cases even S (cf. reference 21) good quantum numbers while L and the grouping of states into multiplets will be more easily destroyed. If approximation 1 makes S a good quantum number it will remain a good quantum number in spite of small perturbations which already affect L. This picture suggests e.g. that the $^2P_{3/2}$ and $^2D_{3/2}$ parts are contained in the normal state of an element with $J=\frac{3}{2}$ to a much greater extent than, say, the $^4S_{3/2}$ part.

It may be worth while to note that according to the considerations presented here the following β-spectra should be simple: He^6, F^{18} and probably Al^{26}, and all elements of Table II in which the ground state is a ^2S state. This is very probable for $A=19$ since the magnetic moment of F^{19} is very nearly equal to the magnetic moment of the proton. These elements should offer a possibility for a simple test of the ideas of reference 6.

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On the Nuclear Magnetic Moments of the Isotopes of Rubidium and Chlorine*

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The molecular beam, magnetic resonance method has been applied to the measurement of the nuclear gyromagnetic ratios of Rb^{87}, Rb^{85}, Cl^{37} and Cl^{35}. The g values are 1.820 ± 0.006, 0.536 ± 0.002, 0.454 ± 0.002 and 0.546 ± 0.002, respectively. The magnetic moments of Rb^{87} and Rb^{85}, obtained from the observed g values and the known nuclear spins, are 2.741 ± 0.009 and 1.345 ± 0.005, respectively. The substantial agreement of the moment ratio μ_{87}/μ_{85}, 2.038, found by this method, with that obtained from atomic beam measurements indicates that any contribution to h.f.s. by a form of interaction between electron and nucleus not electromagnetic in character is small. A nuclear moment of 1.365 ± 0.005 is obtained for Cl^{35} if one takes the band spectra spin value of 5/2 for this nucleus. No information concerning the spin of Cl^{37} is available.

INTRODUCTION

A BRIEF preliminary report[1] of the measurements, by the molecular beam, magnetic resonance method,[2] of the nuclear magnetic moments of the isotopes of rubidium and chlorine has already been published. It is the purpose of this paper to present the results in further detail.

The hyperfine structure of atomic energy states of the rubidium isotopes has been investigated both by spectroscopic methods[3] and by the method of atomic beams.[4] Both methods yield nuclear spins of 3/2 and 5/2 for Rb^{87} and Rb^{85}, respectively. Approximate values of the magnetic moments have been obtained from the h.f.s. of the ground state by use of the Goudsmit, Fermi-Segrè formula. In accordance with our experience with the other alkali nuclei, [2,5] the magnetic moments so calculated may be expected to differ by not more than 10 percent from the values of nuclear moments directly measured by the present method. The differences arise from the fact that exact wave functions for the alkali atoms are not known. On the basis of the assumption that hyperfine structure of atomic energy states is due solely to the magnetic interaction of the nuclear moment with the external electrons, the ratio of the nuclear moments of two isotopes of the same element can be obtained from the ratio of the observed

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[1] P. Kusch and S. Millman, Phys. Rev. **55**, 680 (1939).

[2] I. I. Rabi, S. Millman, P. Kusch and J. R. Zacharias, Phys. Rev. **55**, 526 (1939).

[3] H. Kopfermann, Zeits. f. Physik **83**, 417 (1933); D. A. Jackson, Proc. Roy. Soc. **A139**, 673 (1933).

[4] S. Millman and M. Fox, Phys. Rev. **50**, 220 (1936).

[5] P. Kusch, S. Millman and I. I. Rabi, Phys. Rev. **55**, 1176 (1939).

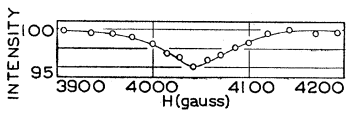

FIG. 1. Rb^{87} resonance curve in Rb_2, with a frequency of 5.604 megacycles per second and an oscillating current of 7 amp.

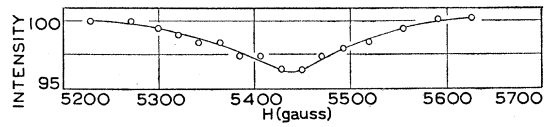

FIG. 2. Rb^{85} resonance curve in Rb_2, with a frequency of 2.230 megacycles and a current of 23 amp.

h.f.s. of a given atomic energy state without the use of the semi-empirical G.F.S. formula, since the electronic wave functions are the same for the two isotopes. This assumption can be subjected to an experimental test by comparing the moment ratio of two isotopes deduced from h.f.s. measurements with that directly measured by the molecular beam, magnetic resonance method. This question was discussed for the case of the lithium isotopes in an earlier paper.[2] In that case the ratio of moments as measured directly was known to a high degree of precision. The ratio of moments as determined from h.f.s.[6] was, however, subject to a considerable uncertainty, and the observed discrepancy of about 2 percent between the two ratios, although outside the experimental error, was not considered sufficiently great to give conclusive indication of a real physical effect. The ratio of the moments of the two isotopes of rubidium is known from h.f.s. data[4] to within 0.2 percent. A comparison of this ratio with one directly determined is of considerable interest, therefore, for testing the validity of the hypothesis that magnetic interactions alone account for observed h.f.s. patterns.

No measurements of the spins and nuclear magnetic moments of the chlorine isotopes are available from the work on the h.f.s. of chlorine. Because of his inability to observe h.f.s. for chlorine, Tolansky[7] concludes that the nuclear g values must be abnormally small. Elliot[8] has found the most probable value of the spin of Cl^{35} to be 5/2 from observations on the alternating intensities in band spectra. No information is available as to the spin of Cl^{37}.

EXPERIMENTAL

The apparatus and the experimental method of determining both the magnitude and the sign of the nuclear gyromagnetic ratios have been previously described.[2, 9] Rb_2 molecules were used in this work in a manner similar to that described[5] for the use of the molecules Na_2 and K_2 in the determination of the magnetic moments of Na^{23} and K^{39}. The principal difficulty in the observation of the resonance curves of rubidium arose from the limited intensity of the *molecular* beam. The molecular content of the beam was only about 0.6 percent. Raising the oven temperature served only to increase the *atomic* beam intensity and left the absolute *molecular* intensity practically unchanged. This occurred because of the greater dissociation that accompanies higher temperatures. The molecules LiCl and RbCl were used for the observation of the resonance minima of the chlorine isotopes.

RESULTS

The two resonance curves shown in Figs. 1 and 2 are typical of curves observed in Rb_2. The beam-intensity ordinate is plotted to a relatively small scale, reflecting the generally low intensities obtainable in these cases. The resonance minima give rise to the g values 1.820 ± 0.006 and 0.536 ± 0.002 in units of $e/2Mc$, when referred to the g of Li^7 which we take to be 2.167. These values are not exactly the same as those obtained from the oscillating frequencies and applied fields given in Figs. 1 and 2 because of the fact that for any one field direction the end effects of the oscillating field produce a shift in the minimum.[9] This error is eliminated from the final result by obtaining data for opposite field directions for a given oscillating frequency and averaging the two apparent g values so obtained. The principal factor limiting the precision of these g values was the difficulty of locating the minima of the resonance curves, which were broad and shallow. The signs of both g's and therefore the signs of the corresponding moments were found to be positive, verifying

[6] J. H. Manley and S. Millman, Phys. Rev. **51**, 19 (1936).
[7] S. Tolansky, Zeits. f. Physik **73**, 470 (1931); S. Tolansky, Zeits. f. Physik **74**, 336 (1932).
[8] A. Elliot, Proc. Roy. Soc. **A127**, 638 (1930).
[9] S. Millman, Phys. Rev. **55**, 628 (1939).

results obtained by other methods.[3, 10] The depths of the observed resonance curves were not sufficiently large to permit an assignment of the observed g values to the appropriate isotopes by comparing the known abundance of the isotopes with the relative depths of the curves. However, a comparison of the ratio of the observed g's, 3.397, with that accurately determined from atomic beam measurements[4] can lead to but one assignment, i.e., that the larger g is to be attributed to Rb^{87} and the smaller to Rb^{85}. The observed nuclear magnetic moments of Rb^{87} and Rb^{85} are then 2.730 ± 0.009 and 1.340 ± 0.005 nuclear magnetons. Since we are dealing with atoms of high atomic number we must apply a correction arising from the diamagnetism of the atom. The correction serves to increase the measured value of the magnetic moment. The contribution, $\bar{H}$, to the magnetic field at the nucleus by the electronic structure is given[5] in terms of the applied field, H, and the atomic number, Z, by $\bar{H}/H=0.32\times10^{-4}Z^{4/3}$. In the present case the correction is 0.4 percent. The corrected values of the moments of Rb^{87} and Rb^{85} are then 2.741 ± 0.009 and 1.345 ± 0.005 nuclear magnetons, respectively. The ratio μ_{87}/μ_{85} is 2.038. Errors in the individual moments, as referred to Li^7, because of gradual shifts in the apparent calibration constant of the homogeneous magnet, do not enter in the evaluation of the ratio of the moments since the resonance curves were obtained under identical experimental conditions. We estimate the precision of this ratio to be 0.5 percent.

It has not been possible to observe resonance curves for rubidium with either RbF or RbCl molecules. The depths of the resonance curves, even with Rb_2 molecules, were small. The factor which limits the depths of the resonance curves is not due to insufficient deflecting power of the inhomogeneous magnets since similar g's have, in many cases, produced deeper minima. The small depths probably arise from some sort of an interaction between the nuclear spin and the molecule. The specific nature of this interaction is not as yet understood. Variations in the depths of resonance minima, depending on the nature of the molecule in which the nucleus exists, have been found for other nuclei as well.[5]

Chlorine resonance minima were observed in the LiCl and the RbCl molecules. Figs. 3 and 4 show typical resonance curves. The observed g values are 0.454 ± 0.002 and 0.546 ± 0.002. The signs of these g's were found to be positive. The assignment of these g's to the appropriate isotopes may be made by comparing the observed depths of the resonance curves with the known ratio of the abundance of Cl^{35} to Cl^{37}, about 76 to 24. The ratio of the depth of the resonance curve of the larger g to that of the smaller g, when LiCl is loaded in the oven, is 3.4 and 3.1 for currents in the wires which produce the oscillating field of 20 and 10 amperes, respectively. At 20 amp. the depth of the resonance curve of the larger g was about 10 percent of the total beam intensity. The observed ratio of the depths of the resonance curves points strongly to the conclusion that the g value of 0.546 is to be assigned to Cl^{35}. An assignment on this basis, of course, assumes that any interaction which might affect the depth of the resonance curve is the same for the $LiCl^{35}$ and the $LiCl^{37}$ molecules. The fact that the widths of the resonance curves are about the same for both isotopes probably shows that these interactions are not markedly different for the two nuclei. A more cogent argument arises from a consideration of the observed depth, 10 percent, of the resonance curve of the larger g. If this is to be ascribed to Cl^{37} and if we assume that the molecules in the beam are LiCl, then 42 percent

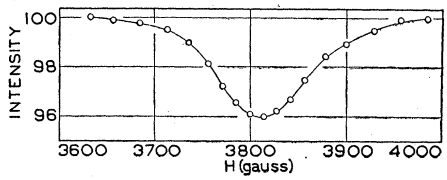

FIG. 3. Cl^{37} resonance curve in LiCl, with a frequency of 1.318 megacycles and a current of 40 amp.

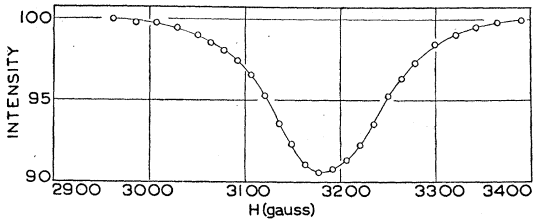

FIG. 4. Cl^{35} resonance curve in LiCl, with a frequency of 1.318 megacycles and a current of 20 amp.

[10] S. Millman and J. R. Zacharias, Phys. Rev. **51**, 1049 (1937).

of the molecules containing Cl^{37} have missed the detector because of reorientations in the transition field. This amount is much greater than can be expected to occur for a nucleus whose g is as small as 0.55. We have no knowledge, however, that the molecules in our beam are LiCl rather than $(LiCl)_n$ with $n \geq 2$. If $n=2$ then 42 percent of the molecules in the beam will contain Cl^{37}, and the assignment of the larger g to Cl^{37} would imply that 24 percent of the molecules in the beam have missed the detector due to reorientations. This fraction is also greater than can reasonably be expected, especially for a curve as broad as that in Fig. 3. It therefore seems quite certain that the g value of 0.546 is to be assigned to Cl^{35} and that of 0.454 to Cl^{37}. If we take the band spectra[8] value of 5/2 for the spin of Cl^{35} its moment is 1.365 ± 0.005 nuclear magnetons. It must be borne in mind, however, that determinations of spin from measurements of alternating intensities in band spectra are not decisive for spin values as large as 5/2. The correction due to diamagnetic susceptibility is less than 0.1 percent and can be neglected. Since the spin of Cl^{37} is not known its magnetic moment cannot be obtained from the observed g.

Discussion

Our values, 2.741 and 1.345, for the magnetic moments of Rb^{87} and Rb^{85}, respectively, are to be compared with 2.67 and 1.32, calculated from the h.f.s. of the ground state by the use of the G.F.S. formula.[11] It is seen that the results obtained from the G.F.S. formula are in good agreement with those obtained from our direct measurements. The value which we obtain for the ratio, 2.038 ± 0.010, is to be compared with the ratio obtained by Millman and Fox[4] from atomic beam measurements, 2.026 ± 0.004. The discrepancy of 0.6 percent lies within the limits of experimental error. Any contribution to the h.f.s. of an atomic energy state by a form of an interaction, not electromagnetic in character, between the nucleus and the electronic structure is certainly very small.

This research has been aided by a grant from the Research Corporation.

[11] The results given by Millman and Fox are slightly high because of an error in the use of the relativity correction factor, $(1-ds/dn)$, in the G.F.S. formula. The moments here given have been recalculated from their data.

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The Electron-Positron Field Theory of Nuclear Forces

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A simple, spin-independent interaction is assumed between heavy particles (neutrons and protons) and electrons. Saturation of resulting forces between heavy particles is assured by choosing a bounded interaction. The change in energy of electrons in negative levels which is caused by the presence of a heavy particle is calculated. Certain general restrictions on the choice of interactions between electrons and heavy particles are discussed.

Introduction

1.

IT has been suggested[1] that nuclear forces are characterized by an exchange of electron-positron pairs between the interacting particles. This type of field theory was conceived of as a possible explanation of the equality of proton-proton and neutron-proton forces which became apparent from the results of scattering of protons

[1] G. Gamow and E. Teller, Phys. Rev. **51**, 289 (1937).