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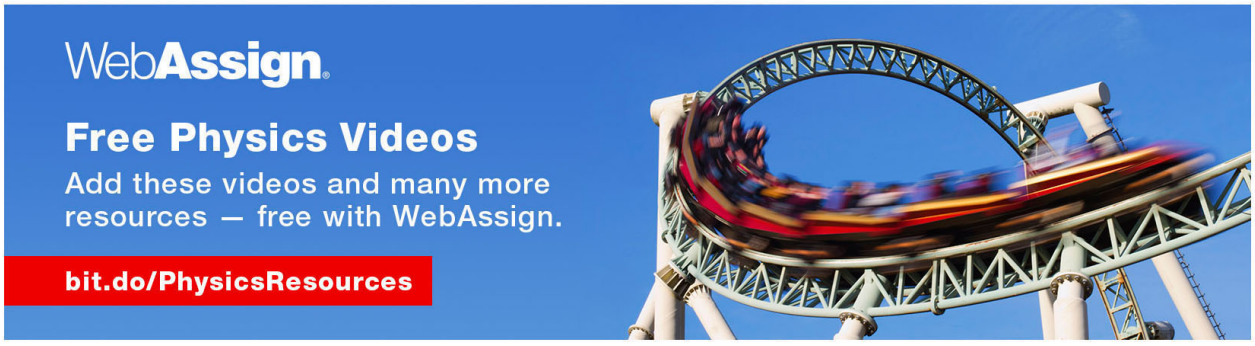
Citation: American Journal of Physics **45**, 38 (1977); doi: 10.1119/1.10902
View online: http://dx.doi.org/10.1119/1.10902
View Table of Contents: http://scitation.aip.org/content/aapt/journal/ajp/45/1?ver=pdfcov
Published by the American Association of Physics Teachers



Hyperfine structure in the triplet states of cadmium

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(Received 6 February 1976; revised 12 May 1976)

An experiment is described which investigates the hyperfine structure of the 6^3S_1 and $5^3P_{0,1,2}$ excited levels of cadmium. The nuclear spin of the odd isotopes and the hyperfine constants for the levels are derived.

I. INTRODUCTION

Atomic physics provides a wide range of examples from which a student may gain familiarity with the concepts and methods of quantum mechanics, and many of these examples can be illustrated by spectroscopic experiments requiring only modest experimental equipment. In this paper we describe an experiment of the project type which is suitable for a student with a basic understanding of atomic structure and angular momentum. The analysis of the results requires only an understanding of the Landé interval rule applied to hyperfine structure, whereby the hyperfine energies are given by

$$\Delta E = (A/2)[F(F+1) - I(I+1) - J(J+1)]. \quad (1)$$

Here $F\hbar$ is the angular momentum of the hyperfine level and is the resultant of the nuclear spin $I\hbar$ and the total electronic angular momentum $J\hbar$.

The hyperfine structure is large in many of the lines in the spectra of the alkaline earth elements.[1,2] Since the ground state configuration is of the type $(ns)^2$ and the excited configurations of the neutral atoms are $(nsn'l)$, the hyperfine interactions of the ns electron are present in all configurations, and in the triplet levels where the spins of the two electrons are coupled to the orbital angular momentum, the hyperfine structure exhibits this interaction. The singlet levels, for which the spins are antiparallel, have no hyperfine structure in pure Russell–Saunders coupling. Cadmium provides an excellent example in that the two odd isotopes ^{111}Cd and ^{113}Cd, which are present in about equal concentrations and together make up 25% of the natural mixture, have identical spins and closely equal nuclear g factors.

Three lines, λ-4678, 4800, and 5086 Å, arise from transitions between the triplet levels of the $(5s\ 6s)$ and $(5s\ 5p)$ configurations, and a high-resolution study of their hyperfine structure can lead to determination of the nuclear spin of the odd isotopes and the hyperfine constants A for the levels involved.

II. EXPERIMENT

A. Apparatus

The experimental arrangement is indicated in Fig. 1 and consists of a conventional Fabry–Perot scanning system.[3] The etalon is enclosed in a pressure vessel with windows of reasonable optical quality, and the fringe system is focused on the entrance slit of a medium dispersion spectrograph. The entrance slit is replaced by a "pinhole" which samples a small fraction of an order at the center of the pattern, and the dispersion required from the spectrograph is determined by the necessity to separate the pinhole images of the three spectral lines in the focal plane of the spectrograph. A Hilger constant deviation spectroscope is satisfactory, and the eyepiece for viewing the final image is replaced by an RCA IP28 photomultiplier. To obtain operation over a wide range of intensity, the photomultiplier output is fed to a Keithley picoammeter 414A with a 1-V full-scale output suitable for an inexpensive x-t chart recorder.

The pressure in the etalon chamber is scanned linearly with time using a flow system based on the Platon Gapmeter and Flowstat MN control valve, with the flow being highly linear for a pressure difference greater than 5 psi. A needle valve provides control of the pump-out rate, and the experimental results are taken when the chamber is being filled with carbon dioxide, with a 1-atm pressure difference providing sufficient orders of interference.

Two sets of etalon plates are used in the experiment. These are of 1-in. diameter and are coated for approximately 90% reflectivity in the region 4600–5100 Å. The etalon spacers used are 3.10 and 7.08 mm, respectively. An Osram cadmium or mercury/cadmium lamp run from a mains autotransformer provides a convenient source of cadmium lines.

The experimental results essentially consist of six traces, since the three lines are each examined with the two etalons. Approximately 5–6 orders are recorded in each case, and the linearity of the pressure scanning system can be tested by using the larger spacer. Several experimental parameters affect the ultimate resolution that can be obtained with this system, and the best combination of conditions should be sought for each combination of line and spacer.

(1) The effect of increasing the discharge current is predominantly to increase the population of the $5^3P_{2,1,0}$ levels which are in equilibrium with each other due to collisional transfer[4] and have a high population due to trapping of the intercombination line 5^3P_1–5^3S_0. Thus self-absorption becomes evident in the central, even isotope, peak as is seen in trace (b) of Fig. 2 for 4678 Å. This effect masks the marginal changes in Doppler- or pressure-broadened widths.

(2) The finite diameter of the entrance pinhole of the spectrometer introduces a smearing of the spectral profile. Increasing the diameter increases the magnitude of the signal and typically up to about half the full half-width of the peak may be sampled without degrading the resolution significantly.

(3) The most significant parameter is the area of the etalon plates used. All plates show some imperfections which are often in the form of a systematic variation from center to edge with some additional random variation. The plates used to obtain the traces of Fig. 2 were approximately flat to $\lambda/50$ overall, but the imperfection contribution to the peak width could be reduced significantly by stopping down

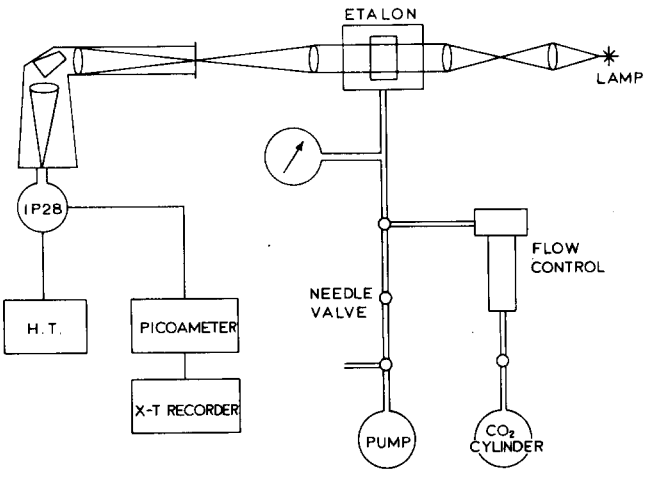

Fig. 1. Experimental arrangement.

the etalon aperture. The attendant loss of intensity is significant, and a compromise between resolution and signal/noise must be made. Thus trace (a) of Fig. 2 for 4678 Å was obtained by using only the central 5 mm of the plates at close to the minimum lamp voltage. The choice of reflectivity for the plate coatings is decided on the basis that the instrumental width of the peaks should be just greater than the imperfection contribution. Further increase in reflectivity leads to reduction in the peak intensity, given by $T^2/(T+A)^2$, where T and A are the fractional transmission and absorption of the coatings, respectively (see Ref. 1, p. 84) while the resolution is limited by the imperfections.

The traces (b) represent the final resolution that may be obtained for the three lines.

B. Results and analysis

Figure 2 contains the term analysis for the odd isotope components of the three lines. The intense central peak of the experimental traces is due in all cases to the ~75% concentration of even isotopes. The analysis proceeds as follows. Since 4678 Å ($^3S_1 \rightarrow {}^3P_0$) has zero electronic angular momentum in the lower level, the hyperfine structure must be due to the upper level, $^3S_1$, alone. The structure due to the odd isotopes consists of two components only with an intensity ratio of approximately 2:1, so that we immediately determine the nuclear spin to be $\hbar/2$ and the F values of the $^3S_1$ level to be 3/2 and 1/2. The interval between the two components is, from the Landé interval rule, $(3/2)A(6^3S_1)$. From the direction of scan we see that the $F = 3/2$ level lies lowest, so that the nuclear g factor is negative.

Proceeding to the 4800-Å line, the trace with the 3-mm etalon indicates that the hyperfine structure lies between the two weak components approximately equally spaced from the even isotope peak. The increased resolution obtained with the 7-mm etalon resolves the inner peak on the high-frequency side of the even isotope component. The intensities of the hyperfine components conform with those obtained from the standard tables,[2] and measurements of the intervals combined with the $A(6^3S_1)$ value already determined yield $A(5^3P_1)$.

The line 5086 Å exhibits the least resolved hyperfine structure, and the interval between the odd isotope components yields a further measurement of $A(6^3S_1)$. From a detailed analysis of the other two lines it appears that the center of gravity of the odd isotope patterns is shifted by -10 ± 6 mK with respect to the even isotope peak, and from the interval between the even isotope component and the well-resolved component due to the odd isotopes we obtain $(3/2)A(5^3P_2) + (1/2)A(6^3S_1)$ after allowance for the isotope shift.

Table I. Hyperfine constants for the cadmium (5s 6s) and (5s 5s) configurations.

Level	A (mK)	$\Delta\nu_{hfs}$ (MHz)
6^3S_1	− 261 ± 3	11 745 ± 300
5^3P_1	− 146 ± 6	4 380 ± 180
5^3P_2	− 117 ± 8	8 775 ± 700

C. Results and interpretation

The values of the hyperfine constants and the energy intervals between the two hyperfine components of the levels as obtained from this experiment are given in Table I. These values agree well with the weighted means for the odd isotopes of the very accurately known constants for the 6^3P_1, and 6^3P_2 levels.[5,6] On the basis of the vector model of the atom these constants can be interpreted in terms of the hyperfine interactions of the two valence electrons (Ref. 1, p. 143). For good Russell–Saunders coupling, with the p-electron contribution neglected,

$$A(6^3S_1) = (1/2)(a_{5s} + a_{6s}) \tag{2}$$

and

$$A(^3P_2) = A(^3P_1) = (1/4)a_{5s}. \tag{3}$$

The inequality of the A values for the $^3P_1$ and $^3P_2$ levels immediately indicates the breakdown of strict L-S coupling. This is well known from the deviations from the Landé interval rule shown by the $^3P_{0,1,2}$ levels and the existence of the strong intercombination line 3261 Å (5^3P_1

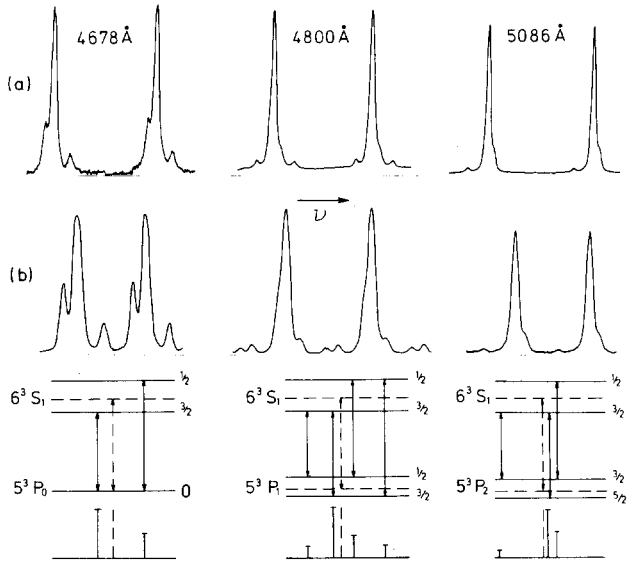

Fig. 2. Hyperfine structure of the lines λ = 4678, 4800, and 5086 Å of cadmium recorded with etalon spacers 3.10 mm [traces (a)], and 7.08 mm [traces (b)]. Pressure increases to the left.

$\rightarrow 5^1S_0$), indicating that the $^1P_1$ and $^3P_1$ levels of the ($5s$ $5p$) configuration are mixed. Complete expressions to replace (3) are given by Eqs. (21) and (22) of Ref. 6.

From the $A(^3P_2)$ we obtain

$$a_{5s} = 13.2 \pm 0.7 \times 10^3 \text{ MHz},$$

and hence from (2)

$$a_{6s} = 1.6 \pm 0.8 \times 10^3 \text{ MHz}.$$

III. DISCUSSION

This experiment, which requires only modest experimental skill, provides a real insight into the atomic structure of cadmium, including hyperfine structure.

ACKNOWLEDGMENTS

We wish to thank the many colleagues and students who have contributed to the formulation of this experiment. The dielectric coatings for the etalons were generously prepared by Dr. D. N. Stacey and Mr. C. Goodwin of the Clarendon Laboratory, Oxford.

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–New York Times, Wednesday, 11 August 1976.