The Nuclear Mechanical Moment of Cobalt

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The hyperfine structure of the lines λλ4191, 4234, 6082, 6231, 6450 and 6592 of the arc spectrum of cobalt has been studied. The number of components and the interval ratios give a value of $I=7/2$. The nuclear magnetic moment is estimated to be of the order of 2 to 3 small magnetons.

INTRODUCTION

THE nuclear spin of cobalt ($Z=27$, $M=59$) has been reported by Grace[1] to be probably 7/2. This value was based on a study of partially resolved hyperfine structure of the lines λ3454, $3d^84s\ {}^4F_{9/2}-3d^84p\ {}^4G_{11/2}$; λ3466, $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^4G_{11/2}$ and λ3909, $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^6G_{11/2}$. A value of $I=5/2$ was set as the lower limit while a value of $I=9/2$ was considered to be possible. In an attempt to determine the nuclear moment more definitely the hyperfine-structure patterns of λλ4191, 4234, 6082, 6231, 6450 and 6592 have been examined. The nuclear spin is found to be 7/2. During the course of the present investigation Kopfermann and Rasmussen[2] published a note on the hyperfine structure of the lines λλ4234 and 4268, from which they found that $I=7/2$. Their results on λ4234 are in agreement with those obtained in the present investigation.

EXPERIMENTAL

The Co I spectrum was excited in a liquid air cooled Schüler tube the hollow cathode of which was made from a cobalt rod. Argon was introduced into the tube and the pressure varied until the discharge took place entirely in the base of the tube. Discharge currents of the order of 0.2 amp. were used.

The spectrum was photographed with a three-prism flint glass spectrograph and silvered Fabry-Pérot etalons. Eastman 33 plates were used for the violet portion of the spectrum and Eastman hypersensitive panchromatic plates which were sensitized with ammonia were used for the red region. Exposure times varied from ten minutes to five hours.

RESULTS

A reproduction of a portion of a plate taken with 7.5 mm etalons is given in Fig. 1. Many of the lines are resolved into several components. Of the clearly resolved lines with uniformly degrading intensities and intervals the ones arising from transitions between levels for which $J>7/2$ show eight components. The number of components in a line arising from levels for which $J>I$ is $2I+1$ if the splitting of one of the levels is large compared with that of the other. If the

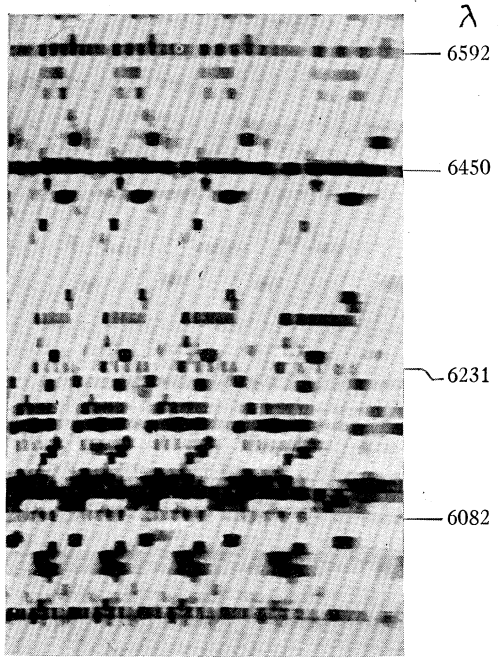

FIG. 1. Reproduction of a plate showing hyperfine structure in the red region of the Co I spectrum.

[1] N. S. Grace, Phys. Rev. **43**, 762 (1933).
[2] H. Kopfermann and E. Rasmussen, Naturwiss. **22**, 291 (1934).

levels have splittings of the same order of magnitude the off-diagonal components appear, giving more than $2I+1$ components. In such cases the intervals and intensities do not vary uniformly. The lines λλ4234, 6082 and 6592, for which $J>7/2$, show eight components of uniformly degrading intensities and intervals. This leads to the value $I=7/2$.

The mechanical moment is also determined by the application of the Landé interval rule to the hyperfine-structure intervals of any fine-structure level for which $J>1/2$. While the intervals in a line are not the same as the intervals in one of the levels from which the line arises unless the other level involved is not split, the interval ratios are nearly the same if the splitting in one level is large compared with that in the other. The intervals and interval ratios observed, together with the theoretical interval ratios for spins of 5/2, 7/2 and 9/2, are given in Table I. The theoretical values are not given for spins of 3 and 4 because integral spins have not been found for other elements of odd mass number. For several of the lines, however, the ratios observed are nearer to the theoretical values for $I=7/2$ than to those for $I=3$ or $I=4$. For most of the lines only the first four intervals can be measured with sufficient accuracy to warrant giving the interval ratios. In all cases the overall splitting is measured and its ratio to the first interval compared with the theoretical ratio.

In the following the different lines will be discussed in some detail.

λ4191, $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^6F_{9/2}$, shows a flag type pattern degrading toward the red. This indicates that ${}^6F_{9/2}$ is split normally and that ${}^4F_{9/2}$ is relatively sharp. This is to be expected because the ${}^6F$ term arises from a configuration with an unbalanced s electron. In this line only the first interval and the overall splitting could be measured because of the presence of an overlapping line in the center of the pattern.

λ4234, $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^6F_{11/2}$, definitely shows at least seven components and almost certainly eight. The pattern is degraded toward the red indicating that ${}^6F_{11/2}$ is split normally.

λ6082, $3d^74s4p\ {}^4F_{9/2}-3d^84s\ {}^4F_{9/2}$, shows eight components degraded toward the violet. The splitting is attributed to the $4s4p\ {}^4F_{9/2}$ level, which would thus be normal, because this is

TABLE I. *Hyperfine-structure intervals and interval ratios.*

Intervals observed cm^{-1}	Interval ratios observed	Theoretical interval ratios $I=5/2$	$I=7/2$	$I=9/2$
	λ4191 $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^6F_{9/2}$			
0.116	100	100	100	100
		Overall splitting		
0.504	434	400	437	500
	λ4234 $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^6F_{11/2}$			
0.137	100	100	100	100
0.120	87.7	87.5	88.9	90.0
0.109	79.6	75.0	77.8	80.0
0.095	69.4	62.5	66.7	70.0
0.08	58	50.0	55.6	60.0
		Overall splitting		
0.650	475	375	467	540
	λ6082 $3d^74s4p\ {}^4F_{9/2}-3d^84s\ {}^4F_{9/2}$			
0.111	100	100	100	100
0.097	87.4	85.7	87.5	88.9
0.083	74.8	71.1	75.0	77.8
0.071	64.0	57.1	62.5	66.7
0.06				
0.04				
		Overall splitting		
0.490	442	357	437	500

Intervals observed cm^{-1}	Interval ratios observed	Theoretical interval ratios $I=5/2$	$I=7/2$	$I=9/2$
	λ6231 $3d^84s\ {}^4P_{1/2}-3d^74s4p\ {}^4D_{3/2}$			
0.117	100	100	100	100
0.095	81.5	75.0	80.0	83.3
0.095	81.5	75.0	80.0	83.3
0.072	61.1	50.0	60.0	66.7
	λ6450 $3d^84s\ {}^4P_{5/2}-3d^74s4p\ {}^4D_{7/2}$			
0.145	100	100	100	100
0.124	85.5	83.3	85.7	87.5
0.104	71.7	66.7	71.4	75.0
0.083	57.2	50.0	57.1	62.5
		Overall splitting		
0.581	402	333	400	437
	λ6592			
0.106	100			
0.097	91.5			
0.088	83.0			
0.079	74.5			
0.072	67.9			
0.061	57.5			
0.04	38			

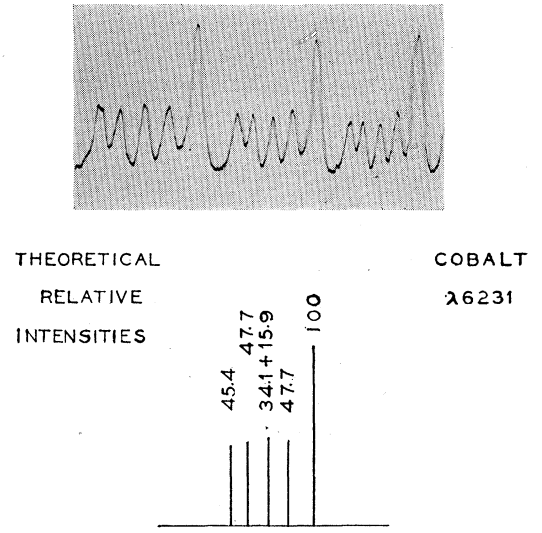

FIG. 2. Photometer curve of the hyperfine structure of λ6231.

consistent with the partially resolved structure found for λ3527, $3d^74s^2\ {}^4F_{9/2}-3d^74s4p\ {}^4F_{9/2}$, and with the structure of λλ4191 and 4234 already discussed.

λ6231, $3d^84s\ {}^4P_{1/2}-3d^74s4p\ {}^4D_{3/2}$, consists of five components. Both levels are split, the upper one being normal and the lower inverted, with the splitting of the lower level equal to the second interval of the upper. A photometer curve of this line and the pattern to be expected theoretically from the above interpretation are given in Fig. 2. The relative intensities of the components were determined by the method used by Anderson[3] in his work on the nuclear moment of lanthanum. The results agree with the theoretical values, thus checking the interpretation of the structure. The overall splittings of the levels are 0.284 cm^{-1} and 0.095 cm^{-1} for the $^4D_{3/2}$ and $^4P_{1/2}$ levels, respectively.

λ6450, $3d^84s\ {}^4P_{5/2}-3d^74s4p\ {}^4D_{7/2}$, shows several components degraded toward the red. It is certain that there are more than six components. Only the first four intervals could be measured because of the presence of an overlapping line in the tail of the pattern. The splitting is attributed to the $^4D_{7/2}$ term which would thus be normal.

λ6592 is an unclassified line for which the J values are not known. It consists of eight components, as is shown by the photometer curve in Fig. 3. Thus either I or J equals 7/2. The interval ratios are very high indicating that $I+J$ is at least 20/2. Since the results from the other lines show that $I=7/2$, definitely excluding any value as high as 11/2, the J value must be high and $I=7/2$.

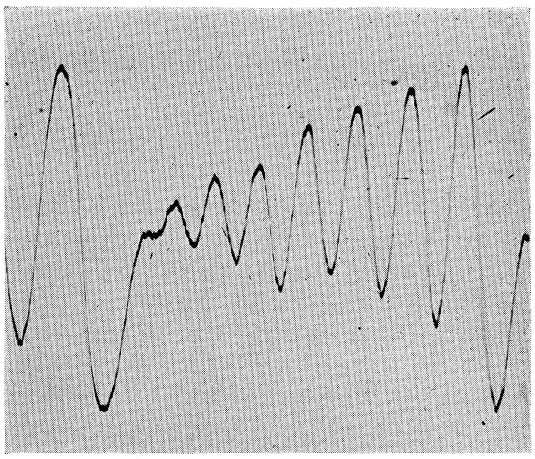

FIG. 3. Photometer curve of the hyperfine structure of λ6592.

It is thus concluded from a study of the hyperfine-structure patterns observed in the Co I spectrum that the nuclear mechanical moment of cobalt is given by $I^*h/2\pi$, where $I^*=[I(I+1)]^{\frac{1}{2}}$ and $I=7/2$.

The determination of the nuclear magnetic moment by the application of the Bacher-Goudsmit equations to the observed splittings is very inaccurate because even if all the splitting of a line is attributed to one level, it is not known what portions of the splitting are due to the s, p and d electrons. There is definite evidence that the p and d electrons, as well as the s electron, contribute an appreciable amount to the splitting. It is possible however to make an estimate of the magnitude of the magnetic moment by assuming that all the splitting is due to the s electron. If the splitting observed in λ4234 is assigned to the upper level, $3d^74s4p\ {}^6F_{11/2}$, the value of the magnetic moment is found to be 3.5 small magnetons. If there is a small splitting in the lower level the splitting in the upper level would be slightly larger or smaller than the line splitting, depending on whether the splitting of the lower level is normal or inverted. This would change the value of the magnetic moment

[3] O. E. Anderson, Phys. Rev. **45**, 685 (1934).

slightly from the value given. The other lines for which J is high give values that agree reasonably well with the above value. There seems to be little doubt but that the value found is high because an appreciable part of the splitting observed is due to the p and d electrons, while for purposes of calculation it was assumed to be due to the s electron only. Estimations of the contributions of the p and d electrons, by analogy with the results obtained in the different lines in cobalt as well as in other elements, would set as a probable value of the nuclear magnetic moment of cobalt 2 to 3 small magnetons.

In concluding I wish to thank Professor H. E. White for many valuable discussions of this problem.

The Nuclear Magnetic Moment of Lanthanum

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The hyperfine structure of some twenty-five lines has been investigated in order to determine the absolute overall widths of each member of the $5d^26s\ ^4F$ levels. From these a nuclear g-factor of 0.719 and a magnetic moment of 2.5 small magnetons have been computed. The Landé interval rule applied to the hyperfine structure of a three-electron configuration was found to hold. It was found that the interaction energy between the s electron and the nucleus as given by the Bacher-Goudsmit equations is not sufficient to account for the observed intervals but that the interaction energy between the d electrons and the nucleus must also be considered.

AS reported earlier,[1] the hyperfine structure of the arc spectrum of lanthanum has been investigated in order to determine the nuclear mechanical moment. All three of the independent methods, maximum number of components in a line involving sufficiently high J values, relative intervals of the hyperfine structure levels and relative intensities of the components, gave good agreement with $I=(7/2)h/2\pi$. In this investigation the h.f.s. separations, chiefly in the metastable ^4F levels, have been determined and from these absolute values the g-factor and hence the nuclear magnetic moment have been evaluated. Also it is possible from these values of the h.f.s. intervals to determine to what extent the Landé interval rule and the Bacher-Goudsmit equations apply to a three-electron configuration.

In their preliminary work, Meggers and Burns[2] found that the $5d^26s\ ^4F$ levels of lanthanum showed wide h.f.s. whereas the normal state $5d6s^2\ ^2D$ was relatively sharp. The widths of some twenty-five lines have now been measured in order to determine the width of each of the ^4F levels. These lines are given by transitions from the triad of quartets $^4D°$, $^4F°$ and $^4G°$ arising from the electronic configuration $5d^26p$ to the metastable $5d^26s\ ^4F$ levels.

The apparatus and experimental procedure are explained in detail in the previous paper.[1] The plates were calibrated for intensity measurements by the use of a step-slit as described earlier. The overall width of each line was carefully measured in several orders in each pattern, then corrected for dispersion and the average value adopted.

From flag patterns, i.e., patterns in which the intensities and intervals degrade uniformly, only the sum or difference of the energy level widths can be determined very accurately unless the absolute width of one of the levels is known. To assume that one level is sharp because many components in a uniformly degrading line are clearly resolved can easily introduce an error as high as 15 percent in the value of the computed level. Hence to determine accurately the widths of the levels of a multiplet, detailed measurements must be made on at least one line which has the off-diagonal components resolved. Most of the lines measured in this investigation degrade uniformly or are only partially resolved. Fortunately, however, two lines in which the off-diagonal components are clearly resolved fix the absolute width of one of the ^4F levels.

[1] O. E. Anderson, Phys. Rev. **45**, 685 (1934).
[2] W. F. Meggers and K. Burns, J. O. S. A. and R. S. I. **14**, 449 (1927).

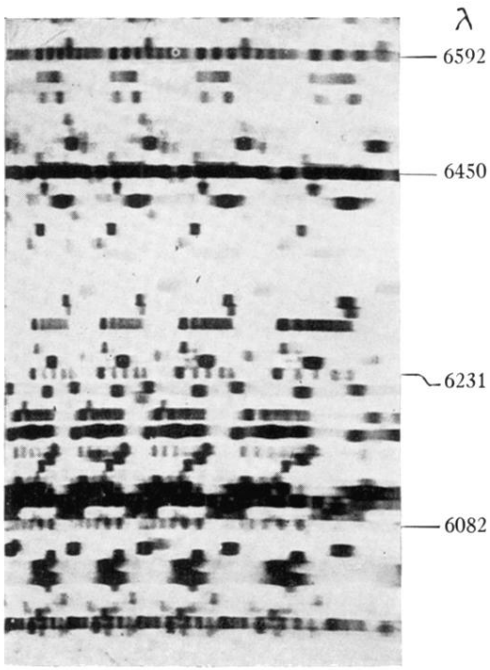

FIG. 1. Reproduction of a plate showing hyperfine structure in the red region of the Co I spectrum.

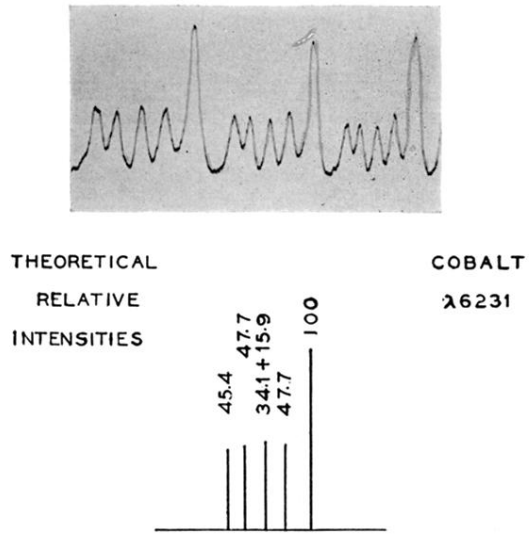

FIG. 2. Photometer curve of the hyperfine structure of λ6231.

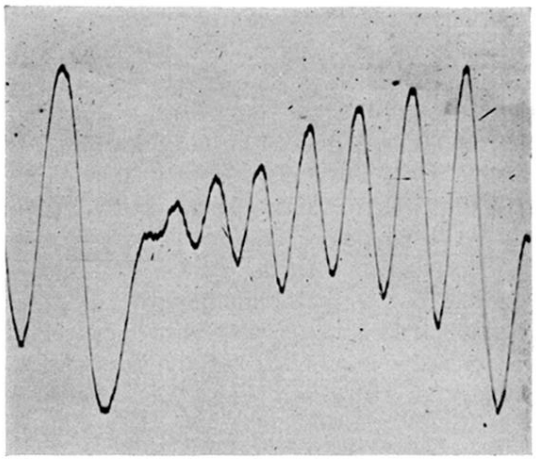

FIG. 3. Photometer curve of the hyperfine structure of λ6592.