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## $N^{14} \ ^4S_{3/2} \ g_J$ Factor Measured by an Atomic-Beam Universal-Detector Technique\*

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The atomic-beam magnetic-resonance technique has been used to measure the  $g$ -factor ratio of the ground state of nitrogen to the ground state of potassium. The result is  $g_J(N^{14}, \ ^4S_{3/2})/g_J(K^{39}, \ ^2S_{1/2}) = 0.999\ 919\ 6(20)$ , where the quoted error represents the 90% confidence level. Combining this result with that of other researchers, we find the absolute  $g_J$  factor for nitrogen to be  $g_J(N^{14}, \ ^4S_{3/2}) = 2.002\ 134(5)$ . This value is in much better agreement with the result of a recent calculation carried out according to the theory of Kambe and Van Vleck than is the earlier measured value, which was obtained by electron paramagnetic resonance. The discrepancy between experiment and theory is reduced from  $13.5 \pm 2$  to  $4 \pm 2.5$  ppm. The atomic nitrogen was generated in an electrodeless discharge and detected with a new mass-spectrometer universal detector; this latter instrument is described in some detail.

### I. INTRODUCTION

In the last few years, several calculations of atomic  $g_J$  factors have been made using the theory of Kambe and Van Vleck and high-accuracy Hartree-Fock wave functions.<sup>1</sup> The theoretical  $g_J$  factors calculated for the  $^3P_1$  and  $^3P_2$  states of atomic oxygen, as well as for the  $^2P_{3/2}$  state of fluorine, were found to agree with experiment to within 1 ppm or better<sup>2</sup>; this result fostered the hope that such accuracy could be obtained for all states of first-row atoms for which Hartree-Fock wave functions of comparable accuracy were available. Recent theoretical results for nitrogen, however, did not encourage this hope; for the  $^4S_{3/2}$ ,  $^2D_{5/2}$ , and  $^2D_{3/2}$  states the discrepancies with measured  $g_J$  values were found to be  $13.5 \pm 2$ ,  $30 \pm 8.5$ , and  $15 \pm 25$  ppm, respectively.<sup>3</sup> The contrast between such exact agreement in fluorine and oxygen and such striking discrepancies in nitrogen suggested that a remeasurement of these latter  $g_J$  values was in order. The results of the remeasurement of the  $g_J$  value of the  $^4S_{3/2}$  state are reported here.

### II. THEORY OF EXPERIMENT

The ground configuration of nitrogen is  $1s^2 2s^2 2p^3$ , giving rise to three multiplets: the  $^4S_{3/2}$  ground state, the  $^2D_{5/2, 3/2}$  states, and the  $^2P_{3/2, 1/2}$  states, which are 19 230 and 28 840  $\text{cm}^{-1}$  above the ground state, respectively.<sup>4</sup> The Hamiltonian describing the hyperfine structure (hfs) and Zeeman effect of the  $^4S_{3/2}$  ground state of nitrogen is<sup>5</sup>

$$\mathcal{H} = ah\vec{I} \cdot \vec{J} + bh \frac{3(\vec{I} \cdot \vec{J})^2 + \frac{3}{2}(\vec{I} \cdot \vec{J}) - I(I+1)J(J+1)}{2I(2I+1)J(2J+1)}$$

$$+ g_J \mu_B (\vec{J} \cdot \vec{H}) - g_I \mu_B (\vec{I} \cdot \vec{H}), \quad (1)$$

where  $a$  is the hfs magnetic-dipole interaction constant,  $b$  the nuclear-quadrupole interaction constant,  $I\hbar$  the nuclear angular momentum,  $J\hbar$  the electronic angular momentum,  $g_I = \mu_I/I$  and  $g_J = -\mu_J/J$  the corresponding  $g$  factors (where  $\mu_I$  and  $\mu_J$  are measured in  $\mu_B$  and  $I=1$  for  $N^{14}$ ), and  $\vec{H}$  the magnetic field. The energy levels for any value of  $H$  are obtained by diagonalizing this Hamiltonian on the set of hyperfine states ( $I, J, F, M_F$ ) associated with the electronic state of interest. Because the dominant configuration contains no unpaired  $s$  electrons, the hfs magnetic-dipole constant  $a$  is quite small. Owing to the spherical symmetry of the half-filled  $p$  shell ( $S$  state), the quadrupole coupling constant is very nearly zero in the ground state.

The operation of an atomic-beam apparatus has been adequately described elsewhere.<sup>5</sup> Here it suffices to note that the apparatus used in this experiment is of the "flop-in" variety; thus, in order to be observable, transitions must change the sign of the projection of the magnetic moment along the direction of the magnetic field, and also satisfy the usual selection rules for magnetic-dipole transitions between Zeeman-split hyperfine levels.

The two transitions between hyperfine levels of the  $^4S_{3/2}$  ground state of  $N^{14}$  studied in this experiment are designated  $\alpha$  and  $\beta$ ; see Fig. 1. They connect states characterized by the low-field quantum numbers ( $F, M_F$ ) given by

$$\alpha: (2.5, -0.5) \leftrightarrow (2.5, -1.5),$$

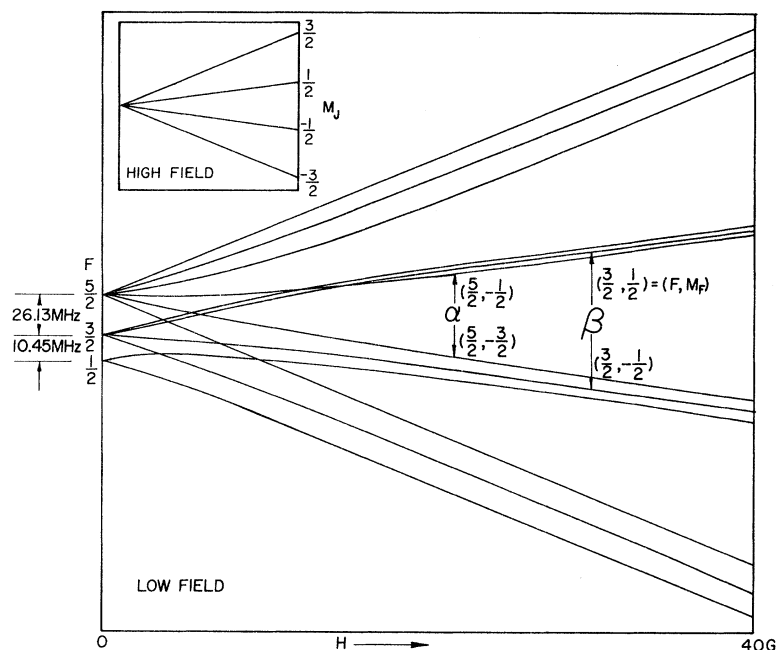


FIG. 1. Energy vs magnetic field for the hyperfine level of the  $4S_{3/2}$  ground state of  $N^{14}$ .

$$\beta: (1.5, +0.5) \leftrightarrow (1.5, -0.5).$$

In order to make a high-precision measurement of the  $g_J$  factor, these transitions were observed at magnetic fields between 3 and 4 kG; in this region, the dependence of the transition frequency upon the  $g_J$  values is large [ $\partial\nu/\partial g_J = 5 \times 10^3$  MHz/(unit  $g_J$ )].

### III. APPARATUS

The atomic-beam apparatus used in this experiment has been described previously.<sup>6</sup> Only those features pertinent to this experiment will now be discussed.

Atomic nitrogen is produced in a nitrogen microwave discharge powered by a 2450-MHz 100-W diathermy unit. The beam source is very similar to that described by Brink.<sup>7</sup> Approximately 3% of the gas effusing from the source slit is atomic nitrogen, and virtually all of the atomic nitrogen is in the  $4S_{3/2}$  ground state. Searches for the  $2P$  and  $2D$  states were unsuccessful.

The hairpin which causes the transitions consists of a 50- $\Omega$  terminated coaxial line; the entrance and the exit slits are located off axis to allow the beam to pass without interference from the center conductor. The radio-frequency equipment which

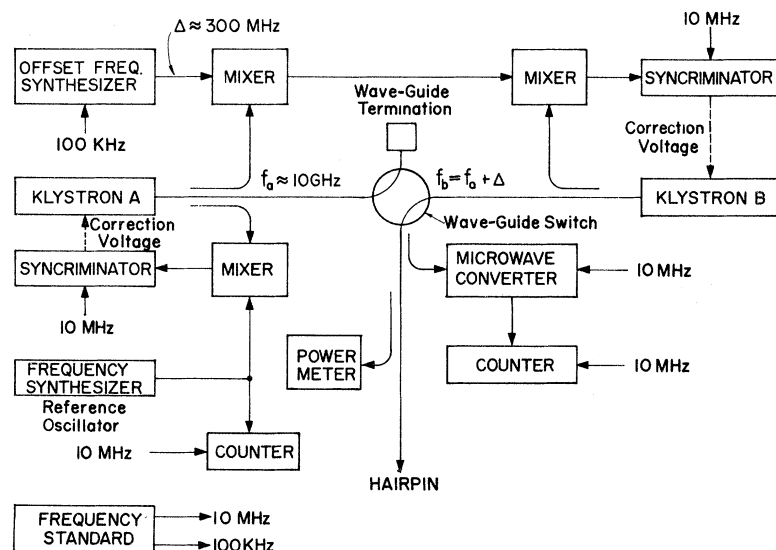


FIG. 2. x-band microwave generation and frequency control equipment.

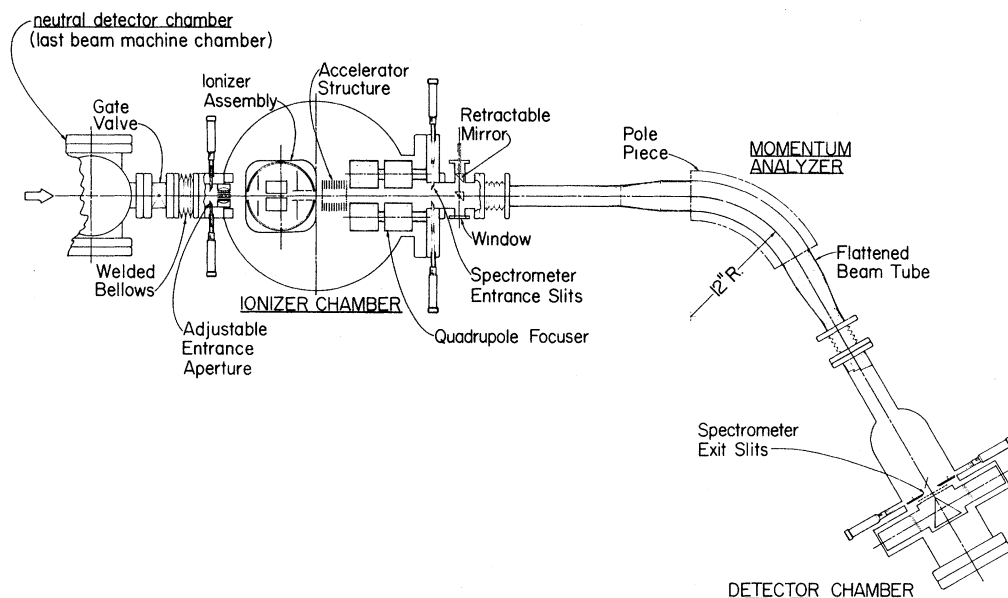


FIG. 3. Mass-spectrometer universal detector.

drives the hairpin is shown in Fig. 2. A waveguide switch allows either of two x-band klystrons to be connected to the hairpin. Klystron *A* is tuned to the  $K^{39}$  calibration resonance, which is used to measure the magnetic field at the hairpin; klystron *B* is tuned to the frequency of the  $N^{14}$  transition being studied. The output frequencies of both klystrons are locked to a harmonic of the reference oscillator, a Hewlett-Packard model 5105A frequency synthesizer. Klystron *A* is directly phase locked by means of a Schomandl FDS-3 syncriminator, while klystron *B* is phase locked to a frequency displaced by approximately 300 MHz. Sweeping the reference-oscillator frequency scans the output frequency of both klystrons simultaneously. The two frequencies are measured with a microwave frequency converter and a digital frequency counter.

#### A. Universal Detector

Detection of the nitrogen beam is accomplished by means of an electron-bombardment universal detector (Fig. 3). Since this device is new, it will be briefly described.

The beam is allowed to enter the ionizer of the universal detector, where it is cross bombarded with electrons. The ions created are then extracted from the ionization region, accelerated, and directed into a magnetic mass analyzer. The mass analysis is necessary because most of the ions created are from residual gas in the ionizer rather than from the tenuous beam. During data taking, the magnetic field is set so that only ions with masses corresponding to beam atoms are de-

tected by the electron multiplier behind the mass-analyzer exit slit.

Details of the ionizer construction are shown in Fig. 4. The anode is formed by winding 0.002-in.-diam tungsten wire on two lightly threaded alumina support rods. On one of the rods, No. 26 nichrome wire was wound in the threads prior to the winding of the anode so that, in the finished device, each successive turn of the tungsten would come in contact with each successive turn of the nichrome wire. By passing a current through this nichrome resistor one applies an extraction potential to the ionization region within the anode structure. The electron-emission current creates a space-charge potential well within the anode structure, preventing ions from escaping out the sides of the structure. The operating characteristics indicate that the trapping within the structure is more effective than the extraction; beyond some critical emission current, detection efficiency declines rather than increases. As can be seen in Fig. 4, the ionization region is contained in the gap of a magnet. It was found that stable reproducible operation could only be obtained at zero magnet current, so the windings were removed to reduce the gas load in the ionizer.

In order to minimize detection problems caused by interfering residual-gas components, the mass spectrometer was designed to maintain as clean a vacuum as possible. It is constructed primarily of 304 stainless steel; the vacuum seals are of the Varian copper gasket type, and the entire beam-detector vacuum system is bakable to 400 °C. The ionizer is cooled to liquid-nitrogen temperature,

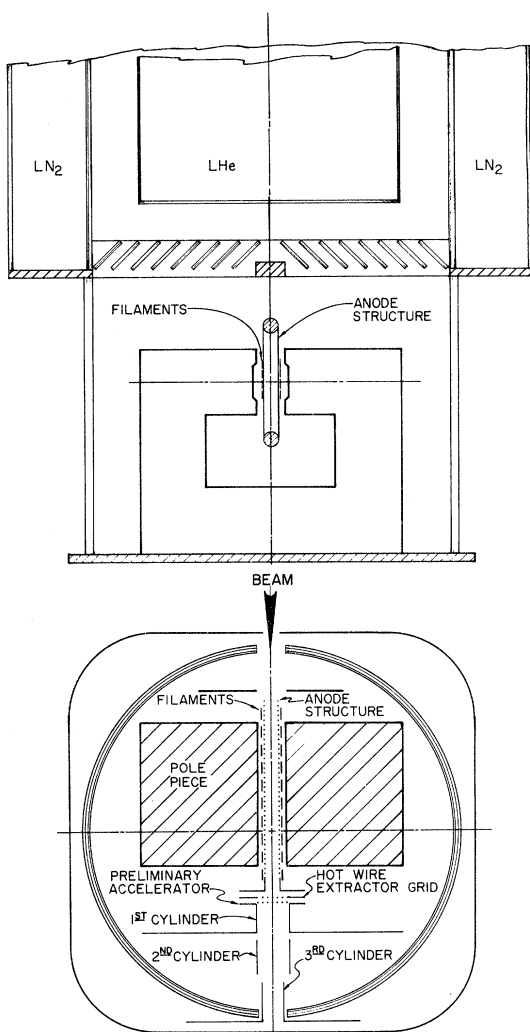


FIG. 4. Two views of the electron-bombardment ionizer.

and provision is made for cryogenically pumping the ionization region with a liquid-helium-cooled surface. The effectiveness of these measures is demonstrated by a spectrum showing a cesium beam in the presence of residual gas (Fig. 5). During operation, the residual-gas pressure in the spectrometer is about  $5 \times 10^{-11}$  Torr, although the beam apparatus proper operates at  $2 \times 10^{-7}$  Torr. This pressure differential was made possible by replacing the last chamber of the beam apparatus with a fast-pumped metal-gasketed stainless-steel chamber, and by separating the mass spectrometer from the beam apparatus with a highly efficient directional entrance; this entrance consists of a matrix of 0.040-in.-diam 0.002-in.-wall 0.5-in.-long stainless-steel tubes mounted in the rectangular aperture connecting the two machines.

The spectrometer ion path has a 12-in. radius

of curvature, so it is capable of reasonably good resolution; since the entrance and exit slit widths are externally controllable, the resolution may be varied from about  $\frac{1}{20}$  to  $\frac{1}{200}$ .

#### B. Data-Collection System

Data are taken automatically by a system built around a PDP-11 computer (Fig. 6). When the experiment is in progress, the computer digitally sets the output frequency of the reference oscillator; the counter, which records the arrival of  $N^{14}$  ions at the mass-spectrometer detector, is gated on for a preset period (usually 2–3 sec). At the end of this period, the counter is read by the computer and the information stored; the reference oscillator is then stepped to the next programmed frequency, the counter reset, and counting at the new frequency commenced. Thus, the computer steps the frequency of klystron *B* back and forth across the nitrogen resonance. In the present experiment, 20 equally spaced frequencies are used

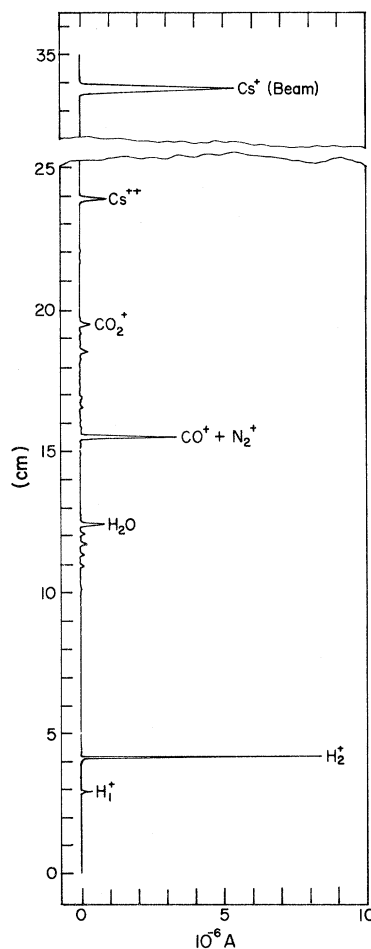


FIG. 5. Residual-gas spectrum plus a full beam of cesium. The cesium-beam source is 3 m distant from the ionizer of the universal detector.

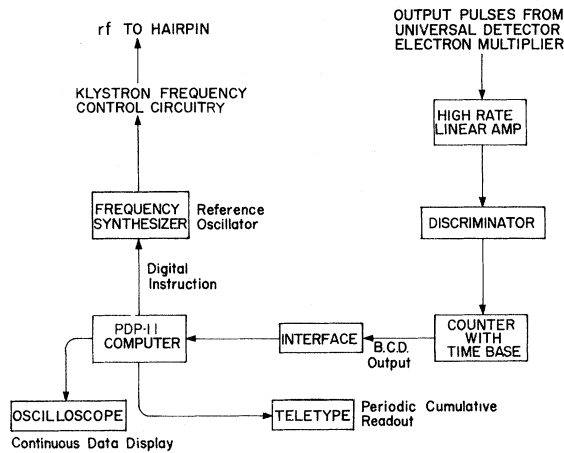


FIG. 6. Data-collection system.

and the counts stored in 20 separate channels; the total number of counts in each channel vs frequency is continuously displayed on an oscilloscope. When a sufficient number of counts in each channel have been accumulated to give the desired signal-to-noise ratio, data taking is terminated and the number of counts in each channel is printed. A signal-to-noise ratio of between 5 and 10:1 is obtained after 30 min of data taking—90 sec/(frequency point), distributed over 30 scans. A long integration time is necessary owing to the inefficiency of the atomic nitrogen source and to the high residual-gas background count at mass 14.

#### IV. EXPERIMENTAL PROCEDURE

Each resonance observation consists of a measurement of the magnetic field, 30 min of data taking on the nitrogen resonance followed by a final field measurement. The magnetic field is

measured by observing the  $K^{39}$  calibration resonance on a hot-wire detector. Each field measurement involves recording six frequencies: The first and last locate the peak of the  $K^{39}$  resonance; the other four frequencies give two pairs of points symmetrically located on the shoulders of the resonance, the first pair 10% below the maximum hot-wire current and the second about 20% below the peak current. The calibration transition frequency is taken to be the average of these six frequencies. To account for magnetic field drift during the 30-min integration time, the magnetic field for a given  $N^{14}$  resonance is assumed to be the average of the field measured just before and just after the nitrogen resonance was observed. The error assigned to the magnetic field measurement is one-half the total field drift during the integration period, or three parts in  $10^7$ , whichever is greater; experience with the field indicated that random fluctuations are of this order. For more than two-thirds of the resonances observed the assigned error in the magnetic field measurement is  $\pm 3$  parts in  $10^7$ .

The data analysis for both the nitrogen and the calibration resonances is carried out by computer. The nitrogen resonances are least-squares fitted to a Lorentzian line shape superimposed upon a nonzero baseline; the computer program varies the center frequency, width, and amplitude of the Lorentzian curve, as well as the amplitude and slope of the baseline. An example of a fitted nitrogen resonance is given in Fig. 7.

#### V. RESULTS

A total of 93 resonances observed at 3.0, 3.5, and 4.0 kG were used in the final calculation of  $g_J$ . The  $g_J$  value was obtained from the observed nitrogen and potassium transition frequencies with

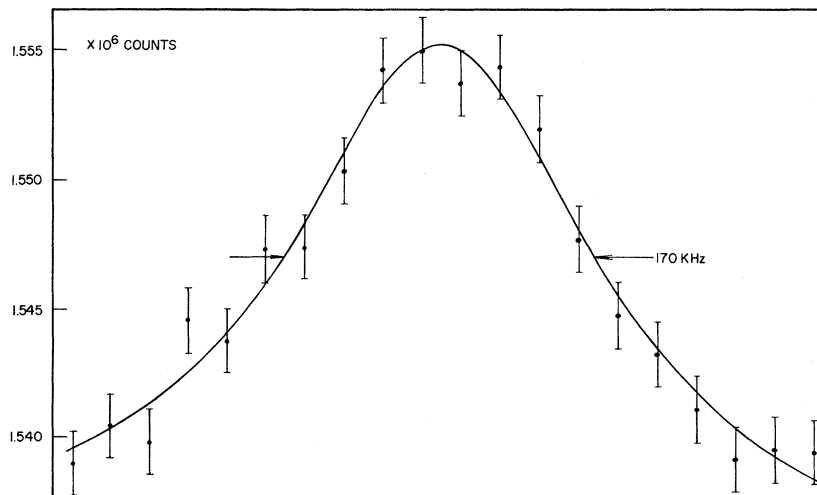
FIG. 7. Fitted  $N^{14}$  resonance.

TABLE I. Values of physical constants used.

	$\mu_B/\hbar=1.399\,610\,8\ (5)\ \text{MHz/G}^a$
	$M_p/m_e=1836.10\ (4)^b$
$K^{39}$	$g_J=2.002\,295\ (2)^c$ $g_I=1.419\,24\ (8)\times 10^{-4}$ ( $\mu_I$ expressed in $\mu_B$ ) <sup>d</sup> $\Delta\nu=461.719\,723\ (30)^e$
$N^{14}$	$g_I=0.4035\ (1)$ ( $\mu_I$ expressed in $\mu_N$ ) <sup>f</sup> $a=10.450\,929\ (2)\ \text{MHz}^g$ $b=0.000\,001\,32\ (50)\ \text{MHz}^g$

<sup>a</sup>E. R. Cohen and J. W. Dumond, *Rev. Mod. Phys.* **37**, 537 (1965); L. C. Balling and F. M. Pipkin, *Phys. Rev.* **139**, A19 (1965).

<sup>b</sup>Cohen and Dumond, in Ref. a.

<sup>c</sup>Reference 8.

<sup>d</sup>V. S. Shirley, in *Hyperfine Structure and Nuclear Radiation* (North-Holland, Amsterdam, 1968), p. 985.

<sup>e</sup>S. Penselin (private communication); Y. W. Chan, V. W. Cohen, and H. B. Silsbee, *Bull. Am. Phys. Soc.* **15**, 1521 (1970).

<sup>f</sup>G. H. Fuller and V. W. Cohen, *Nuclear Data Tables* **A5**, 433 (1969).

<sup>g</sup>R. E. Weiss, R. H. Lambert, and L. C. Balling, *Phys. Rev. A* **2**, 1745 (1970).

the aid of a computer program known as HYPERFINE IV. This program, developed over a period of years by the Berkeley Atomic Beams Group, diagonalizes the Zeeman hyperfine Hamiltonian; by an iterative process it finds the values of the various parameters in the Hamiltonian which yield the best least-squares fit to the experimental data. Here, only  $g_J$  was allowed to vary; the values of the fundamental constants assumed in the program, as well as the parameters assumed for  $K^{39}$  and  $N^{14}$ , are given in Table I.

At each of the three values of the magnetic field, the  $\alpha$  and  $\beta$  transitions were observed with both orientations of the magnetic field. The  $g_J$  values obtained for each set of experimental conditions are given in Table II, and the distribution of all 93 measurements is shown in Fig. 8. The high  $\chi^2$  values arise from the presence of a systematic error of about  $\pm 2$  ppm. We believe that the source of this systematic error is magnetic field inhomogeneity in the hairpin combined with the method of measuring the  $K^{39}$  transition frequency and the method of  $N^{14}$  resonance curve fitting employed. The inhomogeneity is known to cause the observed resonances to be asymmetric. The asymmetry affects mainly the wings of the resonance. In the curve-fitting routine for the  $N^{14}$  resonance, the wings are given the same weight as the peak, whereas in the method used for finding the  $K^{39}$  transition frequency, the wings are given zero weight. Systematic error in earlier experiments using the same apparatus for precision measurements of the alkali  $g_J$  values was at least a factor

of 10 smaller; in those experiments, however, both resonances were observed using the technique used here for the  $K^{39}$  calibration resonance.<sup>8</sup>

Taking this systematic error into account, we have measured the ratio  $g_J(N^{14}, ^4S_{3/2})/g_J(K^{39}, ^2S_{1/2})$  to be 0.999 919 6(20). Thus, using  $g_J(K^{39}, ^2S_{1/2})=2.002\,295$ , we find  $g_J(N^{14}, ^4S_{3/2})=2.002\,134(4)$ .<sup>8</sup> Alternatively, we place  $g_J(N^{14})$  on an absolute basis by using the ratios  $g_J(Rb^{87})/g_J(K^{39})$ ,  $g_J(Rb^{87})/g(e)$ , and the latest value of  $g(e)$ .<sup>9</sup> One then finds  $g_J(N^{14}, ^4S_{3/2})=2.002\,134(5)$ ; the additional uncertainty arises mainly from the error in the ratio  $g_J(Rb^{87})/g(e)$ .

## VI. DISCUSSION

The original measurement of  $g_J(N^{14}, ^4S_{3/2})$  was made by Heald and Beringer by an electron-paramagnetic-resonance technique.<sup>10</sup> Our result differs from theirs by  $10\pm 4.5$  ppm; in considering this difference, it should be pointed out that their result was based upon only two observations, and that no study of systematic effects was made.

Their main interest was the hyperfine structure, rather than the  $g_J$  value of nitrogen. In their similar work on the  $g_J$  value of hydrogen, they did observe systematic effects of the same order as the discrepancy between our nitrogen result and theirs.<sup>11</sup>

The value of  $g_J(N^{14}, ^4S_{3/2})$  reported here is nearly in agreement with the most recent calculated value, the discrepancy being  $4.0\pm 2.5$  ppm, where the error quoted is entirely experimental.

Harvey has measured the value of  $g_J(F, ^2P_{1/2})$ , and has found a discrepancy of  $25\pm 3$  ppm<sup>12</sup> with the value calculated by Beltran-Lopez and Gonzalez. It is interesting to note that this discrepancy as well as the 4-ppm discrepancy in the value for

TABLE II.  $g_J$  values obtained for different experimental conditions. The first five digits are 2.0021 in all cases; the residual digits are given below. The statistical error given in parentheses for each number is one standard deviation. These values assume that  $g_J(K^{39}, ^2S_{1/2})=2.002\,295$ .

	Transition	Field normal	Field reversed	Average
4 kG:	$\alpha$	3005(47)	3546(33)	3276(40)
	$\beta$	2904(33)	3502(44)	3203(39)
All 4-kG data (34 observations): $g_J=2.002\,132\,40(19)$ $\chi^2=309$				
3.5 kG:	$\alpha$	3547(60)	3490(62)	3519(61)
	$\beta$	3326(73)	3586(56)	3456(65)
All 3.5-kG data (20 observations): $g_J=2.002\,135\,05(31)$ $\chi^2=44.9$				
3 kG:	$\alpha$	3411(58)	3761(49)	3586(54)
	$\beta$	3620(52)	3616(41)	3618(47)
All 3-kG data (39 observations): $g_J=2.002\,136\,17(24)$ $\chi^2=89.7$				
All data (93 observations): $g_J=2.002\,134\,06(14)$ $\chi^2=604$				

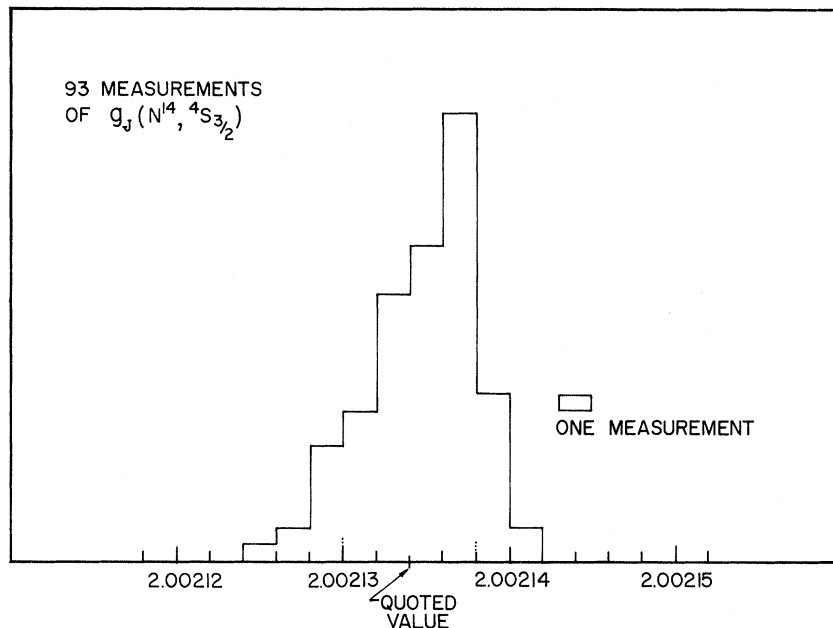


FIG. 8. Histogram of results.

nitrogen are both about 5% of the respective relativistic-diamagnetic corrections; in one case, however, the correction is overestimated, whereas in the other it is underestimated. So, in spite of the improved agreement between experiment and theory for  $g_J(N^{14}, 4S_{3/2})$ , it does not seem likely that part-per-million accuracy can be expected when uncorrelated Hartree-Fock wave functions are used in the Kambe-Van Vleck-theory calculations. In fact, now it is questioned whether a theory which neglects effects of higher order than  $\alpha^2$  can be expected to give results of this accuracy even with exact wave functions. Leduc, Laloë, and Brossel have just completed a very careful measurement of the ratio  $g_J(\text{He}^4, 2^3S_1)/g_J(\text{H}, 1^2S_{1/2})$ .<sup>13</sup>

They have found a discrepancy of 2 ppm with the value of this ratio calculated by Perl and Hughes.<sup>14</sup> They tentatively ascribe this discrepancy to the neglected higher-order terms (for example, to nonadditivity of the anomalous moments of the two electrons), rather than to the use of inaccurate wave functions.

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