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On the Nuclear Magnetic Moments of the Boron Isotopes*

S. MILLMAN, P. KUSCH AND I. I. RABI
Columbia University, New York, New York

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The nuclear Landé g values of $_5B^{10}$ and $_5B^{11}$ have been measured by means of the molecular beam magnetic resonance method, with the alkali tetraborates and metaborates. The values which were found are, in units of $e/2Mc$, 0.597 ± 0.003 and 1.788 ± 0.005. The assignment of the observed g values to the appropriate isotopes is discussed with the result that the former is assigned to B^{10} and the latter to B^{11}. If one assumes a value of 1 and $\frac{3}{2}$ for the nuclear spins of B^{10} and B^{11}, respectively, the magnetic moments are 0.597 ± 0.003 and 2.682 ± 0.008 nuclear magnetons for the B^{10} and B^{11} isotopes, respectively.

THERE exists no spectroscopic data from which any information with regard to the spins or nuclear magnetic moments of $_5B^{10}$ and $_5B^{11}$ can be deduced. Because of its high boiling point and high ionization potential boron is not suitable for study with the method of *atomic* beams. The *molecular* beam magnetic resonance method,[1] however, is not subject to the same limitations because good detectable beams of molecules containing boron can be obtained.

The molecules which were studied in the experiments to be described were $Li_2B_4O_7$, $Na_2B_4O_7$, $K_2B_4O_7$, $NaBO_2$ and KBO_2. The alkali content in these molecules makes their detection possible by means of the surface ionization detector. At temperatures in the neighborhood of 1100°K these compounds have vapor pressures which are sufficiently high (about 1 mm of Hg) to give molecular beams of requisite intensity.

The apparatus used in these experiments and the procedure followed differed in no essentials from those previously described.[1]

We find two resonance minima common to all molecules used in these experiments. We ascribe these minima to the B^{10} and B^{11} nuclei. Typical resonance curves are shown in Figs. 1 and 2. Although we do not know what molecular species issue from our oven at the temperatures used in these experiments, it is certainly true that the molecules consist of boron in chemical combination with alkali and oxygen atoms. Since the O^{16} nucleus has no moment and since the only other constituents common to all the molecules are the boron nuclei, the resonance minima must be ascribed to the two isotopes of boron.

The values of the nuclear gyromagnetic ratios, deduced from the observed frequencies and applied magnetic fields at resonance, are 0.597 ± 0.003 and 1.788 ± 0.005, referred to the g value of Li^7 which we take as standard (for Li^7 $g=2.167$ in units of $e/2Mc$).

The signs of both g's and, therefore, the signs of the nuclear moments are found to be positive from observations on the shift of the resonance minima with reversal of the homogeneous field direction. It has been pointed out in a previous paper[2] that the procedure of obtaining resonance curves for opposite field directions is essential not only for sign determinations but also for accurate g measurements. Resonance curves obtained for only one field direction yield g values that are either too low or too high, depending on the direction of the field and on the sign of the nuclear moment. The g values deduced from the curves exhibited in Figs. 1 and 2 are slightly low.

The next problem in the interpretation of these experiments is the assignment of the observed g values to the appropriate isotopes. For this we have available the known abundance ratio of B^{11} to B^{10}, 4 to 1, and our measurements of the depths of the resonance minima. It is necessary to notice that the fraction of molecules containing at least one B^{10} nucleus is 0.2 only for molecules containing one boron atom. This fraction is raised to 0.36 when there are two boron atoms in the molecule and to 0.59 for molecules containing four boron atoms. In the

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

[2] S. Millman, Phys. Rev. 55, 628 (1939).

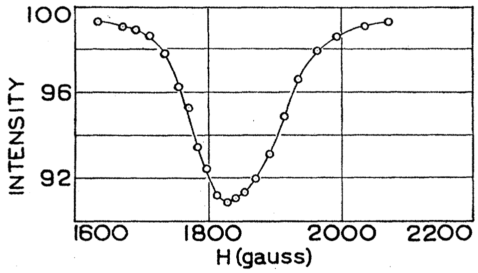

FIG. 1. Resonance curve of B^{11} observed in $Na_2B_4O_7$ with a frequency of 2.494×10^6 sec.$^{-1}$ and an oscillating current of 16 amp.

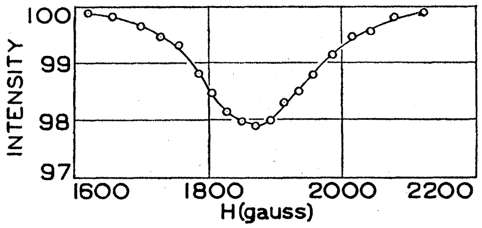

FIG. 2. Resonance curve of B^{10} observed in $K_2B_4O_7$ with a frequency of 0.845×10^6 sec.$^{-1}$ and an oscillating current of 20 amp.

last case very nearly 100 percent of the molecules will contain at least one B^{11} nucleus. Unfortunately we have no knowledge of the exact nature of the molecular species in the beam and consequently can make no prediction as to the fraction of molecules containing at least one B^{10} nucleus. For example, when the oven is charged with a metaborate there is no proof that the vapor is KBO_2 and not $(KBO_2)_n$, with $n\geqslant 2$.

We find that the larger g value is always associated with the deeper resonance minimum for all compounds loaded into the oven and for all amplitudes and frequencies of the oscillating field. The relative depths of the two resonance minima do vary with the value of the current which excites the oscillating field. For example, when the oven is charged with $K_2B_4O_7$ the ratio of the depth of the two resonance minima at 10, 50 and 110 amp. are 7.2, 4.2 and 2.7, respectively. The depth ratios are approximately the same for metaborates as for tetraborates. The largest depth observed for the resonance minimum of the larger g, with a current of 110 amp., was 27 percent of the total beam intensity.

The observed depth ratios seem to point toward the assignment of the larger g value to B^{11}. We must take cognizance, however, of the circumstance that a part of this favorable ratio is due to the greater sensitivity of our apparatus to large g values. The magnitude of the nuclear g determines the change in the over-all magnetic moment of the molecule in the direction of the field when a reorientation takes place, and, therefore, the fraction of reoriented molecules that miss the detector. For this reason alone a g value of 1.8 would give a resonance minimum about twice as deep as one of 0.6. When this effect is taken in consideration the depth ratios cited above become considerably smaller, although they are still in favor of the suggested assignment.

We must consider the possibility that the molecular interaction for the two nuclei is sufficiently different to cause a deeper observed minimum for B^{10} even though this nucleus is not as abundant as B^{11}. This is especially pertinent for the tetraborates, where 59 percent of the molecules contain B^{10}. The difference in molecular interaction does not have to be very large in this case to give an inverted depth ratio. In a previous paper[3] the dependence of the depth of the resonance minimum on molecular interaction has been briefly discussed. The nature of this dependence is as yet not understood. Our interest in this interaction is confined, at present, to its effect on the proper assignment of the observed g values.

The strongest evidence for our assignment is furnished by a consideration of the maximum observed depth of 27 percent for the resonance curve of the larger g. If we assume that this minimum corresponds to B^{10} and further assume the very unfavorable case of a molecule containing four boron nuclei, then 46 percent of the molecules containing at least one B^{10} nucleus have missed the detector due to reorientations of B^{10} nuclei in the oscillating field. From our experiences with other substances we find this to be a very unusual amount for a nucleus which produces a resonance curve as broad as that shown in Fig. 1. In fact we have never observed such a phenomenon. If, on the other hand, we assign the larger g to B^{11}, then 27 percent of the molecules containing B^{11} have missed the detector due to reorientations. This is a reasonable

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

amount and more nearly in line with our expectations.

The preponderance of evidence is thus definitely in favor of the assignment first suggested. We conclude that the g value of 1.788 is to be assigned to B^{11} and the value 0.597 to B^{10}.

To obtain magnetic moments from the experimentally measured g values we must make some assumptions with regard to the nuclear spins. In its present state our method does not measure nuclear spin directly.

The most reasonable assumption for the spin of B^{11} is $\frac{3}{2}$. The fact that the g of B^{11} is positive and has a value of 1.788 makes it difficult to assign a spin of $\frac{1}{2}$ to this nucleus because the moment would then be 0.894 and positive. Now a nuclear spin of $\frac{1}{2}$ arising from the uncompensated proton spin and from some possible angular momentum will form a combination something like $^2S_{\frac{1}{2}}$ or $^2P_{\frac{1}{2}}$. A $^2S_{\frac{1}{2}}$ state should have a moment close to that of the proton, 2.785,[4] as in the case of F^{19}, whose moment is 2.622.[1] A $^2P_{\frac{1}{2}}$ state should have a negative moment because the proton moment, which is considerably larger than the moment arising from the orbital angular momentum, is oriented antiparallel to the total angular momentum. These simple considerations lead to the conclusion that the spin of B^{11} is greater than $\frac{1}{2}$. Whether or not it is greater than $\frac{3}{2}$ is difficult to predict from our experimental results. However, if one assumes $\frac{3}{2}$, the value of the magnetic moment of B^{11} is 2.682 ± 0.008 nuclear magnetons, which is slightly less than the proton moment. The orbital contribution is apparently negative, instead of $+0.47$ as in Li^7 which has a spin of $\frac{3}{2}$. Our results are to be compared with the predictions of Rose and Bethe[5] of a spin of $\frac{3}{2}$ and a moment of 3.43 for the B^{11} nucleus. These authors calculated on the basis of a Hartree model. Sachs,[6] using an α-particle model, predicts a moment of -0.44 if the spin is $\frac{1}{2}$ and a moment between 1.5 and 3.2 if the spin is $\frac{3}{2}$.

B^{10} is one of the four stable nuclei having an odd number of neutrons and a like number of protons. The other members of this group, $_1H^2$, $_3Li^6$ and $_7N^{14}$, are known to have a spin of 1. It is natural to assume the same spin value for $_5B^{10}$, in line with the prediction of Rose and Bethe[5] and that of Feenberg and Wigner.[7] On the basis of this assumption the nuclear magnetic moment of B^{10} is 0.597 ± 0.003 nuclear magneton. Arranged in order of increasing atomic number the moments form a monotonically decreasing progression.

$_1H^2$	0.854[4]
$_3Li^6$	0.820[1]
$_5B^{10}$	0.597
$_7N^{14}$	0.402[3]

This sequence may be due to the gradual inception of a $^3D_1$ state of the nucleus as suggested by Feenberg and Phillips[8] for N^{14}.

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[5] M. E. Rose and H. A. Bethe, Phys. Rev. **51**, 205 (1937).

[6] R. G. Sachs, Phys. Rev. **55**, 825 (1939).

[7] E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937).

[8] E. Feenberg and M. Phillips, Phys. Rev. **51**, 597 (1937).