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On the Nuclear Magnetic Moments of Several Stable Isotopes*

W. G. PROCTOR† AND F. C. YU
Department of Physics, Stanford University, Stanford, California

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The nuclear induction spectrometer which has previously been described was used to measure the magnetic moments of a number of nuclei. These values are without corrections of any kind and are based upon a value for the magnetic moment of the proton of (2.79348 ± 0.00034) nuclear magnetons. The experience gained from the observation of a large variety of nuclei has made it possible to discuss in a general way the selection of a suitable sample compound. Various interesting phenomena which have turned up in the course of these measurements are discussed; some of these are the following. (a) Nuclear resonance frequencies have been found to depend upon the compound used for the sample in some cases. This has been noted for the isotopes of Cl and N, and for Co, the latter having resonances over a region as large as 1.3 percent. This effect has been demonstrated to be of molecular rather than nuclear origin, and it is responsible for our listing the chemical compounds used for each measurement. (b) The magnetic moments of both In^{113} and In^{115} have been found to be 0.64 percent greater than their respective atomic beam values, a discrepancy very similar to that noted for Ga^{69} and Ga^{71}. (c) An hfs anomaly for the isotopes of chlorine has been observed, which is notable, because the atomic beam experiments deal with the $P_{3/2}$ state of atomic chlorine. (d) An unusual structure for the Sb^{121} and Sb^{123} resonances in aqueous solution of $NaSbF_6$ has been observed and is qualitatively explained.

I. INTRODUCTION

RECENTLY various authors[1–3] have emphasized the importance of information concerning the spin and magnetic moment values toward the establishment of nuclear shell theories, and indeed the precise knowledge of nuclear magnetic moments have always played an important role in the development of nuclear theory. In this paper we shall give a detailed report on a series of measurements by which the magnetic moments of nuclei of several stable isotopes were determined. The measurements were made with a nuclear induction spectrometer described in an earlier paper.[4] The results are summarized in Table I; brief reports of these results have been made from time to time.[5]

While in principle nuclear magnetic moments can be compared with the same accuracy with which the ratio of their respective resonance frequencies can be determined, it was recently found that the nuclear magnetic resonance frequency is somewhat different for different molecules containing the nucleus.[6] Relative shifts of the resonance frequency of as much as 1.3 percent have been observed for Co^{59} in various octahedral cobalt complexes. Such shifts, which are at this time not well understood, greatly impair the precision of the values of the magnetic moments obtained. However, certain measurements described in Sec. III, which have been done with different isotopes of nitrogen and chlorine in the same molecular form, indicate that these shifts are characteristic of the molecule itself rather than of the nucleus in question. Therefore, it can be contended at the present time that at least the ratio of the magnetic moments of two isotopes can be obtained with very great precision. Discrepancies between ratios so obtained and those obtained by precise hfs methods are contributing to a new, important body of data which can be interpreted in terms of features concerning the structure of the nucleus.[7]

II. APPARATUS AND METHOD

The measurements described in Sec. III were made with an apparatus described in detail in an earlier paper.[4] Consequently, only a brief review of this apparatus and its use will be given.

A nuclear induction instrument of typical design has been adapted as a recording spectrometer by the following means. The static magnetic field is modulated with a small sweep, so that the component of the signal from the receiver at the sweep frequency is approximately proportional to the derivative of the resonance mode being observed. When the receiver output is detected by a lock-in amplifier, this derivative is plotted by a recording dc milliammeter. The transmitter and receiver tuning condensers are gauged and their common frequency is changed at a slow rate by a clock drive. By using changeable radiofrequency parts, a frequency range of 2.2 to 9.0 Mc is available. The record from the milliammeter is divided into 10- (or 25-) kc intervals by the markers which occur as the transmitter is tuned through the harmonics of a 10- (or 25-) kc commercial multivibrator. Only a single sample is accommodated at a time, and different samples are always located in the same position in the magnetic field.

The electromagnet is supplied with electronically regulated current; its pole-faces are $7\frac{13}{16}$ in. in diameter and spaced $1\frac{3}{4}$ in. A current of two amp produces a field intensity of nearly 12,000 gauss. The homogeneity is such that the variation of the magnetic field over the region occupied by a typical sample is about 0.003 percent.

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* Assisted by the joint program of the AEC and ONR.

† Now at the Department of Physics, University of Basle, Switzerland.

[1] E. Feenberg and K. C. Hammack, Phys. Rev. **75**, 1877 (1949).

[2] L. W. Nordheim, Phys. Rev. **75**, 1894 (1949).

[3] M. G. Mayer, Phys. Rev. **78**, 16 (1950).

[4] W. G. Proctor, Phys. Rev. **79**, 35 (1950).

[5] (a) W. G. Proctor and F. C. Yu, Phys. Rev. **76**, 1728 (1949); (b) **77**, 716 (1950); (c) **78**, 471 (1950).

[6] W. G. Proctor and F. C. Yu, Phys. Rev. **77**, 717 (1950); W. C. Dickinson, Phys. Rev. **77**, 736 (1950).

[7] A. Bohr and V. F. Weisskopf, Phys. Rev. **77**, 94 (1950).

The first task in the process of measuring the gyromagnetic ratio of a nucleus is that of locating the resonance in a suitable material, and its choice is determined by various factors. First, we have chosen, with the exception of Xe, to work with aqueous solutions or liquids, since it is often possible, by the additional dissolution of paramagnetic salts, to control the thermal relaxation time[8] and since sharp lines can be expected.[9] Further, sample substances have been used of such solubilities that signals sufficiently large to be observed could be expected; the choice of the compound was frequently restricted by the condition that it must be mutually soluble with a paramagnetic salt. Finally, we avoided molecules containing unpaired electrons and attempted to choose molecules or ions containing the nucleus in question in a position of high symmetry, if the nucleus was known or anticipated to have a large quadrupole moment; these precautions were dictated by the desire to avoid excessive broadening due to molecular magnetic and inhomogeneous electric fields.

Previous spectroscopic or other measurements of the magnetic moment and spin of a nucleus, which indicate the approximate value of the gyromagnetic ratio, serve as a guide for the region of frequency to be explored with a given magnetic field. Suitable magnitudes of the field intensity H_0, the modulating field and the exciting radiofrequency field are chosen in view of the consideration given in other papers.[4, 8, 10] After the resonance has once been located, the exact gyromagnetic ratio of a nucleus can be measured by comparing, in the same field, its resonance frequency with that of another nucleus, the gyromagnetic ratio of which is known. On the recording chart each resonance is enclosed between frequency markers and the frequency of resonance can be read by interpolation. Since we cannot measure the frequencies of two resonances at the same time, it is necessary to measure the resonances three or four times in turn in order to allow for corrections arising from drifts of the field.

The use of a separate receiver coil perpendicular to the exciting radiofrequency coil makes it possible to infer the sign of a magnetic moment from the phase of the induced r-f voltage. Relative signs of two nuclear magnetic moments can be determined by comparison of the signs of the detected audiofrequency output voltages from the two respective resonances, provided that some care is taken not to disturb the phase of the r-f homodyning voltage with which the r-f nuclear induction signal voltage is detected.

TABLE I. Magnetic moments and magnetic moment ratios.*

Nucleus	Compound used	Magnetic moment in nuclear magnetons
N^{14}	NHO_3	0.40369 ± 0.00006
N^{15}	HNO_3	-0.28312 ± 0.00004
Cl^{35}	HCl	0.8211 ± 0.0001
Cl^{37}	HCl	0.6835 ± 0.0001
Sc^{45}	$Sc(NO_3)_3$	4.7497 ± 0.0008
V^{51}	V_2O_5	$+5.1408 \pm 0.0008$
Mn^{55}	$LiMnO_4$	3.4624 ± 0.0006
Co^{59}	$K_3Co(CN)_6$	4.6399 ± 0.0009
Mo^{95}	K_2MoO_4	-0.9098 ± 0.0002
Mo^{97}	K_2MoO_4	-0.9289 ± 0.0002
In^{113}	$In(NO_3)_3$	5.4972 ± 0.0010
In^{115}	$In(NO_3)_3$	5.5088 ± 0.0010
Sb^{121}	$NaSbF_6$	3.3427 ± 0.0006
Sb^{123}	$NaSbF_6$	2.5341 ± 0.0004
Xe^{129}	Xe	-0.7726 ± 0.0001
Pt^{195}	H_2PtCl_6	0.6005 ± 0.0001
Hg^{199}	$Hg_2(NO_3)_2$	0.4994 ± 0.0001
Bi^{209}	$Bi(NO_3)_3$	4.0400 ± 0.0007

$\mu(N^{15})/\mu(N^{14}) = -0.7013 \pm 0.00007$

$\mu(Cl^{35})/\mu(Cl^{37}) = 1.2014 \pm 0.0001$

$\mu(Mo^{97})/\mu(Mo^{95}) = 1.0210 \pm 0.0001$

$\mu(In^{115})/\mu(In^{113}) = 1.0021 \pm 0.0001$

$\mu(Sb^{121})/\mu(Sb^{123}) = 1.3191 \pm 0.0001$

* With the exception of xenon all samples are aqueous solutions.

To determine spin values, the magnitudes of two signals are compared, one of which originates from nuclei of known spin. From the expression for the absorption mode observed in slow passage[10] it can be shown that the maximum derivative of the signal amplitude is proportional to $nI(I+1)\gamma^3 T_2^2$, where n is the number of resonating nuclei of spin I and gyromagnetic ratio γ, and T_2 is the transverse relaxation time. By measurement of the line widths under slow passage conditions and a knowledge of relative concentrations and gyromagnetic ratios, the quantity $I(I+1)$ is experimentally determined. For nuclei with odd mass number the experimental value can be expected to lie near one of the numbers 3/4, 15/4, 35/4, 63/4, $\cdots$ which makes it an easy matter to distinguish between the lower spin values. However, for spins of 5/2 or greater, small errors in the determination of n, T_2 and the recorded signal maxima for both resonances make a spin determination less certain. Furthermore, it has been observed that T_2 may depend on the state of dissociation in water of the salt being used in a sample. This case occurs for such nuclei and compounds where the relaxation time is largely determined by electric interaction between the quadrupole moment of the nucleus and its molecular surrounding. Hence a given resonance may consist of two or more superimposed lines and can give rise to a complex line shape which invalidates the above relationship used for the determination of spin values.

III. EXPERIMENTAL RESULTS

In order to compute the magnetic moments as listed in Table I, we have used only the measured frequency ratios, known spins, and the known magnetic moments of the nuclei used as standards. In view of the observed dependence of a nuclear magnetic resonance frequency upon the compound used in a sample,[6] it is evident that corrections of a new kind must be applied in many cases before magnetic moments can be listed with good accuracy. Since corrections cannot be made at this time, the results quoted in Table I are without corrections of any kind. The compound which has been

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[8] Bloch, Hansen and Packard, Phys. Rev. **70**, 474 (1946).

[9] Bloembergen, Purcell, and Pound, Phys. Rev. **71**, 466 (1947).

[10] F. Bloch, Phys. Rev. **70**, 460 (1946).

TABLE II. Dependence of frequency on the compound.

Compounds compared	Separation at 3.3 Mc	Separation at 2.1 Mc	Ratio
NH_4^+ and NO_3^- from 7.5-molar NH_4NO_3 in 2.0-molar $MnSO_4$	1.6 kc	0.9 kc	0.58
HNO_3 and $NH_4C_2H_3O_2$	1.0	0.7	0.70
HNO_3 and $(NH_2)_2CO$	1.0	0.6	0.60
NO_3^- and NH_3 from sample (a)	1.2	0.7	0.58

used in each measurement is also listed; the compound used for the standard nucleus may be found by reference to the pertinent paragraph below.

For the purpose of computation, we have used the value $\mu(H^1) = (2.79348 \pm 0.00034)\mu_N$ for the magnetic moment of the proton. This value follows from that given by Taub and Kusch[11] when the uncertainty of the ratio of m_e/M_p equal to 1.1×10^{-2} percent is included and when the calculated diamagnetic correction, without error, of 1.8×10^{-3} percent is removed; hence the above value is a completely experimental number. We have further used the value $\nu(Na^{23})/\nu(H^1) = 0.26450 \times (1 \pm 10^{-4})$ given by Bitter[12] to compute $\mu(Na^{23}) = (2.21663 \pm 0.00035)\mu_N$ and the value $\nu(D^2)/\nu(H^1) = 0.3070117 \pm 0.0000015$ given by Levinthal[13] to compute $\mu(D^2) = (0.857631 \pm 0.00011)\mu_N$. The uncertainties in the final value for a magnetic moment is then the rms value of our experimental frequency ratio error and that of the nucleus which has been used as a standard.

The sign of the nuclear magnetic moment[14] was ascertained in all cases, while the determination of spin values was not carried out unless specific mention is made.

We shall now proceed to describe the measurements on the various nuclei in the order of their atomic number.

1. Nitrogen

From the study of the band spectra of N_2 the spins of the isotopes N^{14} and N^{15}, with natural abundances of 99.62 and 0.38 percent, respectively, were given to be[15, 16] 1 and[17] 1/2. The magnetic moment of N^{14} was determined by the molecular beam method[18] to be $0.402\mu_N$, while that of N^{15} was given[19] as $(0.280 \pm 0.003)\mu_N$, its sign being uncertain. We sought to observe the resonances of these isotopes in order to improve the values of the magnetic moments and to establish the sign of $\mu(N^{15})$.

In the first part of these measurements, dealing with N^{14}, we observed for the first time an effect of the chemical compound on the resonance frequency;[6] at the same time Dickinson[6] found a similar, although somewhat smaller, effect with F^{19}. We used the following sample, which for the purpose of reference we shall designate as sample (a): 5 cc of liquid NH_3, enriched to 7.5 percent in N^{15}, containing 1.18 g of NH_4NO_3 and 1.25 g of $Cr(NO_3)_3 \cdot 9H_2O$ in solution. One weak resonance, apparently arising from the N^{14} in the NO_3^- radical appeared at a frequency of 3.3 Mc, about 1 kc higher than the frequency of a strong resonance, presumably from the N^{14} in the NH_3 and the NH_4^- ion. We associated these resonances with these radicals, because samples of $NH_4C_2H_3O_2$, NH_4NO_3, and NH_4Cl on the one hand and samples of HNO_3, NH_4NO_3, and $Cu(NO_3)_2$ on the other separately gave resonances having frequencies in agreement with those above. Below we shall discuss subsequent observations which show that the resonance frequencies of Cl^{35}, Cl^{37}, and Co^{59} likewise depend upon the chemical compound used in the sample; the effect is particularly large for cobalt, where frequencies differing from one another by as much as 1.3 percent have been found.

With a resolution of 0.1 kc the N^{14} resonances from the above ammonium samples, from the liquid NH_3 as well as NH_4OH, and from KCN in water were found respectively at frequencies 1.0 kc, 1.2 kc, and 0.2 kc lower than that from HNO_3.

The frequency separations for four pairs of compounds were measured at 3.3 Mc and at 2.1 Mc to determine whether or not they were dependent of the applied field intensity; the samples used and the separations measured are given in Table II. They were found, within the resolution of the apparatus, to be proportional to the field, since the ratios of the separations are in agreement with the frequency ratio $2.1/3.3 = 0.64$.

The cause of this effect must evidently be sought in the rearrangement of the electrons which takes place in chemical binding. The fact that the atomic electrons can affect nuclear resonance frequencies has been recognized for a considerable time and has been taken into account in the so-called "diamagnetic corrections" which refer to the shielding of the external field by the electrons; this shielding can indeed be expected to be somewhat modified by the chemical binding and the consequent change in the distribution of electrons. The observed differences in the resonance frequencies of nitrogen are almost twice as large as the total computed shielding effect of the atom; and it does not, therefore, seem possible that they can be explained by a mere modification of this effect, particularly since the inner electrons which contribute mostly to the shielding are hardly affected by the chemical binding. It must be pointed out, however, that in the case of polyatomic molecules there exists another mechanism through which the effective magnetic field, acting upon the nucleus, can be modified by the electrons, and which also affects the susceptibility where it leads to a temperature-independent "induced" paramagnetism, super-

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[11] H. Taub and P. Kusch, Phys. Rev. **75**, 1481 (1949).

[12] F. Bitter, Phys. Rev. **75**, 1326 (1949).

[13] E. C. Levinthal, Phys. Rev. **78**, 204 (1950).

[14] A positive moment is written without the plus sign.

[15] R. Kronig, Naturwiss. **16**, 335 (1928).

[16] L. S. Ornstein and W. R. van Wijk, Z. Physik **49**, 315 (1928).

[17] R. W. Wood and G. H. Dieke, J. Chem. Phys. **6**, 908 (1938).

[18] Kusch, Millman, and Rabi, Phys. Rev. **55**, 1176 (1939).

[19] J. R. Zacharias and J. M. B. Kellogg, Phys. Rev. **57**, 570 (1940).

imposed upon the normal diamagnetism.[20] The need of taking this mechanism into account in the measurements of resonance frequencies has recently been pointed out by Ramsey[21] who was able, by comparison with the rotational moments, to calculate its magnitude for the H_2 molecule. Unfortunately, a similar numerical evaluation is not possible, at present, for other more complicated molecules and it must suffice here to point out that this induced paramagnetic effect can be considerable, particularly in cases where excited electronic states lie relatively close to the ground state of the molecule. Like the diamagnetic corrections, these induced paramagnetic corrections must be proportional to the external field and the above-mentioned observed proportionalities are in agreement with this expectation.

Nevertheless, the assumption that the observed chemical effects are to be ascribed to a modification of the field acting upon the nucleus requires further corroboration. It seemed particularly important to us to verify that they are indeed of molecular origin and not connected with questions concerning nuclear structure and to show that they do not affect the determination of ratios, where one deals with the magnetic moments of isotopes of the same element.

For this purpose we investigated the resonances of both N^{14} and N^{15} in two different compounds. Since the two isotopes have different spins and widely different moments, one would expect a different result for the ratio of their resonance frequencies, measured in different compounds, if one assumes the effect to be of nuclear origin. If, however, the effect can be understood as a modification of the external field by the molecular electrons, this ratio can be expected to be independent of the compound, since the field modification would affect both isotopes equally.

We used the above-mentioned sample (a) for the measurement of $\nu(N^{15})/\nu(N^{14})$ in NH_3 and a sample (b), composed of a 6.2-molar aqueous solution of $NaNO_3$, enriched to 31.4 percent in N^{15} and containing $MnSO_4$ to 1.0-molar concentration, for the measurement of the same ratio in NO_3^- group. We found for sample (a)

$$\nu(N^{15})/\nu(N^{14}) = 1.4026 \pm 0.0001 \tag{1}$$

and for sample (b)

$$\nu(N^{15})/\nu(N^{14}) = 1.4027 \pm 0.0001 \tag{2}$$

so that within our accuracy agreement between the two values was established. This agreement must be considered as significant, since it was ascertained with an error of only about 15 percent of the observed chemical shifts.

Arbitrarily choosing HNO_3 as a standard, we measured

$$\nu(N^{14})/\nu(D^2) = 0.47070 \pm 0.00005, \tag{3}$$

using a General Radio, Model 271, frequency meter. The D^2 resonance was obtained from a 0.6-molar aqueous solution of $MnSO_4$ in 85 percent D_2O. The value (3) corresponds to

$$\mu(N^{14}) = (0.40369 \pm 0.00006)\mu_N, \tag{4}$$

and by applying the average of (1) and (2) leads to

$$\mu(N^{15}) = -(0.28312 \pm 0.00004)\mu_N. \tag{5}$$

As indicated here, the sign of the magnetic moment of N^{15} was observed to be negative. The values (4) and (5) are in good agreement with the molecular beam values. The value (5) is different by 1 part in 2800 from that reported earlier[5b] for $\mu(N^{15})$; this is because (5) was measured relative to the N^{14} resonance in NO_3^- and the earlier value was obtained with NH_3 from sample (a).

2. Chlorine

Kusch and Millman,[22] using the molecular beam method, determined the magnetic moments of the two stable odd chlorine isotopes to be

$$\mu(Cl^{35}) = (0.819 \pm 0.003)\mu_N$$

and

$$\mu(Cl^{37}) = (0.683 \pm 0.003)\mu_N,$$

assuming the present known[23] spin value of 3/2. Bitter found a more accurate value of $(0.8213 \pm 0.0003)\mu_N$ for the former, using the nuclear induction method; we have here observed the resonances of both isotopes. The resonance of the more abundant isotope Cl^{35} (75.4 percent) from a sample of concentrated hydrochloric acid was observed directly on the oscilloscope, and its frequency was compared with a General Radio, Model 271, frequency meter to that of D^2, obtained from a sample of 0.6-molar $MnSO_4$ in 85 percent D_2O. The resonance was near 4.5 Mc, when the field intensity was in the neighborhood of 11 kilogauss. For the ratio of the resonance frequencies we found

$$\nu(Cl^{35})/\nu(D^2) = 0.63827 \pm 0.00006. \tag{6}$$

The resonance of the less abundant isotope Cl^{37} (24.6 percent) was compared with that of $Cl,^{35}$ using the same sample of concentrated hydrochloric acid, but making measurement on the recorded signals, with the result:

$$\nu(Cl^{35})/\nu(Cl^{37}) = 1.2014 \pm 0.0001. \tag{7}$$

The ratio (7) is the ratio of the nuclear magnetic moments, since both isotopes have the same spin 3/2. The values (6) and (7) lead directly to

$$\mu(Cl^{35}) = (0.8211 \pm 0.0001)\mu_N, \tag{8}$$

$$\mu(Cl^{37}) = (0.6835 \pm 0.0001)\mu_N. \tag{9}$$

The ratio of the magnetic dipole interaction constants $a_{35},/a_{37}$, for the two chlorine isotopes in their $^2P_{3/2}$ ground

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[20] J. H. Van Vleck, *Electric and Magnetic Susceptibilities* (Oxford University Press, London, 1932). The mechanism is contained here in the so-called "high frequency terms" in the formula (11), Chapter X.

[21] N. F. Ramsey, Phys. Rev. **77**, 567 (1950); **78**, 699 (1950).

[22] P. Kusch and S. Millman, Phys. Rev. **56**, 527 (1939).

[23] Townes, Holden, Bardeen, and Merritt, Phys. Rev. **71**, 644 (1947).

states has been measured by Davis, Feld, Zabel, and Zacharias[24] and found to be 1.20272±0.00009. The ratio should ordinarily be expected to be equal to the ratio of the magnetic moments of these two isotopes, since the spins are the same and the reduced electron mass corrections are negligible. However, the above value is in disagreement with the ratio (7) by (0.11±0.02) percent. Bitter[25] has suggested that such anomalies may be due to the difference in the distribution of magnetism over the nuclear volumes of the isotopes, since in one case the magnetic field intensity is given by the electron density over the nuclear volume and in the other by the homogeneous applied field. Bohr and Weisskopf[7] have considered this effect for the nuclei of heavy atoms whose electronic configuration is of the type $s_{1/2}$ or $p_{1/2}$ and it has been applied with success to the isotopes of potassium and rubidium. This explanation does not apply, however, to the $p_{3/2}$ ground state with which one has to deal in the atom of chlorine and where the effect of nuclear structure on the hyperfine structure should be very small. A satisfactory explanation of the observed discrepancy between the ratio (7) and that of the corresponding hfs separation has not yet been given.

A shift toward a higher frequency for the same applied field was observed for Cl^{35} and Cl^{37} in solution of $Ba(ClO_4)_2$ and of $HClO_4$, compared to the resonance frequencies of the same isotopes in HCl. Measurements showed that

$$\nu(\mathrm{Cl}^{35}\text{ in HClO}_4)/\nu(\mathrm{Cl}^{35}\text{ in HCl}) = 1.0009\pm0.0001, \quad (10\mathrm{a})$$

$$\frac{\nu(\mathrm{Cl}^{35}\text{ in HClO}_4)}{\nu(\mathrm{Cl}^{35}\text{ in HCl})}\Big/\frac{\nu(\mathrm{Cl}^{37}\text{ in HClO}_4)}{\nu(\mathrm{Cl}^{37}\text{ in HCl})} = 1.0000\pm0.0001. \quad (10\mathrm{b})$$

The assumption that the chemical shift is of molecular origin is supported by the result given in (10b). Because of the similarity of the nuclei Cl^{35} and Cl^{37} this evidence, however, cannot be considered to be as strong as that reported above for the two very different nuclei N^{14} and N^{15}.

3. Scandium

Scandium occurs entirely as the isotope Sc^{45}. Kopfermann and Rasmussen[26] determined its spin as 7/2 and gave a good estimate of its magnetic moment; Kopfermann and Wittke[27] later measured the magnetic moment as 4.8 nuclear magnetons. By dissolving Sc_2O_3 in dilute nitric acid we prepared a 0.65-molar solution of $Sc(NO_3)_3$ which gave a large signal at 7.6 Mc, using a magnetic field of 7.4 kgauss. Its frequency was compared to that of Na^{23} from a saturated aqueous solution of NaCl with 0.5-molar of $MnSO_4$ by means of a General Radio, Model 271, frequency meter. We found

$$\nu(\mathrm{Sc}^{45})/\nu(\mathrm{Na}^{23}) = 0.9183\pm0.0001. \quad (11)$$

Taking for the spin the value 7/2, this leads to a value for the magnetic moment

$$\mu(\mathrm{Sc}^{45}) = (4.7497\pm0.0008)\mu_{\mathrm{N}} \quad (12)$$

in excellent agreement with the spectroscopically determined value. The sign was confirmed to be positive, but no attempt was made to check the spin, since we could not be certain about the degree of dissociation of the molecules in the solution and about the effect of dissociation upon the signal amplitude.

4. Vanadium

The spin of V^{51} (100 percent) has been unequivocally determined as 7/2 by Kopfermann and Rasmussen,[28] while the magnetic moment was measured by Knight and Cohen,[29] using the nuclear induction method. We observed the V^{51} resonance in order to establish the sign of the magnetic moment, although no exceptions are known to the rule that all odd-proton nuclei with spin greater than 1/2 have positive moments. The sign was indeed found to be the same as that of Na^{23}, that is positive. The value, given in brackets in Table I, is that obtained by Knight and Cohen, but we have explicitly indicated the positive sign, since it represents a new result. Our sample was an aqueous solution of $NaVO_3$.

5. Manganese

Manganese occurs only as the isotope Mn^{55}; it is paramagnetic in most compounds because of the unpaired spin of 3*d* electrons. The negative permanganate ion, MnO_4^-, however, is known to possess electrons with paired spins and the very soluble compound $LiMnO_4$ is only slightly paramagnetic. Being guided by the spectroscopic spin value 5/2 obtained by White and Ritschl[30] and the magnetic moment value of 3.0 nuclear magnetons by Fisher and Peck,[31] we found the resonance near 8.3 Mc at a field of 7.9 kgauss, using a 2.0-molar aqueous solution of $LiMnO_4$ as sample. With a General Radio, Model 271, frequency meter we measured the ratio

$$\nu(\mathrm{Mn}^{55})/\nu(\mathrm{Na}^{23}) = 0.9372\pm0.0001. \quad (13)$$

This gives

$$\mu(\mathrm{Mn}^{55}) = (3.4624\pm0.0006)\mu_{\mathrm{N}}. \quad (14)$$

Since the compound $LiMnO_4$ is slightly paramagnetic, there is the possibility that our value for the magnetic moment is too high. However, a frequency dependence upon the temperature, such as that shown by cobalt

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[24] Davis, Feld, Zabel, and Zacharias, Phys. Rev. **76**, 1076 (1949).
[25] F. Bitter, Phys. Rev. **76**, 150 (1949).
[26] H. Kopfermann and E. Rasmussen, Z. Physik **92**, 82 (1934).
[27] H. Kopfermann and H. Wittke, Z. Physik **105**, 16 (1937).
[28] H. Kopfermann and E. Rasmussen, Z. Physik **98**, 624 (1936).
[29] W. D. Knight and V. W. Cohen, Phys. Rev. **76**, 1421 (1949).
[30] H. E. White and R. Ritschl, Phys. Rev. **35**, 208 (1930).
[31] R. A. Fisher and E. R. Peck, Phys. Rev. **55**, 270 (1939).

salts and mentioned below, was not observed for this sample.

6. Cobalt

Cobalt occurs in nature only as the isotope Co^{59}. Its spin was determined by the optical hfs method as 7/2 by Kopfermann and Rasmussen.[32] More[33] confirmed this spin value and gave the magnetic moment as 2.7 nuclear magnetons, although Kopfermann and Rasmussen[34] later showed reason to believe that it is larger.

We have restricted our investigations of the cobalt resonances to those compounds which contain cobalt in essentially covalent octahedral complexes. From simple consideration these compounds should be expected to be only feebly paramagnetic.[20, 35]

We first observed the resonance of Co^{59} in a 1.0-molar aqueous solution of $K_3Co(CN)_6$ and obtained the frequency ratio

$$\nu(Co^{59})/\nu(Na^{23}) = 0.89709 \pm 0.00009. \qquad (15)$$

The resonances of Co^{59} in other compounds were subsequently observed and it was found that the resonance frequency is strongly dependent upon the compound. Table III presents data showing the compounds used and the frequencies of Co^{59} resonances relative to the value (15). It will be noted that the frequencies of these resonances spread over a range as large as 1.3 percent. It is indicated in Table III that $Na_3Co(NO_2)_6$ was observed to manifest two resonances; these two lines may be due to the simultaneous existence of two isomeric forms of this compound. The line widths of both of these lines are the same, 0.72 gauss, and the resonance at the lower frequency is about 16 times more intense than the other. We have searched in the neighborhood of the resonance for each of the other compounds and found no other resonances.

Measurements made on the two lines of $Na_3Co(NO_2)_6$ at four different field values, ranging from 4400 gauss to 7900 gauss, showed that the ratios given in Table III were independent of the field strength to one part in 10,000, suggesting a similar origin of the chemical shift as mentioned above for nitrogen.

As a possible explanation of the large chemical effect observed in cobalt one may assume that it likewise is due to the mechanism of induced paramagnetism as discussed in connection with the measurements on nitrogen. One must then postulate the existence of electronic energy levels very close to that of the ground state and is hence led to the expectation of the dependence of the resonance frequency upon the temperature. The fact that such a dependence exists was indeed demonstrated by the following experiment. Those samples which would not decompose were heated by placing them in boiling water; the resonance frequency of each was compared to that of a like sample at room temperature by exchanging one sample for the other in quick succession and observing the shift of the resonance upon the oscilloscope screen. The compounds, $K_3Co(CN)_6$, $Co(C_2H_4(NH_2)_2)_3Cl_3$, and $Co(NH_3)_6Cl_3$, for which the experiment was performed, showed the same temperature dependence. For about 20 percent increase in temperature, that is, from 20°C to 80°C, the frequency increased by 0.015 percent or about 1 kc out of 7000 kc. Although this small increase is not much greater than the usual experimental error (about 0.006 percent), it is quite certain that there is such a slight temperature-dependence of the Co^{59} resonance, because similar experiments were carried out with NaCl and $LiMnO_4$ and gave no observable shift of Na^{23} and Mn^{55} resonances. It is also interesting to note that the N^{14} resonances in the various compounds listed in Table III showed no unusual frequency shifts, thus indicating that the mechanism, suggested above to explain the shift of the Co^{59} resonance, is mostly concerned with its 3*d* electrons.

TABLE III. Frequencies of Co^{59} resonances in various compounds.

Compound	Relative frequency
$K_3Co(CN)_6$	1.0000
$Co(C_2H_4(NH_2)_2)_3Cl_3$	1.0073±0.0001
$Na_3Co(NO_2)_6$	1.0074±0.0001 1.0081±0.0001
$Co(NH_3)_6Cl_3$	1.0083±0.0001
$K_3Co(C_2O_4)_3$	1.0130±0.0001

If the value (15) is used, we obtain

$$\mu(Co^{59}) = (4.6399 \pm 0.0009)\mu_N. \qquad (16)$$

The sign was observed to be positive. The value (16) is very much larger than the value $2.7\mu_N$ given by More[33] and provides the widest discrepancy known to us between the values of nuclear moments determined from hyperfine structure and from nuclear magnetic resonance. This new higher value agrees with the assumption that the odd proton is in an $f_{7/2}$ orbit as proposed by Mayer;[3] the hfs value indicated an orbit $g_{7/2}$ in disagreement with her single-particle model of the nucleus. Uncertainties in the value (16) of the order of one percent, which arise from the chemical effect, are of course not large enough to affect this assignment.

7. Molybdenum

Molybdenum has two odd isotopes, Mo^{95} and Mo^{97}, which occur naturally to 16.1 percent and 9.6 percent, respectively. The spins of these isotopes have recently been given[36] a probable value 5/2. Mack,[37] from hfs studies, has reported that the ratio of the magnetic moments is 1.07±0.05 with the hfs separation for Mo^{97} definitely larger than that for Mo^{95}. Using a saturated

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[32] H. Kopfermann and E. Rasmussen, Naturwiss. **22**, 291 (1934).

[33] K. R. More, Phys. Rev. **47**, 256 (1935).

[34] H. Kopfermann and E. Rasmussen, Z. Physik **94**, 58 (1935).

[35] L. Pauling, *Nature of the Chemical Bond* (Cornell University Press, Ithaca, 1948), second edition.

[36] J. E. Mack, Rev. Modern Phys. **22**, 64 (1950).

[37] J. E. Mack, private communication.

aqueous solution of K_2MoO_4 as sample, two resonances were found near 3.1 Mc at a magnetic field of 11 kgauss. We obtained

$$\nu(\mathrm{Mo}^{97})/\nu(\mathrm{N}^{14}) = 0.9208 \pm 0.0001 \tag{17}$$

and

$$\nu(\mathrm{Mo}^{97})/\nu(\mathrm{Mo}^{95}) = 1.0210 \pm 0.0001, \tag{18}$$

where we have used the identification made by Mack. The N^{14} resonance was obtained from HNO_3.

The signs were observed to be negative. The single-particle model of Mayer[3] predicts, for nuclei with 53 and 55 neutrons, that, if the spin is 5/2, the single particle orbit is $d_{5/2}$ leading to a magnetic moment with a negative sign; on the other hand, spins of 3/2 and 7/2 would correspond to positive moments. This argument gives weight to the assumption of spin 5/2 for both isotopes. Using this value and the value for $\mu(\mathrm{N}^{15})$ given in (4), we calculated

$$\mu(\mathrm{Mo}^{97}) = -(0.9289 \pm 0.0002)\mu_N, \tag{19}$$

$$\mu(\mathrm{Mo}^{95}) = -(0.9098 \pm 0.0002)\mu_N. \tag{20}$$

These moments have roughly the same magnitude as others for odd-neutron nuclei of spin 5/2. With the assumption of equal spin for both isotopes, the ratio of their magnetic moments is accurately given by (18).

In the ion MoO_4^- the Mo atom is probably contained in the center of a regular tetrahedron of O atoms which together form a shell about the Mo atom and keep it at a certain minimum distance from the solvent water molecules. Since the gyromagnetic ratio of the Mo nuclei is relatively small, it is quite safe to assume that T_1, the thermal relaxation time, is entirely determined by the quadrupole coupling of the nucleus to the electric field gradients at its position. For quadrupole relaxation T_1 goes as Q^{-2}; since in our case T_2 is determined by field inhomogeneities, it is the same for both isotopes. We were not able to measure the relaxation times T_1 for the two isotopes, because they were too long for us to achieve slow passage conditions. We did observe, however, that the intensities of the exciting radio-frequency fields, for which maximum signals in the absorption mode were obtained, were strikingly different for the two isotopes, i.e., greater for Mo^{97} than for Mo^{95}. Since this "saturation intensity" gives a measure for the longitudinal relaxation time T_1 and since we assume this quantity is determined by quadrupole relaxation, we may conclude $|Q(\mathrm{Mo}^{97})| > |Q(\mathrm{Mo}^{95})|$ for the relative order of magnitude of the quadrupole moments of Mo^{97} and Mo^{95}. It was not possible, under our experimental conditions to identify the two isotopes by their signal magnitude and we have therefore used the identification by Mack.[37]

8. Indium

The gyromagnetic ratio of the indium isotopes, In^{113} (4.5 percent) and In^{115} (95.5 percent), were measured with a sample of 0.38-molar $In(NO_3)_3$, which was prepared by dissolving In metal in dilute nitric acid; as will be discussed below, this concentration gave approximately optimum signal conditions. The frequency measurements were first undertaken to find whether a hfs anomaly exists, since a precise measurement of the dipole interaction constants was known.[38] The results of the measurements were

$$\nu(\mathrm{In}^{115})/\nu(\mathrm{Na}^{23}) = 0.82841 \pm 0.00008, \tag{21}$$

$$\nu(\mathrm{In}^{113})/\nu(\mathrm{Na}^{23}) = 0.82667 \pm 0.00008, \tag{22}$$

$$\nu(\mathrm{In}^{115})/\nu(\mathrm{In}^{113}) = 1.0021 \pm 0.0001. \tag{23}$$

The Na^{23} resonance was obtained from a 0.25-molar solution of NaCl with 0.5-molar of $MnSO_4$. The measurements were carried out at a magnetic field of 6600 gauss with radiofrequencies near 6 Mc.

The ratio (24) is in close agreement with the ratio

$$a_{115}/a_{113} = 1.00224 \pm 0.00010 \tag{24}$$

determined by Hardy and Millman,[38] so that no hfs anomaly is found here.

Using spin 9/2 for both isotopes,[38] we calculated

$$\mu(\mathrm{In}^{115}) = (5.5088 \pm 0.0010)\mu_N, \tag{25}$$

$$\mu(\mathrm{In}^{113}) = (5.4972 \pm 0.0010)\mu_N. \tag{26}$$

On the other hand, the diamagnetically uncorrected atomic beam values taken from Taub and Kusch[11] are

$$\mu(\mathrm{In}^{115}) = (5.474 \pm 0.003)\mu_N \tag{27}$$

and

$$\mu(\mathrm{In}^{113}) = (5.463 \pm 0.003)\mu_N. \tag{28}$$

One notes that the resonance values are each 0.6 percent higher than the atomic beam values. A similar discrepancy has already been noted for the isotopes Ga^{69} and Ga^{71} for which the nuclear induction values are 0.7 percent higher than the atomic beam hfs values.[39] Since our measurements were made in rather dilute solution in which the compound $In(NO_3)_3$ can be expected to dissociate, it is not likely that this discrepancy is of the same origin as the observed frequency shifts for N, Cl, and Co. The frequency ratios (21), (22), and (23) were also measured at a field of 3500 gauss and found to be the same.

It was found that a highly concentrated solution of $In(NO_3)_3$ was unfavorable, insofar as it caused an undesirable broadening of the line. To show that this effect was caused by an insufficient degree of dissociation, we performed the following experiment. Solutions of $In(NO_3)_3$, with a constant molarity 0.55 M/l, but with increasing concentration of HNO_3, were compared for line widths, the object being that the presence of the common ion NO_3^- would suppress the dissociation of the salt to a different degree in each sample. It was found that as the NO_3^- concentration was increased, the

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[38] T. C. Hardy and S. Millman, Phys. Rev. **61**, 459 (1942).

[39] R. V. Pound, Phys. Rev. **73**, 1112 (1948); G. Becker and P. Kusch, Phys. Rev. **73**, 584 (1948); see also reference 11.

In^{115} resonance line indeed became broader, achieving a maximum width for 8-molar HNO_3, while a further increase of HNO_3 had no effect. It is reasonable to assume, because of the large quadrupole moment of the In^{115} nucleus, that the line width is given by quadrupole relaxation. Making this assumption, our observation led to the conclusion that the quadrupole interaction with its surroundings is greater for In bound in the molecule $In(NO_3)_3$ than for the dissociated In ion. The maximum observed line width corresponds to a thermal relaxation time of about 10^{-4} sec, while the minimum width leads to a value of about 10^{-3} sec. At intermediate concentrations intermediate widths were of course observed. Viscosity changes were inadequate to account for these differences of the relaxation time.

9. Antimony

Antimony has two odd isotopes, Sb^{121} (56.0 percent) with a spin[40] 5/2 and Sb^{123} (44.0 percent) with a spin 7/2. Spectroscopically Crawford and Bateson[41] have measured their magnetic moments as $3.7\mu_N$ and $2.8\mu_N$, respectively, with a ratio 1.30 ± 0.02. These nuclei are known to have relatively large quadrupole moments[42] and we chose the compound $NaSbF_6$ in aqueous solution as a sample, because in the ion SbF_6^- the Sb nucleus is at the center of a regular octahedron formed by the six fluorine atoms. As a result, the gradient of the electric field to which it is subjected must vanish for symmetry reasons and an excess quadrupole broadening of the line is consequently avoided. The resonance of Sb^{121} was located near 6.7 Mc at a field of 6600 gauss and the resonance of Sb^{123} was found near 6.0 Mc at a field of 11000 gauss. We obtained

$$\nu(Sb^{121})/\nu(Na^{23})=0.90480\pm0.00009, \tag{29}$$

$$\nu(Sb^{123})/\nu(D^2)=0.84423\pm0.00008. \tag{30}$$

The Na^{23} signal was provided from a 0.25-molar solution of NaCl with 0.5-molar of $MnSO_4$ and the D^2 signal was provided from 1.8-molar solution of $MnSO_4$ in 25 percent D_2O. The ratios (29) and (30) give

$$\mu(Sb^{121})=(3.3427\pm0.0006)\mu_N, \tag{31}$$

$$\mu(Sb^{123})=(2.5341\pm0.0004)\mu_N, \tag{32}$$

and

$$\mu(Sb^{121})/\mu(Sb^{123})=1.3191\pm0.0001, \tag{33}$$

all of which are in good agreement with the work of Crawford and Bateson. The recorded signals of both Sb^{121} and Sb^{123}, representing the derivative of the absorption mode, showed an interesting structure which is reproduced in Fig. 1. Each resonance is composed of five lines separated by 1.90 gauss. For reasons presented below we believe that they are caused by the magnetic dipole interaction of the Sb nucleus with the surrounding fluorine nuclei. It follows from this explanation of the structure that the frequency of the central line is unaffected and we have used this line for our frequency measurements.

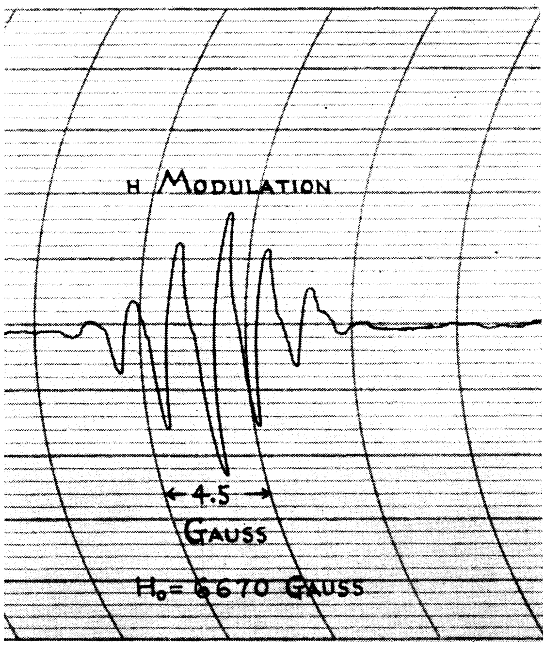

Fig. 1. The experimental derivative of Sb^{121} absorption line in aqueous solution of $NaSbF_6$ and HF.

The features of the shape of the lines from the $NaSbF_6$ solution are qualitatively understood. The Sb atom is contained in the center of an octahedron formed by the six fluorine atoms. For any given orientation of the ion SbF_6^- the magnetic moments of the fluorine nuclei are either parallel or anti-parallel to the external field H_0. This alignment gives rise to a finite number of field perturbations H' at the Sb nucleus. In particular,

$$H'=\sum_i 2M_i\mu(F^{19})(3\cos^2\theta_i-1)/r^3, \tag{34}$$

where M_i is the nuclear magnetic quantum number of the ith fluorine nucleus, θ_i its polar angle with respect to the Sb nucleus with the direction of the external field chosen as polar axis, and r the internuclear distance for the Sb$-$F bond, equal to 1.95×10^{-8} cm.[43] The contribution of one fluorine nucleus to this sum may be as large as $2\mu(F^{19})/r^3=3.54$ gauss. Resonance from Sb nuclei from a large number of molecular ions with the same orientation will give rise to resonance lines at the field values H_0+H', the different values H' corresponding to the values $\pm1/2$ which the quantum number M_i can independently assume. If the molecules are considered to have a stationary but random orientation, one obtains a distribution function for the values H' which shows five lines, separated from each other by $2\mu(F^{19})/r^3$ gauss. The orientation of the molecules in the

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[40] J. S. Badami, Z. Physik **79**, 206 (1932).

[41] M. F. Crawford and S. Bateson, Can. J. Research **10A**, 693 (1934).

[42] K. Murakawa and S. Suwa, Phys. Rev. **76**, 433 (1949).

[43] N. Schrewelius, Z. anorg. u. allgem. Chem. **238**, 241 (1938).

solution is, of course, not stationary but actually undergoes a random rotation; although this step in the analysis has not been carried out, it can be expected that inclusion of the effect of rotation upon the distribution of H' will reduce the separation of the lines.[44]

It is interesting to observe that one cannot measure the thermal relaxation time of the Sb nucleus in $NaSbF_6$ solution by ordinary saturation procedures. To show this, consider the situation in which the frequency of the r-f field is chosen such as to cause resonance absorption within a narrow range of the total line structure. While irradiation takes place, reorientation of the fluorine moments may destroy the resonance conditions for Sb nuclei originally at resonance and temporarily establish resonance conditions for some Sb nuclei of other molecules which would otherwise remain outside of the resonance range. Hence, while one is attempting to saturate a certain group of nuclei, reorientation of the fluorine moments exchanges these for a new group with equilibrium distribution between their magnetic energy states. In the present apparatus the r-f field could not be made large enough to test this effect experimentally, but measurements with higher r-f field are in progress.

10. Xenon

Xenon has two odd isotopes, Xe^{129} (26.2 percent) and Xe^{131} (21.2 percent). Kopfermann and Rindal[45] have determined from hfs measurements that the former has a spin 1/2 and the latter a spin 3/2. Bethe and Bacher,[46] from the work of Kopfermann and Rindal and that of Jones,[47] found that

$$\mu(Xe^{129}) = -0.9\mu_N, \tag{35}$$

$$\mu(Xe^{129})/\mu(Xe^{131}) = -1.11. \tag{36}$$

Being a monatomic gas, pure Xe must be expected to have an exceedingly long thermal relaxation time and it is therefore necessary to provide a paramagnetic catalyst. While the admixture of oxygen could be used in principle for this purpose,[10] calculations indicate that an excessive pressure of O_2 would be necessary. Instead, following a suggestion made by Bloch,[48] we filled the sample volume with powdered Fe_2O_3, so that the impacts of the Xe atoms on the surfaces of the paramagnetic particles could provide the necessary relaxation mechanism. Using a pressure of 12 atmos of Xe and a magnetic field of 5400 gauss, the resonance of Xe^{129} was located near 6.4 Mc with a signal-to-noise ratio of about four. The isotope was identified by the reasonably good agreement of its gyromagnetic ratio with the spectroscopic value. We obtained

$$\nu(Xe^{129})/\nu(Na^{23}) = 1.0457 \pm 0.0001, \tag{37}$$

which leads to

$$\mu(Xe^{129}) = -(0.7726 \pm 0.0001)\mu_N. \tag{38}$$

The sodium resonance was obtained from a 0.25-molar solution of NaCl with 0.5-molar of $MnSO_4$.

The fact that the observed resonance was indeed due to xenon and not to some impurities contained in the Fe_2O_3, was verified, since a sample containing only the powdered Fe_2O_3 gave no resonance. Two other powdered paramagnetic compounds, $CuCl_2$ and Cr_2O_3, were used, but without success. An experiment was also made to see whether, by any unanticipated means, the thermal relaxation time could have been sufficiently short to observe a resonance in the pure xenon gas; as expected, no resonance was observed. In view of its lower gyromagnetic ratio an observable resonance of Xe^{131} cannot be expected from our present samples. If we use the spectroscopic value (36) for the ratio of the magnetic moments, we obtain

$$\mu(Xe^{131}) = 0.696\mu_N. \tag{39}$$

11. Platinum

Platinum has only one stable isotope of odd mass number, Pt^{195}, occurring with an abundance of 35.3 percent. Its spin is known[49] to be 1/2 and its magnetic moment has been determined[50] spectroscopically to be $0.6\mu_N$.

Using a magnetic field of 6600 gauss, the resonance of Pt^{195} was located in the neighborhood of 5.9 Mc. We compared its frequency with that of Na^{23} and found

$$\nu(Pt^{195})/\nu(Na^{23}) = 0.81273 \pm 0.00008, \tag{40}$$

which leads to

$$\mu(Pt^{195}) = (0.6005 \pm 0.0001)\mu_N. \tag{41}$$

The sign of the magnetic moment is positive in agreement with the determination by Schmidt and the signal amplitude is consistent with a spin 1/2. Our sample was prepared by dissolving platinum metal in aqua regia, forming H_2PtCl_6 to 1.0-molar concentration, to which 0.5-molar concentration of $MnCl_2$ was added. The Na^{23} sample was a 0.2-molar aqueous solution of NaCl with 0.2-molar $MnSO_4$. No attempt to observe the Pt^{195} resonance in any other chemical form was made.

12. Mercury

Mercury has two isotopes of odd mass number, Hg^{199} (17.0 percent) and Hg^{201} (13.2 percent), the former having a spin 1/2 and the latter[51] a spin 3/2. The magnetic moment of Hg^{199} was measured spectroscopically by Mrozowski[52] as

$$\mu(Hg^{199}) = (0.547 \pm 0.002)\mu_N. \tag{42}$$

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[44] H. S. Gutowsky and G. E. Pake, J. Chem. Phys. **18**, 162 (1950).

[45] H. Kopfermann and E. Rindal, Z. Physik **87**, 460 (1934).

[46] H. Bethe and R. F. Bacher, Revs. Modern Phys. **8**, 82 (1936).

[47] E. G. Jones, Proc. Roy. Soc. **A144**, 587 (1934).

[48] F. Bloch, to be published.

[49] B. Jaeckel and H. Kopfermann, Z. Physik **99**, 492 (1936); B. Jaeckel, Z. Physik **100**, 513 (1936).

[50] T. Schmidt, Z. Physik **101**, 486 (1936).

[51] H. Schüler and J. E. Keyston, Z. Physik **72**, 423 (1931).

[52] S. Mrozowski, Phys. Rev. **57**, 207 (1940).

The ratio of the magnetic moments

$$\mu(\mathrm{Hg}^{199})/\mu(\mathrm{Hg}^{201}) = -0.9018, \tag{43}$$

given by Schüler and Schmidt,[53] was used by Mrozowski to obtain the value

$$\mu(\mathrm{Hg}^{201}) = -(0.607\pm 0.003)\mu_{\mathrm{N}}. \tag{44}$$

We used a sample containing a 3.5-molar concentration of $\mathrm{Hg_2(NO_3)_2}$, prepared by dissolving mercury in dilute nitric acid and a 0.2-molar concentration of $\mathrm{Mn(NO_3)_2}$. The resonance of Hg^{199} was found in the neighborhood of 6.8 Mc with a magnetic field of 8900 gauss. Comparison of the frequency with that of D^2 from a 1.8-molar aqueous solution of $\mathrm{MnSO_4}$ containing 25 percent $\mathrm{D_2O}$ yields

$$\nu(\mathrm{Hg}^{199})/\nu(\mathrm{D}^2) = 1.1647\pm 0.0001. \tag{45}$$

Taking for the spin the value 1/2, we have

$$\mu(\mathrm{Hg}^{199}) = (0.4994\pm 0.0001)\mu_{\mathrm{N}}. \tag{46}$$

The positive sign was confirmed and the spin was verified to be 1/2.

Computations indicated that for our sample, making even favorable assumption about the relaxation time, the resonance of Hg^{201} could not be observed. However, if (43) is used, we obtain from (46)

$$\mu(\mathrm{Hg}^{201}) = -0.5538\mu_{\mathrm{N}}. \tag{47}$$

13. Bismuth

Bismuth is composed entirely of one isotope Bi^{209}. From hfs work Back and Goudsmit[54] first concluded that the spin of Bi^{209} is 9/2; Mack,[36] reporting upon hfs work from a variety of sources, concluded that the magnetic moment is equal to 4.1 nuclear magnetons. The nuclear resonance of Bi^{209} was found with a 0.69-molar aqueous solution of $\mathrm{Bi(NO_3)_3}$, the quadrupole relaxation providing a satisfactory short thermal relaxation time. The magnetic field used was near 10 kgauss and the radiofrequency near 7.0 Mc. The frequency of resonance was compared with that of D^2 in an aqueous solution of 1.8-molar $\mathrm{MnSO_4}$ with 25 percent $\mathrm{D_2O}$. We found

$$\nu(\mathrm{Bi}^{209})/\nu(\mathrm{D}^2) = 1.0468\pm 0.0001, \tag{48}$$

which leads to the value

$$\mu(\mathrm{Bi}^{209}) = (4.0400\pm 0.0007)\mu_{\mathrm{N}} \tag{49}$$

in good agreement with the spectroscopic value given above.

IV. SUMMARY

The magnetic moments which were obtained from the measurements described in Sec. III are summarized in Table I. It was pointed out in the introduction that the discovery of chemical effects on the resonance frequency introduces an element of uncertainty into the determination of the values of the magnetic moments. In the present state of knowledge of these effects it is sometimes difficult to say to what extent they affect the experimental accuracy. With the exception of Co, where they introduce an error of at least one percent, it seems safe to estimate from the observed magnitude of these effects that the error thus committed is usually well below one percent. However, rather than trying to estimate the error, we felt that the results are presented on a firmer experimental basis if they are given with their full experimental accuracy. The fact that different results may be expected in different compounds is taken into cognizance in Table I by listing the chemical compound used for the sample from which the particular value was derived.

TABLE IV. Diamagnetic corrections.

Element	Diamagnetic correction in percent
Nitrogen	0.03
Chlorine	0.11
Scandium	0.15
Manganese	0.19
Cobalt	0.21
Molybdenum	0.40
Indium	0.49
Antimony	0.52
Xenon	0.56
Platinum	0.93
Mercury	0.96
Bismuth	1.04

Diamagnetic corrections have been totally omitted in Table I, although there is no doubt concerning their existence. Their application, however, would be clearly illusory in the cases like N and Co, while for heavier elements they are large enough to justify their inclusion. For the isolated atom the magnitude of the diamagnetic corrections is closely calculable and in Table IV we list for completeness' sake appropriate diamagnetic corrections for the neutral atom of each element under discussion in this paper. In computing these values we have consistently made use of the following exact expression:[55]

$$-\Delta H/H = (e/3mc^2)V, \tag{50}$$

where $-\Delta H/H$ is the fractional decrease in field intensity at a nucleus which is at a potential $-V$ produced by the atomic electrons, and where the other symbols have their usual meaning. Eight values for V, determined from Hartree field calculations for different atoms, are conveniently listed by Lamb.[55] We have chosen to use values for V which are linearly interpolated or extrapolated between the given points. Calculations of an independent kind, using hydrogen-like wave functions and the empirical shielding constants proposed by Slater,[56] give values for V which agree with

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[53] H. Schüler and T. Schmidt, Z. Physik **98**, 239 (1935).

[54] E. Back and S. Goudsmit, Z. Physik **47**, 174 (1928).

[55] W. E. Lamb, Jr., Phys. Rev. **60**, 817 (1941).

[56] J. C. Slater, Phys. Rev. **36**, 57 (1930).

the above Hartree points to within two percent. The diamagnetic corrections listed in Table IV agree closely with other presentations of the same information.[36, 57]

Very small corrections to these results may still be necessary because of the addition of paramagnetic salts to our samples[58] and have likewise been omitted in Table I. Systematic errors of various instrumental kinds have been examined and found to be negligible.[4]

The authors wish to take this opportunity to express their appreciation for the stimulation and guidance of a year's association with Professor Felix Bloch whose contributions to this work are too manifold to detail. We wish also to thank Dr. F. Alder for his assistance during the period of the measurements upon the isotopes of indium and molybdenum.

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[57] Properties of Atomic Nuclei, Publication BNL 26 (T-10), Brookhaven National Laboratories, October 1, 1949.

[58] N. Bloembergen and W. C. Dickinson, Phys. Rev. **79**, 179 (1950).

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The Disintegration of Rb^{88}*

M. E. Bunker, L. M. Langer,† and R. J. D. Moffat†
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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The radioactive disintegration of Rb^{88} (17.8 min) has been investigated in a magnetic lens spectrometer. Three beta-ray groups are observed having maximum energies of 5.13 ± 0.03, 3.29 ± 0.10, and 2.04 ± 0.15 Mev, with intensities of 66, 19, and 15 percent, respectively. The 5.13 Mev group has a forbidden shape indicating a spin change of 2 units and a parity change. Gamma-rays are found with energies of 0.90, 1.86, and 2.8 Mev. A unique decay scheme is presented giving levels in Sr^{88} at 1.86 and 2.8 Mev. These levels are substantiated by a previous investigation of the disintegration of Y^{88} to Sr^{88}. Spins and parities of Rb^{88}, Sr^{88}, and Y^{88} are discussed in the light of the one particle shell model.

I. INTRODUCTION

The radioactivity of Rb^{88} has been studied by various investigators. Glasoe and Steigman[1] have identified a 17.8-min. beta-activity with Rb^{88} and have measured the beta-ray end point as 4.6 Mev by absorption in aluminum. G. L. Weil,[2] by cloud chamber measurements, observed two beta-ray groups with energies of 5.0 and 2.5 Mev. The period was measured as 17.5 min. Thus log*ft* for the high energy group was determined as ~7.0, suggesting a forbidden transition.

The gamma-rays of the product nucleus Sr^{88} have been investigated by several groups.[3–7] There is general agreement on gamma-ray energies of approximately 0.908, 1.86, and 2.8 Mev. These investigators have used sources of Y^{88}, which decays to Sr^{88} by positron emission and *K* electron capture with a half-life of 108 days.

A further investigation of the Rb^{88} beta-radiation employing higher resolution seemed desirable, since the previous work indicated complexity of the spectrum and the possibility of a unique shape.

II. EXPERIMENTAL METHOD

The investigation of the beta- and gamma-radiation from Rb^{88} (17.8 min) was performed with the aid of a large magnetic lens spectrometer.[8] An end-window Geiger tube with a 3.6-mg/cm^2 mica window and 0.5-inch diameter aperture was employed as a detector. This aperture, together with sources of similar diameter, yielded 6-percent resolution.

Two circular beta-ray sources were prepared from finely powdered Rb_2SO_4. The first was 26 mg/cm^2 on a 0.0002-inch Al backing and covered with a thin Zapon film. The second source was 30 mg/cm^2 on a backing of 0.7-mg/cm^2 nylon, which had been coated with Aquadag to maintain it at ground potential. A thin Zapon cover was again employed.

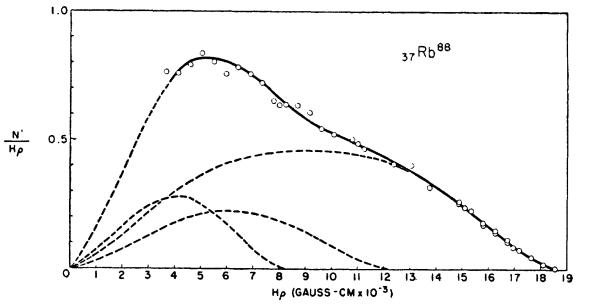

FIG. 1. Beta-spectra of Rb^{88}. The partial spectra are determined from the Fermi plot analysis.

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† Indiana University, Bloomington, Indiana.

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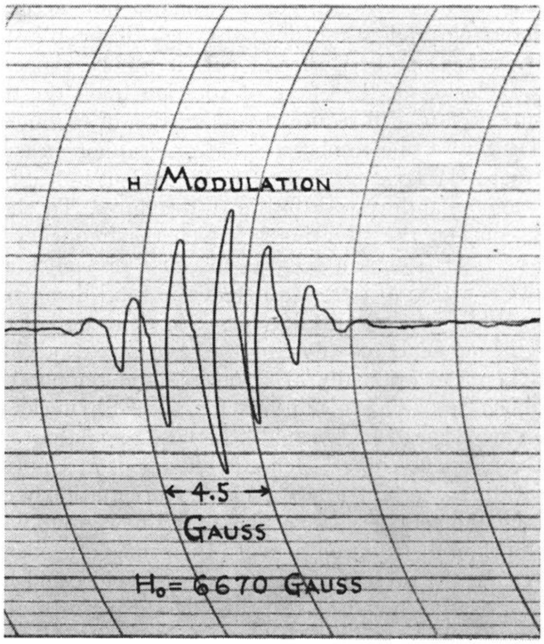

FIG. 1. The experimental derivative of Sb^{121} absorption line in aqueous solution of $NaSbF_6$ and HF.