VII. NUCLEAR MAGNETIC RESONANCE AND HYPERFINE STRUCTURE

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A. HYPERFINE STRUCTURE OF RADIO-THALLIUM

The hyperfine structure and isotope shift of two radioactive isotopes of thallium, Tl^{199}(7.4 hours) and Tl^{200}(27 hours), have been studied spectroscopically. The isotopes were produced by alpha bombardment of gold in the M.I.T. cyclotron. The irradiated gold-foil target was melted under vacuum to drive off the radio-thallium, which was then trapped in a section of quartz tubing. Argon at a pressure of 1-2 mm Hg was admitted to the quartz tube to make an electrodeless discharge lamp. A typical lamp contained between 10^{12} and 10^{13} atoms or 10^{-4} to 10^{-3} μgm of thallium.

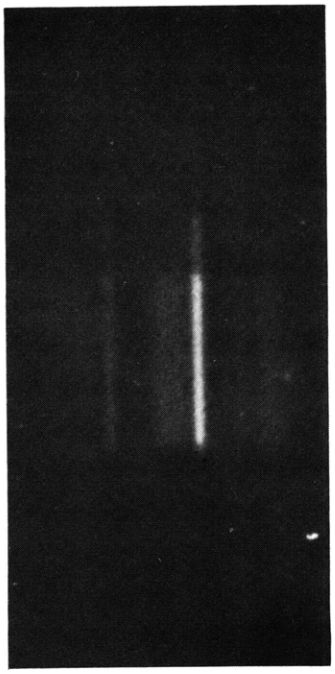

Fig. VII-1. Hyperfine structure of 5350 A line of Tl^{199}.

The hyperfine structures of the 5350.47 A and the 3775.73 A lines were studied in the Spectroscopy Laboratory with the use of a 10-inch grating in the 40-ft spectrograph; the grating was ruled by G. R. Harrison's ruling engine (1). The lamp was excited by means of a 50-mc oscillator. Continuous intense heating (800°-900° C) is required for exciting the spectrum of thallium. Exposure times varying from 1 to 5 hours were used to obtain the desired information.

To eliminate impurities in the lamps, a thorough bake-out of all glassware is required, and the section of quartz that is used for the discharge tube must be outgassed at a temperature just below the melting point of quartz. By using this technique, we have produced "clean" lamps, one of which has been operated red-hot for 10 hours.

Preliminary measurements of the 3776 A line show that the nuclear spin of Tl^{199} is 1/2, which is in agreement with the measurements of Brink et al. (2). The isotope shift 199-203 is 106 ± 5 millikaysers (10^{-3} cm^{-1}). The hfs separations in the $6s^2 6p^2 P_{1/2}$

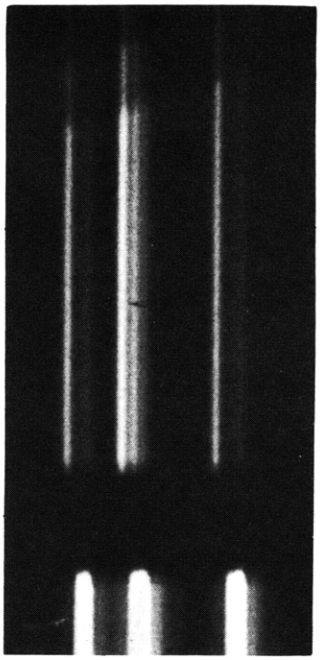

Fig. VII-2. Hyperfine structure of 3776 A line of Tl^{199} and Tl^{200}. From left to right: the first, third, and sixth lines are Tl^{199}; the second, fourth, fifth, and seventh are Tl^{200}. The heavy lines below are overexposed stable Tl^{203} and Tl^{205} spectra.

and the $6s^2 7s^2 S_{1/2}$ states are 694 mk and 405 mk, respectively. Further analysis of the spectrogram of these resonance lines of the two radio-isotopes of thallium is now being carried out, and it is expected to yield the magnitude and sign of the magnetic moment of Tl^{200}. The photographs in Figs. VII-1 and VII-2 show some of the radio-isotope spectra.

Tl^{199} exhibits a normal hyperfine-structure pattern. From the magnetic moments and $\Delta\nu$ values of the stable isotopes, and with the use of the Fermi-Segrè formula, we obtain

$$\mu(Tl^{199}) = +1.57 \text{ n.m.}$$

as a preliminary value. On the basis of the configuration-mixing model of Arima and Horie (3), with contributing configurations $p:(1h_{11/2})^{12}s_{1/2}$, $n:(3p_{3/2})^4(1i_{13/2})^8$, we obtain the theoretical value $\mu^{199} = 1.344$ n.m. The Schmidt limit for an $s_{1/2}$ odd proton nucleus is 2.793 n.m.

R. J. Hull, H. H. Stroke

References

1. We wish to thank Dr. S. P. Davis of the Spectroscopy Laboratory for his kind assistance with the spectrograph in our initial run.

2. G. O. Brink, J. C. Hubbs, W. A. Nierenberg, and J. L. Worcester, Phys. Rev. 107, 189 (1957).

3. A. Arima and H. Horie, Configuration mixing and magnetic moments of odd nuclei, Prog. Theor. Phys. (Japan) 12, 623 (Nov. 1954).

B. THE RELATION BETWEEN THE g-FACTORS AND THE LIFETIMES OF EXCITED STATES OF TWO-ELECTRON ATOMS

If atoms with two electrons outside a closed shell, such as Zn, Cd, or Hg, strictly obeyed the Russell-Saunders coupling scheme $\vec{J} = \vec{L} + \vec{S}$, the level $nsnp\,^3P_1$ would have a g-factor of 3/2, and the electric dipole transition between this level and the ground state would be strictly forbidden. As a matter of fact, because the coupling between the two electrons is intermediate between L-S and j-j coupling, this transition exists and the g-factor of the level is slightly less than 3/2.

We can expand the actual wave function for the nominal $^3P_1$ state in terms of a sum of orthogonal Russell-Saunders wave functions. If the state has a definite configuration, the summation is restricted to just those states in that configuration which have the same total angular momentum $\vec{J}$. In particular, if our configuration is nsnp and we are interested in levels with J = 1, our sum will have just two terms: one for the $^3P_1$ wave function, and one for the $^1P_1$ wave function. By expanding the expressions for the spontaneous radiation transition probability and the g-factor in this way (1), we find that the g-factor for the nominal $^3P_1$ level is $g = 3/2 - 1/2\, x^2$, where

$$x^2 = \frac{\frac{1}{\tau_1}}{\frac{1}{\tau_1} + \frac{\lambda_2^3}{\lambda_1^3}\frac{1}{\tau_2}}$$

In this expression, τ_1 is the actual lifetime of the $^3P_1$ level; τ_2 is the lifetime of the $^1P_1$ level; and λ_1 and λ_2 are the wavelengths of the corresponding radiation. The g-factor of the $^1P_1$ level is $g = 1 + 1/2\, x^2$.

For mercury, the g-factor of the $^3P_1$ level has been measured (2) as 1.4838 ± 6. Mitchell and Zemansky (3) quote the following values: for the 2537 A line, τ_1 is given as 1.08×10^{-7} sec; for the 1849 A line, τ_2 is given as 1.3×10^{-9} sec or as 1.6×10^{-9} sec. From the first value of τ_2, we calculate 1.4851 for g; and from the second value, 1.4818. For cadmium, a similar calculation gives a value of 1.4986 of g for the $5s5p\,^3P_1$ level.

R. F. Lacey

References

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2. J. Brossel and F. Bitter, Phys. Rev. 86, 308 (1952).
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C. A HIGH-RESOLUTION DISPERSION AND INTENSITY SPECTROGRAPH

The spectrographic study of the hyperfine structure of radioactive atoms makes it desirable to have a spectrograph that is not only of high resolution and dispersion but also able to make most efficient use of the available light flux. We have mounted a new type of spectrograph in the Spectroscopy Laboratory which, with favorably blazed gratings, and highly reflecting gratings, can gain as much as a factor of 3 in intensity in comparison with the mounting used at the present time. We shall first describe the properties of this mounting, which is a single-grating "Ebert" arrangement.

From the grating formula, we have

$$\sin i_1 + \sin i'_1 = \frac{n_1 \lambda}{a_1} \tag{1}$$

where λ is the wavelength, n_1 the order in which the spectrum is observed, a_1 the

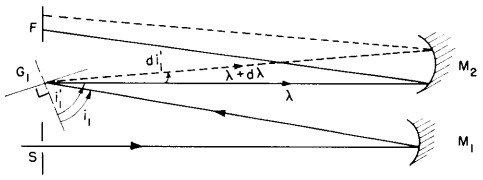


Fig. VII-3. Single-grating "Ebert" mounting.

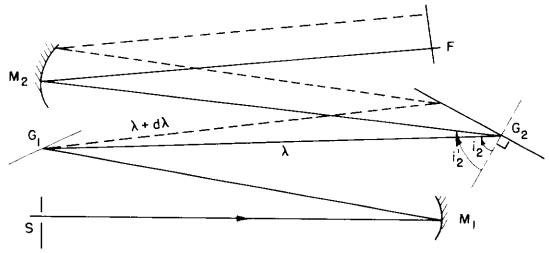


Fig. VII-4. New high-intensity and dispersion two-grating mounting.

grating spacing; the angles are indicated in Fig. VII-3. By differentiating Eq. 1, and noting that, for two wavelengths λ and $\lambda + d\lambda$, the angle i_1 is the same, we have

$$\cos i'_1 \, di'_1 = \frac{n_1 d\lambda}{a_1} \tag{2}$$

Furthermore, since the grating is used almost in autocollimation, $\sin i'_1 \approx \sin i_1$, so that by combining Eqs. 1 and 2 we obtain

$$\frac{di'_1}{d\lambda} = \frac{2 \tan i'_1}{\lambda} \tag{3}$$

In our new mounting we have the arrangement shown in Fig. VII-4. Now, at G_2 we have

$$\frac{n_2\lambda}{a_2} = \sin i_2 + \sin i_2' \tag{4}$$

and since we also use G_2 almost in autocollimation, we have

$$\frac{n_2\lambda}{a_2} \approx 2 \sin i_2' \tag{4a}$$

Differentiating Eq. 4 yields

$$\cos i_2 \, di_2 + \cos i_2' \, di_2' = \frac{n_2 d\lambda}{a_2} \tag{5}$$

Combining Eqs. 4, 4a, and 5, and noting that $\cos i_2 \approx \cos i_2'$, we obtain

$$\frac{di_2'}{d\lambda} = \frac{2 \tan i_2'}{\lambda} - \frac{di_2}{d\lambda} \tag{6}$$

Since we use the gratings as closely as possible to the blaze angle (which is approximately the same for both gratings), from the geometry of Fig. VII-5, we have $\beta \approx \gamma$, $\alpha + \beta + \gamma = \pi$, and α is constant, so that $d\beta = -d\gamma$, or alternatively

$$di_1' = -di_2 \tag{7}$$

Therefore from Eqs. 6 and 7, we have

$$\frac{di_2'}{d\lambda} = \frac{2 \tan i_2'}{\lambda} + \frac{di_1'}{d\lambda} \tag{8}$$

and by using Eqs. 3 and 8, we obtain

$$\frac{di_2'}{d\lambda} = \frac{2 \tan i_2'}{\lambda} + \frac{2 \tan i_1'}{\lambda} \tag{9}$$

or approximately

$$\frac{di_2'}{d\lambda} \approx \frac{4 \tan i_2'}{\lambda} \tag{10}$$

If we compare Eqs. 10 and 3, we see that our new two-grating arrangement gives twice the dispersion of the single-grating mounting for the same focal length of the camera mirror M_2. The limit of resolution in this two-grating arrangement, exactly as in the single-grating arrangement, is determined solely by the ruling uniformity of the gratings and is the same in both cases for gratings of equal quality.

The great advantage with the two gratings is that, for the same linear dispersion in the focal plane of the spectrograph, we can use half the focal length that is necessary with a single grating, with the result that air paths are reduced and compactness is

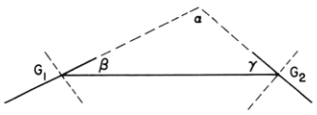
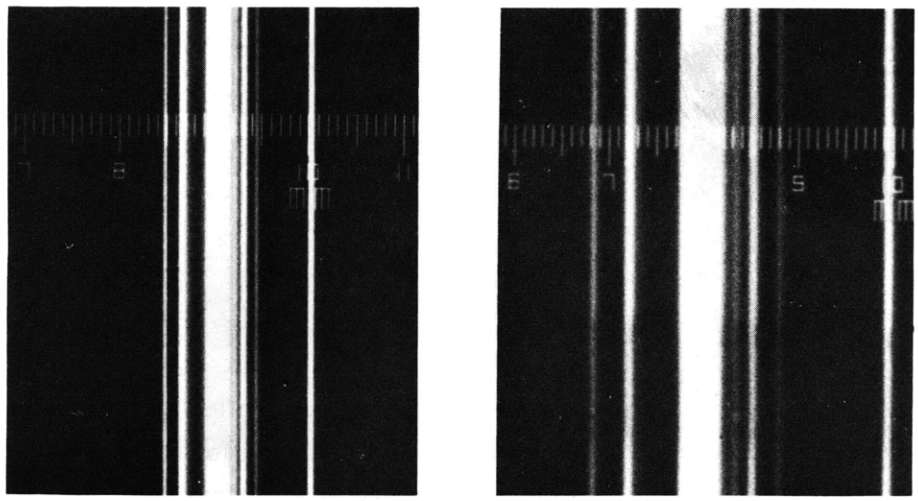


Fig. VII-5. Geometry of two-grating mounting.

achieved. The greater gain is that the available light intensity in the focal plane can be increased by a very large factor, which would be 4 if only solid-angle considerations were involved. The power incident on the image F per unit area is BA/ℓ^2, where B is the brightness of the source; A, the area of the camera mirror (i.e., limited by grating area); and ℓ is the distance from the camera mirror to the detector. Therefore, we see that, in going from a one-grating system of focal length 2ℓ to a two-grating system of focal length ℓ, and if we consider the solid angle alone, the gain in intensity is, indeed, 4. However, we have introduced an additional grating into the optical path. Harrison (1) stated that approximately 50 per cent of the incident light goes into a desired order, and, in more recent work, Harrison and others (2) find that with good blaze the amount can be larger than 75 per cent for the mercury green line, which would therefore represent an over-all gain in intensity of a factor of 3.

Some preliminary results on the mercury green line (λ = 5460.74 A) are shown in the spectrograms of Fig. VII-6a and b. The results of photometric intensity comparisons show, in this case, a photographic gain of greater than 30 per cent over the single-grating,double-focal-length arrangement. The light source that was used is a



(a) (b)

Fig. VII-6. Mercury green line hyperfine structure, 17-ft spectrograph: (a) single grating, 64°, exposure, 1 minute; (b) two gratings, G_1 and G_2, approximately 64°, exposure, 3 minutes.

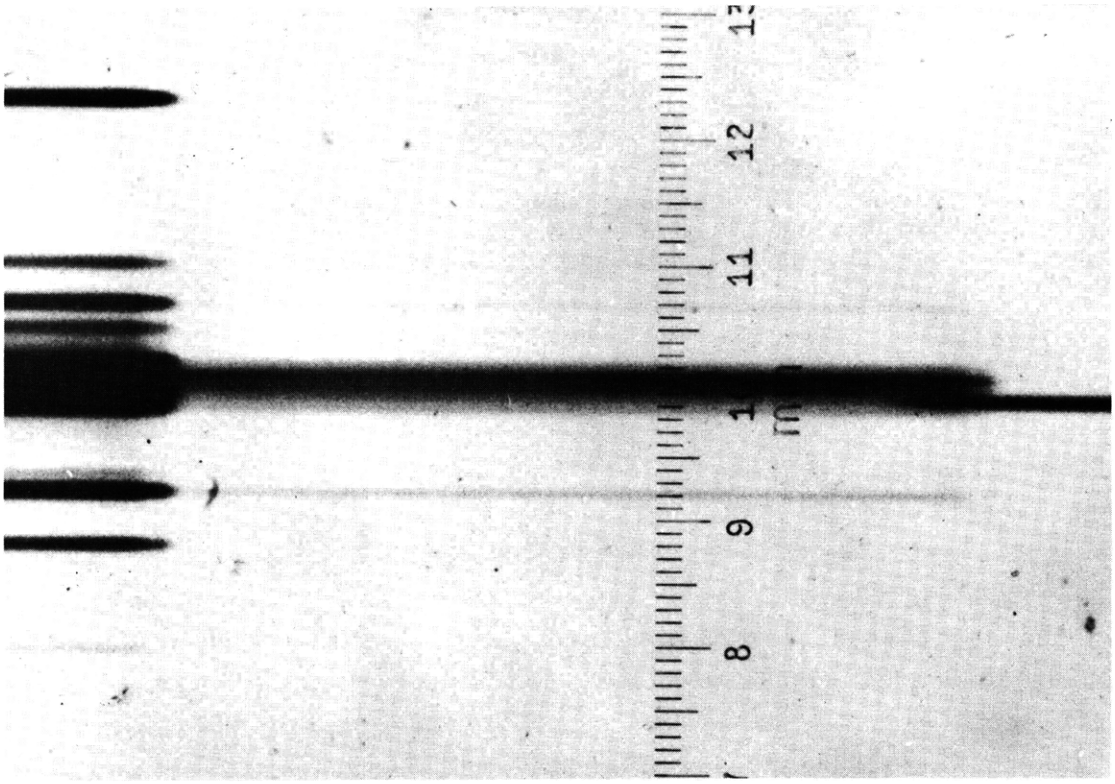


Fig. VII-7. Mercury green line hyperfine structure, 40-ft spectrograph. Left: mercury cold arc. Center: mercury electrodeless discharge, showing resolution of central fire components. Right: Hg^{198}.

cold mercury dc arc. G_1 (Spectroscopy Laboratory grating No. 107, 8 inches used, a = 6.1 λ) was used at 64°; and G_2 (Spectroscopy Laboratory grating No. 96, 8 inches wide, a = 25 λ) at approximately 64°. The slit S was set at 18 microns. Figure VII-7 shows, for comparison, the spectrum obtained in the 40-ft spectrograph with the MIT-ruled, 10-inch grating No. 97. Measurements of the spectrum spread show the following comparative linear dispersions: 1.91 mm, 3.83 mm, and 4.33 mm for the 17-ft single grating, 17-ft two gratings, and 40-ft single grating, respectively.

We must note finally, that this new two-grating mounting requires either one or three fewer mirror reflections than comparable dispersion double-pass arrangements with one grating, which is of importance when intensity is a major consideration, as it is in the present work. With the greater availability of the large, well-blazed, high-angle-of-incidence gratings ruled by G. R. Harrison's ruling engine in the Spectroscopy Laboratory, the advantages and limitations of going to still shorter focal lengths, and of using two or more gratings for a specific dispersion and intensity, will be studied (3).

G. W. Stroke, H. H. Stroke

References

1. G. R. Harrison, R. C. Lord, and J. R. Loofbourow, Practical Spectroscopy (Prentice-Hall, Inc., New York, 1948), p. 43.

2. Private communication to G. W. Stroke from G. R. Harrison, N. Sturgis, S. P. Davis, and Y. Yamada, 1958.

3. Dean G. R. Harrison, when he had become acquainted with the present work, suggested the possible use of concave gratings to eliminate even the two mirrors, when concave gratings become available in sizes comparable to those of plane gratings.

D. HALL EFFECT IN THE PLASMA OF A LAMP CONTAINING MERCURY VAPOR IN ARGON

A study has been made of the Hall effect in the plasma of a lamp containing mercury vapor in argon. The tube was similar to a standard 40-watt fluorescent lamp, but it had three small probes inserted into the middle section. The first and second probes were placed diametrically opposite each other, and the third was in line with the second, 15.4 cm away from it. When a magnetic field of approximately 10 gauss was applied perpendicular to the plane of the probes, Hall voltages of several hundred millivolts appeared between probes 1 and 2. Considerable difficulty was encountered in measuring the small voltages because of slow fluctuations in the contact potentials of the electrodes. In order to avoid this difficulty, the Helmholtz coils that provided the magnetic field were driven by alternating current. The Hall voltage was then measured with an ac differential voltmeter. The voltage was not found to be the simple function of coil frequency and tube current that would be expected. In general, it decreased with increasing current and fell off rapidly with frequency, but it did not approach a limiting value as the frequency was lowered, even at frequencies as low as 20 cps.

The usual equations of ambipolar diffusion theory were modified to include the effect of a transverse magnetic field, and a solution was obtained for rectangular geometry. After applying approximate relations appropriate to the mercury-vapor discharge, we concluded that the voltage produced per unit magnetic field should be one-half of the value of the electronic drift velocity. If we compare values for the drift velocity taken from the theory of Waymouth and Bitter (1) with our data, fairly good agreement is obtained.

H. P. Jolly, Jr.

References

1. J. F. Waymouth and F. Bitter, J. Appl. Phys. 27, 122 (1956).