PHYSICAL REVIEW VOLUME 140, NUMBER 5A 29 NOVEMBER 1965

Lifetime of the $6s6p\ ^1P_1$ State of Mercury

ALLEN LURIO
IBM Watson Laboratory, Columbia University, New York, New York
(Received 14 July 1965)

The lifetime of the $6s6p\ ^1P_1$ state of mercury has been determined by the zero-field level-crossing technique (Hanle effect) to be $\tau=(1.31\pm0.08)\times10^{-9}$ sec. This result yields a value of $f=1.18$ for the oscillator strength of the 1850-Å line. From this lifetime result and other experimental data we have calculated the intermediate coupling coefficients for the mixing of the $6s6p\ ^3P_1$ and $^1P_1$ states by three different methods. All three methods are in good agreement.

INTRODUCTION

THE measurement of the lifetime of the $(6s6p)\ ^1P_1$ state of mercury provides a good test of the theory of intermediate coupling in sp configurations since the intermediate coupling coefficients can be determined independently from the following three different experimental results[1]; (1) the $^3P_{2,1,0}$, $^1P_1$ fine structure, (2) the g_J value of the $^3P_1$ state, and (3) the lifetimes of the $^1P_1$ and $^3P_1$ states. All of the required experimental values are known accurately except the lifetime of the $^1P_1$ state for which there is considerable disagreement among the previous results.[2] It is interesting to note that although the lifetime of the $^3P_1$ state has been measured a number of times and is known quite accurately, the most recent previous determination of the $^1P_1$ state lifetime was in 1933.[2]

The use of the zero-field level-crossing technique (Hanle effect) to measure the lifetime of the first excited $^1P_1$ state of the Group II elements has bee described in detail in several previous papers.[3] W present here, therefore, only a brief description of tl method, and those details which pertain to the prese experiment on mercury. In Fig. 1 is shown the ener; levels of the ground- and the lowest excited-state co figuration of mercury. In Fig. 2 is shown a schemat diagram of the apparatus. Briefly, the experiment method is as follows: incident 1850-Å resonance ra(ation is scattered by a sample of mercury atoms co tained in a cell or in an atomic beam. The radiati scattered at 90° to the incident light direction detected as a function of a static magnetic field appli to the scattering atoms in a direction perpendicular the incident and observing directions. From the ha width of the Lorentzian-shaped zero-field level-crossi signal, the lifetime of the $^1P_1$ state is determined.

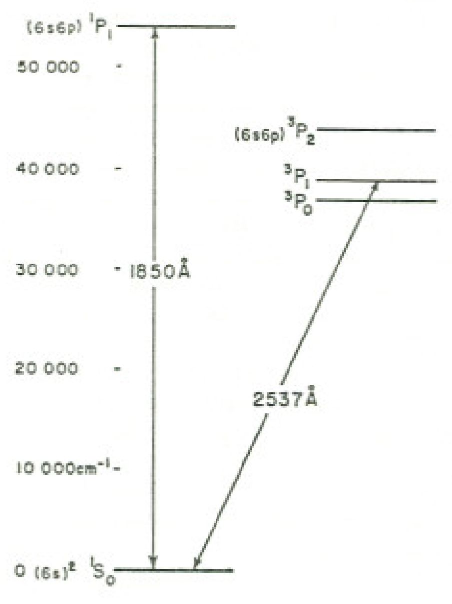

FIG. 1. Ground- and lowest-excited-state levels of the neutral mercury atom.

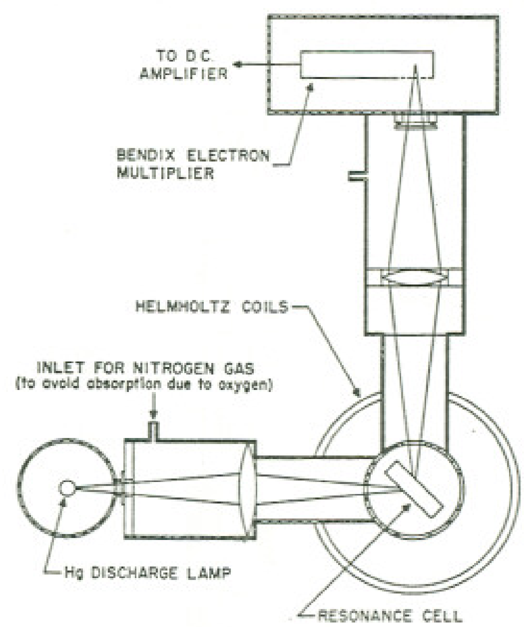

FIG. 2. Schematic diagram of the apparatus. A horizontal sect through the center of the apparatus is shown.

[1] A. Lurio, M. Mandel, and R. Novick, Phys. Rev. 126, 1758 (1962).

[2] See footnotes in Table II.

[3] A. Landman and R. Novick, Phys. Rev. 134, A56 (196 A. Lurio and R. Novick, *ibid.* 134, A608 (1964); A. Lurio, R. DeZafra, and R. Goshen, *ibid.* 134, A1197 (1964); A. Lurio, *i* 136, A376 (1964).

APPARATUS

The mercury resonance lamp used in the experiment was supplied by Englehard Hanovia, Inc.[4] It was a shortened version of their type 93 A-1 low-pressure ozone producing lamp, which when operated on 60 cycles/sec at 3000 V produced a very stable discharge. In order to optimize the resonantly scattered 1850-Å line, the lamp was cooled as shown in Fig. 3. Nitrogen gas which was precooled by passage through liquid nitrogen was flowed through the cooling coils surrounding the lamp. Dow Corning type 550 silicone oil filled the lower part of the cooling jacket and maintained the lower third of the discharge lamp at about $-20°C$ by means of conduction through the silicone oil. This temperature was found to yield the largest scattering from the mercury atoms. The reduced lamp temperature in addition to optimizing the 1850-Å radiation, also greatly reduced the intensity of the 2537-Å line. A later modification which proved useful was the provision for applying a magnetic field parallel to the axis of the capilliary discharge lamp (see Fig. 3). A permanent magnet, which could be removed, provided a field at the lamp of from 400 to 1150 G by means of aluminum spacers between the permanent magnet and the poles. The use of this magnetic field will be discussed in the next section. The stray field produced by this magnet at the scattering atoms when in the direction opposed to the earth's field was 1.5 G. This field was taken into account in evaluating the data.

The detector for the 1850-Å radiation was a Bendix parallel-plate electron multiplier with a brass input

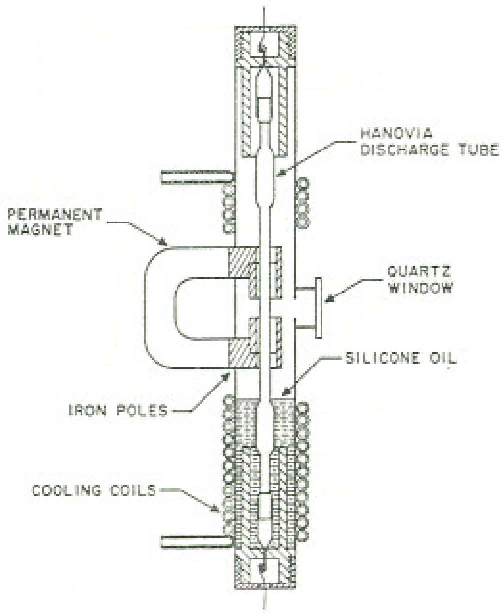

FIG. 3. Cross-section view through lamp and its housing.

[4] Englehard Hanovia, Inc., 100 Chestnut Street, Newark 4, New Jersey.

dynode. The photoelectric efficiency of this surface very much greater for 1850-Å radiation than for 2537 radiation and this fact led to the choice of an electr multiplier rather than a photomultiplier for the c tector. The electron multiplier operating with a gain about 10^7, and with a 10^6-Ω anode resistor had a da current of less than 10 μV, which corresponds to a equivalent cathode current of less than 16 electrons/se

All lenses and windows were made of ultraviol silica. It was found necessary to flush nitrogen throu all optical paths between the light source and tl detector since 1850-Å radiation is strongly absorbed b oxygen. This fact provided an easy way to distinguis how much 1850-Å compared to 2537-Å radiation is beir detected. In our experiment, the substitution of nitroge for air in the optical paths increased the scattered ligl signal by about 10 times. The magnetic field at th scattering atoms was provided by a Helmholtz co which produced 48.9 G/A. It was calibrated by proto resonance.

EXPERIMENTAL PROCEDURE

All preliminary measurements were done by scatter ing unpolarized resonance radiation from an atomi beam of natural mercury. Although the incident and outgoing light directions were visually set to be ortho gonal, before each run the lenses were slightly adjuste to make the level crossing signal symmetric about zer gauss (the 1.5 G stray field was taken into account ir this procedure). A run consists of observing the scat tered radiation as the magnetic field was varied from 400 G in one direction (up) to 400 G in the opposite direction (down). A difficulty which appeared immediately was the following: The scattered light intensity which should have an inverted Lorentzian shape, instead of leveling out at high magnetic fields (i.e., for $H>150$ G the intensity should only rise about 8%), continued to slowly rise as much as 25% on increasing the field from 150 to 400 G. It was thought that this might be caused by self-reversal in the lamp since, if the lamp is self-reversed, as the magnetic field at the scatterers is increased, the $\Delta m=\pm 1$ Zeeman levels scan a higher intensity part of the lamp's intensity profile. After some preliminary tests seemed to confirm this idea, the lamp was modified to permit the application of up to about 1150 G parallel to the axis of the discharge tube. The field applied to the lamp and the field applied to the scatterers were along the same direction. The use of a magnetic field at the lamp both increased the level crossing signal and essentially eliminated the anomalous rise of the level crossing signal at high fields. This improvement was independent of the magnetic field from about 800 to 1500 G. Our explanation of this effect is as follows: The π line emitted by the lamp is unaffected by the magnetic field and will continue to be self-reversed. The σ lines are each displaced from their zero-field position by about 1600 Mc/sec (for 1150 G).

These σ lines which are self-reversed at the center of their shifted positions now add to give a relatively flat profile at the unshifted position.

An exact profile calculation requires a knowledge of the zero-magnetic-field profile and this is complicated by the isotope shifts in the natural mercury mixture used in the lamp.

The final data was taken with a 40-mg sample containing 84.7% Hg^{202} and 92.45% even mercury isotopes. In addition to scattering from an atomic beam of the enriched isotope, data was also taken by scattering from a quartz cell containing the enriched isotope. A typical curve of the atomic beam scattering is shown in Fig. 4. The data was analyzed by plotting the experimental curves against a family of Lorentzian-shaped curves calculated from the equation

$$I=1-\left[1+\tau^2\left(\frac{2g_J\mu_0H}{\hbar}\right)^2\right]^{-1} \tag{1}$$

for different values of τ. In order to normalize the experimental curves one must know the asymptotic value of the scattered intensity for large fields. This was obtained from an approximate value of the lifetime and the data taken for H greater than 100 G.

LIFETIME RESULTS AND DISCUSSIONS

The preliminary data taken with natural mercury yielded a lifetime for the $^1P_1$ state of $\tau=(1.2\pm0.1)\times10^{-9}$ sec. The data taken with the enriched Hg^{202} isotope gave a value of $\tau=(1.31\pm0.08)\times10^{-9}$ sec. The difference between these two results is consistent with the fact that the odd isotopes have a smaller g value than the even isotopes. A similar effect has been reported by Anderson for xenon.[5] The effect of multiple scattering narrowing was observed as the density of the scattering atoms was increased. Most of the data were taken at mercury vapor pressures of $1\text{–}3\times10^{-7}$ Torr and

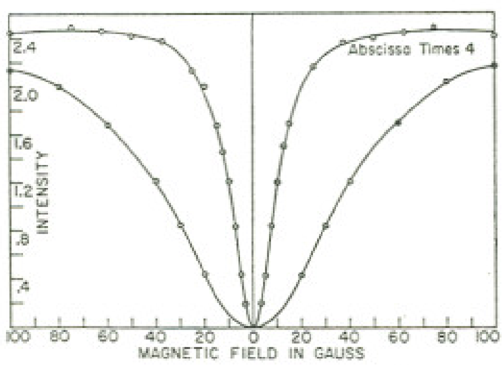

FIG. 4. Hanle-effect line shape for the 1850-Å line. The zero of the ordinate is chosen to be the scattered intensity at zero magnetic field.

[5] D. K. Anderson, Phys. Rev. 137, A21 (1965).

TABLE I. g_J values for the $^1P_1$ and $^3P_1$ states.

$g_J(^3P_1)$	1.486118(16)	Smith[a]
$g_J(^3P_1)$	1.486094(8)	Kohler and Thaddeus[b]
$g_J(^1P_1)$	1.019(6)	Green and Loring[c]
$g_J(^1P_1)$	1.0218(88)	Van Kleef and Fred[d]

[a] W. W. Smith, Phys. Rev. 137, A330 (1965).
[b] R. Kohler and P. Thaddeus, Phys. Rev. 134, A1204 (1964).
[c] J. B. Green and R. A. Loring, Phys. Rev. 46, 888 (1934).
[d] Th. A. M. Van Kleef and M. Fred, Physica 29, 389 (1963).

the coherence time was extrapolated to its zero-pres value which introduced a correction of 3%.

From Eq. (1) we note that the level crossing si depends on the product g_JH. In Table I are given measured values of g_J for the $^1P_1$ and $^3P_1$ state. We l used the average result $g_J(^1P_1)=1.020\pm0.00$7 analyzing our data. Within experimental error th for the $^1P_1$ and $^3P_1$ states satisfy the g sum rule Table II are given our value and previous values fo lifetime of the $^1P_1$ state. The agreement between result and Wolfsohn's is excellent which is very plea since of the earlier results Wolfsohn's is expected t most reliable.

With our result for the lifetime of the $6s6p\,^1P_1$ s we obtain a value $f=1.18$ for the oscillator strengt the 1850-Å line. This is to be compared with the B and Damgaard prediction of 1.48.[6]

We may now proceed to our objective, mentione the Introduction, the calculation of the intermed coupling coefficients by the three different methods line 1, Table III are given the intermediate coup coefficients c_1 and c_2 (also α and β) obtained from $^3P_{2,1,0}$, $^1P_1$ fine structure by the method of Wolfe.[7]

In line 2 are given the coefficients calculated from deviation of the $^3P_1$ state g_J value from its value for Russell-Saunders coupling. The $g_J{}^0$ values for

TABLE II. Lifetime of the $^1P_1$ and $^3P_1$ states.

Quantity	Lifetime (sec)	Author
$\tau(^1P_1)$	0.3×10^{-9}	Garrett[a]
	1.6×10^{-9}	Ladenburg and Wolfsohn
	1.30×10^{-9}	Wolfsohn[c]
	1.31×10^{-9}	Present work
$\tau(^3P_1)$	1.14×10^{-7}	Ladenburg and Wolfsohn
	1.15×10^{-7}	Kaul[d]
	1.18×10^{-7}	Barrat[e]
	1.14×10^{-7}	Schuler[f]

[a] P. H. Garrett, Phys. Rev. 40, 779 (1932).
[b] R. Ladenburg and G. Wolfsohn, Z. Physik 63, 616 (1930).
[c] G. Wolfsohn, Z. Phys. 83, 234 (1933).
[d] R. D. Kaul, thesis, Case Institute of Technology, Cleveland, Ohio, (unpublished).
[e] J. P. Barrat, J. Phys. Radium 20, 541, 633, 657 (1959).
[f] C. J. Schuler, Quarterly Progress Report, No. 64, 1964, Massachu Institute of Technology, Research Laboratory for Electronics, Cambr Massachusetts (unpublished).

[6] D. R. Bates and A. Damgaard, Phil. Trans. Roy. (London) A242, 101 (1949).
[7] H. Wolfe, Phys. Rev. 41, 443 (1932); G. Breit and L. A. W *ibid.* 44, 470 (1933).

Meth[illegible]	
Fine struc[illegible]	[illegible]
$^3P_1$ state g[illegible]	[illegible]
Lifetime ra[illegible]	[illegible]
Pure LS co[illegible]	[illegible]

Russell-Saunde[illegible]
intermediate coup[illegible]

$$g_J(^3P_1) = \alpha\ [illegible]$$

where α and β are [illegible]
and c_2, and we [illegible]
$g_J{}^0(^1P_1) = 0.999$[illegible]
estimate of -2[illegible]
corrections. T[illegible]
$g_J(^3P_2) = 1.5009$[illegible]
and the theor[illegible]
From a trea[illegible]
corrections [illegible]
Van Vleck f[illegible]
to both the [illegible]
and are s[illegible]

[8] A. Abrag[illegible]