POLARIZATION OF RESONANCE RADIATION AND HYPERFINE STRUCTURE: THE CADMIUM RESONANCE LINES

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Abstract

The cadmium resonance lines λλ 2288 and 3261A excited by unpolarized radiation in a magnetic field parallel to the exciting light beam are found to be 76.3 percent and 86–87 percent polarized respectively. From spectroscopic evidence Schüler has assigned nuclear moments of 0 and 3/2 to the even and odd isotopes of Cd. Separations in 2288 are small compared to Doppler breadth, while in 3261 the strong component of the 3/2 isotope pattern merges with the 0 isotope line. If we suppose that the introduction of spin does not change the net transition probabilities between the gross levels concerned these polarization values both yield 2.53 for the ratio of abundance of even and odd isotopes. A recent calculation of C. G. Mitchell leads to other results, but is based on the apparently incompatible assumptions that intensities in the source are proportional to the isotope abundance but in absorption are determined by assigning equal weights to Zeeman levels making absorption by the spin isotope twice that by the non-spin isotope for equal abundance and uniform spectral distribution, conflicting with Kirchhoff's law.

THE attempt to account for hyperfine structure of spectral lines by attributing a magnetic moment to the atomic nucleus[1,2] which may have different values for the several isotopes of a single element[3,4] has been attended with a considerable measure of success at least as respects the qualitative features of such spectra.[5] As Goudsmit,[6] Breit,[7] and also Racah[8] have shown the quantitative agreement, at least with the heavy elements, is very bad. However it appears fairly certain that the introduction of a "fine" quantum number as originally suggested by Ruark and Chenault,[9] probably associated in some way with the nucleus, is necessary in order to account for the phenomena in question. Whether interval and intensity relations of the same type which prevail in gross multiplets also obtain for hyperfine multiplets is of course a question of interest.

Where hyperfine structures are on a sufficiently large scale so that the various components of a hyperfine pattern may be separately resolved intensities may be compared directly,[5] although the comparison of intensities

[1] Pauli, Naturwiss. **12,** 741 (1924).
[2] Back and Goudsmit, Zeits. f. Physik **43,** 321 (1927).
[3] Schüler and Brück, Zeits. f. Physik **56,** 291 (1929).
[4] Schüler and Keyston, Zeits. f. Physik **67,** 433 (1931).
[5] Kronig and Frisch, Phys. Zeits. **32,** 457 (1931).
[6] Goudsmit, Phys. Rev. **37,** 663 (1931).
[7] Breit, Phys. Rev. **38,** 463 (1931).
[8] Racah, Zeits. f. Physik **71,** 431 (1931).
[9] Ruark and Chenault, Phil. Mag. **50,** 937 (1925).

when resolution is effected by interference spectroscopes is not a simple matter.[10] In many cases however the separation of the hyperfine levels comprising one or both of the gross levels concerned in the emission of a given line is on a scale so small that complete resolution is impossible because of limitations imposed by the Doppler effect. Schüler has indeed succeeded in devising a source[11] which greatly reduces Doppler broadening of lines and has utilized it with noteworthy success.[12] However there is a point beyond which it is impossible to go even with Schüler's elegant technique and in such cases indirect evidence is the best that we can hope for. As one of us[13] has pointed out, the polarization of resonance radiation affords such evidence as it depends upon the intensity relations within the hyperfine multiplet.

Mitchell[14] has computed the polarization to be expected for the λ3261A cadmium line on the basis of Schüler's[15] ideas regarding the assignment of

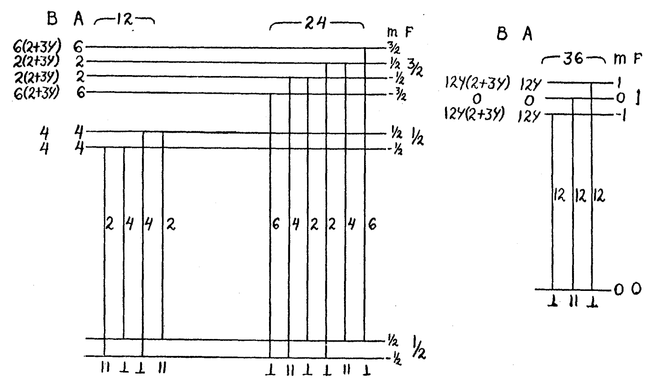

Fig. 1. Transition probabilities and relative populations for the levels 6^1P_1, 6^3P_1, and 5^1S_0 of the even and odd isotopes of Cd.

nuclear moments and using Schüler's[15] estimate of the relative abundance of odd and even isotopes, and has compared his results with Soleillet's[16] observations. However Mitchell has assumed as Schüler does that the total intensity of radiation from odd and even isotopes is proportional to their relative abundance, but has based his transition intensities governing absorption upon the assumption of equal weights of Zeeman levels, applying this assumption to both isotopes. This results in giving the assemblage of fine levels making up the 6^3P_1 gross level of the odd isotopes twice the weight of the same level of the even isotopes. This procedure is evidently not admissable, as it leads to conflict with Kirchhoff's law.

We have accordingly recalculated the results assigning to the levels such

[10] Hansen, Ann. d. Physik **78**, 558 (1925).
[11] Schüler, Zeits. f. Physik **35**, 323 (1926).
[12] Schüler and Keyston, Zeits. f. Physik **71**, 413 (1931).
[13] Ellett, Phys. Rev. **35**, 588 (1930).
[14] Mitchell, Phys. Rev. **38**, 473 (1931).
[15] Schüler and Keyston, Zeits. f. Physik **67**, 433 (1931).
[16] Soleillet, Comptes Rendus **185**, 198 (1927); **187**, 212 (1928).

weights that both emission and absorption shall be proportional to the relative abundance of the two kinds of isotopes. Fig. 1 shows the Zeeman levels involved in the emission and absorption of $\lambda 3261$ for both even and odd isotopes. γ is the ratio of abundance of even to odd isotopes. The same diagram will serve for $\lambda 2288$A ($6^1P_1-5^1S_0$), since the J values of the upper and lower levels are the same here as for $\lambda 3261$A ($6^3P_1-5^1S_0$).

The polarization of $\lambda 2288$A may be calculated on the assumption of constant intensity of exciting light across the entire pattern, as we may safely infer from the observations of Schrammen[17] and the narrowness of the cadmium red line $\lambda 6438.47$A ($7^1D_2-6^1P_1$). For nonpolarized exciting radiation this gives

$$P = \frac{3 + 9\gamma}{11 + 9\gamma} 100 \qquad (1)$$

a function of γ.

$\lambda 3261$A is double, which is accounted for by supposing that the line due to the even (nonspin) isotopes coincides with the stronger component of the pattern due to the odd (spin) isotopes. The intensity of the two observed components will then be proportional to 1 and $2+3\gamma$. Using these as the intensities in the source we obtain, again for the case of nonpolarized existing light

$$P = \frac{27\gamma^2 + 27\gamma + 22}{27\gamma^2 + 39\gamma + 34} 100. \qquad (2)$$

Experimental

Soleillet[16] has measured the polarization of $\lambda 3261$ excited by nonpolarized exciting light and obtained a value of 85 percent. Using a source of the type described previously[18] we have obtained values ranging from 85 to 87 percent as long as the vapor pressure of cadmium in the source was kept fairly low, that is, low enough so that the discharge appeared a light blue in the vicinity of the side tube from which the cadmium diffused into the main discharge. Under these circumstances the cadmium red line and Hα appeared about equally intense, and the intensity of $\lambda 3261$A radiation was such that it was feasible to work with a monochromator of large aperture between source and resonance bulb. However as higher values of the polarization appeared to correlate with low cadmium pressure in the source we dispensed with the monochromator in an effort to obtain sufficient intensity of resonance with the corresponding low intensities of cadmium radiation from the source. This was possible by using an absorption cell of potassium hydrogen phthalate between source and resonance lamp to cut out $\lambda 2288$, the other resonance line, and a cell containing bromine vapor to eliminate the strong lines in the violet, which otherwise gave rise to troublesome scattered light. With this arrangement the source could be operated with so little cadmium that it appeared not a true blue but rather milky or almost colorless even at the

[17] Schrammen, Ann. d. Physik **83,** 1161 (1927).
[18] Ellett, J.O.S.A. and R.S.I. **10,** 427 (1925).

junction of the side tube from which the cadmium was introduced. The cadmium red line was very faint compared to $H\alpha$. Using this source we obtained a value of 86–87 percent for the polarization. We think that the effect of self reversal in this source is negligible.

During these measurements the resonance lamp was maintained at a temperature of 146°C in order to eliminate any depolarization due to secondary resonance. Upon increasing the temperature, the decrease in polarization first became perceptible at 168°C where it was 85 instead of 86–87 percent. As this increase of temperature corresponds to a fivefold[19] increase of vapor pressure it is evident that at the lower temperature the depolarizing effect of secondary resonance is negligible.

For excitation of the λ2288A line the monochromator was necessary, as there was no other way to eliminate λ3261. The polarization of this line, 76.3 ± 0.3 percent, appears not to depend upon the condition of the source, which is to be expected if the fine structure is very narrow, that is narrow enough that the lines of the hyperfine multiplet effectively coincide so that the intensity of exciting light is the same for all of them by virtue of their proximity. The resonance bulb was operated at 98–105°C, again safely below the temperature at which depolarization became apparent. That a lower temperature could be used for λ2288A is due to the fact that it is much more intense than the intercombination line λ3261A.

The observations were not made in zero magnetic field but in a field of 40 gauss parallel to the exciting light beam. Observation showed that the polarization did not depend upon the field for values from 20 gauss to 400 gauss and such an applied field reduces the chance of error due to stray magnetic fields. This is especially important in the case of λ3261A as the mean life of the upper state is about 2.5×10^{-6} seconds and the polarization consequently perceptibly reduced by a stray field of a few thousandths of a gauss along the line of observation.

Measurements of polarization were made photographically by the Cornu method, with two quartz Wollaston prisms, as in the work of Olson[20] on λ2537A of Hg.

Discussion

Inserting the observed value of the polarization of the λ2288A line, 76.3 ± 0.3 percent, in Eq. (1) above we find that γ, the ratio of abundance of even and odd isotopes, is 2.53 ± 0.05 .This value inserted in Eq. (2) gives 86.1 ± 0.2 percent for the polarization of the λ3261A line agreeing with observation. Schüler[13] from observation of relative intensities in the hyperfine structure of λ4678A ($6^3S_1 - 6^3P_0$) obtained $\gamma = 3.34$ so that the agreement of our result and his is not good. The effect of small changes in γ upon the computed polarization of λλ2288 and 3261A lines may be seen in Table I. Schüler's value of γ gives

[19] The vapor pressure was calculated from the formula given in I.C.T., for cadmium in the region of 150°C.

[20] Olson, Phys. Rev. **32**, 443 (1928).

polarizations of 80 percent and 89 percent for the λλ2288 and 3261A lines respectively, and these values are well beyond the limits of error in measurement of polarization. Our computed value depends upon the assumption of Russell-Saunders type coupling between J, F, I through the use of intensity relations appropriate to such coupling, and at the same time the strongest

TABLE I.

	P (2288) calc.	P (2288) obs.	P (3261) calc.	P (3261) obs.
2.40	75.5		85.6	
2.50	76.1		86.0	
2.53	76.3	76.3	86.1	86–87
2.60	76.7		86.4	
3.34	80.5		89.	

evidence for the accuracy of Schüler's intensity measurements is the fact that his results agree with the intensity scheme appropriate to this type of coupling, so that the most obvious source of the disparity, namely that the intensity relations which we have used are not appropriate, seems to be ruled out. As one of us has pointed out previously,[13,5] it is difficult to say how the polarization should be computed when the separation of levels in a hyperfine multiplet becomes less than the breadth of the line due to the finite life of stationary states, and we cannot be certain that this situation does not exist in the λ2288A hyperfine structure. This however does not affect the situation with respect to λ3261A as the levels here are widely separated.