beam method of zero moments.[2] The latter experiment was based upon the measurement of the difference between the field values at which two zero moment peaks, arising from two states with like m and unlike F values, were observed in the beam intensity. In this case the moment is obtained directly from the observed field separation of the peaks without the use of any semi-empirical formula. In the light of the more thorough study of the nature of zero-moment peaks by Hamilton,[8] it appears that the error in the zero-moment experiment resulted from the assumption that a peak in the curve, obtained by plotting beam intensity *versus* field, was actually the position of a zero-moment field. Since the separation between these peaks was small, a slight departure of the position of the maximum from the zero-moment field value resulted in a large error in the nuclear moment.

We wish to thank Professor I. I. Rabi for his interest in this work and Professor J. R. Zacharias for his assistance in the preliminary stages of these experiments. The research has been aided by a grant from the Research Corporation.

APRIL 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 61

Resonance Broadening of Caesium

CHRIS GREGORY*
California Institute of Technology, Pasadena, California

(Received January 19, 1942)

The resonance broadening of homogeneous Cs vapor in absorption was studied by means of the contour method. The intensities were obtained via the method of "astigmatic photometry" by utilizing the astigmatism of the Rowland grating. The pressure of the homogeneous absorbing vapor ranged from 10^{-2} to 17.5 mm Hg. The half breadth (γ) varied rather linearly with the number of atoms per unit volume, with $(\gamma_1/N)\times 10^7=1.45$, $(\gamma_2/N)\times 10^7=0.84$ for the $^2P_{3/2}$ and $^2P_{1/2}$ components of the resonance lines, respectively. The average value of the ratio of half breadths γ_1/γ_2 was found to be 1.8. The experimental half-width γ is found to be about $1\frac{1}{2}$ times larger than that predicted by W. V. Houston. Below pressures of 10 mm Hg the lines exhibited symmetrical broadening according to the "dispersion" formula. At higher pressures indications of a violet and red asymmetry are present for the $^2P_{3/2}$ and $^2P_{1/2}$ components, respectively. A definite band on the red side of the $^2P_{3/2}$ and one on the violet side of the $^2P_{1/2}$ was observed.

THE present paper is chiefly concerned with shape of the absorption line contours of the resonance lines of homogeneous Cs vapor. In particular, it is wished to ascertain the line contour characteristics as a function of the number of Cs atoms per unit volume N within the absorption cell. The work of Lloyd and Hughes,[1] Watanabe,[2] and Ch'en[3] with K, Na, and Rb, respectively, yielded results which were not in complete accord with various theories on line proadening, not to mention the lack of coherence of their respective data. This lack of coherence, then, can be said to be a secondary incentive for the work on Cs. These difficulties, clearly, can be resolved only by improvements in both theory and experiment. Consequently, an attempt to improve the technique, especially the photographic photometry by the autocalibration or astigmatism method,[4] is made. With regard to the theory, however, it is hoped that this work will prove useful in suggesting the path to be followed in its modification if it is there that the difficulty lies.

* Now at the University of Hawaii, Honolulu, T. H.
[1] D. S. Hughes and P. E. Lloyd, Phys. Rev. **52**, 1215 (1937).
[2] K. Watanabe, Phys. Rev. **59**, 151 (1940).
[3] Shang-Yi Ch'en, Phys. Rev. **58**, 884 (1940).
[4] G. H. Dieke, J. Opt. Soc. Am. **23**, 280 (1933); M. I. Bresch, J. Opt. Soc. Am. **28**, 493 (1938).

I. EXPERIMENTAL AND THEORETICAL PARAMETERS

First of all the absorption coefficient which is usually denoted by α_ν is defined to be

$$\alpha_\nu = -(d/dx)\log_e i_\nu, \qquad (1)$$

where di_ν is the intensity of radiation of frequency ν withdrawn from the radiation of intensity i_ν when it traverses a path length dx. If α_ν is not a function of path length (1) is equivalent to

$$i_\nu = i_0 \exp(-\alpha_\nu x), \qquad (2)$$

where i_0 is the incident intensity of radiation on a slab of thickness x and i_ν the intensity which emerges.

On the other hand the intensity of absorption A_ν at frequency ν is defined as the energy absorbed per unit cross section in unit time by a slab of thickness x:

$$A_\nu = i_0(1-\exp(-\alpha_\nu x)). \qquad (3)$$

One concludes, then, that when $\alpha_\nu x \ll 1$, $A_\nu \approx i_0\alpha_\nu x$.

$I(\nu)$, the intensity distribution of a broadened absorption line, is defined to be proportional to α_ν the absorption coefficient

$$I(\nu) \propto \alpha_\nu \qquad (4)$$

and its physical significance is apparent from (3), for $\alpha_\nu x \ll 1$. It is found convenient to normalize $I(\nu)$ so that

$$\int_0^\infty I(\nu)d\nu = 1. \qquad (5)$$

In case $I(\nu)$ is a function symmetric about $\nu=\nu_0$ at which frequency $I(\nu)$ is a maximum, then a convenient characteristic of the absorption line, $\Delta\nu_{\frac{1}{2}}$, the so-called half breadth is defined by the following equation

$$I(\nu_0 \pm \tfrac{1}{2}\Delta\nu_{\frac{1}{2}}) = \tfrac{1}{2}I(\nu_0). \qquad (6)$$

It may so happen that $I(\nu)$ is not symmetrical about $\nu=\nu_0$, say. In this case no satisfactory quantity has been found to characterize the distribution $I(\nu)$. Several suggestions have been set forth[5] but it is doubtful that these are of much use.

[5] C. Fuchtbauer and F. Gossler, Zeits. f. Physik **87**, 89 (1933); H. Margenau and W. W. Watson, Phys. Rev. **44**, 92 (1933).

It has been shown[6] that the Einstein coefficient of absorption B_{ij} is connected with α_ν in the following manner

$$B_{ij} = \frac{C}{h\nu_{ij}N}\int_{\text{over line}} \alpha_\nu d\Delta\nu, \qquad (7)$$

where C is the velocity of light, h Planck's constant, ν_{ij} the frequency, and N the number of atoms per unit volume. Furthermore the so-called f-value is defined[7] as

$$f_{ji} = B_{ij}mh\nu_{ij}/\pi e^2, \qquad (8)$$

m being the mass of an electron and e its charge in e.s.u. (7) and (8) enables one to obtain the constant of proportionality in (4).

II. PROCEDURE

Aside from the application of astigmatic photometry the method of procedure is somewhat the same as that used by Hughes and Lloyd[1] and includes the improvement of temperature measurement made by Watanabe.[2] The source consisted of a high intensity tungsten lamp. The concave grating of 21-foot focal length mounted in the Rowland manner had a dispersion of 2.64A/mm. Its resolving power in the first order amounted to approximately 70,000. In the case of the first members of the principal series a red Wratten F No. 49 filter was placed over the slit of the spectrograph to cut off the second-order violet.

The geometry of the Rowland grating is such as to render feasible intensity measurements by utilizing the astigmatic nature of the image or the plate. This astigmatism manifests itself in the following manner. The spectrum produced by the grating has a constant intensity portion near the center, and as one proceeds in a direction transverse to directions of increasing or decreasing λ the intensity falls off in a calculable manner (linearly) if the intensity distribution along the slit length is constant and if the grating is uniformly reflecting. One can, then, for any part of the spectrum obtain calibration marks without any auxiliary apparatus. This method was first suggested by G. H. Dieke[4] and later was subjected to extensive tests by M. I. Bresch[4] who

[6] R. C. Tolman, Phys. Rev. **23**, 609 (1924).

[7] R. Ladenburg, Zeits. f. Physik **4**, 451 (1921); R. Ladenburg and F. Reiche, Nature **11**, 596 (1923).

applied the method to the study of line spectra where it was found that the astigmatic method compared favorably with others. It is obvious that errors inherent in the calibration of step weakeners as in the procedure of Lloyd and Hughes, Watanabe, and Ch'en are absent.

The grating used was found to satisfy the conditions whereby the following equations are valid

$$\begin{aligned} L_T &= L \sin \varphi \tan \varphi + s/\cos \varphi, \\ L_C &= L \sin \varphi \tan \varphi - s/\cos \varphi, \end{aligned} \tag{9}$$

where L_T is the total length of the image and L_C is the length of the constant central portion. L is the length of the grating rulings, s the slit length and φ the angle of incidence. In the study of the red Cs lines an aperture for the grating and decker for the slit were designed so as to give as large an image as possible with as small as possible central portion consistent with limitations of measurement and width of usable plate.

For the first members of the principal series $\lambda^2P_{3/2}=8521.12$, $\lambda^2P_{1/2}=8943.36$. Eastman IP plates were used.† In the neighborhood of the $^2P_{3/2}$ component the sensitivity of the plate was quite constant and could be considered so for the rather narrow lines. On the other hand in the region of the $^2P_{1/2}$ component the sensitivity varied considerably—because it is impossible to study the broadening at higher pressures ($P>15$ mm Hg). In the case of wide lines astigmatism traces on either side were taken and corresponding corrections for varying sensitivity of the plate were made.

From the known temperature of the absorption cell containing an excess of Cs, the vapor pressure was obtained from the empirical formula[8]

$$\log_{10} p_{mm} = 11.0531 - 1.35 \log_{10} T - 4041/T, \tag{10}$$

where P_{mm} is the pressure in mm of Hg and T the absolute temperature. This enables one to find N, the number of Cs atoms per unit volume.

III. SYNTHESIS. MEASUREMENTS

1. Experimental Evaluation

Two cases are to be distinguished here, namely, the case for narrow lines ($P_{mm}<10^{-2}$) and for wide lines ($P_{mm}>10^{-2}$).

(a) Narrow Lines

In this case because of insufficient resolution of the spectrograph and microphotometer due to finite slit width, the contour cannot be adequately compared with a theoretical one without knowing *a priori* the effect of finite slit width. Here, however, resort to the method of total absorption[9] is made. The distribution to be tested is

$$\alpha x = -\log_e \frac{i}{i_0} = \frac{Kx/2\pi}{(\Delta\nu)^2+(\gamma/2)^2}, \tag{11}$$

where use has been made of (2), (7), and (8) with

$$K = \pi e^2 N f/mc \tag{12}$$

and x refers to the tube length in cm. According to Ladenburg and Reiche[9]

$$\int_{-\infty}^{+\infty} \left(1-\frac{i}{i_0}\right) d\Delta\lambda = \text{const.} = A, \tag{13}$$

which assertion had been tested by Minkowski.[10] Putting (11) in (13) and integrating one obtains

$$C = 3.46 \times 10^{-18} \mathrm{A}^2, \tag{14}$$

where

$$C = \lambda_0{}^4 e^2 N f x \gamma / 2mc^3 \log_e 10. \tag{15}$$

Knowledge of f and A enables one to obtain γ if the distribution of the form (11) is assumed. This assumption can be readily tested. For the $^2P_{3/2}$ and $^2P_{1/2}$ lines of Cs we have for the f-values, respectively, 0.66 and 0.32,[11] so that (15) yields

$$\begin{aligned} 10^{40} C_1 &= 0.707 N x \gamma_1, \\ 10^{40} C_2 &= 0.416 N x \gamma_2. \end{aligned} \tag{16}$$

We denote the $^2P_{3/2}$ by subscript 1 and $^2P_{1/2}$ by subscript 2.

(b) Wide Lines

For pressures greater than 10^{-2} mm Hg resort to the so-called "straight line" method is made. Here again use is made of (11) which is put in

† These plates were hypersensitized in a 4 percent solution of NH_4OH in the usual manner.

[8] J. B. Taylor and I. Langmuir, Phys. Rev. **51**, 753 (1937).

[9] R. Ladenburg and F. Reiche, Ann. d. Physik **42**, 181 (1913).

[10] R. Minkowski, Zeits. f. Physik **36**, 839 (1926).

[11] S. A. Korff and G. Breit, Rev. Mod. Phys. **4**, 471 (1932).

the form

$$(\Delta\lambda)^2 = C[\log_{10}(i_0/i)]^{-1} - \gamma^2\lambda_0^4/4C^2, \quad (17)$$

where C is given by (16) or in general (15). The second term on the right is quite small compared with the first term, so it can be neglected. Examination of (17) discloses, then, that if one plots $(\Delta\lambda)^2$ against $[\log_{10}(i/i_0)]^{-1}$ a straight line results whose slope is C and which passes essentially through the origin. Consequently, the ascertainment of this slope enables us to obtain γ_1 and γ_2 by means of (16).

(c) *Asymmetry and Shift*

For $P_{mm} > 1$ mm Hg asymmetries were evident. Attempts were made to fit the contours to the "$-\frac{3}{2}$" type of curve.[12] This attempt proved futile, so that both wings of the lines were subject to the same tests and considerations as is b.

Because of total absorption at the center of the line it is impossible to measure the shift, so that no consideration is given to this phase here. Under ideal conditions the shift, if it existed, could be measured if a short enough workable absorption tube could be constructed.

2. Experimental Results

In all three successful runs were made. However, in run No. 2 the thermocouple was not in its proper position so that temperature determination was not made. Nevertheless, the results are useful in the evaluation of γ_1/γ_2 which presumably is independent of temperature. For lower pressures $\approx 10^{-2}$ mm Hg the γ obtained experimentally is corrected for natural breadth according to the circumstance of the additivity of the breadths due to the two causes.

TABLE I. Data on broadening.

Plate	T	P_{mm} Hg	γ_1	γ_2	γ_1/γ_2
		Run No. 1. $x=7.25$ cm			
54	414.0	5.75×10^{-3}	1.70×10^{7}	1.07×10^{7}	1.60
55	429.9	1.26×10^{-2}	4.60×10^{7}	2.59×10^{7}	1.78
56	460.8	5.01×10^{-2}	1.73×10^{8}	9.11×10^{7}	1.90
57	490.0	1.59×10^{-1}	5.16×10^{8}	3.64×10^{8}	1.42
58	512.4	3.16×10^{-1}	7.56×10^{8}	2.86×10^{8}	2.65
		Run No. 2. $x=7.00$ cm			
70					1.43
72					1.61
79			(?)		1.74
80					2.17
74					1.92
		Run No. 3. $x=0.1905$ cm			
87	512.2	0.334	1.07×10^{9}	7.55×10^{8}	1.42
88	532.6	0.640	1.93×10^{9}	7.45×10^{9}	2.58
89	564.8	1.60	4.05×10^{9}	2.51×10^{9}	1.61
90	583.9	2.47	4.31×10^{9}	3.60×10^{9}	1.20
91	609.7	4.71	6.75×10^{9}	5.35×10^{9}	1.26
92	672.7	17.50	1.02×10^{10}	?	?

[12] H. Kuhn, Phil. Mag. **18**, 987 (1934).

TABLE II. Comparison of results.

	$10^7\gamma_1/N$	$10^7\gamma_2/N$	γ_1/γ_2
Na	1.10 (0.49)	0.712 (0.49)	1.16 (1.00)
K	3.2 (0.63)	3.2 (0.63)	1.0 (1.00)
Rb	0.96 (0.65)	0.55 (0.65)	1.60 (1.00)
Cs	1.45 (0.71)	0.84 (0.71)	1.80 (1.00)

It was found that for pressures below ~ 1 mm Hg the lines were rather symmetrical in compliance with the theory. For pressures >1 mm Hg (see Table I) the lines exhibited asymmetry and/or irregularities. C_1 and C_2 for both wings of each line were obtained and averaged. At higher pressures band-like structures at the wings of the lines introduced difficulties of measurements.

Averaging the results of the table we obtain, leaving out runs No. 91 and No. 92,

$$10^7\,\gamma_1/N = 1.45;\ 10^7\,\gamma_2/N = 0.84;\ \gamma_1/\gamma_2 = 1.8. \quad (18)$$

3. The Line Contours

Examination of the contours indicated that for $P_{mm} < 1$ the broadening was essentially symmetrical and the plots of $(\Delta\lambda)^2$ *vs.* $-[\log(i/i_0)]^{-1}$ were fairly linear. For higher pressures, however, the contours seemed to exhibit irregularities at the wings which may be attributed to several causes. It was concluded that these irregularities are due to Cs_2 bands. In particular, plate No. 92 exhibited a band of width $\sim$16A whose center is $\sim$45A from the center of the $^2P_{3/2}$ component towards the red. Plate No. 91 showed also the corresponding band. A band was also observed on the violet side of the $^2P_{3/2}$ component with width $\sim$20A and $\sim$40A from the center of the doublet. Also the $^2P_{1/2}$ component seems to have a distinct band on the violet side of width $\sim$20A and $\sim$40A away from the line center. Ch'en[3] has observed the corresponding bands for

Rb. Kuhn[13] has also observed bands on the violet side of the second doublet of the principal series of Cs and some bands for K and Na. In view of these band-like structures and non-uniform plate characteristics the ascertainment of the presence of asymmetry was rather difficult. It is very likely, as the plates showed, that asymmetry sets in at about $p=10$ mm Hg, namely a violet and red asymmetry for the $^2P_{3/2}$ and $^2P_{1/2}$ components, respectively.

4. Theory *vs.* Experiment

According to Weiskopf,[14] Margenau and Watson,[15] Furrsow and Wlassow,[16] and Houston,[17] we have the following theoretical dependence of γ on N for Cs.

W	$10^7\,\gamma_1=0.37N$	$10^7\,\gamma_2=0.20N$
M & W	$=0.79N$	$=0.42N$
F & W	$=1.32N$	$=0.69N$
H	$=0.71N$	$=0.71N$

as compared with the results of measurements $10^7\,\gamma_1=1.45N$, $10^7\,\gamma_2=0.84N$. Thus it appears that the F & W formulae are more consistent with the results than the others.

On the basis of prior work on Na,[2] K,[1] and Rb[3] we can construct Table II in which the values in parentheses are those predicted by Houston.[17] The disagreement seems to be most in the case of K. The majority of results shows that the ratio γ_1/γ_2 is not unity. If we do not include the results for K the table indicates an increase in the ratio γ_1/γ_2 with principle quantum number: 0.2 per quantum number.

I wish to express my gratitude to Professor Bowen for many helpful suggestions and guidance and to Professor Houston for having so kindly discussed the theoretical aspects of the problem.

[13] H. Kuhn, Zeits. f. Physik **76**, 782 (1932).
[14] V. Weiskopf, Zeits. f. Physik **75**, 287 (1932).
[15] H. Margenau and W. W. Watson, Rev. Mod. Phys. **8**, 28 (1936).
[16] Furrsow and Wlassôw, Physik. Zeits. d. Sowjetunion **10**, 378 (1936).
[17] W. V. Houston, Phys. Rev. **54**, 888 (1938).

APRIL 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 61

Resonance Absorption of Neutrons in Rhodium, Antimony, and Gold

H. Feeny, C. Lapointe, and F. Rasetti
Department of Physics, Laval University, Quebec, Canada
(Received January 19, 1942)

The following experiments were performed on the resonance neutrons of Rh, Sb^{121}, and Au: absorption in the element itself, absorption in boron, measurement of the total activation in an extended volume of hydrogenous material. The constants evaluated are the resonance energy E_r, the absorption coefficient for self-indication K_r, and the level width Γ. We found: for rhodium, $\Gamma=0.16$ ev; for antimony, $E_r=14$ ev, $K_r=4$ cm^2/g, $\Gamma=0.8$ ev; for gold, $E_r=2.6$ ev, $K_r=40$ cm^2/g, $\Gamma=0.11$ ev. In antimony and gold, the measurements indicate that a small fraction of the resonance activity induced in thin detectors is due to levels of higher energy. The observed absorption coefficient for thermal neutrons K_{th} in rhodium and gold is found to agree with the one calculated from the Breit and Wigner formula, by taking into account only the resonance level observed. In Sb, the calculated K_{th} is about six times larger than the one observed, which suggests the interference effect of negative levels.

INTRODUCTION

The resonance absorption of slow neutrons affords the best means of investigating the position and width of nuclear levels. A considerable amount of data are already available for the few elements in which the intensity of the activity produced by slow neutrons and the convenient length of the decay period make the investigation practicable. Among the few suitable activities that have not been thoroughly investigated, there appear to be left the 2.8-day activity due to Sb^{122} and the 2.7-day activity due to Au^{198}. These