affords an approximate determination of the wave function ratio. The result for Ag^{109} is $\langle|\psi_k(0)|^2\rangle_{Av}/|\psi_a(0)|^2=0.66$. Taking this value as appropriate also for Rh, we find for the Knight shift $\Delta H/H=0.0022$. Applying this correction to the magnetic moment of Rh^{103} as calculated from (3), we find

$$\mu(Rh^{103})=-0.08790\pm0.00007 \text{ nm}, \tag{4}$$

without diamagnetic correction.

The spin of W^{183} has been determined to be $\frac{1}{2}$ by Grace and More,[9] Kopfermann and Meyers,[10] and Fowles[11] from optical hfs; the magnetic moment has been reported to be +0.080 nm by Vreeland and Murakawa.[12] We have observed the magnetic resonance of W^{183} in 14 grams of the powdered metal at a frequency of 1.79 Mc/sec in 10 000 gauss with a signal-to-noise ratio of about 10 at room temperature. We have verified that the magnetic moment is positive. The ratio of the W^{183} resonance frequency in the metal to that of D in D_2O containing 1-molar Mn^{++} ions is found to be

$$\nu(W^{183})/\nu(D)=0.27395\pm0.00003. \tag{5}$$

Chemical difficulties in obtaining sufficiently concentrated ionic solutions with paramagnetic catalysts have to date prevented observation of the resonance in any other compounds besides the metal. In order to obtain a reliable value for the magnetic moment of W^{183}, we have made an attempt to estimate the Knight shift, as was outlined above for Rh^{103}. However the atomic hfs splitting in the ground state has not been measured for W; also, the metallic/atomic wave function ratio cannot be conveniently estimated from an analogous known case as was possible for Rh. If one estimates the hfs splitting from that of Ta, which is known, and furthermore if one assumes a wave function ratio of unity, the resulting Knight shift can be estimated to be about 1.5 percent. Applying this correction to the magnetic moment of W^{183} as determined from (5), one obtains

$$\mu(W^{183})=+0.115\pm0.001 \text{ nm}. \tag{6}$$

Informative discussions with W. D. Knight are gratefully acknowledged.

Since the completion of the work reported we have learned that Aamodt and Fletcher[13] have independently measured the magnetic moment of Cl^{36} by microwave spectroscopy. Their result, $\mu(Cl^{36})=+1.32\pm0.08$ nm, is in agreement with our value quoted above.

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[9] N. S. Grace and K. R. More, Phys. Rev. **45**, 166 (1934).

[10] H. Kopfermann and D. Meyers, Z. Physik **124**, 685 (1948).

[11] G. R. Fowles, Phys. Rev. **78**, 744 (1950).

[12] J. A. Vreeland and K. Murakawa, Phys. Rev. **83**, 229 (1951).

[13] P. C. Fletcher and L. C. Aamodt, Bull. Am. Phys. Soc. **30**, No. 3, 13 (1955); L. C. Aamodt and P. C. Fletcher, Phys. Rev. **98**, 1317 (1955).

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Magnetic Moment and Mass of Chlorine-36*

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The magnetic moment of the Cl^{36} nucleus was measured by observing the Zeeman splitting of the $F=2\rightarrow2$ line in the electric quadrupole hyperfine pattern of the molecule CH_3Cl^{36} ($J=0\rightarrow1$, $K=0$ transitions). It was found to be 1.32 ± 0.08 nuclear magnetons. The magnitude of the magnetic moment was measured by using a rectangularly cross-sectioned absorption cell with plane polarized microwave radiation, and observing the $\Delta M=\pm1$ transitions. The sign of the magnetic moment was measured by using a circularly cross-sectioned absorption cell with circularly polarized microwave radiation. This allowed the $\Delta M=1$ and the $\Delta M=-1$ transitions to be observed separately. The magnetic field was calibrated by observing the Zeeman splitting of the spectrum of CH_3Cl^{35}. This value of magnetic moment indicates a nuclear configuration $(d_{\frac{3}{2}})_N(d_{\frac{3}{2}})_P$.

Measurements of the quadrupole spectrum without the Zeeman perturbation gave the following additional information: the spin of Cl^{36} was confirmed to be 2, the mass difference ratio $[m(Cl^{36})-m(Cl^{35})]/[m(Cl^{37})-m(Cl^{36})]$ was found to be 1.00168 ± 0.04 percent, the molecular rotational constant of the CH_3Cl^{36} molecule was found to be 13187.604 ± 0.015 Mc/sec, and its quadrupole coupling constant to be -15.83 ± 0.20 Mc/sec.

INTRODUCTION

THE $_{17}Cl^{36}{}_{19}$ nucleus is one of the interesting group of β-active nuclei with an odd number of both protons and neutrons. Townes and Aamodt[1] have previously determined the spin of this nucleus to be 2 and its quadrupole moment to be small and negative. This information was insufficient to allow any predictions concerning nuclear configurations of the Cl^{36} nucleus. Determination of the magnetic moment gives enough information to distinguish between possible configurations. Such a determination was the primary object of the present experiment.

The magnitude of the magnetic moment was measured

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[1] C. H. Townes and L. C. Aamodt, Phys. Rev. **76**, 691 (1949).

by observing the $\Delta M=\pm 1$ Zeeman splittings of the $F=2\rightarrow 2$ line in the quadrupole hyperfine pattern of the $J=0\rightarrow 1$ rotational transition of the molecule CH_3Cl^{36}. The sign of the magnetic moment was determined by observing the $\Delta M=\pm 1$ and the $\Delta M=-1$ Zeeman transitions separately.

EXPERIMENTAL APPARATUS

The spectrometer used in these measurements was a conventional Stark spectrometer using an adaptation of Pound's ac stabilizing circuit[2] to allow the microwave frequency source to be swept at a very slow rate. The purpose of the slow sweep was to allow the absorption line signal to be transmitted without distortion through circuits having an exceptionally long time constant. The long time constant was used to narrow the noise band width and improve sensitivity. Another variation from the usual spectrometer was the short absorption cells used. These cells have several advantages which will be mentioned later.

The microwave source was a 2K50 reflex klystron. It fed microwave energy directly into the stabilizing circuit with a small portion of the power coupled into the absorption cell. The signal received at the detecting crystal was amplified, first, by a tuned-plate tuned-grid three-stage amplifier, and then by a regenerative narrow-band amplifier. The output band width of the narrow-band amplifier was adjustable down to 50 cycles per second. This small band width was necessary to avoid saturation of the phase detector which followed. The microwave frequency was measured by beating the microwave power with the harmonics of a crystal oscillator whose frequency was compared with that of *WWV*.

The magnitude of the magnetic moment was measured by using an 18-inch long rectangular *K*-band wave guide (with a Stark septum) as an absorption cell. The total volume of the absorption cell, including input leads and thermocouple gauge, was 40 cc. The thermocouple gauge accounted for approximately one-fourth of this volume. With the small amount of sample material available, this small volume allowed the cell to be filled several more times than would have been possible with absorption cells of longer lengths. The sign of the magnetic moment was measured using a 36-inch long circular-cylindrical wave guide as an absorption cell. The Stark septum consisted of a circular-cylindrical rod along the axis of the cell.

These short cells reduced some of the effects caused by power reflections in the microwave system. In a Stark spectrometer the process of Stark modulation reduces, but does not completely eliminate, the effects of power fluctuations. The short cells decreased the rate at which these power fluctuations occurred (with respect to variations in frequency).

The Zeeman field for the rectangular guide was provided by permanent magnets. The field covered an area of 18 inches by $2\frac{3}{4}$ inches with a gap of $\frac{5}{8}$ inch. It was produced by using six magnetron magnets (horn type) and connecting all of the corresponding poles of the six magnets with rectangular pole pieces of the dimensions mentioned above. The average field was 2166 gauss. Because six separate magnetic sources were used in the assembly there was some inhomogeniety. The minimum field differed from the maximum field by 6 percent. This variation broadened the spectral lines slightly. The measurement of g_J was made with smaller pole pieces and a field of 3186 gauss.

The magnet assembly and circular wave guide used in the measurement of the sign of the magnetic moment will be described in detail in a later paper. Briefly it consisted of a solenoid with the circular wave-guide absorption cell along the solenoid axis. Circular polarization of the microwave radiation was obtained by squeezing a short section of the circular wave guide immediately preceding the absorption cell into a slightly elliptical shape (making it a quarter-wave section). At the[3] receiving end of the absorption cell the unwanted component of the circularly polarized radiation was removed by an attenuator.

The slow-sweep microwave source utilized Pound's ac stabilizing circuit[2] with the balanced bridge arrangement of Zafferano.[4] The slow sweep was produced by tuning the reference cavity slowly with a clock motor. The sweep speeds used varied from 50 kc/min to 1 Mc/min. The slow tuning of the klystron allowed the use of filter time constants at the output of the phase detector as large as one minute without excessive distortion of the line shape. This corresponds to an output band width of the order of 0.02 cycle per second. Since the noise power was proportional to band width under the conditions of operation, this small band width resulted in considerable reduction of noise with consequent increased in sensitivity. For sweep speeds as slow as those used, some form of klystron frequency stabilization was required; otherwise the klystron would have drifted back and forth over the absorption line and thus averaged it out and obscured it.

PREPARATION OF THE SAMPLE

The sample material was obtained in form of a 2 normal solution of HCl enriched in Cl^{36} at the Oak Ridge National Laboratory. The abundance of Cl^{36} in the sample material was 1.6 percent. The synthesis into methyl chloride was as follows: 0.25 millimole of HCl was precipitated with $AgNO_3$ in a 5-ml centrifuge tube. The AgCl precipitate was centrifuged, washed, and dried. The dried AgCl was wrapped in aluminum foil and heated *in vacuo* until reaction occurred. The $AlCl_3$ produced was sublimed into another vessel to which an

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[2] R. V. Pound, Rev. Sci. Inst. **17**, 490 (1946).

[3] F. Coester, Phys. Rev. **77**, 454 (1950).

[4] Tuller, Galloway, and Zaffarano, Technical Report No. 53, Nov. 20, 1947, Research Laboratory of Electronics, Massachusetts Institute of Technology (unpublished).

TABLE I. The H_Q+H_M matrix for $J=1$, $K=0$, and $I=2$. $E_1=-0.175eqQ$, $E_2=0.175eqQ$, $E_3=-0.05eqQ$; $A=\frac{2}{3}\alpha+\delta$, $B=\frac{5}{6}\alpha+\delta$, $C=\frac{3}{2}\alpha+\delta$; $\alpha=\mu_N H(g_I-g_J)$, $\delta=\mu_N H g_J$.

		$M'=3$	2		1			0			−1			−2		−3
M	F	$F'=3$	3	2	3	2	1	3	2	1	3	2	1	3	2	3
3	3	E_3-3A														
2	3		E_3-2A	$\frac{1}{3}\sqrt{2}\alpha$												
	2		$\frac{1}{3}\sqrt{2}\alpha$	E_2-2B												
1	3				E_3-A	$(4\sqrt{5}/15)\alpha$										
	2				$(4\sqrt{5}/15)\alpha$	E_2-B	$(3/2\sqrt{5})\alpha$									
	1					$(3/2\sqrt{5})\alpha$	E_1-C									
0	3							E_3	$(\sqrt{\frac{2}{5}})\alpha$							
	2							$(\sqrt{\frac{3}{5}})\alpha$	E_2	$(\sqrt{\frac{3}{5}})\alpha$						
	1								$(\sqrt{\frac{3}{5}})\alpha$	E_1						
−1	3										E_3+A	$(4\sqrt{5}/15)\alpha$				
	2										$(4\sqrt{5}/15)\alpha$	E_2+B	$(3/2\sqrt{5})\alpha$			
	1											$(3/2\sqrt{5})\alpha$	E_1+C			
−2	3													E_3+2A	$\frac{1}{3}\sqrt{2}\alpha$	
	2													$\frac{1}{3}\sqrt{2}\alpha$	E_2+2B	
−3	3															E_3+3A

excess of CH_3OH was added. The vessel was then opened to air and allowed to stand one hour after which the excess CH_3OH was pumped off leaving a glossy deposit of the complex $CH_3O\cdot AlCl_2$. The complex was decomposed at 140°C and the volatile products (CH_3Cl and HCl) were collected in a trap cooled by liquid nitrogen. The HCl was removed by distillation over KOH.

ENERGY LEVELS AND SPECTRUM

The Cl^{36} nucleus has a spin of 2 and an electric quadrupole moment of -0.017×10^{-24} cm^2.[1] Without Zeeman effects the rotational transition is perturbed by the quadrupole interaction giving a quadrupole hyperfine pattern. For the rotational transition used, ($J=0\rightarrow1$, $K=0$), the resulting pattern consisted of three lines. The small quadrupole coupling (−15.8 Mc/sec) of the Cl^{36} nucleus in the CH_3Cl molecule made the separation between lines small, the distance between the outer two lines being only about 5.5 Mc/sec. This resulted in several experimental difficulties when the spectrum was split by a Zeeman field.

The Hamiltonian for the molecule may be written $H=H_R+H_Q+H_M$, where H_R represents the part of the Hamiltonian due to rotation of the molecule; H_Q and H_M are due to quadrupole and Zeeman effects respectively. The last two terms of the Hamiltonian are small compared with the rotational term and produce only a small perturbation of the rotational energy levels. However, since experimental conditions required that these last two terms be approximately equal, neither could be considered as a perturbation on the other. This produced an intermediate coupling situation and required the solution of a secular equation. In solving these equations it proved most convenient to express the H_Q+H_M energy matrix in the $IJKFM_F$ representation. In this representation $\mathbf{F}=\mathbf{I}+\mathbf{J}$, and M_F is the component of $\mathbf{F}$ along the axis of quantization.

While the quadrupole matrix is diagonal in K, F, and M_F, it has off-diagonal elements in J. The quadrupole coupling constant is small enough, however, so that these terms shift the energy levels less than 150 cycles and may be neglected. The diagonal quadrupole matrix elements are given by the relationship (for $K=0$)

$$(IJKFM_F|H_Q|IJKFM_F)=-eqQ\frac{\frac{3}{4}C(C+1)-I(I+1)J(J+1)}{2I(2I+1)(2J-1)(2J+3)},$$

where $C=F(F+1)-I(I+1)-J(J+1)$, $e=$ electronic charge, $Q=$ quadrupole moment of the Cl^{36} nucleus, and $q=$ the second derivative of the electric field of the molecule (at the Cl^{36} nucleus) with respect to the coordinate along the molecular axis.

Since the interaction between the magnetic moment of the hydrogen nuclei and the magnetic field merely gives a constant energy term, it may be neglected. The Zeeman Hamiltonian may then be written (in operator form) $H_M=-\mu_N g_J(\mathbf{H}\cdot\mathbf{J})-\mu_N g_I(\mathbf{H}\cdot\mathbf{I})$,[3] where μ_N is the nuclear magneton, g_I the nuclear g factor (for the Cl^{36} nucleus), g_J the rotational g factor, and $\mathbf{H}$ the external magnetic field. By using angular momentum relationships given by Condon and Shortley,[5] the Zeeman matrix elements are easily calculated. The values obtained (for $J=1$) are indicated in Table I where they are included in the H_Q+H_M matrix shown there. (The matrix for $J=0$ is diagonal and has elements proportional to the quantum number M_F.)

The solution of the secular equations obtained from

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[5] E. U. Condon and G. H. Shortley, *The Theory of Atomic Spectra* (Cambridge University Press, London, 1935), Chap. 3.

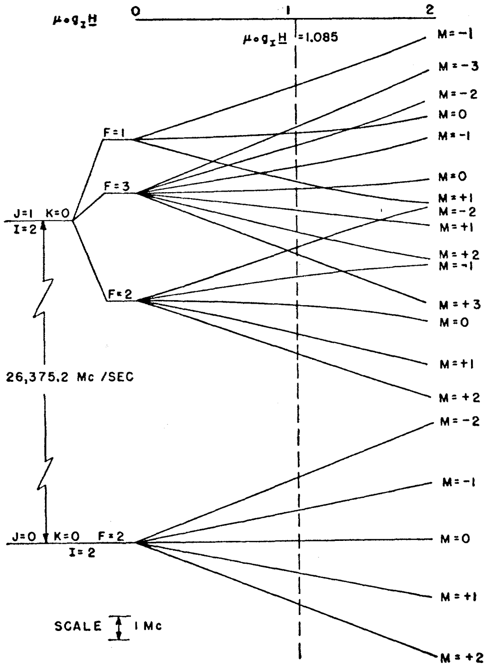

FIG. 1. The Zeeman energy levels for the CH_3Cl^{36} molecule plotted as a function of the parameter $\mu_N g_I H$.

the H_Q+H_M matrix gives the energy levels shown in Fig. 1. These have been plotted by using the product $\mu_N g_I H$ as a parameter and under the assumption that $g_J=0$. This assumption is in agreement with observation within experimental error. The dotted line indicates the value of the parameter under experimental conditions.

For plane polarized radiation in a rectangular wave guide two different sets of Zeeman transitions are possible. These depend upon the relative orientation of the external magnetic field **H** and the microwave electric field vector **E**. For the case where **E** and **H** are parallel, the selection rules are $\Delta F=0, \pm 1$; $\Delta M=0$; while for **E** and **H** perpendicular (crossed fields), the rules are $\Delta F=0, \pm 1$; $\Delta M=\pm 1$. When g_I and g_J are both unknown, and are of comparable magnitude, these two spectra supply sufficient information to evaluate both of these quantities. An ambiguity in sign remains, however, because of symmetries in the spectral pattern. In order to remove this symmetry circularly polarized microwave radiation must be used allowing the observation of the $\Delta M=1$ or the $\Delta M=-1$ transition separately.

In the case where the value of g_J is known, and only the value of g_I need be determined, the two spectra ($\Delta M=0$ and $\Delta M=\pm 1$) overdetermine g_I. For the molecule CH_3Cl^{36} this proved to be the case. In evaluating g_I, the crossed-field spectrum ($\Delta M=\pm 1$) gave g_I to much greater accuracy than did the parallel-field spectrum. Therefore the parallel-field spectrum was used merely to provide a qualitative check. Figure 2 shows the position of the lines in the crossed-field Zeeman spectrum as a function of the parameter $\mu_N g_I H$ (again under the assumption $g_J=0$). The dashed line indicates the value of the parameter under experimental conditions.

That the sign of g_I is ambiguous because of the symmetry of the $\Delta M=\pm 1$ spectrum, can be seen by noting the symmetry of the H_Q+H_M energy matrix. If one assumes the experimental condition $g_J=0$, it will be noted that changing the sign of g_I, (i.e., changing the signs of A, B, C, and α), merely interchanges the M and $-M$ energy levels. (This is true since the off-diagonal terms always appear squared in the secular equations, and therefore their sign is of no importance.) The consequence of this is that the $\Delta M=1$ and the $\Delta M=-1$ transitions are also interchanged. Since both transitions

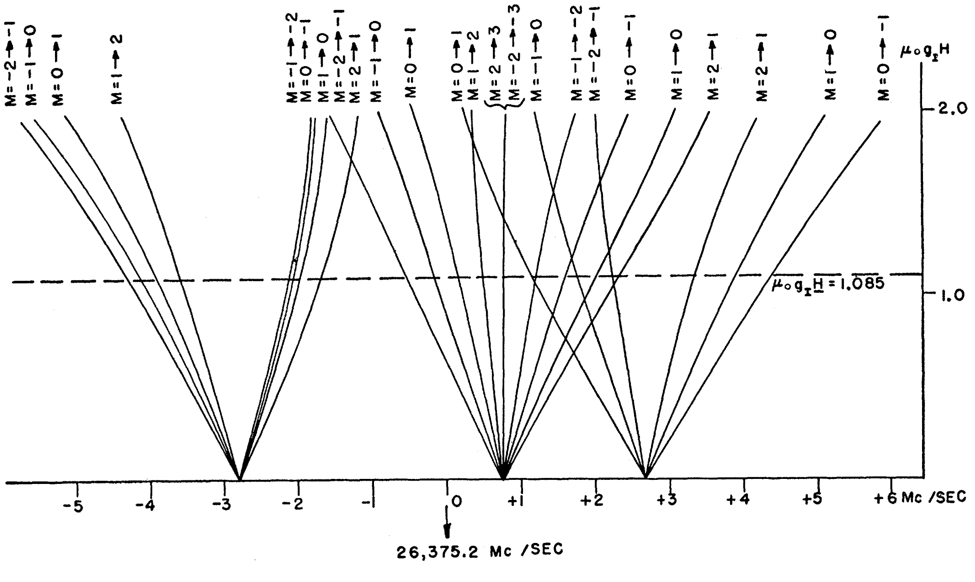

FIG. 2. The frequency position of the lines in the Zeeman (crossed-fields) spectrum of the CH_3Cl^{36} molecule plotted as a function of the parameter $\mu_N g_I H$.

are present, however, the spectrum itself is not altered. Thus, either sign of g_I gives the same spectrum and consequently the sign of g_I is ambiguous. It can be seen that the symmetry is such that measurements involving the $\Delta M=0$ transitions cannot be used to resolve this ambiguity; however, the use of circularly polarized radiation, where the $\Delta M=1$ and the $\Delta M=-1$ transitions are observed separately, yields a spectrum dependent on the sign of g_I.

The Zeeman perturbation mixes the quadrupole energy levels having different F values but the same M_F values, since with this perturbation M_F is still a good quantum number although F is not. The amount of mixing depends upon the strength of the Zeeman field (and consequently upon the value of the parameter $\mu_N g_I H$). This mixture affects the intensity of the spectral lines and makes these intensities also a function of this parameter. For the experimentally determined value of $\mu_N g_I H$, the calculated intensity (and position) of the lines in the observed spectrum are indicated in Fig. 3. Experimentally the individual lines were too close together to be resolved. The envelope in Fig. 3 shows how the lines should theoretically appear if they had a half-width of 300 kc/sec.

SPECTRUM WITHOUT ZEEMAN EFFECTS

The three frequencies at which the various curves in Fig. 2 converge, indicate the relative position of the lines in the quadrupole hyperfine pattern of the CH_3Cl^{36} molecule ($J=0\rightarrow1$, $K=0$ transitions). The observed frequencies of these three lines are listed in Table II and agree within experimental error with those computed using the constants indicated there. This agreement confirms the nuclear spin assignment of two for the Cl^{36} nucleus.

The value of B_0 given in Table II along with the corresponding rotational B_0 values for the molecules CH_3Cl^{35} and CH_3Cl^{37} allows the determination of the mass difference ratio $(m^{36}-m^{35})/(m^{37}-m^{36})$. The relationship involved, and the value obtained, are as follows:

$$\frac{m^{36}-m^{35}}{m^{37}-m^{36}}=\frac{M^{35}}{M^{37}}\frac{B_0^{37}}{B_0^{35}}\frac{B_0^{35}-B_0^{36}}{B_0^{36}-B_0^{37}}=1.00168\pm0.0004,$$

where m is the nuclear mass, M the molecular mass, and B_0 the rotational constant. The superscript indicates the isotope of chlorine which is involved. In this calculation the rotational constants for CH_3Cl^{35} and CH_3Cl^{37} that were used were those obtained by White[6] [$B_0(CH_3Cl^{35})=13\,292.840\pm0.008$ Mc/sec and $B_0(CH_3Cl^{37})=13\,088.136\pm0.002$ Mc/sec]. If the value of $m(Cl^{35})/m(Cl^{37})$ (0.945978 ± 0.000003) given by Honig, Stitch, and Mandel[7] is used, the mass ratio $m(Cl^{36})/m(Cl^{37})$ is found to be 0.973012 ± 0.00002.

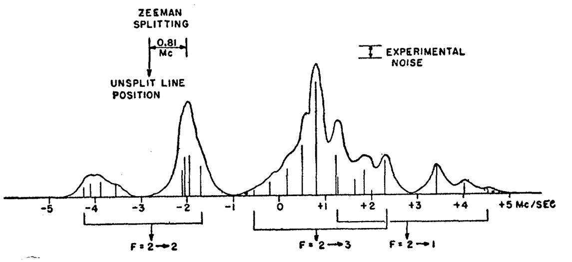

FIG. 3. The Zeeman (crossed-fields) spectrum of the CH_3Cl^{36} molecule ($J=0\rightarrow1$ rotational transition). The envelope assumes a half-width of approximately 300 kc/sec.

The quadrupole coupling constant of the CH_3Cl^{35} molecule has been determined as -74.770 ± 0.015 Mc/sec,[8] making the ratio $eqQ(CH_3Cl^{36})/eqQ(CH_3Cl^{35})$ $=0.2117\pm0.0027$. Since the value of q is essentially the same for both molecules, this ratio is also the ratio of the quadrupole moments of the two chlorine isotopes. This gives the value of the quadrupole moment of the Cl^{36} nucleus as -0.017×10^{-24} cm^2. The uncertainties in the determination of the quadrupole moment are primarily due to shielding effects.[9] It will be noted that the value of eqQ, and consequently the quadrupole moment, agree with those given by Gilbert[10] and by Johnson, Gordy and Livingston,[11] but are of somewhat higher precision.

ZEEMAN MEASUREMENTS

Figure 3 indicates that the $F=2\rightarrow3$ and the $F=2\rightarrow1$ lines in the quadrupole hyperfine pattern of the CH_3Cl^{36} molecule are separated by such a small amount (2 Mc/sec) that their Zeeman components overlap considerably even for relatively weak fields. This made it impossible to use them for measuring purposes and left only the $F=2\rightarrow2$ line as a feasible line to work with.

The $F=2\rightarrow2$ line has eight Zeeman components grouping themselves into two separate groups as indicated in Fig. 2. The individual lines within each group could not be resolved. (The experimental half-widths were of the order of 300 kc/sec.) Because of this, the

TABLE II. Comparison of the observed and calculated frequencies of the absorption lines in the quadrupole hyperfine pattern of CH_3Cl^{36} ($J=0\rightarrow1$).

Transition F'	Transition F''	Frequencies (Mc/sec) Observed	Frequencies (Mc/sec) Theoretical
2	1	26377.96±0.025	26377.977
2	2	26372.42±0.025	26372.437
2	3	26376.03±0.035	26375.999

$B_0=13187.604\pm0.015$ Mc/sec
$eqQ=-15.83\pm0.20$ Mc/sec
$I=2$
$m(Cl^{36})/m(Cl^{37})=0.973012\pm0.000017$

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[6] R. L. White (private communication).

[7] Honig, Stitch, and Mandel, Phys. Rev. **92**, 901 (1953).

[8] Geshwind, Gunther-Mohr, and Townes, Phys. Rev. **81**, 288 (1951).

[9] R. Sternheimer, Phys. Rev. **84**, 244 (1951).

[10] D. A. Gilbert, Phys. Rev. **85**, 716 (1952).

[11] Johnson, Gordy, and Livingston, Phys. Rev. **83**, 1249 (1951).

observed Zeeman pattern appeared as the two components indicated by the envelope in Fig. 3. The theoretical decrease in intensity of the low-frequency component of this line was actually observed; in fact the decrease was sufficient to make this component only two or three times noise. This made it impossible to use it for accurate measurements; and therefore, the value of g_I was determined by using the frequency difference between the unsplit quadrupole line and its largest observed Zeeman component.

The experimental accuracy was severely limited by the small separation between quadrupole components, since in order to obtain high accuracy the ratio of Zeeman splitting to the uncertainty in line position must be large. Large Zeeman fields could not be used, since at these fields Zeeman components from the $F=2\rightarrow3$ line began to overlap the $F=2\rightarrow2$ Zeeman components. A magnetic field of 2166 gauss gave close to optimum conditions. In this field the widening of the Zeeman component gave an uncertainty of 20 kc/sec in line position while the line itself was moved only 0.81±0.02 Mc/sec from the unsplit position. Another alternative would have been to use the strong-field case but magnetic fields of the required magnitude were not available.

The method of evaluating the nuclear g factor of the Cl^{36} nucleus was simplified by being able to determine the rotational g factor of the CH_3Cl^{36} molecule independently. This was possible since the rotational g factors of the CH_3Cl^{36} and CH_3Cl^{35} molecules differ only by the ratio of their rotational frequencies; and this difference is small enough to be neglected. Hence, the Zeeman spectrum of the CH_3Cl^{35} molecule was used to evaluate g_J. The value of g_J was determined to be 0.00 ± 0.05 by measuring the Zeeman splitting of the $F=\frac{3}{2}\rightarrow\frac{1}{2}$ transition in the quadrupole hyperfine structure of CH_3Cl^{35}. The error in g_I caused by the uncertainty in g_J was of the order of 1.5 percent. The small value of g_J confirmed a previous observation of Jen.[12]

The value of g_I was obtained by the following procedure: Since the value of g_J was found to be zero within experimental error, preliminary calculations were made by setting $g_J=0$ in the $H_Q\pm H_M$ matrix. This made the secular equations, and consequently the frequencies and intensities of the individual Zeeman components, functions of the parameter $\mu_N g_I H$ only. Since the experimental Zeeman component of the $F=2\rightarrow2$ line consisted of four separate components (Fig. 3), and since all four of these components were within the experimental halfwidth, it was assumed that the peak of the observed line coincided with the center of intensity of these four components. The frequency of this center of intensity was determined theoretically, as a function of $\mu_N g_I H$, and this expression set equal to the frequency of the peak of the observed line. This allowed the value of $\mu_N g_I H$ to be obtained.

Using the experimental value of $\mu_N g_I H$, g_I could then have been obtained by measuring the magnetic field. However, since the field was rather inhomogeneous, a determination of its effective value by direct measurement would not have been easy. To avoid this difficulty, the field was calibrated by using the nuclear g value[13] of Cl^{35}. Thus, the Zeeman splitting of the $F=\frac{3}{2}\rightarrow\frac{1}{2}$ line in the CH_3Cl^{35} quadrupole spectrum was measured, (using the same magnetic field as before), and the value of $\mu_N g_I H$ determined for this molecule. In this case, since the quadrupole moment of Cl^{35} is considerably larger than that of Cl^{36}, the quadrupole lines were separated sufficiently to allow the use of first-order theory.

The ratio of the two quantities, $(\mu_N g_I H)_{Cl^{36}}$ and $(\mu_N g_I H)_{Cl^{35}}$, gave the ratio of the g factors (since the other terms were common to both expressions). The result obtained was the following:

$$|g_I(Cl^{36}/g_I(Cl^{35})|=1.20\pm0.07.$$

By using the value of the magnetic moment of Cl^{35} given by Ramsey[13] (i.e., $\mu=0.82191\pm22$), and taking into account the relative spins of Cl^{35} and Cl^{36}, the absolute magnitude of the magnetic moment of the Cl^{36} nucleus was found to be 1.32±0.08 nuclear magnetons.

The sign of the magnetic moment was determined by observing the $\Delta M=1$ and $\Delta M=-1$ transitions separately rather than simultaneously as in the magnitude determination. This was accomplished by using the circular wave guide and elliptical quarter-wave section previously described. The CH_3Cl^{35} spectrum and the CH_3Cl^{36} spectrum were both observed and the $\Delta M=1$ and $\Delta M=-1$ transitions in both spectra were correlated. The sign of the nuclear g factor of the Cl^{36} nucleus was then determined from the known sign of the Cl^{35} nuclear g factor. The Cl^{36} magnetic moment was found to be positive.

DISCUSSION

In the $j-j$ coupling nuclear shell model, using an oscillator potential, the fifteenth to twentieth nucleons occupy the third shell and are either in the $s_{\frac{1}{2}}$ or $d_{\frac{3}{2}}$ state. This model, as proposed by Mayer[14] and Jensen,[15] is based on the assumption of independent particles, and therefore, the aforementioned is assumed to hold for neutrons and protons independently. In the Cl^{36} nucleus, which has 19 neutrons and 17 protons, 5 neutrons and 3 protons are in this shell, the other nucleons forming closed shells.

The usual assumption in the case of even-odd nuclei (in regard to the particles with the odd number) is that all of these particles, except the last added one, pair off to give zero spin and nuclear moments. This leaves the last particle to determine the properties of the nucleus. A reasonable assumption in the case of odd-odd nuclei is that this pairing process occurs for the neutrons and

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TABLE III. The magnetic moment of possible nuclear configurations involving one $s_{\frac{1}{2}}$ state and one $d_{\frac{3}{2}}$ state and giving a spin 2.

Configuration	Calculated magnetic moment (nuclear magnetons)
$(d_{3/2})_N(d_{3/2})_P$	0.846
$(s_{1/2})_N(d_{3/2})_P$	−1.794
$(d_{3/2})_N(s_{1/2})_P$	3.944
	μ(observed) = 1.32±0.08

TABLE IV. The magnetic moment of possible nuclear configurations involving more than two nucleons and giving a spin 2.

Configuration	Calculated magnetic moment (nuclear magnetons)
$(s_{1/2})_N[(s_{1/2})(d_{3/2}{}^2)_2]_{3/2P}$	−3.498
$(s_{1/2})_N[(s_{1/2})(d_{3/2}{}^2)_2]_{5/2P}$	4.034
$(d_{3/2})_N[(s_{1/2})(d_{3/2}{}^2)_2]_{3/2P}$	−0.256
$(d_{3/2})_N[(s_{1/2})(d_{3/2}{}^2)_2]_{5/2P}$	2.294
	μ(observed) = 1.32±0.08

protons independently, and then the last added odd neutron and last added odd proton couple together to determine the nuclear properties.

If this were true, and if the states in the third shell filled in the order expected, then the configuration of the Cl^{36} nucleus would be $(d_{\frac{3}{2}})_N(d_{\frac{3}{2}})_P$, where N and P indicate the neutron and proton configurations, respectively. In this case, since the spin of Cl^{36} is known to be two, the spins of the odd proton and neutron would neither be parallel nor antiparallel.

The possibility exists, however, that the odd nucleon is in an s state, allowing three other possible configurations. Furthermore, none of these configurations may be correct, and the configuration may actually involve a more complex coupling.

Of the four configurations involving all possible combinations of the two states, $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$, the configuration $(s_{\frac{1}{2}})_N(s_{\frac{1}{2}})_P$ is ruled out from spin considerations. The other three configurations are possible, however. The magnetic moments calculated for these three configurations appear in Table III. It can be seen that the observed magnetic moment favors the first configuration.

That the nuclear magnetic moment is not due to the coupling of more than two nucleons in the third shell is illustrated by Table IV. In this table the four possible coupling schemes are shown that involve more than two nucleons and give the proper nuclear spin. It can be seen that none of the calculated moments are close to the observed value.

The quadrupole moment of Cl^{36} is not inconsistent with the configuration $(d_{\frac{3}{2}})_N(d_{\frac{3}{2}})_P$, which would have a quadrupole moment of zero if it were pure. The measured quadrupole moment is in fact quite small, being only $\frac{1}{5}$ that of Cl^{35}.

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