The Hyperfine Structure of the $^2P_{3/2}$ State of Al^{27}. The Nuclear Electric Quadrupole Moment

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The hyperfine structure of the $3p\ ^2P_{3/2}$ state of Al^{27} has been measured by the atomic beam magnetic resonance method. The magnetic dipole and electric quadrupole interaction constants a and b have been found to be

$$a=94.25\pm0.04 \text{ Mc/sec.}, \quad b=18.76\pm0.25 \text{ Mc/sec.}$$

From these, the electric quadrupole moment of the nucleus has been calculated to be

$$Q=(0.156\pm0.003)10^{-24} \text{ cm}^2.$$

INTRODUCTION

THE experiment on Al^{27}, which is the subject of this paper, was undertaken as part of the program of this laboratory to measure the nuclear spins and quadrupole moments of light nuclei by the atomic beam magnetic resonance method. Among the nuclei in which there is theoretical interest are the boron nuclei. The high boiling point and the high ionization potential make the problems of generation and detection of an atomic beam of boron rather formidable. As a step towards boron, it was decided to try aluminum, which has a lower boiling point than boron, but a higher boiling point than any that had previously been done by the atomic beam magnetic resonance method. Its ionization potential is lower than that of boron but is sufficiently high so that it was not certain whether it could be detected by the familiar surface ionization method. It is related to boron in belonging to the same chemical family. Both have a $^2P_{1/2}$ atomic ground state and a $^2P_{3/2}$ atomic metastable state. The interaction between the atomic electrons in these two states and the respective nuclei is thus similar in the two elements. The theory of this interaction is exactly the same as that for chlorine described in the preceding paper,[1] hereafter referred to as DFZZ.

The nuclear spin and magnetic moment of Al^{27} were known prior to the present experiment. Further, the hyperfine splitting in the atomic ground state had been measured. A spin of $(5/2)\hbar$ for Al was first found by Heyden and Ritschl[2] using optical spectroscopic methods. This has been confirmed by the present experiment. The first accurate determination of the g-value of the nucleus was made by Millman and Kusch[3] by the magnetic resonance method using a beam of molecules. They obtained a nuclear g-factor of $-1.451\pm0.004\ \mu_n/\hbar$. With $I=5/2$, the nuclear magnetic moment of Al^{27} is 3.628 ± 0.010 nuclear magnetons and positive. The hyperfine separation of the $3p\ ^2P_{1/2}$ ground state of Al was measured by Jackson and Kuhn,[4] who found

$$\Delta\nu(F=3\rightarrow F=2)=0.048\pm0.001 \text{ cm}^{-1}$$
$$=1440\pm30 \text{ Mc per sec.}$$

It is the purpose of this paper to report the measurement of the hyperfine separations of the atomic $^2P_{3/2}$ metastable state and to calculate from them the nuclear electric quadrupole moment.

THEORY

The interaction between the atomic electrons in the $^2P_{3/2}$ state and the nucleus with $I=5/2$ gives rise to four hyperfine levels corresponding to total quantum numbers $F=1$, 2, 3, and 4. When the atom is placed in an external magnetic field H, each hyperfine level is split up into $2F+1$ magnetic levels. There are therefore $(2I+1)(2J+1)=24$ magnetic levels belonging to the $^2P_{3/2}$ term. These levels are the eigenvalues of the Hamiltonian

$$\mathcal{H}/h=aI\cdot J+bQ_{0p}+g_J\mu_0 J\cdot H+g_I\mu_0 I\cdot H,$$

where the meanings of the symbols are as explained in DFZZ. This assumes that perturbations due to states near the $^2P_{3/2}$ are negligible, an assumption which will subsequently be examined. The calculation of the eigenvalues is exactly similar to that for chlorine described in DFZZ, except that I is 5/2 instead of 3/2. The results for $b=0$ are shown in Fig. 1. It is noted that the h.f. separations are given in terms of the constants a and b by

$$\begin{aligned}\Delta\nu(F=4\rightarrow F=3)&=4a+4b/5,\\ \Delta\nu(F=3\rightarrow F=2)&=3a-9b/20,\\ \Delta\nu(F=2\rightarrow F=1)&=2a-4b/5.\end{aligned} \tag{1}$$

Thus, when any two separations are known, the constants may be calculated.

The interval factor a may be estimated from the fine structure separation $3\ ^2P_{3/2}-3\ ^2P_{1/2}=112.01 \text{ cm}^{-1}$. This is done through the use of the relations for a and δ in Section IIC of DFZZ. Using $g_I=-1.451\ m/M$ and $Z_i=Z-3.5$, we get for the $^2P_{1/2}$ state $a\cong500$ Mc/sec. and for the $^2P_{3/2}$ state $a\cong100$ Mc/sec.

Once a and b have been determined from the h.f.

* This work has been supported in part by the Signal Corps, the Air Materiel Command, and the ONR.
[1] Davis, Feld, Zabel, and Zacharias, Phys. Rev., this issue.
[2] M. Heyden and R. Ritschl, Zeits. f. Physik **108**, 739 (1938).
[3] S. Millman and P. Kusch, Phys. Rev. **56**, 303 (1939).
[4] D. A. Jackson and H. Kuhn, Proc. Roy. Soc. **A164**, 48 (1938).

separations, the quadrupole moment of the nucleus is calculated by the method described in DFZZ.

THE METHOD OF THE EXPERIMENT

The method used in the present experiment is the atomic beam magnetic resonance method. The particular variation used is that described in detail by Davis, Nagle, and Zacharias in a preceding paper.[5] Of the transitions between levels of the hyperfine multiplet which are allowed by the selection rules, only those are observable in which m_J at high magnetic fields changes sign between the initial and final states. In the present experiment, the gradients in the deflecting fields are such that only transitions between levels with equal and opposite m_J are observable. Hence, the observable transitions are governed by the selection rules:

$$\left.\begin{aligned}\Delta F&=0,\pm1\\ \Delta m_F&=0,\pm1\end{aligned}\right\}\text{in the } C \text{ field},$$
$$m_J=\tfrac{1}{2}\rightleftarrows m_J=-\tfrac{1}{2} \text{ in the deflecting fields.}$$

APPARATUS

The apparatus in which the present experiment was performed is the one described in the paper of DNZ. Except for the source of atoms, all of the components used in the radioactive nuclei experiments are also used in the aluminum experiment. There are some differences in the operating conditions, however, and these differences are discussed below.

In a high magnetic field the effective magnetic moment of Al atoms in the $^2P_{3/2}$ metastable state with $m_J=\pm\frac{1}{2}$ is $\mp\frac{2}{3}$ Bohr magneton as compared to one Bohr magneton for the alkalis. The temperature of the Al atoms is about 1650°K as compared to, for example, 540°K for Na. Hence, greater deflecting power or narrower slit widths are required for Al. The deflecting power used is the maximum that the apparatus is capable of, *viz.*, about 7000 gauss/cm in the B magnet and about 16,000 gauss/cm in the A magnet. The widths of the various slits used are as follows: source slit 0.01 cm, collimator slit 0.01 cm, detector slit 0.015 cm. Calculations indicate that with this geometry, about 90 percent of the atoms should be deflected completely away from the detector. Actually about 50 percent of the beam was never deflected, possibly because of a high percentage of aluminum molecules in the beam.

To stop the insufficiently deflected atoms or molecules from reaching the detector, an obstacle wire of 0.013 cm in diameter is placed in the direct path of the beam at the end of the B magnet. Atoms which undergo the proper transitions are caused to go around the obstacle wire to reach the detector.

The detector used for aluminum is the one described in DNZ. The wire used for ionization is commercial tungsten. Its operating temperature is about 1780°K. At this temperature, the surface of the wire is probably free from tungsten oxide. Hence, the work function of the surface is that of pure tungsten, i.e., 4.5 volts. The efficiency of this surface in the ionization of aluminum atoms, which have an ionization potential of 5.98 volts, is experimentally estimated to be about 10^{-6}. The efficiency goes up with an increase in temperature of the tungsten. However, it has been found that tungsten of commercial purity, when heated to temperatures of 1700°K and above, gives off ions of elements which are present in the tungsten as impurities. In a mass spectrographic analysis of the ions, the atoms Na^{23}, Al^{27}, K^{39}, K^{41}, and Cs^{133} are identified. These Al ions always constitute an undesirable background. The intensity of ions from impurities in the filament increases with its temperature. Although this intensity decreases with age and with flashing, it was not possible to reduce it to zero. The temperature of 1780°K used in the present experiment seemed to be the best compromise between background and detection efficiency under the conditions of the experiment.

The ions from the detector, after having been analyzed by a mass spectrograph, are allowed to strike the first plate of an electron multiplier. Electrons liberated from this plate are multiplied by a succession of surfaces of high secondary-emission ratio and finally cause a pulse of voltage to appear at the last stage. This voltage pulse is amplified by a vacuum-tube amplifier and counted in a pulse counting system.

Prior to the experiments described in the present series of papers, the ions from the surface ionization detector have always been measured as an ion current by means of a d.c. amplifier and galvanometer. The practical limit of sensitivity of which this method is capable is set by the maximum time constant that can be tolerated. In atomic beam work, the maximum tolerable time constant is about ten seconds, for otherwise, the search for transitions would be very tedious and severe requirements would be imposed on the constancy of the atomic beam. Under these restrictions, a usable sensitivity of about 3×10^{-17} amp./mm is about the best that has been attained. By counting individual ions, however, it is possible to do better than this. An electron multiplier can be constructed which has a background counting rate of less than one a second. The time constant of the instrument is less than a microsecond. The time required for an individual reading, however, is dictated by statistical considerations. When the transition intensities are appreciably above the background, the short time constant permits a rapid search for transitions.

The construction of the multiplier used in this experiment and in the experiments of Davis, Nagle, and Zacharias is shown in Fig. 2. The geometry of the plates is copied from that of the RCA 931-A.** The material of the electrodes is commercial beryllium

[5] Davis, Nagle, and Zacharias, Phys. Rev., this issue.

** The author wishes to thank Dr. A. M. Glover of RCA for providing him with several sets of nickel dynodes of the 931-A with which some preliminary experiments were done.

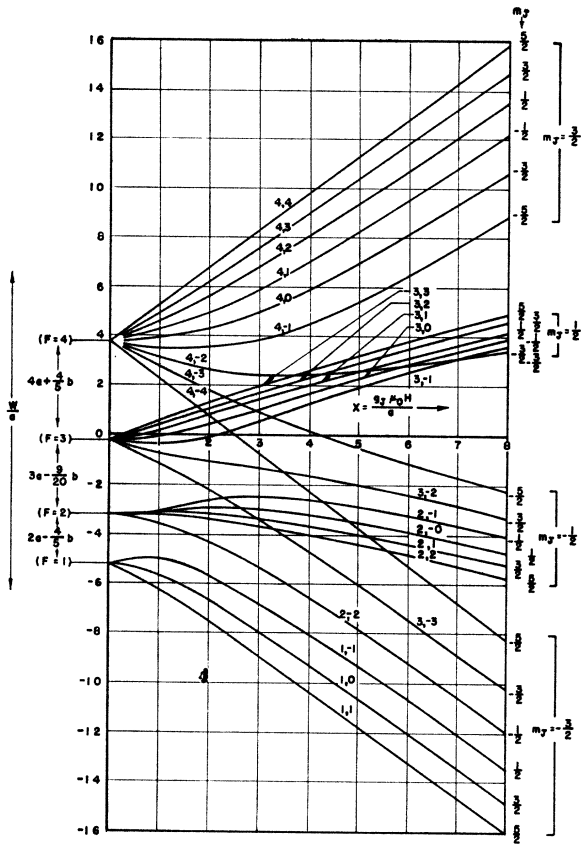

FIG. 1. Energy levels of the $^2P_{3/2}$ state of aluminum in an external magnetic field with the nuclear quadrupole moment assumed zero.

copper alloy (4 percent Be, 96 percent Cu), 0.012 cm thick. The two end pieces between which the dynodes are mounted are of Lavite. Just before the dynodes are mounted in position between the Lavite pieces, they are scrubbed with fine emery cloth and washed in acetone. The assembly is then placed in a vacuum and heated for about fifteen minutes at 900–1100°K, as recommended by Allen.[6] The vacuum should be about 10^{-5} mm Hg. The heating may be by induction or by radiation. When this temperature range is greatly exceeded, it is found that the Be–Cu deposits metal on the Lavite, resulting in leakage between the dynodes. All matter which has a higher vapor pressure than Be–Cu, such as cadmium and solder, should be excluded from the vicinity of the multiplier during the heat treatment. After the firing, the multiplier is immediately mounted in its housing. The housing is a rectangular iron box lined with thin mica. It holds, in addition to the multiplier, a bank of eleven resistors mounted on a piece of Lavite. Ten of these resistors constitute a voltage divider whereby the proper operating voltages for the multiplier are obtained; the eleventh resistor is the output load resistor. The resistors are of $\frac{1}{2}$-watt, 10-megohm rating and are of the commercial type with composition bodies. Although they probably have a high vapor pressure, the gas they give off is insufficient to affect the vacuum of the apparatus in which they are used. Connection between the dynodes and the proper terminals on the resistor bank is made by 0.06 cm nickel wire insulated with glass tubing. A total of 3000 volts is applied to the voltage divider, thus providing 300 volts between successive stages of the multiplier. For positive ion detection, the first dynode is at −3000 volts with respect to the box or ground. Thus, ions entering the front slit of the box acquire an additional 3000 electron-volts of energy before striking the multiplier.

A multiplier constructed in the above manner has been found to have an efficiency of 15 percent in the detection of Na and K ions of 3600 ev total energy. That is, 15 percent of the incident ions give measurable pulses.

In the apparatus of DNZ, the multiplier is located near the inlet port of an oil diffusion pump of 600 liters/sec. capacity. It has been observed that, with the multiplier in this position, the background counting rate is of the order of 30 a second. This is ten or twenty times as high as it is when the multiplier is situated several feet from the mouth of a well-baffled pump. It may therefore be that there are ions in the oil vapor. At any rate, when a copper baffle cooled with liquid air is placed immediately in front of the multiplier, the background counting rate goes down to less than one a second. The baffle has a slit which is in line with the entrance slit of the multiplier.

When the ion intensity incident on the multiplier is so great that the counting rate exceeds 10,000 per second, it is not convenient to count the individual pulses from the multiplier with the counting circuits we have on hand. However, the ion current is then large enough to be measured with a d.c. amplifier and galvanometer. The ions are collected on a probe mounted just beside and parallel to the slit of the multiplier. The ion beam is deflected onto the probe by changing the accelerating voltage in the ion source. It is obvious that one can measure the counting efficiency of the multiplier with this arrangement.

The oven which is the source of aluminum atoms is shown in Fig. 3. It consists essentially of an aluminum oxide crucible placed within a thin-walled graphite jacket. Tantalum foil is wrapped around the crucible to prevent it from being in contact with the graphite. The aluminum to be evaporated is placed in the crucible in the form of wire. This design of the oven was arrived at through trial and error. Our first attempt was to use a molybdenum tube of the same shape as the graphite jacket and to put the aluminum to be evaporated in direct contact with the molybdenum. It was found that the aluminum crept up the walls of the tube and clogged the slit. Then we tried replacing the molybdenum with graphite. We found then that the molten aluminum

[6] J. S. Allen, Rev. Sci. Inst. **18**, 739 (1947).

went into the pores of the graphite and cracked it. Containing the aluminum in a tantalum cup placed within the graphite jacket did not overcome the trouble because the aluminum crept over the sides of the cup and down into the graphite again. An aluminum oxide crucible was then tried and found to contain the aluminum satisfactorily. It was necessary, however, to isolate the crucible with tantalum foil from direct contact with the graphite in order to prevent its reduction by the carbon.

The heating of the oven is accomplished by passing alternating current directly through the graphite jacket. With water-cooled radiation shielding surrounding the oven, 800 watts of power is necessary to raise the temperature of the oven in the region of the slit to 1670°K, the operating temperature. The maximum usable temperature of this oven is about 1700°K for, beyond this, the aluminum oxide seems to decompose and liberate enough oxygen to cause the pressure in the oven chamber to exceed 5×10^{-5} mm Hg. The intensity of the aluminum beam then drops because of scattering.

Although the temperature of the central region of the oven is about 1670°K, that of the coolest part is probably somewhat below this. This temperature has not been measured but it may be estimated by the amount of time a given charge of aluminum lasts in the oven. A charge of 0.17 gram lasts about six hours. The effusion rate through the slit is then about 3×10^{-7} mole/sec. Using a well-known formula for the rate of effusion of atoms through a hole in a thin wall,[7] the vapor pressure in the oven is calculated to be 0.17 mm Hg. This vapor pressure corresponds to a temperature of 1650°K[8] and therefore the coolest part of the oven is at this temperature. This estimate is rough because some of the aluminum combines with the graphite to form yellow Al_4C_3 and is therefore lost from the beam. On the other hand, the decomposition of the Al_2O_3 of the crucible yields Al atoms which contribute to the beam.

At 1650°K, about 65 percent of the atoms are in the $^2P_{3/2}$ metastable state which is 112 cm^{-1} above the $^2P_{1/2}$ ground state. The mean life of an atom in the metastable state is long compared to the transit time in the apparatus.

For the alignment of the apparatus and the calibration of the homogeneous C field during measurements on aluminum, a beam of sodium atoms is used. An oven for the generation of a sodium beam is mounted beside the aluminum oven. It is of iron and is heated by radiation from a tungsten coil. It may be moved in front of the aluminum oven through an external control to the proper oven position.

The sources of radiofrequency power are a General Radio Type 805C signal generator which covers the range from 16 kc to 50 mc and a F-4800 Lighthouse Tube Airborne Transmitter which covers the range from 270 mc to 2500 mc. Frequency is measured in their respective ranges on a General Radio Type 620A heterodyne frequency meter and calibrator and a U. S. Army Signal Corps Type TS-175/U frequency meter.

EXPERIMENTAL PROCEDURE

When all the components of the apparatus except the Al oven are lined up by means of a sodium beam, the aluminum oven is brought up to a temperature of about 1670°K, as observed by an optical pyrometer. The obstacle wire is swung out of the line of the beam and the Al oven is moved into a position which gives the maximum detected beam intensity. With the tungsten ribbon detector at about 1780°K, the detected beam intensity as measured by the galvanometer should correspond to a counting rate of the order of 300,000 a second. This figure may vary by as much as 50 percent, for it depends strongly on the temperature of the tungsten ribbon. In any run, the latter is adjusted to give the maximum ratio of transition signal to background.

After the positioning of the Al oven, the obstacle wire is swung back into position. This cuts off the beam entirely and the counts registered by the multiplier on mass number 27 are due mostly to Al ions given off by the tungsten detector itself. Under our conditions of operation, the counting rate is about 500 a second. When the A and B deflecting fields are turned on, however, but without any r-f power in the C region, the counting rate goes up to from 2000 to 5000 a second. The reason for this is that high velocity atoms in the penumbra of the beam are deflected so little that the joint effect of the two deflecting fields working in the

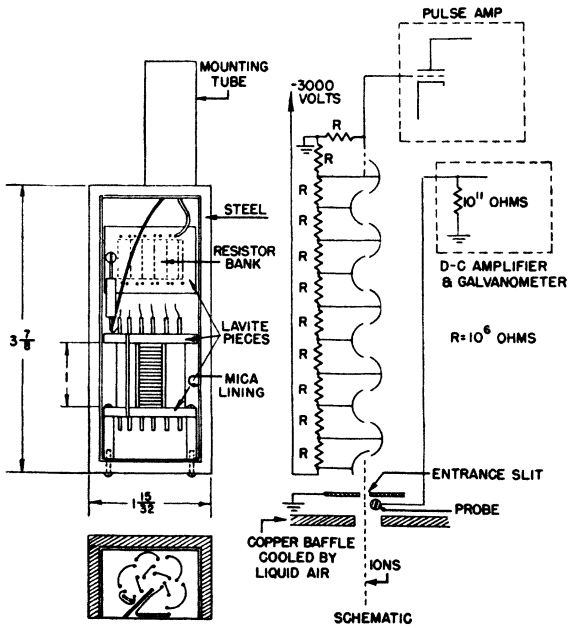

FIG. 2. Electron multiplier and circuit.

[7] I. Esterman, Rev. Mod. Phys. 18, 300 (1946).
[8] R. W. Ditchburn and J. C. Gilmour, Rev. Mod. Phys. 13, 310 (1941).

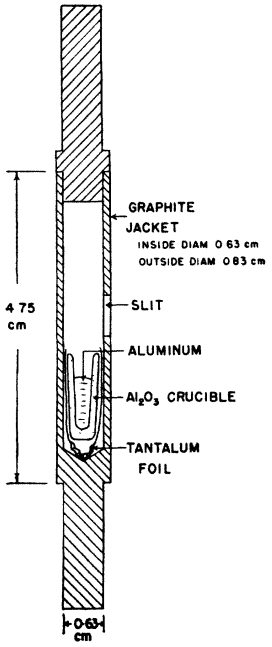

FIG. 3. Oven for generating a beam of aluminum atoms.

same direction is to throw these atoms around the obstacle wire into the detector. The trajectory of such atoms is shown by the solid lines in Fig. 4 while the dotted lines show what the trajectory would be if there were greater deflecting power in proportion to the width of the slits used. Although narrowing the slits would remove this source of background, it would reduce the beam intensity and consequently the intensity of the induced transitions. The weak transitions might then be buried in the background from the tungsten ribbon itself. A transition, to be observed, must show up above the background. The latter has been found to fluctuate about 10 percent in intensity, probably due to fluctuations in the intensity of the aluminum beam. When, in a search for transitions, a change in the counting rate of the multiplier is observed and it is suspected that this is due to transitions, the r-f oscillator is tuned through the suspected peak repeatedly. If the occurrence of the peak coincides with the tuning of the oscillator over a certain frequency range, it is considered probable that a genuine transition is being observed. This technique has been used on all the observations. The strongest lines observed are about 75 percent above background. No detailed plots of the shapes of the lines have been made but it has been estimated that the line widths are about 200 kilocycles. The accuracy of each observation is approximately ± 100 kilocycles.

RESULTS

$^2P_{3/2}$

By the selection rules mentioned earlier, there are fourteen observable transitions between the magnetic levels of the hyperfine multiplet of the $^2P_{3/2}$ state. These are listed in Table I. The transition probabilities are also shown. Two of the lines involve no change in the quantum number F; twelve involve a change of ± 1. At very low magnetic fields, the frequencies of the $\Delta F=0$ lines are given by

$$\nu = g_F \mu_0 H/h,$$

where

$$g_F = g_J \frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)} + g_I \frac{F(F+1)-J(J+1)+I(I+1)}{2F(F+1)}$$

Neglecting the second term in g_F, the frequencies of the two $\Delta F=0$ lines are

$$\nu(4, -2 \rightarrow 4, -3) = \tfrac{1}{2}\mu_0 H/h,$$
$$\nu(3, -1 \rightarrow 3, -2) = (7/18)\mu_0 H/h.$$

Agreement has been found between these theoretical expressions and the observed frequencies, using the $(F=2,\ m_F=-1 \rightarrow F=2,\ m_F=-2)$ line of Na as the calibration of the field H. This agreement is interpreted as confirming a spin of 5/2 for Al.

Of the lines involving $\Delta F=\pm 1$, five are π-lines $(\Delta m_F=0)$ and seven are σ-lines $(\Delta m_f=\pm 1)$. The former are induced by components of the oscillating magnetic field parallel to the constant homogeneous field and the latter are induced by components perpendicular to the constant field. The ribbon which carries the radiofrequency power is such that the oscillating field is mainly perpendicular to the constant field. Thus σ-lines are expected to be stronger than π-lines. The points in Figs. 5 and 6 show the observed transitions plotted against the intensity of the C field. Figure 6 shows the $(4, -2) \rightarrow (3, -2)$ line, the only line which is observable between the $F=4$ and $F=3$ levels. Figure 5 shows transitions between $F=3$ and $F=2$ levels. The association of the experimental points with various lines is done by trial and error. In the figures, the curves shown are calculated for $\Delta\nu(F=4 \rightarrow F-3)=392.0$

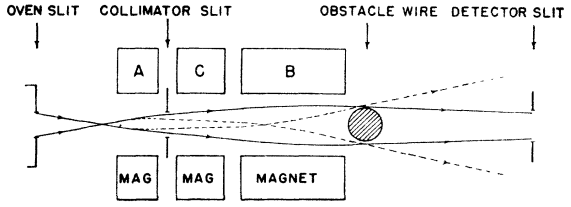

FIG. 4. Diagram of the essentials of an atomic beam system illustrating the effect of insufficient deflecting power.

Mc/sec. and $\Delta\nu(F=3 \rightarrow F=2)=274.3$ Mc/sec. The fit between the curves and the experimental points is fairly good in spite of the fact that not all the points fall on some curve. Further evidence of the correctness of the identification is seen in the fact that, in Fig. 5, the

σ-lines (solid curves) contain more experimental points than the π-lines (dashed curves). In fact, except for the line $(3, 0)\rightarrow(2, 0)$, the π-lines are not definitely observed, indicating that the parallel component of the oscillating field is too weak. Perhaps the reason that the $(3, 0)\rightarrow(2, 0)$ line is observed is that its transition probability is slightly higher than that of the other π-lines, as seen in Table I. As to the reason why the π-line $(4, -2)\rightarrow(3, -2)$ is so strong, it may be that the r-f oscillator delivers more power to the r-f hairpin ribbon at 392 Mc than around 274 Mc. From the data

TABLE I. Observable transitions and transition probabilities. For absolute values, the above probabilities should be multiplied by $(\pi t\mu_0 g_J/\hbar)^2$ where t is the time the atom spends in the transition field $H'=H_x i+H_z k$. See DFZZ.

$^2P_{3/2}$ state		$^2P_{1/2}$ state	
Transition	Probability	Transition	Probability
$3, 3\rightarrow 2, 2$	$0.53\ H_x^2$	$3, 3\rightarrow 2, 2$	$0.035\ H_x^2$
$3, 2\rightarrow 2, 2$	$0.9\ H_z^2$	$3, 2\rightarrow 2, 2$	$0.09\ H_z^2$
$3, 2\rightarrow 2, 1$	$0.9\ H_x^2$	$3, 2\rightarrow 2, 1$	$0.09\ H_x^2$
$3, 1\rightarrow 2, 2$	$0.09\ H_x^2$	$3, 1\rightarrow 2, 2$	$0.009\ H_x^2$
$3, 1\rightarrow 2, 1$	$1.4\ H_z^2$	$3, 1\rightarrow 2, 1$	$0.1\ H_z^2$
$3, 1\rightarrow 2, 0$	$0.53\ H_x^2$	$3, 1\rightarrow 2, 0$	$0.035\ H_x^2$
$3, 0\rightarrow 2, 1$	$0.26\ H_x^2$	$3, 0\rightarrow 2, 1$	$0.017\ H_x^2$
$3, 0\rightarrow 2, 0$	$1.6\ H_z^2$	$3, 0\rightarrow 2, 0$	$0.11\ H_z^2$
$3, 0\rightarrow 2, -1$	$0.26\ H_x^2$	$3, 0\rightarrow 2, -1$	$0.017\ H_x^2$
$3, -1\rightarrow 2, 0$	$0.53\ H_x^2$	$3, -1\rightarrow 2, 0$	$0.035\ H_x^2$
$3, -1\rightarrow 2, -1$	$1.4\ H_z^2$	$3, -1\rightarrow 2, -1$	$0.11\ H_z^2$
$3, -1\rightarrow 3, -2$	$0.38\ H_x^2$	$3, -2\rightarrow 3, -3$	$0.017\ H_x^2$
$4, -2\rightarrow 4, -3$	$0.87\ H_x^2$		
$4, -2\rightarrow 3, -2$	$0.7\ H_z^2$		

available, the most probable values of the hyperfine separations are, with estimated errors,

$$\Delta\nu(F=4\rightarrow F=3)=392.0\pm0.2\text{ Mc},$$
$$\Delta\nu(F=3\rightarrow F=2)=274.3\pm0.1\text{ Mc}.$$

Using Eq. (1) the constants a and b are

$$a=94.25\pm0.04\text{ Mc},\quad b=18.76\pm0.25\text{ Mc},$$
$$b/a=0.199\pm0.003.$$

The nuclear electric quadrupole moment is calculated by the technique described in Section IIC of DFZZ. For a $^2P_{3/2}$ state arising from a single p electron, we have for the interaction constant a,

$$a=-16g_I\mu_0^2\langle r^{-3}\rangle_{Av}/15h,$$

and for the interaction constant b,

$$b=2e^2Q\langle r^{-3}\rangle_{Av}/5h,$$

where in both relations we have neglected small relativistic corrections. Eliminating $\langle\langle r^{-3}\rangle\rangle_{Av}$ from these relations and using previously quoted values of g_I and b/a, we obtain for the value of the nuclear electric quadrupole moment

$$Q=(0.156\pm0.003)10^{-24}\text{ cm}^2.$$

$^2P_{1/2}$

Of the possible transitions between magnetic levels of the $3p\ ^2P_{1/2}$ state, only one is observable for which

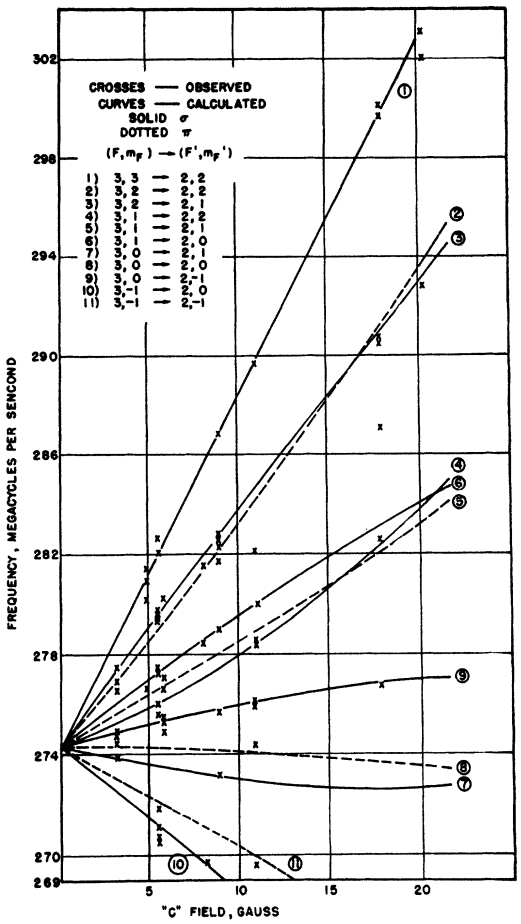

FIG. 5. Observed transitions between $F=3$ levels and $F=2$ levels of the $^2P_{3/2}$ state of Al plotted as a function of the external magnetic field.

$\Delta F=0$, *viz.*, $(3, -2)\rightarrow(3, -3)$. The frequency of this line has been measured as a function of the magnetic field up to a field of 250 gauss. The transition intensities were very weak. When the magnetic field was increased beyond the above value, it was necessary to change from the General Radio Type 805C oscillator to one of lower power and the line was not picked up again. From

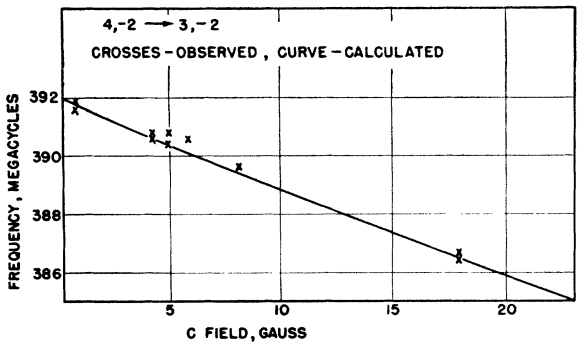

FIG. 6. Observed line $(F=4, m_F=-2)\rightarrow(F=3, m_F=-2)$ of the $^2P_{3/2}$ state of Al plotted as a function of external magnetic field.

the measurements at 250 gauss, the hyperfine separation of the $^2P_{1/2}$ state was calculated to be 1500±50 megacycles per second. Several attempts were then made to find transitions between $F=3$ and $F=2$. Both because of the lower power output of the Lighthouse Tube oscillator in the region around 1500 Mc and because of the lower transition probabilities of the lines relative to those of the $^2P_{3/2}$ state, as seen in Table I, no transition with $\Delta F=\pm 1$ was detected. The inaccurate value of $\Delta\nu$ obtained, however, serves as further indication that the element that has been studied is aluminum, since it overlaps the spectroscopic value found by Jackson and Kuhn.

Perturbations between Fine Structure Levels

We have so far ascribed the deviation from the interval rule of the hyperfine structure of the $^2P_{3/2}$ state to the effect of a nuclear quadrupole moment. The same effect, however, may be caused by perturbations due to neighboring fine structure levels. Casimir[9] has shown that levels with the same F and differing in J by 0 or 1 repel each other with an interaction energy of the order of (hyperfine splitting)^2/(fine structure separation). Thus the $F=3$ and $F=2$ levels of the $^2P_{3/2}$ state interact with the corresponding levels of the $^2P_{1/2}$ state. The total width of the hyperfine structure of the former state is about 900 Mc/sec. and the $^2P_{3/2}-{}^2P_{1/2}$ separation is about 3.36×10^{12} cycles. The magnitude of the repulsion is therefore 0.25 Mc or about one percent of the observed deviation from the interval rule.Thus we are justified in ascribing the latter to the effect of a nuclear electric quadrupole moment.

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Extensive Air Showers at High Altitudes

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The latitude dependence, density properties, and lateral extension of extensive cosmic-ray air showers have been studied at 9200 m elevation, with coincidence counters in a B-29 airplane. On a flight between 0° and 63°N geomagnetic latitude, no significant variation of shower frequency with latitude has been detected.

Relations between the counting rates of coincidence counter sets of different orders from threefold to ninefold are in agreement with a power law density spectrum for the showers, with constant negative exponent. The measured value of this exponent is 1.73±0.04 at 9200 m, 1.82±0.07 at 11,000–12,000 m, and 1.53±0.07 at 720 m. The counting rate of a threefold coincidence counter set was found to decrease 33 percent as the total spread of the counters was increased from 2.8 m to 13 m at 9200 m altitude. The corresponding decrease at 720 m is 21 percent. The altitude dependence of the extensive showers was measured up to 12,300 m, and a definite maximum shower rate has been found near an altitude of 8000 m.

I. INTRODUCTION

SINCE their discovery more than ten years ago,[1–3] large cosmic-ray air showers have been studied intensively in the lower atmosphere. However, the rapid increase in number of showers with altitude in the lower atmosphere indicates that most of them are being absorbed in this region, and that their source is high in the upper atmosphere. Investigations conducted nearer to the origin of the showers should provide a more sensitive test of hypotheses concerning their production and growth than similar studies at lower altitudes. Therefore, coincidence counter measurements of the properties of extensive air showers have been undertaken in a B-29 airplane flying between 6000 and 12,000 m above sea level. The altitude dependence has been measured up to 12,300 m. The density structure of the air showers was studied at 9200 m and higher altitudes, by determining the counting rate as a function of the number of counters in coincidence. Observations were also made of the variation of shower frequency with latitude and with total spread of the coincidence counters. Preliminary reports of the altitude dependence have been published previously.[4,5]

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