. This result, with the result of the present experiment, implies nearly equal strength functions for the Ag^{107} and Ag^{109} isotopes.

The value of $R'=6.3\pm0.1$ F is somewhat lower than the value of Sheer and Moore[4] of 6.6 ± 0.1 F, obtained from a scattering experiment at 5 eV. Zimmerman and Hughes[15] obtained a result of 6.6 ± 0.6 F from total-cross-section data. The present result is obtained by fitting over a much wider energy region that is done in previous work. As noted previously, the value of R' in this A region should be very nearly equal to the radius parameter R of the optical model. For the value of $r_0=1.35$ in the relation $R=r_0A^{1/3}$, a value for Ag^{109} of 6.4 F is obtained, which is in excellent agreement with the present result.

ACKNOWLEDGMENT

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Nuclear Spin and Moment of Ag^{110m} by Paramagnetic Resonance*

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Paramagnetic resonance was observed in 253-day Ag^{110m}, present as Ag^{2+} in the $[(\text{iso-}C_3H_7)_2NCS_2]_2Ag$ complex. Eleven hfs lines were observed, the positions of the other two lines being obscured by other absorptions present in the sample, and the nuclear spin of 6 was confirmed. A hfs constant $a_{110m}=(7.108\pm0.02)\times10^{-3}$ cm^{-1} was determined. A hyperfine anomaly of $\Delta_{107,109}=-0.40\%\pm0.1\%$ was observed for stable Ag^{2+} in this complex, indicating that the hfs arises from contact interaction. A nuclear moment of $\mu_{110m}=+3.55\pm0.04$ nm was derived after a 3.7% hyperfine-anomaly correction. It is pointed out that hyperfine anomalies can be infinitely large for very small moments, and that the anomaly may cause a finite moment to exhibit vanishing hyperfine structure or conversely. The nuclear moment does not agree with shell-model predictions using empirical g factors, being low by 1 nm. It is suggested that the $(g_{9/2})^7$ proton configuration might be coupled to spin $\frac{7}{2}$. This yields a moment of +3.54 nm. The hyperfine fields for Ag in Fe and Ni are corrected to -282 ± 20 kG and -87 ± 8 kG, respectively.

I. INTRODUCTION

HYPERFINE magnetic fields at nuclei of 3*d*, 4*d*, and 5*d* transition-group metals in iron, nickel, and cobalt hosts have been the subject of several recent investigations.[1] These fields are measured by means of the Mössbauer effect, nuclear orientation, low-temperature specific heats, perturbed angular correlations, or nuclear magnetic resonance (NMR). Irrespective of the method employed, the measured parameter gives the product of either the nuclear gyromagnetic ratio or the magnetic moment times the hyperfine magnetic field, H_{hf}. In those instances where the nuclear spins and magnetic moments are known, the hyperfine fields are easily calculated. The quantity μH_{hf}, in Ni and Fe lattices, and the nuclear spin of Ag^{110m} have been measured.[2,3] In this paper we report measurements of the nuclear moment of Ag^{110m}.

The quantities of Ag^{110m} available and safe to handle excluded the possibility of a direct NMR measurement of the gyromagnetic ratio. The two most feasible techniques are atomic-beam magnetic resonance and paramagnetic resonance (PMR). We report herein the results of paramagnetic resonance measurements.

Pettersson and Vänngård have reported the PMR spectra of Ag^{2+} diisopropyl dithiocarbamate in solution

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[3] W. B. Ewbank, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, Phys. Rev. 110, 595 (1958).