

sembled around the 8-in. microwave cell, and the transition was observed in the absence of the field with a half-width at half-height of about 15 kc/sec. The magnetic field gave rise to the expected doublet with splitting equal to $2\mu_N H_z g_{bb}$ as given in Eq. (1). All measurements were taken at dry-ice temperatures.

The results of a series of measurements on the $J=0 \rightarrow J=1$ and $J=1 \rightarrow J=2$ transitions gives:

$$J=0 \rightarrow J=1$$

$$\left| \frac{\Delta\nu}{2\mu_N H_z} \right| = g_{bb} = |0.02851 \pm 0.0004|,$$

$$J=1 \rightarrow J=2$$

$$\left| \frac{\Delta\nu}{2\mu_N H_z} \right| = g_{bb} = |0.02915 \pm 0.0005|.$$

The signs are negative as determined previously.³ Al-

though the value for the $J=0 \rightarrow J=1$ appears less than the average in $J=1 \rightarrow J=2$, the two values are identical within experimental error. Both values are also, within experimental error, identical to the value obtained by Cederberg, Anderson, and Ramsey.⁵ Our value for the $J=1 \rightarrow J=2$ transition also disagrees with the result of $g=0.025 \pm 0.002$ of Eshbach and Strandberg.

It appears that the microwave and molecular beam results are now in good agreement in the measurement of the molecular magnetic moment in OCS. It appears somewhat surprising, however, that the molecular beam measurement does not give rise to a different g value due to the average obtained over the large number of rotational states populated at room temperatures.

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Rare-Gas Collision Broadening in the Lowest 3P_1 Level of Cd

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Alignment depolarization collision cross sections have been measured for the lowest 3P_1 level of cadmium broadened by the rare gases. Cross sections obtained with the Hanle effect (zero-field level crossing) and the method of modulated-light double resonance are the same within approximately 5%. They agree with theoretical predictions except in the case of helium, for which the measured cross section is nearly twice as large as the theoretical value. Average experimental values (units of 10^{-16} cm²) for He, Ne, Ar, Kr, and Xe, respectively, are 51, 52, 81, 118, and 165.

I. INTRODUCTION

ACCURATE width measurements of upper electronic levels of optical transitions can be obtained without optical frequency Doppler broadening through use of the Hanle effect^{1,2} (zero-field level crossing) and the recently developed method of modulated-light double resonance.^{3,4} In the present investigation the cadmium 3P_1 - 1S_0 intercombination line (3261 Å) has been observed for measurement of alignment depolarization cross sections for the 3P_1 level broadened by collisions with the rare gases helium, neon, argon, krypton, and xenon.

Observation of this cadmium level is advantageous

since the level width is small (approximately 70 kc), allowing measurement of small collision frequencies. Also, the 3P_1 level has low excitation energy (3.8 eV) and is well separated from other cadmium energy levels. Thus, bombardment with electrons of nominal energy spread can produce excitation to this level without excitation of other cadmium levels or of gas atom levels. This eliminates cascade effects and ensures that collisions are with ground-state rare gas atoms.

The Hanle effect has been used for these measurements with both resonance fluorescence and electron excitation. The modulated-light technique has been used only with electron excitation. It was of interest to obtain a comparison of cross sections measured with the two methods since the observed levels are degenerate for the Hanle effect and well resolved for the modulated-light technique.

II. THEORY

The Hanle effect is a variation in the polarization of emitted light as a function of magnetic field strength H ,

¹ W. W. Smith and A. Gallagher, Phys. Rev. **145**, 26 (1966).

² A. Lurio, R. L. DeZafra, and R. J. Goshen, Phys. Rev. **134**, A1198 (1964).

³ A. Corney and G. W. Series, Proc. Phys. Soc. (London) **83**, 213 (1964).

⁴ E. B. Aleksandrov and V. P. Kozlov, Opt. i Spektroskopiya **16**, 533 (1964) [English transl.: Opt. Spectry. (USSR) **16**, 289 (1964)].

the effect having a resonance when $H=0$. For the geometry used here (see Fig. 1) and the $^3P_1-^1S_0$ transition, the light intensity is given by the inverted Lorentzian distribution²

$$I(H) = C \{ 1 - \Gamma^2 / [\Gamma^2 + (2g_J \mu_0 H / \hbar)^2] \}. \quad (1)$$

Here Γ is the width of the upper level in radians per second, g_J is the Lande g factor (1.5 for the cadmium 3P_1 level), μ_0 is the Bohr magneton, \hbar is Planck's constant, and C is a constant depending on geometrical factors, excitation intensity, and density of emitters.

Modulated light double resonance is a resonance in the percent modulation of emitted light arising when the Zeeman splitting of the magnetic sublevels is equal to the excitation modulation frequency. For excitation modulated in time as $\cos \omega t$ and the geometry of Fig. 1, the resonance is described by³

$$I(H) \propto \frac{\Gamma \cos \omega t}{\Gamma^2 + (\omega - 2g_J \mu_0 H / \hbar)^2} + \frac{(\omega - 2g_J \mu_0 H / \hbar) \sin \omega t}{\Gamma^2 + (\omega - 2g_J \mu_0 H / \hbar)^2}. \quad (2)$$

Detection of the in-phase ($\cos \omega t$) component yields a Lorentzian distribution similar to that obtained for the Hanle effect.

The width Γ is determined² from the change in magnetic field $2\Delta H_{1/2}$ required to scan between the half-maximum intensity points of Eq. 1 or 2:

$$\Gamma = 2g_J \mu_0 \Delta H_{1/2} / \hbar \text{ sec}^{-1}. \quad (3)$$

This width is a sum of widths due to radiative lifetime of the level, multiple scattering narrowing, and collisional broadening. The collisional width, the difference between widths for gas density N and density zero, is related to the cross section by¹

$$\Gamma_{\text{coll}} = N \bar{v}_{12} \sigma, \quad (4)$$

where $\bar{v}_{12} = [(8/\pi)RT(1/M_1 + 1/M_2)]^{1/2}$ is the mean relative velocity between cadmium and gas atoms, and σ is the alignment depolarization collision cross section. The slope of the width versus density curve yields the desired cross section.

The theory of Byron and Foley⁵ is used here to calculate theoretical cross sections. The theory of Omont⁶ is more explicit in that it treats both "alignment" and "orientation" cross sections, but the difference between cross sections predicted by the two theories is less than the expected uncertainties. The Byron-Foley theory assumes dipole-dipole interatomic potentials, collision times short compared to radiative decay times, and makes use of second-order sums over intermediate states to predict foreign gas broadening.

⁵ F. W. Byron, Jr., and H. M. Foley, Phys. Rev. **134**, A625 (1964).

⁶ A. Omont, J. Phys. Radium **26**, 26 (1965).

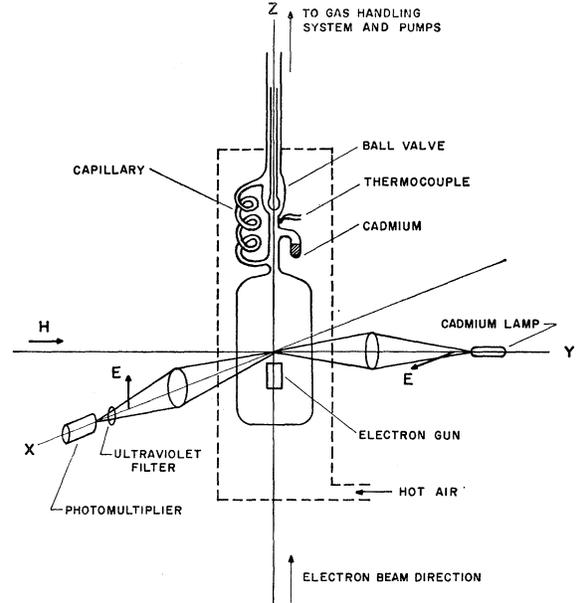


FIG. 1. Schematic diagram of apparatus.

Their Eq. 17 applies to these experiments:

$$\sigma = 1.70 \left\{ \frac{e^4 a_0^4}{\langle \Delta E \rangle_{\text{av}} \hbar \bar{v}_{12}} \left[\frac{n^{*2} (n^* + \frac{1}{2}) (n^* + 1)}{Z^{*2}} \right]_{\text{coll}} \times \left[\frac{n^{*2} (n^* + \frac{1}{2}) (n^* + 1)}{Z^{*2}} \right]_{\text{Cd}} \right\}^{2/5}. \quad (5)$$

Here e is the electron charge, a_0 is the Bohr radius, \hbar is Planck's constant, \bar{v}_{12} is the relative velocity of colliding atoms, n^* and Z^* are Slater's principle quantum number and effective charge, and the subscript "coll" refers to the colliding rare-gas atoms. $\langle \Delta E \rangle_{\text{av}}$ is an average excitation energy for the rare gas and cadmium atoms determined in the way described in Ref. 5.

III. EXPERIMENTAL

The experimental apparatus is represented in Fig. 1. Helmholtz coils of 1-m diameter were used to reduce the earth's magnetic field at the origin to less than $\frac{1}{4}$ mG. The scanning field H was produced with two 30-cm diam coils concentric with the y axis and was calibrated with modulated light double resonance at a known frequency. Variation of H over a 2-cm cube at the origin was less than $\frac{1}{2}$ mG (about 1/60 of the depolarization line width).

The quartz cadmium-vapor cell was contained in an oven (represented by dashed line in Fig. 1) heated with a flow of hot air from remote heating coils. Observations were made at about 200°C, giving a cadmium vapor pressure of about 3.5×10^{-4} Torr.

Gas densities were obtained in the following way. Gas pressure was measured with a Pirani gauge, located in

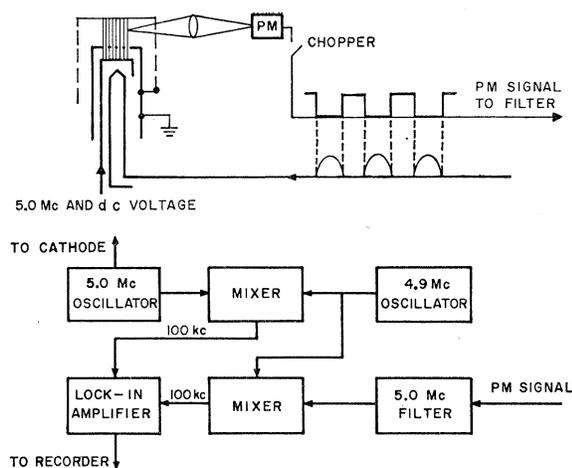


FIG. 2. Schematic diagram of electron gun and 5-Mc modulation system.

the gas-handling system and calibrated with a McLeod gauge for each run. Cell temperature was measured with a thermocouple attached to the cell. A small gas leak (closed ground glass ball valve) between gas handling system and cell allowed equalization of pressures in the two regions while allowing gas in the cell to reach cell temperature. As a check on these assumptions, an additional leak was installed which consisted of a 30-cm long small-diam capillary. No change in measured line widths was observed, indicating that the assumptions were valid. Densities were calculated from the measured pressures and temperatures using the ideal gas equation. Uncertainties in densities found in this way are believed to be about 10%.

In the experiments with electron excitation, gas in the observation region was heated by the cathode. This resulted in a systematic shift of a few percent in calculated densities and cross sections. Approximate corrections were obtained by equating cross sections for the electron excitation Hanle effect (cathode on) to those for the resonance fluorescence Hanle effect (cathode off). The percent corrections necessary for this were then applied to the cross sections for modulated-light double resonance (cathode on). The corrections for this gas heating effect were small enough to be partially obscured by the 10% uncertainties in the measurement of densities discussed above, and were negligible for the lighter rare gases (He and Ne) and approximately 15% for the heavier gases (Ar, Kr, and Xe).

Electron excitation was accomplished with a 5-mm diam beam of electrons obtained from the cylindrical electron gun represented in Fig. 2. The gun was a diode constructed of nonmagnetic materials with a 2-mm cathode-anode spacing. The cathode, to which were applied the dc and ac accelerating voltages, was entirely surrounded by the grounded anode. A mesh-covered 5-mm diam hole in the anode transmitted the beam into the field-free observation region which extended about

1 cm above the anode. Beam current was about $200 \mu\text{A}$ at 6 V. Beam divergence was not more than a few degrees, and beam deflection was negligible for the small scanning magnetic fields used.

The magnetic field from the cathode filament current was large enough to distort the observed line contours. To eliminate this effect, the filament current was $\frac{1}{2}$ -wave rectified and the photomultiplier signal was observed only during the off $\frac{1}{2}$ -cycle as indicated in Fig. 2. Cathode heat capacity was large enough so that this did not result in time variation of electron emission.

Excitation (dc) for the resonance fluorescence Hanle effect was produced by absorption of 3261 \AA light incident from a cadmium electrodeless discharge lamp. This incident light was transmitted through a polarizer with E vector parallel to X , and the fluorescent 3261 \AA light was transmitted through a polarizer with E vector parallel to Z , as indicated in Fig. 1. For the electron-excitation Hanle effect, a dc electron beam was used with electron energy slightly above excitation threshold; the fluorescence was detected as above. The detection system had a 1-sec time constant.

The modulated electron beam required for modulated-light double resonance was produced by application to the cathode of superimposed dc and ac voltages. The dc voltage was chosen to give electrons with energy just above excitation threshold; the addition of approximately $\frac{1}{2}$ -V ac then modulated the electron energy through threshold. The modulation frequency was 5.0 Mc/sec, high enough to completely resolve the two pressure-broadened peaks found for plus and minus H . The phase-sensitive 5-Mc detection system is shown in Fig. 2. A 1-sec time constant was used. Phase of detection was adjusted to detect the $\cos\omega t$ term of Eq. (2), yielding the Lorentzian line shape.

IV. RESULTS

Measurements were obtained of the broadening produced by the gases He, Ne, Ar, Kr, and Xe at pressures from zero up to that sufficient to give widths several times greater than the natural width. The tracings of original data for Xe in Fig. 3 are typical of line contours

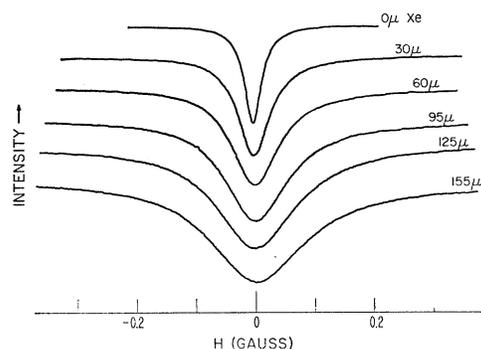


FIG. 3. Tracings of original line contours for resonance fluorescence Hanle effect; broadening by xenon.

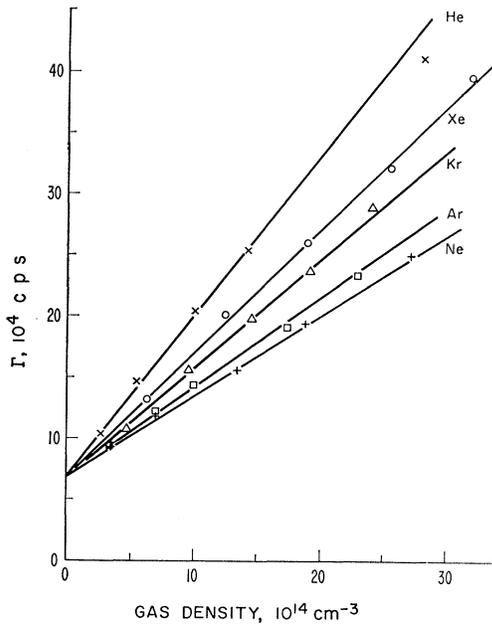


FIG. 4. Linewidth versus density for resonance fluorescence Hanle effect.

obtained for the Hanle effect with resonance fluorescence. The line contours were Lorentzian to within about 2%. The signal-to-noise ratio obtained for electron excitation was approximately the same as that in Fig. 3 for low gas pressures, but deteriorated to about 10:1 for the highest pressures used possibly owing to scattering of the electron beam.

Values of Γ in cycles per second were determined with Eq. (3) and are plotted versus density in Fig. 4 for the

TABLE I. Comparison of depolarization cross sections σ in units of 10^{-16} cm².^a

| | σ_{exp} | | $\sigma_{\text{th}}^{\text{b}}$ |
|----|-----------------------|-----------------|---------------------------------|
| | Hanle effect | Modulated light | |
| He | 51 | 52 | 28 |
| Ne | 53 | 52 | 38 |
| Ar | 77 | 86 | 73 |
| Kr | 121 | 116 | 99 |
| Xe | 156 | 174 | 121 |

^a Estimated uncertainties for all values are $\pm 15\%$.

^b σ_{th} are calculated according to Byron and Foley (see Ref. 5).

resonance fluorescence Hanle effect. The data fit straight lines to within the estimated error of 15%. Intercepts on the ordinate correspond to the known natural width of the 3P_1 level (7×10^4 cps) slightly narrowed by multiple scattering.

The alignment depolarization collision cross sections were obtained from slopes of the lines using Eq. (4) and are listed in Table I. In the first column are those measured with the Hanle effect. Results for resonance fluorescence and electron excitation coincide because of corrections for gas heating during electron excitation, as discussed above. Results for modulated-light double resonance are given in the second column. Theoretical cross sections from the theory of Byron and Foley⁵ (Eq. 5) are listed in column 3. The 15% uncertainties for the theoretical values correspond to the estimated error quoted in Ref. 5; the 15% experimental error is due mainly to uncertainties in determination of gas densities and temperatures.

The two experimental cross sections for a given gas, measured with the Hanle effect and with modulated-light double resonance, are in good agreement, indicating that the same collision cross sections apply for the cases of degenerate and resolved levels. The two values differ by an average of about 5%; however, the absolute values must be assigned the larger uncertainty of about 15% because of the uncertainties in the determination of absolute gas densities.

All experimental cross sections are larger than the theoretical ones, but the differences are within the combined experimental and theoretical estimated uncertainties for all gases except helium. For these gases, the average difference is about 20%. For helium, the experimental cross section is nearly twice as large as the theoretical value.

The Byron-Foley theory for foreign gas broadening has been compared with experiment in one other case, the lowest 3P_1 level of mercury.⁷ There, also, all experimental cross sections were larger than the theoretical ones, the average difference being about 15%. Unlike the present case for cadmium, for mercury the experimental and theoretical cross sections for helium were in satisfactory agreement.

⁷ C. A. Piketty-Rives, F. Grossetête, and J. Brosset, *Compt. Rend.* **258**, 1189 (1964).