Hyperfine Structure of the ^3P States of Zn^{67} and Mg^{25}

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The hyperfine structure of the metastable $(4s4p)\,^3P_2$ state of Zn^{67} and the metastable $(3s3p)^3P_2$ and $^3P_1$ states of Mg^{25} have been measured by the atomic beam magnetic-resonance technique. The magnetic dipole and electric quadrupole-coupling constants obtained from these measurements are: $Zn^{67}(^3P_2)$, $A=531.987\pm0.005$ Mc/sec, $B=35.806\pm0.005$ Mc/sec; $Mg^{25}(^3P_2)$, $A=-128.445\pm0.005$ Mc/sec, $B=16.009\pm0.005$ Mc/sec; $Mg^{25}(^3P_1)$, $A=-144.977\pm0.005$ Mc/sec, $B=-8.308\pm0.005$ Mc/sec. These results are compared in detail with the Breit-Wills and Casimir theory of two-electron hyperfine structure. The electric quadrupole moments of these nuclei are found to be: $Q(Zn^{67})=0.16\times10^{-24}$ cm^2, $Q(Mg^{25})=0.22\times10^{-24}$ cm^2. The quadrupole moment of Mg^{25} is shown to be in very good agreement with that value obtained from other experiments thru the use of the collective model in strong coupling. The detection of a beam of metastable $^3P_1$ Mg atoms places a lower limit on the lifetime of this state of about 10^{-3} sec.

I. INTRODUCTION

THE group II elements of the periodic table, of which zinc and magnesium are members, all have a $^1S_0$ ground atomic state. There is no hyperfine structure in a $^1S_0$ state; however, all these elements do have metastable excited states which for $I>0$ have hyperfine structure (hfs). At least one of these excited states has a lifetime sufficiently long so that it can be investigated by the atomic-beam magnetic-resonance method. The first metastable states to be investigated by the atomic-beam method were those of the noble gases and hydrogen, since they can be produced in a Woods discharge tube.[1] Recently, Lichten, McDermott, and Faust[2] have succeeded by means of electron bombardment in producing beams of mercury and cadmium in their metastable $^3P_2$ state. This paper describes the application of their technique in the measurement of the hfs of the $^3P_2$ state of Zn^{67} and the $^3P_2$ and $^3P_1$ states of Mg^{25}.[3]

The outer electron configurations of Mg and Zn are $(3s)^2$ and $(4s)^2$, respectively, which lead to a $^1S_0$ ground state. When one of these s electrons is excited to the nearest higher-lying p state one of the $^3P_{2,1,0}$ or $^1P_1$ fine structure levels will be populated. All these ^3P levels are metastable because singlet-triplet transitions are forbidden. In addition, transitions from the $^3P_2$ and the $^3P_0$ levels are further forbidden by the J selection rules. If the coupling between the s and p electron is not pure Russell-Saunders, the $^3P_1$ state mixes with the shortlived $^1P_1$ state and can have a metastable lifetime so short that a beam of atoms initially in the $^3P_1$ state does not survive in that state over a useful distance. For zinc it is known that the lifetime of the $^3P_1$ state is 3.2×10^{-5} sec,[5] so that for atoms with the mean velocity in the beam, the survival distance is only 1.5 cm. For magnesium the lifetime of the $^3P_1$ state is expected to be considerably longer and it is found experimentally that a sizable fraction of the $^3P_1$ state atoms reaches the detector. Atoms in the $^3P_0$ state have no electronic magnetic moment and cannot be deflected but are present as a constant background signal.

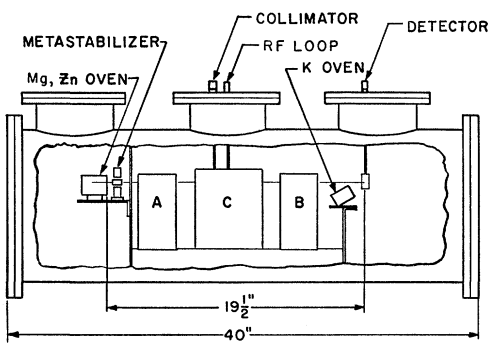

FIG. 1. Schematic diagram at apparatus.

The beam of ^3P metastable-state atoms is produced by electron bombardment of a beam of ground-state atoms, and is detected by the ejection of an electron when a metastable-state atom in the beam strikes an alkali-coated surface and is de-excited. Mg^{25} with an abundance of 10% and Zn^{67} with an abundance of 4% are the only stable isotopes of these elements with a spin other than zero. In both cases $I=\frac{5}{2}$.

The present measurements are more difficult than the measurements performed on Hg and Cd since, (1) the intensity, as a fraction of the total metastable beam, of a transition between individual hyperfine levels is smaller because of the larger nuclear spin and the smaller isotopic abundance, and (2) the excitation energy of the metastable state above the ground state is less and, hence, both production and detection of the metastable-state is less efficient.

From the measurement of the hyperfine-structure splittings the magnetic dipole, the electric quadrupole,

[1] John E. Nafe and Edward B. Nelson, Phys. Rev. **73**, 718 (1948); A. Lurio, G. Weinreich, C. W. Drake, V. W. Hughes, and J. A. White, *ibid.* **120**, 153 (1960). References to earlier papers are given in these papers.

[2] M. N. McDermott and W. Lichten, Phys. Rev. **119**, 134 (1960); W. Faust, M. N. McDermott, and W. Lichten, *ibid.* **120**, 469 (1960).

[3] These results have been presented in abstracts at the following meetings: A. Lurio, Bull. Am. Phys. Soc. **4**, 429 (1959); **4**, 419 (1959); A. G. Blachman and A. Lurio, *ibid.* **6**, 74 (1961).

[4] Von Klaus Böckmann, Hubert Krüger, and Ekkehard Rechnagel, Ann. Physik **20**, 250 (1957).

[5] Landolt-Börnstein Tables (Springer-Verlag, Berlin, Germany, 1950), Vol. I.

and the magnetic octupole, interaction constants may be obtained. The nuclear electric-quadrupole moment of Zn^{67} and Mg^{25} have been calculated from the quadrupole interaction constant. In addition, a knowledge of the value of the dipole-coupling constant in both the $^3P_2$ and the $^3P_1$ states enables one to obtain the contribution to these dipole interaction constants from the s and p electron separately, and to compare these contributions with the Breit-Wills and Casimir theory for two-electron hfs.[6]

II. APPARATUS

A. Vacuum Chamber

A schematic diagram of the essential features of the apparatus is shown in Fig. 1. The vacuum envelope consists of a welded stainless steel cylinder 39 in. long and 12 in. in diameter which was fabricated, leak tight, by the Ladish Company.[7] The apparatus is divided into two chambers, a source chamber and a main chamber, each of which is pumped by a freon baffled MCF 700 oil-diffusion pump having a common MB 100 booster. With liquid-air trapping, vacuums of 10^{-7} mm of Hg are achieved in both chambers.

B. Source and Bombarder

The source for the Mg and Zn beams was a stainless steel oven operated at about 500°C for Mg and at about 325°C for Zn. The source slit was 0.003 in. wide through which a beam of Mg or Zn atoms in their ground $^1S_0$ state effused. Just in front of the oven, within the source chamber, is the electron gun for exciting the atoms to their metastable state. The bombarder, shown in Fig. 2, is a diode whose plate consists of a stainless steel block with a 9-mil wide slot, 25-mils high and 0.5 in. long, through which a magnetically-collimated beam of electrons passes in the vertical direction. The electron source is a 5-mil thoriated tungsten filament which is placed just below and protruding about 1-mil into the slot in order to obtain the largest possible space charge limited current. Because the spacing between the filament and the slot walls is of the order of 3- or 4-mils, the filament is heated with 70-kc/sec current to avoid appreciable deflection of the filament in the magnetic-collimating field. The operating conditions were: (1) for Mg, a plate to filament voltage of 4.5 v and a plate current 5 ma; (2) for Zn, a plate to filament voltage of 6 v and a plate current of 6 ma. On the left side of the slot in the metastabilizer plate (see Fig. 2) are two holes for heaters which maintain the plate at a temperature of about 250°C to 300°C in order to prevent condensation of Mg or Zn on the sides of the slot.

The advantages of the electron-bombardment method of metastable-atom production over the discharge-tube

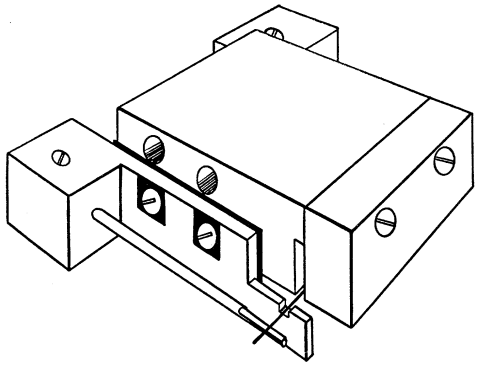

FIG. 2. Electron bombardment gun for production of metastable atoms.

method of production are: (1) Electron bombardment production can be used easily for both gaseous and nongaseous elements; (2) the pressure in the source is arbitrary and not dependent on the criteria for the best discharge conditions; (3) the metastable state may be selectively excited; (4) the photon background is low; (5) the purity of the gas in the source is unimportant except for foreign gases which might poison the filament emission; and (6) several elements (gases for example) may be run simultaneously.

The disadvantages are: (1) recoil scattering of the beam and (2) low bombardment current for low-energy metastable atoms due to space-charge limiting in the electron gun.

C. Detector

If the excitation energy of a metastable atom exceeds the work function of a metal surface, it is energetically possible for a collision of the second kind to take place in which the atom returns to the ground state and an electron is freed from the surface to take up the excess energy.[8] Since this process should be most efficient on an alkali surface,[8] an alkali[9] surface was produced at the detector by continuous evaporation from an oven located between the B magnet and the detector. A very simple way to tell when the detector is being sufficiently coated with cesium to detect efficiently is by using the photoelectric effect. When the surface is properly coated, shining a flashlight at the detector produces a signal which saturates the electrometer amplifier. The detector is a 0.125-in. wide vertical brass strip with a 0.015-in. vertical slot cut in the center. Through this center slot passes the $^3P_0$ state atoms and those atoms in the $^3P_2$ and $^3P_1$ states which have not undergone transitions. The atoms which undergo transitions are deflected onto the cesium-coated sides and detected. With this arrangement the detected signal in the absence of transitions is from 6–10% of the total beam. The presence of this large

[6] G. Breit and L. A. Wills, Phys. Rev. **44**, 470 (1933); H. B. G. Casimir, *On the Interaction between Atomic Nuclei and Electrons* (Teylers Tweede Genootschap, Haarlem, Holland, 1936).

[7] Ladish Company, Cudahy (Milwaukee suburb), Wisconsin.

[8] H. Webb, Phys. Rev. **24**, 113 (1924); W. Lichten, Phys. Rev. **109**, 1191 (1958).

[9] *Note added in proof.* Both potassium and cesium surfaces have been used for detection of the metastable state atoms.

background signal in the absence of transitions is probably due to recoil scattering in the bombarder. The electrons freed from the cesium-coated surface by the metastable atomic beam are collected and amplified with an electrometer circuit whose output is further amplified by a H. P. type 425 A microvolt ammeter which drives a Leeds and Northrup recorder. The time constant of this circuit with a 10^{11}-ohm grid resistor is about 2 sec.

D. Magnetic Fields

The A and B magnets are of conventional design. For the equivalent two wire field, $2a$ is 0.78 cm and hence the ratio of gradient to field is 2.47. The magnets are constructed of Armco iron with Permendur poles. The A and B magnets are each 3-in. long and are wound with 64 turns of Fiberglas-covered $\frac{3}{16}$-in. diameter hollow copper tubing. The magnets, arranged for flop out operation, are run in series and the current is supplied by a modified Garwin circuit.[10] This circuit has a long term stability of about 1 part in 4000. The magnets produce approximately 330 gauss/amp.

III. THEORY OF THE EXPERIMENT AND PROCEDURE

A. Energy Levels

The expression for the energy of the ^3P hyperfine levels in the presence of a weak external magnetic field H_0 is given by

$$W(^3P_J)_{F,M_F}=W_0(^3P_J)+\frac{A_JK}{2}+\frac{3B_J[K(K+1)-\frac{4}{3}I(I+1)J(J+1)]}{8IJ(2I-1)(2J-1)}+W_2(^3P_J)_F+\mu_0 g_F M_F H_0$$
$$+\left[\frac{\alpha^2}{W(^3P_J)_F-W(^3P_J)_{F+1}}+\frac{\beta^2}{W(^3P_J)_F-W(^3P_J)_{F-1}}\right](\mu_0 g_J H_0)^2, \quad (1)$$

where $K=F(F+1)-J(J+1)-I(I+1)$,

$$\alpha^2(F-1)=\beta^2(F)=\frac{(F-I+J)(F+I-J)(I+J+1+F)(F^2-M_F^2)(I+J+1-F)}{4F^2(2F-1)(2F+1)},$$

and I, J, and F are the nuclear, electronic, and total angular-momentum quantum numbers, respectively. A_J and B_J are, respectively, the magnetic dipole and electric quadrupole interaction constants. C_J, the octupole interaction constant, is estimated to be so small for these light elements that it may be ignored within the precision of the present measurements (one in 10^5). $W_2(^3P_J)_F$ is the second-order-hyperfine interaction energy which is smaller than the first order energy by approximately the ratio of the hyperfine-structure separation to the fine-structure separation. $W_2(^3P_J)_F$ has been evaluated recently for ls configurations.[11] For the abundant zero-spin isotopes of Mg and Zn, $W(^3P_J)_{J,M_J}=\mu_0 g_J M_J H_0$ and since g_J is known to at least three places for an unperturbed $^3P_2$ state, the magnetic field H_0 in the transition region may be determined from the frequency of the Zeeman transitions in these isotopes.

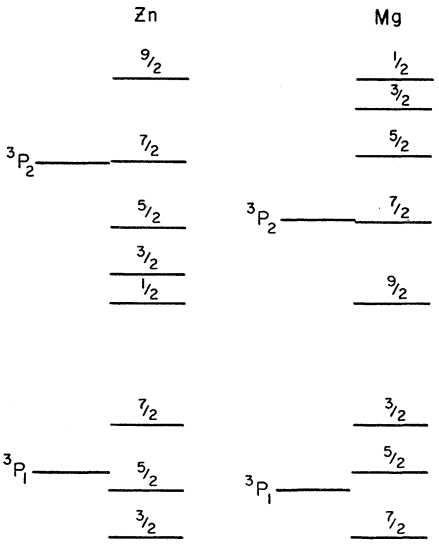

FIG. 3. Hyperfine structure of $^3P_2$ and $^3P_1$ states of Mg^{25} and Zn^{67}.

Figures 3 and 4 show the term level scheme and the zero-field hfs for Zn^{67} and Mg^{25}. The ordinate of Fig. 5 is the relative transition probability for $\Delta F=\pm 1$ π and σ transitions induced with H_{rf} parallel to H_0 for σ, and perpendicular to H_0 for π transitions. Along the abscissa is plotted the deviation of these Zeeman transition frequencies from their zero field value for a static field in the transition region of 0.15 gauss. Only those transitions which may be observed with a flop-out arrangement of the A and B magnets are shown.

B. Procedure

The $^3P_2$ fine structure level for the zero-spin isotopes splits in the magnetic field H_0 into five equally spaced magnetic sublevels. If transitions are induced between these levels a signal of approximately 50% of the total metastable beam is obtained. This signal was very useful

[10] R. L. Garwin, Rev. Sci. Instr. **29**, 223 (1958).
[11] A. Lurio, M. Mandel, and R. Novick, preceding paper [Phys. Rev. **126**, 1758 (1962)].

for measuring the strength and homogenity of the C magnetic field and for estimating the signal-to-noise ratio to be expected in a transition between the hyperfine levels of the $I=\frac{5}{2}$ isotope.

An estimate of the zero-field hfs was first obtained by measuring the frequency of the observable $\Delta F=0$, $\Delta M_F=\pm 1$ transitions in a magnetic field H_0 sufficiently large that these transitions in a given F state were clearly resolved. The magnitude of the frequency difference between these resolved lines is due to terms quadratic in H_0 which depend on $M_F{}^2$, provided H_0 is sufficiently small that terms cubic and higher order in H_0 may be neglected. The last term in Eq. (1) relates the magnitude of this splitting to the hfs separations. The signal-to-noise ratio for these transitions between individual hfs levels varied between two and five during the early measurements. Because of this small signal-to-noise ratio and because the $\Delta F=\pm 1$, $\Delta M_F=0$ transition frequencies are symmetrically displaced about their zero-field frequency (see Fig. 5), some of the data were taken with a sufficiently low magnetic field in the transition region such that all these σ lines overlapped. The center of this composite line was then measured to obtain the hfs separations.

C. Results

The measured hfs separations in the $^3P_2$ state of Zn^{67} are:

$$\begin{aligned}&\Delta\nu(9/2,7/2)=2418.111\pm 0.025 \text{ Mc/sec},\\&\Delta\nu(7/2,5/2)=1855.690\pm 0.015 \text{ Mc/sec},\\&\Delta\nu(5/2,3/2)=1312.065\pm 0.015 \text{ Mc/sec},\\&\Delta\nu(3/2,1/2)=\ 781.865\pm 0.015 \text{ Mc/sec}.\end{aligned}\tag{2}$$

The measured hfs separations in the $^3P_2$ state of Mg^{25} are:

$$\begin{aligned}&\Delta\nu(9/2,7/2)=567.291\pm 0.010 \text{ Mc/sec},\\&\Delta\nu(7/2,5/2)=452.338\pm 0.010 \text{ Mc/sec},\\&\Delta\nu(5/2,3/2)=329.044\pm 0.010 \text{ Mc/sec},\\&\Delta\nu(3/2,1/2)=199.82\pm 0.04 \text{ Mc/sec}.\end{aligned}\tag{3}$$

The measured hfs separations in the $^3P_1$ state of Mg^{25} are:

$$\begin{aligned}&\Delta\nu(7/2,5/2)=516.140\pm 0.010 \text{ Mc/sec},\\&\Delta\nu(5/2,3/2)=349.987\pm 0.010 \text{ Mc/sec}.\end{aligned}\tag{4}$$

By use of an appropriately placed stop wire which blocked out states with certain high-field M_J values, the dipole coupling constant A in the $^3P_2$ state of Mg^{25} was shown to be negative in agreement with the expected result in view of the known negative sign of the Mg^{25} nuclear magnetic moment.

The detection of a beam of atoms in the $^3P_1$ state places a lower limit of approximately 1 msec on the mean lifetime of this state which is in agreement with other experimental results which give a value for this lifetime of 5.3×10^{-3} sec.[5] This lower limit is obtained from the calculated transit time of the $^3P_1$ state atoms in going from the bombarder to the detector and from the observation that the size of the transitions in the $^3P_1$ state have approximately the same intensity as those in the $^3P_2$ state.

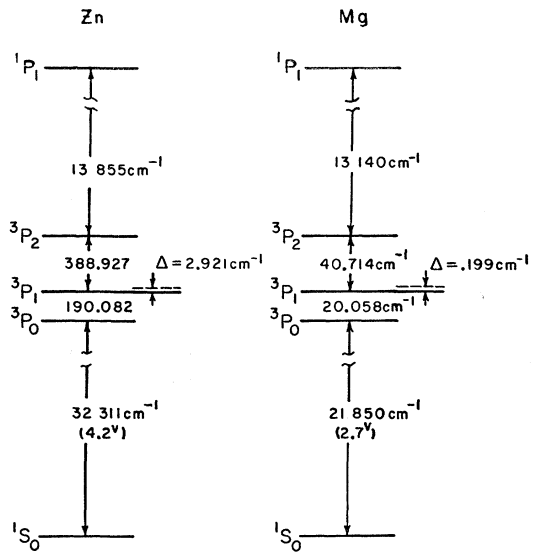

FIG. 4. Term level scheme of Mg and Zn. The dashed line is located one third of the distance between the $^3P_0$ and $^3P_2$ states and is the position that the $^3P_1$ state would have if the ^3P separations obeyed a Landé interval rule.

IV. DISCUSSION OF RESULTS

A. Calculation of hfs Interaction Constants

From Eq. (1) the zero-field hfs separations in the $^3P_2$ state for an atom having a nuclear spin $I=5/2$ are:

$$\begin{aligned}\Delta\nu(9/2,7/2)&=(9/2)A_2+(27/40)B_2\\&\quad+[W_2(^3P_2)_{9/2}-W_2(^3P_2)_{7/2}],\\\Delta\nu(7/2,5/2)&=(7/2)A_2-(7/40)B_2\\&\quad+[W_2(^3P_2)_{7/2}-W_2(^3P_2)_{5/2}],\\\Delta\nu(5/2,3/2)&=(5/2)A_2-(1/2)B_2\\&\quad+[W_2(^3P_2)_{5/2}-W_2(^3P_2)_{3/2}],\\\Delta\nu(3/2,1/2)&=(3/2)A_2-(9/20)B_2\\&\quad+[W_2(^3P_2)_{3/2}-W_2(^3P_2)_{1/2}].\end{aligned}\tag{5}$$

For the zero-field hfs separations in the $^3P_1$ state we obtain:

$$\begin{aligned}\Delta\nu(7/2,5/2)&=(7/2)A_1+(21/20)B_1\\&\quad+[W_2(^3P_1)_{7/2}-W_2(^3P_1)_{5/2}],\\\Delta\nu(5/2,3/2)&=(5/2)A_1-(3/2)B_1\\&\quad+[W_2(^3P_1)_{5/2}-W_2(^3P_1)_{3/2}].\end{aligned}\tag{6}$$

In the above expressions the terms in the brackets are the second-order energies in the perturbation expan-

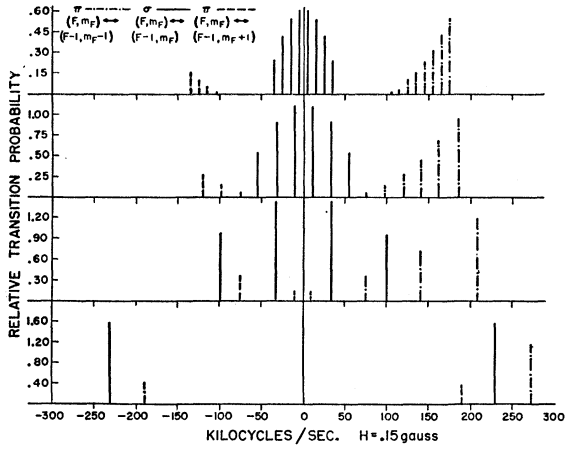

FIG. 5. Frequency shift of the observable $\Delta F=1$ hfs transitions in a magnetic field of 0.15 gauss from their value at zero field.

sion of the hyperfine operator.[9] The manner by which the A_1, A_2, B_1, and B_2 constants are evaluated is the following: a preliminary value is obtained from the experimental $\Delta\nu$'s by ignoring the second order corrections. Then these preliminary values are used to estimate the second-order correction and a new set of A and B values are obtained. For both Mg and Zn a single iteration is sufficient to determine the A's and B's within the experimental error.

In Table I are given the constants necessary to evaluate the second-order corrections. These constants are defined in reference 11. These constants are calculated according to the method of Casimir[5] and Schwartz[12] except for c_1 and c_2 which were evaluated by the method of Wolfe.[13] In Table II are given the uncorrected and the corrected values of the dipole and quadrupole coupling constants for both states and both elements. We have used the data of Böckmann, Krüger, and Recknagle[4] for the $^3P_1$ state of Zn^{67}.

B. Calculation of Individual-Electron hfs Coupling Constants and Comparison with Theory

The dipole interaction constants for the $^3P_2$ and $^3P_1$ states may be written in terms of the individual electron

TABLE I. Constants used in evaluating the second-order hfs corrections.

Constant	Zinc	Magnesium
c_1	0.5656	0.5742
c_2	0.8246	0.8187
ξ	1.01	1.00
η	1.03	1.00
θ	1.095	1.014

[12] C. Schwartz, Phys. Rev. **105**, 173 (1957); **97**, 380 (1955).
[13] Hugh C. Wolfe, Phys. Rev. **41**, 443 (1932).

TABLE II. Values of the hfs interaction constants before and after second-order corrections.

Hfs interaction constant	Zinc Uncorrected (in Mc/sec)	Zinc Corrected (in Mc/sec)	Magnesium Uncorrected (in Mc/sec)	Magnesium Corrected (in Mc/sec)
$A(^3P_2)$	531.987	531.996	−128.445	−128.440
$B(^3P_2)$	35.806	36.024	15.871	16.009
$A(^3P_1)$	608.99	609.15	−144.977	−144.945
$B(^3P_1)$	−19.37	−18.65	−8.304	−8.029

interaction constants as follows:

$$\begin{aligned}
&A(^3P_2)=\tfrac{1}{4}a_s+\tfrac{3}{4}a_{\frac{3}{2}},\\
&A(^3P_1)=\tfrac{1}{4}(2c_2{}^2-c_1{}^2)a_s\\
&\qquad\qquad+[(5/4)c_1{}^2-(5\sqrt{2}/16)c_1c_2\xi]a_{\frac{3}{2}}+\tfrac{1}{2}c_2{}^2a_{\frac{1}{2}},\\
&B(^3P_2)=b_{\frac{3}{2}}=\tfrac{2}{5}e^2QR\langle 1/r^3\rangle_{\rm av},\\
&B(^3P_1)=\tfrac{1}{2}(c_1{}^2-2\sqrt{2}c_1c_2)b_{\frac{3}{2}},
\end{aligned}\tag{7}$$

and

$$a_{\frac{1}{2}}=5\theta(1-\delta)(1-\epsilon)a_{\frac{3}{2}}.$$

In these expressions the subscripts s and $\frac{3}{2}$ refer to the s electron and the $j=\frac{3}{2}$ state of the p electron, respectively. R, ϵ, and δ are small corrections which are tabulated by Kopfermann. The solution of these equations is given in Table III.

It is difficult to estimate a_s from the Fermi-Segrè-Goudsmit[14] formula but, as expected, its value is bounded by the following two values: (1) the measured a_s in the singly ionized ground state of zinc or magnesium and (2) the measured a_s, appropriately scaled for the different magnetic moment, in the ground state of copper and sodium which have one less electron than zinc and magnesium, respectively. The value of $a_{\frac{3}{2}}$ may be calculated from the Fermi-Segrè-Goudsmit formula by using $\langle 1/r^3\rangle_{\rm av}$ taken from the ^3P fine structure and yield the values:

$$a_{\frac{3}{2}}(\mathrm{Zn})=45.2\ \mathrm{Mc/sec},$$

and

$$a_{\frac{3}{2}}(\mathrm{Mg})=-13.7\ \mathrm{Mc/sec}.$$

Here we have assumed that the p-electron fine-structure separation is equal to the $^3P_2-{}^3P_0$ separation. If we correct this separation as indicated by Wolfe, we obtain the values $a_{\frac{3}{2}}(\mathrm{Zn})=39.4$ Mc/sec and $a_{\frac{3}{2}}(\mathrm{Mg})=-9.82$

TABLE III. Value of the s and p electron interaction constants calculated from Eq. (7) using the corrected values of A and B given in Table II.

Individual electron interaction constant	Zinc (Mc/sec)	Magnesium (Mc/sec)
a_s	1996.6	−474.00
$a_{\frac{3}{2}}$	43.8	−13.25
$b_{\frac{3}{2}}$	36.024	16.009

[14] See for example H. Kopfermann, *Nuclear Moments* (Academic Press Inc., New York, 1958), 2nd ed., pp. 129–131.

Mc/sec. The Wolfe correction is in the right direction but is much too large. Z_i in the fine-structure formula[14,15] was taken to be 26 for Zn and 8.8 for Mg.

From Eq. (7) it follows that the ratio $B(^3P_2)/B(^3P_1)$ should be -1.933 for zinc and -1.992 for magnesium. If one takes the correct values of B from Table II we see that the agreement between experimental and theoretical ratio is better than 1%. This excellent agreement may be fortuitous but indicates the necessity for including these corrections.

C. Calculation of the Quadrupole Moments and Comparison with Theory

In order to calculate the quadrupole moment we make use of the value of $a_{\frac{3}{2}}$ to estimate $\langle 1/r^3\rangle_{\text{av}}$. Then from (7) and the Fermi-Segrè-Goudsmit formula we have

$$Q=-\frac{8}{3}\frac{\mu_0^2 g_I F_r b_{\frac{3}{2}}}{e^2 R a_{\frac{3}{2}}}. \tag{8}$$

From this formula we find $Q(Zn^{67})=0.16\times10^{-24}$ cm^2 and $Q(Mg^{25})=0.22\times10^{-24}$ cm^2. The value of $Q(Zn^{67})$ found by Böckmann, Krüger, and Recknagel was 0.18×10^{-24} cm^2 and was based on the measurements of the hfs of the $^3P_1$ state only with Wolfe correction, but no second-order corrections. The value quoted here is believed to be more reliable. There is no detailed nuclear model of the Zn^{67} nucleus with which to compare our results. Many of the properties of the low lying nuclear states of Mg^{25}, however, have been successfully interpreted on the basis of the collective model in strong coupling.[16] It is of interest, therefore, to compare our value of $Q(Mg^{25})$ with the predictions of this model. In the strong-coupling model the quadrupole moment is given by

$$Q=\frac{I(2I-1)}{(I+1)(2I+3)}Q_0=\frac{5}{14}Q_0, \tag{9}$$

where Q_0, the intrinsic quadrupole moment, is defined by

$$Q_0=[3/(5\pi)^{\frac{1}{2}}]ZR_0^2\beta(1+0.16\beta^2). \tag{10}$$

In this expression Z is the atomic number, R_0 is the nuclear radius, and β is the deformation parameter, where β for a spheroidal nucleus is defined by the relation

$$R=R_0(1+\beta Y_0^2), \quad R_0=1.2\times10^{-13}A^{\frac{1}{3}}\text{ cm}, \tag{11}$$

and $Y_0^2(\theta,\phi)$ is the spherical harmonic. The value of β which yields the measured quadrupole moment is $\beta=0.45$. This value of β is in excellent agreement with the experimental results found for Q_0 from Coulomb excitation.[15]

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