The Zeeman Effect of the Cr Ground State

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The linear Zeeman effect of the ground state of Cr^{52} has been studied using the atomic beam magnetic resonance method at magnetic fields up to 850 gauss. The Cr atoms were detected by means of an electron-bombardment type ionizer. Using the known g factors for the ground states of K^{39} and Cs^{133}, the g factor of the $^7S_3$ ground state of neutral Cr was determined to be $g_J=2(1.00081\pm0.00005)$.

INTRODUCTION

THE Zeeman effect of atomic hyperfine structure has been investigated for the ground and metastable states of various elements by the atomic beam magnetic resonance technique. Thus far, however, this technique has not been applied to the study of the Zeeman effect of a ground state without hyperfine structure. The reason for this is that those elements to which the familiar methods of detecting atomic beams are applicable either do show hyperfine structure ($I\neq0$) or have a $^1S_0$ ground state ($J=0$). The construction in this laboratory of an electron-bombardment type of ionizer[1] has increased the variety of elements that can be detected and made possible the study of elements with $I=0$ and $J\neq0$. Though a large amount of experimental material on the Zeeman effect of fine structure levels is available from optical investigations, there remains a need for precise data. As an example of the information that may be obtained by the atomic beam method along these lines, we have studied the ground state of Cr^{52}.

Chromium is of interest because its ground state is an S state of high multiplicity ($3d^54s\ ^7S_3$), and because it is a light element for which Russell-Saunders coupling is expected to hold. In the absence of perturbations, an S state should have a g factor close to the anomalous spin g factor of the electron[2] $g_s=2(1.001146\pm0.000012)$. It can be reasonably expected in the case of chromium that the terms mainly effective in perturbing the g factor originate from the six valence electrons and not from a breaking up of lower closed shells. Such perturbations can arise only from states with $J=3$ and even parity. All atomic levels with $J=3$ resulting from six electrons have Landé g factors which are not larger than 2. Landé g factors larger than 2 can come about only when, in the language of the vector model, the total spin angular momentum **S** and the total orbital angular momentum **L** are antiparallel, and when, in addition, **S** is larger than **L**. This cannot happen for $S\leq3$, $J=3$. An admixture of higher states to the ground state of Cr should, therefore, cause g_J(Cr) to be less than g_s. Since the published optical value[3] g_J(Cr) $=2.007$ suggested that g_J exceeded g_s, it was thought worth while to obtain an accurate value for g_J(Cr) by comparing it with the well-known g factors of the ground states of K^{39} and Cs^{133}.

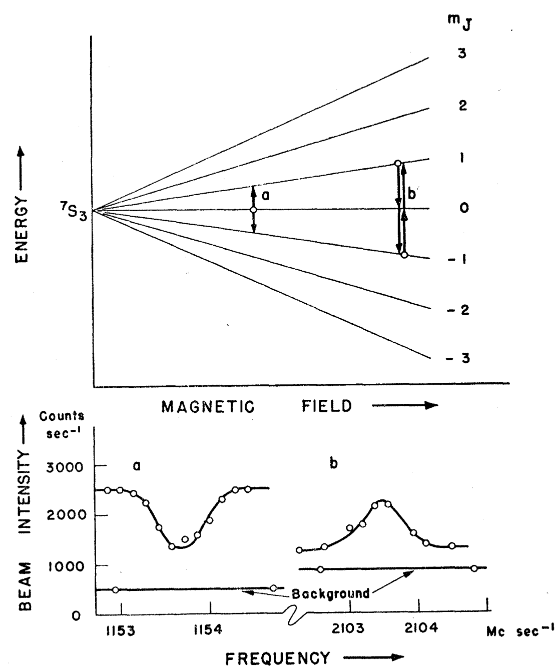

FIG. 1. Zeeman levels and observed transitions for the ground state of chromium. The upper part of the figure shows the energy levels as a function of an external magnetic field. The transitions referred to in the text as "flop-out" and "flop-in" are marked (a) and (b), respectively, in the figure and are set at arbitrary values of the abscissa. In the lower part of the figure the observed changes in beam intensity near the resonances are shown for two typical runs.

EXPERIMENTAL METHOD AND RESULTS

The atomic beam apparatus used in the present experiment has been described previously.[1,4] A beam of Cr atoms was produced by evaporating chromium powder from a thoria crucible inside a graphite oven at about 1500°C. It was found necessary to use oven

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[1] G. Wessel and H. Lew, preceding paper [Phys. Rev. **92**, 641 (1953)].
[2] Koenig, Prodell, and Kusch, Phys. Rev. **88**, 191 (1952).
[3] *Atomic Energy Levels*, National Bureau Standards Circular 467 (U. S. Department of Commerce, Washington, D. C., 1952), Vol. II. No experimental error is quoted.
[4] H. Lew, Phys. Rev. **91**, 619 (1953).

TABLE I. Individual data for the run taken at $H=849$ gauss. The frequencies in ordinary type are averages of four individual settings, the decimal places printed in italics have been interpolated.

Time	Frequency (mc/sec) Cr	Cs	$g_J(\text{Cr})/g_J(\text{Cs})$
19.03	2378.44		
13	*0.32*	379.724	0.99952
31	2378.11	*0.681*	53
38	*0.04*	379.664	53
49	2377.94	*0.637*	55
59	*0.79*	379.613	53
20.07	2377.67	*0.582*	55
16	*0.61*	379.547	59
24	2377.56	*0.529*	61
28	*0.48*	379.520	60
33	2377.38	*0.510*	58
38	*0.35*	379.500	58
49	2377.30	*0.490*	58
21.03		379.478	
		Mean	0.99956 $\pm$0.00005

slits of the order of 0.4 mm which is somewhat wider than the slit widths usually used. Narrower slits had a tendency to become clogged.

The Cr beam was detected by means of the universal ionizer described in the preceding paper.[1]

The upper part of Fig. 1 shows the energy levels of an atomic state with $J=3$, $I=0$ as a function of the magnetic field H. The atoms in the beam are distributed equally between the seven magnetic substates. The atoms in one of these ($m_J=0$) have zero magnetic moment and are therefore not affected by the inhomogeneous A and B fields of the apparatus. The remaining atoms of the beam have nonvanishing magnetic moments, and since the field gradients in the A and B fields are parallel in our arrangement, they will fail to reach the detector when the deflecting fields are on. A rough measurement of the ratio of beam intensities with the deflecting fields on and off gave $1:(7.0\pm0.2)$. The ratio remained unchanged when the B field alone was used.

An atom originally in the substate $m_J=0$ may undergo transitions to the states $m_J=\pm1$ in the C-field region when a radio-frequency field of the appropriate frequency is superimposed on the C field. With both deflecting fields on, these transitions manifest themselves by a decrease in beam intensity at the detector, and such "flop-out" transitions are readily observed with low rf power. By increasing the rf power and intercepting the undeflected atoms in the state $m_J=0$ by means of an obstacle wire, it was also possible to observe the double transitions $m_J=\pm1\rightarrow m_J=0\rightarrow m_J=\mp1$. Atoms undergoing such transitions are refocused on the detector after being deflected in opposite directions in the A and B fields, so that the beam intensity increases when such "flop-in" transitions are being induced. The two types of transitions have been schematically drawn at arbitrary fields in the upper part of Fig. 1. The lower part of the figure illustrates typical line widths, beam intensities, and ionizer backgrounds encountered in the present experiment.

The Cr resonance frequencies were compared with the transitions $\Delta F=0$, $m_F=-I-\frac{1}{2}\rightarrow m_F=-I+\frac{1}{2}$ of K^{39} or Cs^{133}. All frequency settings were made by listening to the intensity of the 10-cps signal from the detector without the use of the lock-in amplifier system described in reference.[1] A counting rate meter was used to obtain line shapes. Table I gives the results of the run taken at a field of 849 gauss. It will be noticed that H drifted slowly in the course of the run. The Cs frequency belonging to a given Cr frequency was obtained by linear interpolation between the two adjacent measured Cs frequencies and vice versa. The interpolated frequencies are shown in italics.

The Cr transition frequencies are given by $\nu(\text{Cr})=g_J(\text{Cr})\mu_0H/h$, where μ_0 is the Bohr magneton. The Breit-Rabi formula[5] gives the K and Cs frequencies as functions of μ_0H/h. By eliminating μ_0H/h, the ratios $g_J(\text{Cr})/g_J(\text{K})$ and $g_J(\text{Cr})/g_J(\text{Cs})$ can be evaluated. The following numerical data were used in this calculation:

K^{39}: $\Delta\nu=461.723$ Mc/sec,[6] $g_I/g_J=-0.0000708.$[6–8]

Cs^{133}: $\Delta\nu=9192.632$ Mc/sec,[9] $g_I/g_J=-0.0001993.$[6]

To check the linearity of the Zeeman effect of the state under study, observations were made at various values of H. These results are shown in Table II. Columns 1 and 2 give the magnetic field and Cr resonance frequency for each run. Since these values changed slightly in the course of a run, nominal values are quoted. The uncertainties given in column 5 were conservatively estimated from the scatter of individual evaluations for each run. In calculating $g_J(\text{Cr})$ (column 6 of Table II) we used the values $g_J(\text{K})$ and $g_J(\text{Cs})$ listed in Table III. It can be seen that no variation in $g_J(\text{Cr})$ with H is apparent. A weighted average was obtained by weighing the different runs according to

TABLE II. Measured ratios of g factors.

Nominal field (gauss)	Cr frequency mc/sec	$g_J(\text{Cr})/g_J(\text{K})$	$g_J(\text{Cr})/g_J(\text{Cs})$	Error 10^{-5}	$g_J(\text{Cr})$	Weight
170	476[a]	0.99946		50	2(1.00060)	0
318	892	0.99947		20	2(1.00061)	1
412	1154	0.99963		12	2(1.00077)	2
458	1284		0.99966	30	2(1.00091)	1
582	1632		0.99974	15	2(1.00099)	1
751	2104[a]		0.99954	10	2(1.00079)	2
849	2378		0.99956	5	2(1.00081)	5
			Weighted mean		2(1.00081)	

[a] Measured as "flop-in," all others as "flop-out."

[5] G. Breit and I. I. Rabi, Phys. Rev. **38**, 2072 (1931).
[6] P. Kusch and H. Taub, Phys. Rev. **75**, 1477 (1949).
[7] T. L. Collins, Phys. Rev. **80**, 103 (1950).
[8] Eisinger, Bederson, and Feld, Phys. Rev. **86**, 73 (1952).
[9] H. Lyons, Ann. N. Y. Acad. Sci. **55**, 831 (1952).

their errors. Essentially the same weights were obtained independently from a consideration of the line widths and rates of drift in the various runs. If we take into account the small uncertainties of $g_J(\mathrm{K})$ and $g_J(\mathrm{Cs})$ we obtain

$$g_J(\mathrm{Cr}) = 2(1.00081 \pm 0.00005).$$

DISCUSSION AND CONCLUSION

Our measurements show that the ground state of Cr is a much "better" S state than was indicated by the less accurate optical value for g_J. However, $g_J(\mathrm{Cr})$ does differ by approximately 3 parts in 10^4 from g_s, the pure electron spin g factor. This discrepancy can be due to several factors: (a) interaction terms in the radiative correction,[10,11] (b) nonradiative relativistic correction,[12] (c) diamagnetic correction,[13] and (d) perturbations due to higher states. The effects (a) and (b) have been calculated for some spectra with one or two[11] valence electrons and have been found to be much smaller than 3×10^{-4}. No calculations are available for Cr which has six valence electrons. The diamagnetic correction (c) is negligible[13] (-2×10^{-6} for Cr). The deviation of $g_J(\mathrm{Cr})$ from g_s that has been found is indeed in the direction to be expected from a perturbation (d), but no quantitative conclusions can be drawn until the corrections (a) and (b) are known.

[10] G. Breit, Phys. Rev. **39**, 616 (1932).
[11] W. Perl and V. Hughes, Phys. Rev. **89**, 886 (1953).
[12] G. Breit, Nature **122**, 649 (1928); H. Margenau, Phys. Rev. **57**, 383 (1940).
[13] W. E. Lamb, Phys. Rev. **60**, 817 (1941).

TABLE III. Experimental results used in the derivation of $g_J(\mathrm{K})$ and $g_J(\mathrm{Cs})$. The quantities designated A to E are experimental results obtained by various investigators. Values for $g_J(\mathrm{K})/g_l$ and $g_J(\mathrm{Cs})/g_l$ are derived from these in the manner shown in the last two rows. Throughout the text of the present paper, wherever the g_J's of K and Cs have been used, g_l has been set equal to 1, as is done in optical spectroscopy.

Symbol	Quantity	Value
A	$2g_l/g_p$	-657.475 ± 0.008[a]
B	$g_J(\mathrm{K})/g_p$	-658.2274 ± 0.0023[b]
C	$g_p/g_J(\mathrm{Cs})$	$-(15.1911 \pm 0.0003)\times10^4$ [c]
D	$g_J(\mathrm{Cs})/g_J(\mathrm{Na})$	1.000134 ± 0.000007[d]
E	$g_J(\mathrm{Na})/g_J(\mathrm{K})$	1.00000 ± 0.00002[d]
$2B/A$	$g_J(\mathrm{K})/g_l$	$2(1.00114 \pm 0.00001)$
Av of $2/CA$ and $2BDE/A$	$g_J(\mathrm{Cs})/g_l$	$2(1.00125 \pm 0.00003)$

[a] J. H. Gardner and E. M. Purcell, Phys. Rev. **76**, 1262 (1949); J. H. Gardner, Phys. Rev. **83**, 996 (1951).
[b] P. Franken and S. Koenig, Phys. Rev. **88**, 199 (1952).
[c] H. Taub and P. Kusch, Phys. Rev. **75**, 1481 (1949).
[d] See reference 6.

Apart from these theoretical considerations, it should be mentioned that, with the accurately known g_J of the ground state, the Zeeman splittings of the resonance lines of Cr I (e.g., of the transitions $^7S_3-{}^7P^\circ_{2,3,4}$ at 4290A, 4275A, and 4254A) are now very suitable for the calibration of magnetic fields in optical Zeeman spectroscopy.[14]

We are much indebted to Dr. G. Herzberg for helpful criticism.

[14] See, e.g., the pattern of λ4254A as reproduced in A. Sommerfeld, *Atombau und Spektrallinien* (F. Vieweg & Sohn, Braunschweig, 1931), fifth edition, Vol. I, p. 523.

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The 7.68-Mev State in C^{12}

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Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68±0.03 Mev. At $E_d=620$ kev, $\theta_{\mathrm{lab}}=90°$, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

SALPETER[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of $O^{16}:C^{12}:He^4$ that this reaction should have a resonance at 0.31 Mev or at 7.68 Mev in C^{12}.

An early measurement of the range of the alpha particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in C^{12} at 7.62 Mev.[4] However, a recent magnetic analysis of this reaction failed to detect a transition to any level in this region of excitation,[5] nor did the level show up in the neutron spectrum[6] from $B^{11}(d,n)C^{12}$. From the

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[1] E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.
[2] E. J. Öpic, Proc. Roy. Irish Acad. **A54**, 49 (1952).
[3] F. Hoyle (private communication).
[4] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).
[5] R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).
[6] W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 586 (1949); V. R. Johnson, Phys. Rev. **86**, 302 (1952).