Nuclear Magnetic Moment Ratio and Linewidths of N^{14} and N^{15}

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The ratio of the nuclear magnetic moment of N^{14} to that of N^{15} in liquid nitrogen has been measured using the technique of nuclear magnetic resonance. The value obtained is $\mu(14)/\mu(15)=1.4257641\pm0.0000010$. The true linewidths (between points of maximum slope) have been determined to be 24 ± 4 cps for N^{14} and <4 cps for N^{15}.

INTRODUCTION

THE strong, narrow, nuclear magnetic resonances (NMR) found in N^{14} and N^{15} in liquid nitrogen offer a straightforward way to measure the magnetic moment ratio of these isotopes. A liquid nitrogen sample, half N^{14} and half N^{15}, would enable one to measure the resonance frequencies of both isotopes in the same sample coil with the same magnetic field and the same chemical environment for both. Previous measurements[1,2] of this ratio have been made in chemical solutions in which the linewidths were broader. The result presented here is in excellent agreement with the result of Anderson, *et al.*[3] who measured the moment ratio in a solution of NH_4Cl using the technique of nuclear double resonance.

EXPERIMENTAL DETAILS

The sample used was 964 cc (NTP) of nitrogen gas in which the N^{15} content had been enriched to 46.8%.[4] This was condensed into a 1.5-cc glass vial by pumping on an external liquid nitrogen bath. Measurements were made at about 68°K or about 5° above the triple point.

In order to reduce microphonics which arise when an rf coil is placed in a bubbling helium bath, the sample vial was placed inside a brass tube which contained nitrogen exchange gas. This tube also served as the ground coaxial lead to the rf coil wound around the vial. The cryostat was a typical metal Dewar with a tail that fitted between the poles of an electromagnet.

The magnet was a 12-in. Varian with a $2\frac{1}{2}$-in. gap. Regulation of the magnet current (as specified by the manufacturer) was within 1 part in 10^7. The marginal oscillator was a modified Pound-Watkins-Knight[5] type. The detected signal was amplified by a narrow-band amplifier, displayed on an oscilloscope, passed through a lock-in detector, and recorded on a Brown recorder. Frequencies were read from a Hewlett-Packard 524-D counter.

Magnetic modulation was used, and because of the very narrow linewidths it was necessary to use low modulation frequencies (10, 20, and 30 cps) and low modulation amplitudes (0.05 gauss peak-to-peak) in order to avoid excessive modulation broadening[6] of the lines. The rf level was also kept low to reduce the degree of saturation and the associated line distortion. The rate of sweep of the oscillator frequency was of the order of 0.2 cps/sec which was about the short time limit of stability of the oscillator.

The resonance frequency was determined by observing the point at which the signal on the oscilloscope passed through zero. At this instant the frequency counter was read. Since the counter counts for 1 sec and displays for 1 sec, and since it counts only to the nearest cycle, the error in any one reading was of the order of 1.5 cps. However, this error was averaged out by taking a large number of readings with both upward and downward sweep. Measurements of the N^{14} resonance were alternated with measurements of the N^{15} resonance at about 20-min intervals. By plotting a smooth curve of resonance frequency versus time for each isotope, one could interpolate between points to obtain the resonance frequencies at the same time, thus compensating for the slow drift in magnetic field.[7] This drift, caused by a slow variation in temperature and/or current was of the order of 1.2 cps/min and usually monotonic for periods of many hours. The magnetic field was approximately 7966 gauss.

Linewidths were measured by making frequency markers on the recorder trace.

RESULTS AND DISCUSSION

NMR Moment Ratio

The average of 50 readings using 10-cps modulation is

$$\nu(15)/\nu(14)=2\mu(15)/\mu(14)=1.4027566\pm0.0000010$$

or

$$\mu(14)/\mu(15)=1.4257641\pm0.0000010.$$

The errors indicated are three times the probable error, the factor three being introduced to make allowance for any systematic error which might remain unknown. This error corresponds to a frequency error of 1.5 cps.

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[6] K. Halbach, Phys. Rev. **119**, 1230 (1960).
[7] M. W. Rice, thesis, Harvard University, 1958 (unpublished) Chap. II-c.

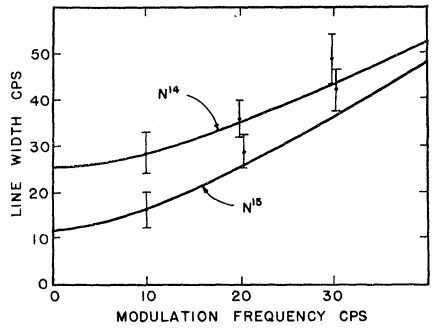

FIG. 1. Experimental linewidths between points of maximum slope plotted versus modulation frequency. The solid curves are plotted from Eq. (3), where ν_{ms} has been taken as 24 cps and 0 cps for N^{14} and N^{15}, respectively.

The maximum deviation for any one reading was only 0.0000011. Errors due to interpolation on the graph were found to be negligible; the ratio changing by less than 0.0000001 when linear interpolation was used.

The result of Anderson *et al.*[3] is

$$\nu(15)/\nu(14) = -1.4027576 \pm 0.0000015,$$

where the error is six probable errors.

Linewidths

The effect of modulation frequency on the linewidth is illustrated in Fig. 1. In order to obtain the true linewidths from these data, it is necessary to account for the effects of modulation frequency and amplitude as well as the effects of magnetic-field inhomogeneity and partial saturation by the rf field.

Halbach[6] has dealt with this problem and gives the relationship for second moments as

$$\langle\omega^2\rangle_{exp} = \langle\omega^2\rangle + \omega_m^2/3 + (\gamma H_m)^2/4, \quad (1)$$

where $\langle\omega^2\rangle_{exp}$ and $\langle\omega^2\rangle$ are the experimental and true values of the second moment, respectively, ω_m is 2π times the modulation frequency, γ is the magnetogyric ratio, and H_m is the peak modulation amplitude. In order to utilize this relationship for determining true linewidths between points of maximum slope (hereinafter designated simply as "linewidths") it is necessary to know the relationship between second moment and the linewidth. This in turn requires a knowledge of the shape function. If one assumes, for example, that both the true line shape and the experimentally observed line shape are of Gaussian form, the relationship between second moment and linewidth is[8]

$$\langle\omega^2\rangle = \omega_{ms}^2/4, \quad (2)$$

where ω_{ms} is 2π times the linewidth between points of maximum slope. Using this in Eq. (1) and changing to frequencies instead of angular frequencies gives

$$(\nu_{ms}^2)_{exp} = \nu_{ms}^2 + 4\nu_m^2/3 + (\gamma H_m)^2/4\pi^2, \quad (3)$$

The line shapes of N^{14} and N^{15} in the liquid state are probably closely Lorentzian so Eq. (3) cannot be rigorously true. However, since the second moment of a Lorentzian line is infinite, we use a Gaussian shape here in order to arrive at an equation which will at least be approximately true. Furthermore, it must be pointed out that this equation is valid only for negligible saturation and negligible broadening due to magnetic-field inhomogeneity—conditions which are not quite satisfied for N^{14} and certainly not satisfied for N^{15}. The correction to the right-hand side of Eq. (3) due to magnetic-field gradient would be of the order of $(\gamma\Delta H_0/2\pi)^2$, where ΔH_0 is the variation in the static field across the sample. But all these effects would certainly modify Eq. (3) in the following manner: Since the observed line is distorted, there should be a multiplicative factor in front of $(\nu_{ms}^2)_{exp}$ which would be a function of ν_m, H_m, ΔH_0, and H_1 where H_1 is the rf field in the coil. Table I shows the magnitude of the corrections due to ν_m, H_m, and ΔH_0, and along with Fig. 1 shows that the agreement is worse for higher modulation frequencies because of the effects mentioned. In view of the relatively large errors in $(\nu_{ms}^2)_{exp}$ (determined mainly by oscillator instability) improvement in the theory would not greatly improve the results. Extrapolation of the curve in Fig. 1 to zero modulation frequency eliminates the major source of broadening and also ensures that the assumption that both the experimental and true line shapes are the same is more nearly correct. This also reduces the error arising if

TABLE I. Contributions to the observed linewidths $(\nu_{ms})_{exp}$ due to modulation frequency, ν_m; modulation amplitude, H_m; and magnetic field inhomogeneity, ΔH_0. The true linewidths, ν_{ms}, have been taken as 24 and 0 cps for N^{14} and N^{15}, respectively.

1 Isotope	2 Modulation frequency (cps)	3 $(\nu_{ms}^2)_{exp}$	4 ν_{ms}^2	5 $4\nu_m^2/3$	6 $(\gamma H_m)^2/4\pi^2$	7 $(\gamma\Delta H_0)^2/4\pi^2$	8 Sum of columns 4+5+6+7
N^{14}	10	810±240	576	133	69	10	778
N^{15}	10	260±130	0	133	137	20	290
N^{14}	20	1280±290	576	533	69	10	1178
N^{15}	20	810±160	0	533	137	20	690
N^{14}	30	2360±530	576	1200	69	10	1845
N^{15}	30	1760±380	0	1200	137	20	1357

[8] E. R. Andrew, *Nuclear Magnetic Resonance* (Cambridge University Press, New York, 1956), p. 105.

$g(\nu)$ is not Gaussian. For N^{14} the difference between $(\nu_{ms})_{exp}$ and ν_{ms} for $\nu_m=0$ is only 4%. The true linewidths have been set at

$$\nu_{ms}(14)=24\pm4 \text{ cps},$$
$$\nu_{ms}(15)<4 \text{ cps}.$$

The true linewidth of N^{15} is probably less than 1 cps due to lack of an efficient relaxation mechanism. From these data and with the assumption of Lorentzian line shapes, the relaxation times are

$$T_2(14)=1/(\sqrt{3}\pi\nu_{ms})=0.007\pm0.001 \text{ sec},$$
$$T_2(15)>0.05 \text{ sec}.$$

The relaxation T_1 has been determined for N^{14} by the method of progressive saturation. The value found is

$$T_1(14)=0.004\pm0.002 \text{ sec}.$$

Due to the long T_1 for N^{15} it was not possible to use the method of progressive saturation. Experiments to measure relaxation times T_1 and T_2 for both isotopes by means of spin echo techniques are being planned.

Note added in proof. These measurements are now in progress and reveal a very interesting and complex behavior for the relaxation of liquid nitrogen. In addition to the T_1 detected here, there is a second one about ten times longer in the isotopic mixture. These are presumably associated with N^{14} in the $N^{14}-N^{14}$ and $N^{14}-N^{15}$ molecules. The resonance with the longer relaxation time was almost totally saturated relative to the other resonance throughout the cw work reported here and so was not noticed. A full discussion will be submitted for publication shortly.[9]

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[9] P. C. Canepa and T. A. Scott (to be published).

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Stripping Analysis of the $Be^9(Li^6,\alpha)B^{11}$ Reaction*

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An analysis of the angular distributions of α particles from the $Be^9(Li^6,\alpha)B^{11}$ reactions has been carried out using a simple "lump" stripping model. Both the normal stripping mode and that exchange mode commonly called "heavy-particle stripping" have been incorporated in the analysis. The model assumes that the Li^6 and the Be^9 nuclei may be represented by the two-cluster configurations "alpha particle plus deuteron" and "alpha particle plus He^5" respectively. The angular distribution calculated for the first excited state reaction provides a satisfactory fit to previously published experimental results at a laboratory bombarding energy of 3.25 Mev. The theoretical angular distribution for the ground state reaction is less successful but does show the principle features of the experimentally observed angular distribution.

I. INTRODUCTION

ANGULAR distributions of α particles from the $Be^9(Li^6,\alpha)B^{11}$ reactions leading to the ground and the first-excited state of B^{11} have recently been published[1] for laboratory bombarding energies ranging from 2 to 4 Mev. It was suggested in that report that the character of the angular distributions indicated some direct-interaction mechanism for the reaction. An analysis based on an elementary form of stripping theory has therefore been attempted. Both the normal or "projectile stripping" mode and that exchange mode called "heavy-particle stripping"[2] or "target stripping" have been included in the analysis, as has the interference term between the two modes. No compound nucleus contribution has been included.

II. CLUSTER MODEL OF THE INTERACTING NUCLEI

In calculating the scattering amplitude for the projectile-stripping mode it is assumed that the Li^6 projectile may be represented by the two-cluster configuration $\alpha(1)+d$, where d indicates a deuteron. The internal structures of both clusters are neglected. $\alpha(1)$ and d are taken to be in a relative S state.[3] In the projectile-stripping mode the deuteron is stripped from the Li^6 and captured by the Be^9 target nucleus, leaving $\alpha(1)$ as the outgoing α particle. For the target-stripping mode the Be^9 target is assumed to be described at the time of interaction by the two-cluster configuration $\alpha(2)+He^5$. Again the internal structures of the two clusters are

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