Nuclear Magnetic Moments from the Polarization of Resonance Radiation

Sodium, $3^2S_{1/2}-3^2P_{3/2,\ 1/2}$

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The polarization of sodium D line resonance radiation excited by plane polarized light in a magnetic field parallel to the electric vector of the exciting light increases from 16.5 percent in zero field to almost 50 percent in a field of 300 gauss as a consequence of the Paschen-Back effect of the hyperfine structure. The experimental results are well fitted by a curve calculated with $A(3^2P_{3/2})=7.45\times10^{-4}$ cm^{-1} and $\tau(3^2P_{3/2})=1.64\times10^{-8}$ sec. These results are for a nuclear moment of $3/2(h/2\pi)$ which was at first thought to give too low zero field polarization (15.27 percent). The higher polarization is the effect of proximity of hyperfine levels in $3^2P_{3/2}$.

IT has long been known that a magnetic field applied parallel to the electric vector of plane polarized exciting light would increase the polarization of sodium D line resonance radiation. This change in polarization, due to the Paschen-Back effect of the hyperfine multiplet, is discussed in detail in the following paper of Ellett and Heydenburg on the λ3303A resonance radiation of sodium. The writer has calculated the Paschen-Back effect of the hyperfine multiplet which constitutes any $^2S_{1/2}-{}^2P_{3/2}$ line for a nuclear moment of one (in units of $h/2\pi$) but as it is now evident, from atomic beam measurements,[1] from intensities in the hyperfine structure pattern[2] of the D lines, and from alternation of intensities in the band spectrum[3] that the nuclear moment of sodium is 3/2 the discussion of results will be based on the Paschen-Back calculations for this value of the nuclear moment, kindly placed at the writer's disposal by the authors of the following paper.

EXPERIMENTAL PROCEDURE AND RESULTS

The resonance radiation was excited by light from a hydrogen-sodium discharge tube. The temperature of that portion of the tube from which the light was taken was kept just below the softening point of the glass (softening point of Pyrex is between 600°C and 700°C). Pure metallic sodium was distilled into the discharge from a side tube. The rate of distillation was so controlled that the discharge was faintly yellow just at the junction of the side tube and main discharge tube. The color of the rest of the discharge was the characteristic red of the hydrogen spectrum.

Any increase in the vapor pressure of sodium in the discharge would increase the intensity of resonance radiation up to a certain pressure, but ultimately would cause self-reversal in the source. This would decrease the polarization by decreasing the intensity ratio of D_2/D_1, since the effect of self-reversal on two lines of unequal intensity is greater for the line of greater intensity.

The exciting radiation was brought to a focus at the center of the resonance bulb. An Ahrens prism was placed between the lenses of the condenser to plane polarize the incident beam. The depth of focus of the lens system was sufficiently great that the beam of incident radiation showed no divergence over the region covered by the slit of the polariscope.

The resonance bulb was made of thin-walled Pyrex. Tubing of 1–1½ inches in diameter was sealed off and blown out to a spherical bulb about two inches in diameter. In order to reduce reflected light the walls of the bulb were flattened to a square. A side tube containing a small quantity of pure sodium was sealed to the bottom of the resonance bulb. The bulb was connected through a liquid air trap to a mercury diffusion pump run continuously.

After the system had been thoroughly evacuated sodium was distilled into the resonance lamp until a thin film of metal was formed over the top of the bulb.

The polarization was measured visually by the Cornu method. The Cornu polariscope consisted of a slit, a Wollaston double image prism,

[1] Rabi and Cohen, Phys. Rev. **43**, 582 (1933).
[2] C. M. Van Atta and L. P. Granath, Phys. Rev. **44**, 60 (1933); **44**, 935 (1933).
[3] J. Joffe, Phys. Rev. **45**, 468 (1934).

and an analyzing Nicol mounted in brass telescope tubing. The slit was carefully machined and adjusted so that the sides were parallel and about 4 mm apart. The distance between slit and Wollaston was adjusted until the two fields were separated by a very narrow black line when illuminated by a sodium light. If this adjustment is carefully made the black line disappears when the analyzing Nicol is rotated to the point of equal intensity of the two fields of vision. The vernier on the Nicol could be read accurately to 50 minutes of arc.

The slit of the polariscope was kept two millimeters from the walls of the resonance bulb. Stray light was either eliminated by slits or trapped. All slits were painted black with a lampblack-shellac solution.

The resonance lamp was heated to 115–120°C by an air stream from a non-magnetically wound electric heater placed three feet below the lamp. Experiments have shown that there is no variation of the zero field polarization for a temperature range of 85–120°C and that no appreciable depolarization sets in until the temperature of the resonance bulb is raised to 135°C.

The zero field polarization was measured by three observers, each making a large number of settings of the analyzing Nicol. Before measuring the polarization in any magnetic field readings were taken on the zero field polarization to insure that there was no depolarization from any cause.

The results are given in Table I. The probable errors were computed by the method of least squares, at least 16 observations being made in each field.

Discussion

Fig. 1 shows an attempt to fit the experimental results by means of the curve calculated for $I=1$.

TABLE I. *Percent polarization of sodium resonance radiation in various magnetic fields.*

H	$P_{D_1+D_2}$	Error
0	16.48	0.38
10	16.26	0.30
20	21.37	0.38
50	34.54	0.33
70	38.86	0.33
90	43.0	
170	45.7	
315	46.25	

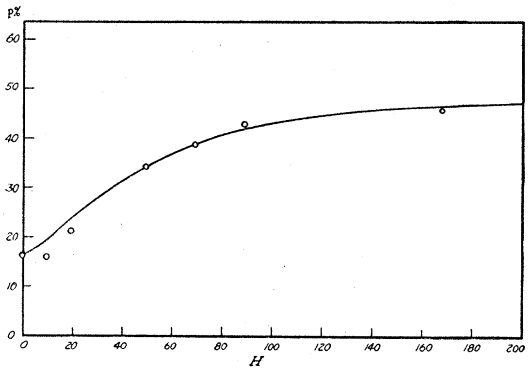

FIG. 1. Polarization as a function of magnetic field. Circles represent observations. Heavy curve computed with $I=1$, $A(3^2P_{3/2})=1.2\times10^{-3}$ cm^{-1}.

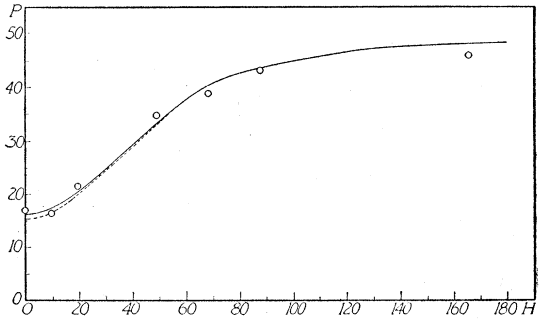

FIG. 2. Polarization as a function of magnetic field. Circles represent observations. Heavy curve computed with $I=3/2$, $A(3^2P_{3/2})=7.45\times10^{-4}$ cm^{-1}, $\tau=1.64\times10^{-8}$ sec. Broken curve computed neglecting effect of proximity of hyperfine levels.

The best fit is secured for A, the hyperfine multiplet separation constant, equal to 0.0012 cm^{-1}, but there is a significant deviation in the region of small fields, the curve at ten and twenty gauss coming well above the observed values. This calculated curve does not take into account the effect of finite breadth of levels,[4] and to do so will make the agreement even worse, as this effect operates to raise the polarization in weak fields so that the apparent agreement in zero field will be destroyed and the gap between calculated and observed values at ten and twenty gauss increased.

With a nuclear moment of 3/2 the situation is quite different. The calculation neglecting the

[4] G. Breit, Rev. Mod. Phys. 5, 117 (1933).

effect of finite breadth of levels gives too low a zero field polarization (15.27 percent), but on taking into account the finite breadth of levels using $\tau=1.64\times10^{-8}$ sec. the zero field polarization comes out 16.25 percent in fair agreement with the observed value. The heavy curve in Fig. 2 is computed for a nuclear moment of 3/2 with $A=7.45\times10^{-4}$ cm^{-1}, $\tau=1.64\times10^{-8}$ sec.[5]

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

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The polarization of sodium $3^2S_{1/2}-4^2P_{1/2,\ 3/2}$ (λ3303A) resonance radiation excited by unpolarized light has been measured as a function of the intensity of a magnetic field applied parallel to the direction of the incident light beam. Detailed Paschen-Back effect calculations have been carried out for the hyperfine multiplet which constitutes a $^2S_{1/2}-^2P_{3/2}$ transition for a nuclear moment of $3/2(h/2\pi)$. From the fitting of the observed polarization field strength curves we find the hyperfine structure separation constant for $4^2P_{3/2}$ to be $1.87\pm0.05\times10^{-4}$ cm^{-1}. The polarization field strength curve shows very clearly the effect of proximity of hyperfine levels in $4^2P_{3/2}$.

IN many cases the splitting of atomic energy levels due to nuclear spin is on a scale so small that the resolution of the hyperfine components of a spectral line is difficult or impossible. The splitting of the $3^2S_{1/2}$ level of sodium has been observed by Schüler[1] and measured by L. Granath and C. M. Van Atta,[2] who also obtained values for the hyperfine separation in $3^2P_{1/2,\ 3/2}$. The separation of the hyperfine levels making up the $4^2P_{3/2}$ and higher states is too small to be resolvable. However, the effect of a magnetic field upon the polarization of resonance radiation affords an indirect means of measuring these separations. The method has the advantage that it is not limited by the resolving power attainable with interference spectroscopes, nor by Doppler breadth. In fact it is only necessary that the separations to be measured should be of the order of magnitude of the natural breadth of the spectral line in question. The existence of structure on a scale smaller than this is not to be expected for one could scarcely recognize levels as distinct unless separated by an amount comparable with their own indefiniteness. That the dependence of the polarization of resonance radiation upon the intensity of an applied magnetic field should afford a means of measuring separations in hyperfine multiplets is due to the fact that such multiplets undergo a Paschen-Back effect. Intensities in the Paschen-Back effect are functions of a single variable, $g(J)(eH/4\pi mcA)$ where A is the separation constant of the hyperfine multiplet. From this, as we shall see, it follows that the polarization of resonance radiation is a function of H and A only through the ratio H/A, and upon this depends the possibility of obtaining the value of A from observation of the polarization as function of H, since the very laborious Paschen-Back effect calculations have to be carried through only for a suitably chosen set of values of H/A. If the dependence were upon H and A separately the task of computing would be so great that one would hesitate to undertake it.

[1] H. Schüler, Naturwiss. **16**, 512 (1926).
[2] L. Granath and C. M. Van Atta, Phys. Rev. **44**, 935 (1933).

THEORY

Where the separation of the levels making up a hyperfine multiplet is large compared to the natural breadth of an energy level, we may calculate polarizations by Heisenberg's method. For this the relative intensities of the Zeeman components of the hyperfine multiplet are re-