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A Precision Measurement of the Ratio of the Nuclear g Values of Li^7 and Li^6

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The molecular beam magnetic resonance method has been used to make a precision measurement of the ratio of the nuclear g factors of Li^7 and Li^6. The central maximum of the Li^7 line and the center of the Li^6 line in the spectra of LiI and LiBr give the ratio g_7/g_6 to a precision limited only by experimental factors. The mean of eight independent determinations, under various experimental conditions, is 2.64094 ± 0.00005. This value of the ratio is compared with that calculated by use of the Fermi formula from the known ratio $\Delta\nu_7/\Delta\nu_6$. The cube of the ratio of the reduced masses of the $2s$ electrons in Li^6 and Li^7 is included as a factor in the calculation by analogy with the corresponding case of the hydrogens. The observed value of g_7/g_6 is greater than the value calculated by (0.012 ± 0.003) percent.

INTRODUCTION

IT is the purpose of this paper to describe a precision measurement of the ratio of the nuclear g factor of Li^7 and that of Li^6 by the molecular beam magnetic resonance method. In the work of Nafe and Nelson,[1] the h.f.s. separations of the ground states of H and D were measured, and the observed ratio $\Delta\nu_H/\Delta\nu_D$ compared with that calculated from the accurately known[2,3] ratio of the magnetic moments, μ_H/μ_D. It was found that the experimental value was lower by 0.017 percent than the calculated value. This discrepancy was explained by Bohr[4] in terms of the compound structure of the deuteron. In that portion of the electron orbit which is close to the nucleus, the electron velocity is much greater than that of the nucleons. Consequently, the electron orbit is centered about the slowly moving proton rather than about the center of mass of the nucleus. When the electron is within the nucleus, the neutron appears as a shell within which a magnetic interaction occurs only between proton and electron. From an analysis of this process, Bohr has shown that the apparent ratio of the nuclear moments, μ_H/μ_D as determined from the h.f.s. must be increased by 0.018 percent. Nelson and Nafe[5] have also measured the h.f.s. separation of the ground state of tritium. Using the ratio of the magnetic moments of the proton and triton, obtained by Bloch, Graves, Packard, and Spence,[6] and the measured value of $\Delta\nu_H$, the tritium h.f.s. can be calculated. The calculated and measured values of $\Delta\nu_T$ agree within 1 part in 10^5. Avery and Sachs[7] have estimated that the fractional reduction of $\Delta\nu_T$ from that calculated from $\Delta\nu_H$ and the ratio μ_H/μ_T would be roughly 5 percent of that which occurs for the deuteron.

In the present paper, the measured ratio g_7/g_6 is compared with that calculated from the known ratio $\Delta\nu_7/\Delta\nu_6$. The $\Delta\nu$'s of Li^6 and Li^7 were originally measured by Kusch, Millman, and Rabi,[8] who obtained $\Delta\nu_7/\Delta\nu_6=3.52090\pm0.00025$. Recently, Kusch and Taub[9] have remeasured these $\Delta\nu$'s with much greater precisionl Their value for the ratio is 3.52096 ± 0.00006. It shoud, be noted that the uncertainty in this value is less than that obtained from the published values of the $\Delta\nu$'s since uncertainties in the frequency of the crystal. against which all frequency measurements were made, have no effect on the ratio of the $\Delta\nu$'s.

METHOD

The resonance line, observed in the spectrum of a diatomic molecule and which arises from a reorientation

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[1] J. E. Nafe and E. B. Nelson, Phys. Rev. **73**, 718 (1948).
[2] Bloch, Levinthal, and Packard, Phys. Rev. **72**, 1125 (1947).
[3] A. Roberts, Phys. Rev. **72**, 979 (1947).
[4] A. Bohr, Phys. Rev. **73**, 1109 (1948).
[5] E. B. Nelson and J. E. Nafe, Phys. Rev. **75**, 1194 (1949).
[6] Bloch, Graves, Packard, and Spence, Phys. Rev. **71**, 551 (1947).
[7] R. Avery and R. G. Sachs, Phys. Rev. **74**, 1320 (1948).
[8] Kusch, Millman, and Rabi, Phys. Rev. **57**, 765 (1940).
[9] P. Kusch and H. Taub, Phys. Rev. **75**, 1477 (1949).

of the nuclear spin with respect to the magnetic field, is the envelope of a large number of unresolved lines which result from the transition $\Delta m_I = \pm 1$ in the various rotational states, J, m_J. The structure of these lines has been discussed by Feld and Lamb[10] and by Nierenberg and Ramsey.[11] The principal interactions which give rise to the line structure are the interaction of the nuclear electric quadrupole moment with the gradient of the electric field at the nucleus, and the interaction of the nuclear magnetic dipole moment with the magnetic field produced at the nucleus by the molecular rotation. When $I = \frac{3}{2}$, as for Li^7, the envelope of the unresolved lines exhibits three maxima. At sufficiently high magnetic fields, the whole structure is symmetrical about the frequency $f_0 = \mu_0 g_I H/h$ and the central maximum is, itself, symmetrical about this frequency. However, at intermediate fields, considerable departures from symmetry may occur. The frequencies of the components of the central maximum ($m_I = \frac{1}{2} \leftrightarrow m_I = -\frac{1}{2}$) are, to the second order, given[11] by:

$$\begin{aligned} f = -g_I\mu_0 H/h - m_J c/h \\ +[3(b/h)^2(1-z^2)(9z^2-1)]/(4g_I\mu_0 H/h) \\ -[(c/h)^2 J^2(1-z^2)]/(2g_I\mu_0 H/h), \quad (1) \end{aligned}$$

where $z = m_J/J$, $b = e^2qQ/4$ and is the energy separation of each of the satellite maxima from the central peak, and c is the energy of interaction of the nuclear magnetic moment with the magnetic field produced by unit molecular rotation.

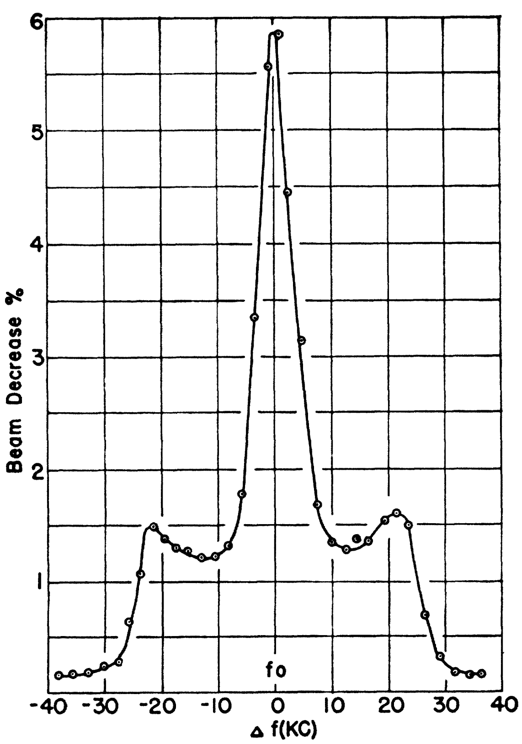

FIG. 1. Nuclear resonance spectrum of Li^7 in LiI.

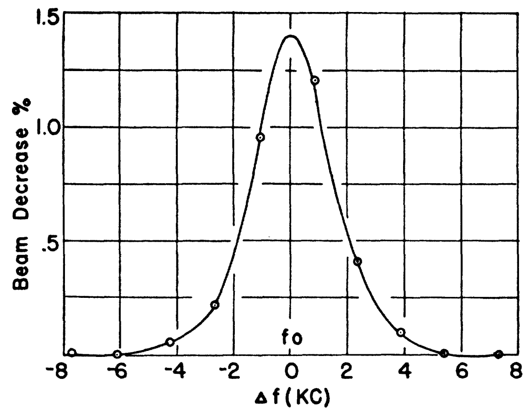

FIG. 2. Nuclear resonance spectrum of Li^6 in LiI.

The first term gives a line whose width is determined by the resolution of the apparatus and which is symmetrical about the frequency f_0. The second term broadens this line symmetrically, since positive and negative m_J are equally probable. The contribution of this term to the width of the line at half-intensity is:

$$\Delta f = 0.954ac/h, \quad (2)$$

where

$$a^2 = h^2/8\pi^2 AkT.$$

To find the effect of the last term in (1), it is necessary to evaluate the term $(c/h)^2 J^2$. For small a, the most probable value of $J \simeq 0.707/a$. For this value of J, $(c/h)^2 J^2 = 0.55(\Delta f)^2$. In the case of Li^7 in LiI, $\Delta f \lesssim 8.5 \times 10^3$ sec.$^{-1}$. If we consider the limiting value of $z = 0$, at a frequency of observation $f_0 = 16 \times 10^6$ sec.$^{-1}$ ($H = 10^4$ gauss), the value of the last term becomes about 1.3 sec.$^{-1}$. The effect is entirely negligible and becomes even smaller for Li^6. The third term in the expression for the frequency has a maximum value at $z^2 = 5/9$. For Li^7 in LiI, $b/h = 21.5 \times 10^3$ sec.$^{-1}$. For $f_0 = 16 \times 10^6$ sec.$^{-1}$, and $z^2 = 5/9$, the third term becomes about 40 sec.$^{-1}$. This represents the maximum shift of any one of the components of the line from its position at infinite field. The over-all effect on the envelope of all the lines is less than this and is, therefore, negligible to within 1 part in 500,000. The effect of the quadrupole term on the position of the resonance line of Li^6 is even smaller. The case of LiBr is almost identical to that of LiI.

The central maximum of the Li^7 line and the center of the Li^6 line may thus serve to determine the ratio of the two nuclear g values to a precision limited only by experimental factors.

APPARATUS AND PROCEDURE

The apparatus used in this experiment is the same as that used in the work on the nuclear electric quadrupole

[10] B. T. Feld and W. E. Lamb, Jr., Phys. Rev. 67, 15 (1945).
[11] W. A. Nierenberg and N. F. Ramsey, Phys. Rev. 72, 1075 (1947).

moment of Li^6,[12] and in the determination of the proton moment.[13] A beam of LiI molecules was obtained by heating LiI in a gold-plated iron oven. The gold-plating was found very useful in preventing free iodine, presumably produced by thermal dissociation, from reacting with the iron. The LiBr beam was produced directly from an iron oven. The resolution half-width of the apparatus, for a perfectly homogeneous magnetic field, is about 1.2 kc/sec. for LiI and about 1.5 kc/sec. for LiBr. The observed half-widths are, for Li^6 in LiI and LiBr, 2.85 and 4.4 kc/sec., respectively, and, for the central maximum of Li^7 in LiI and LiBr, 8.5 and 12.3 kc/sec., respectively. Figures 1 and 2 show the nuclear resonance lines of Li^7 and Li^6 in LiI. The line structure has been observed to be entirely independent of magnetic field. The spectra for LiBr are essentially similar.

The data of this experiment are the frequencies of the Li^6 and Li^7 lines measured in the same constant magnetic field. Since the magnetic field does, in fact, vary with time during the period of observation, it is necessary to correct for this variation by observing the current in the magnet winding at each frequency reading. The method of making this correction has been described in detail previously,[13] and no further discussion will be given here. It should be mentioned that the direction of the magnetic field was reversed between successive runs as in the experiment[13] on the determination of the g value of the proton. The frequency of a line was determined by observations of the frequencies of two points on the resonance curve at which equal reduction of beam intensity was observed. The resonance curve was alternately traversed in opposite directions, and the fractional reduction of intensity at the points of observation was varied in order to reduce the possibility of systematic errors. The frequencies were measured with a General Radio heterodyne frequency meter, Type 620A. In the course of the experiment, two different meters were used with an identical result. The limitation on the precision of this experiment was imposed primarily by fluctuations in the magnetic field, not readily correlated to fluctuations in magnet current.

A careful study was made of the perturbing effects of power supplies on the magnetic field, the effect of the magnitudes of r-f current within a reasonable range, and the effect of different r-f generators coupled separately to the molecular beam apparatus. The maximum observed variation in the frequency of the Li^7 line under widely varying experimental conditions was too small to be meaningful.

TABLE I. Results of individual determinations of g_7/g_6.

Run	Field direction	$H\times10^{-3}$ gauss	g_7/g_6	Molecule
1	N	14	2.64099	LiI
2	R	10	2.64088	
3	R	10	2.64088	
4	N	10	2.64091	
5	R	10	2.64091	
6	N	10	2.64105	
7	N	10	2.64095	LiBr
8	R	10	2.64091	

RESULTS AND CONCLUSIONS

The results of this experiment are given in Table I. At least five separate determinations of the ratio g_7/g_6 were made in each run. Each determination involved a minimum of two measurements of the resonant frequencies of both Li^6 and Li^7. The mean of these values is 2.64094 ± 0.00005, where the error is the average deviation.

It is possible to calculate the ratio g_7/g_6 from the known value of the ratio of the $\Delta\nu$'s by means of the Fermi[14] formula, in which the compound structure of the nucleus is not considered. This gives:

$$\begin{aligned} g_7/g_6 &= [(2I+1)_6/(2I+1)_7](m_{r6}/m_{r7})^3\Delta\nu_7/\Delta\nu_6 \\ &= 2.64061\pm0.00005, \end{aligned} \tag{3}$$

where $m_{r6,r7}$ are the reduced masses of the $2s$ electrons in Li^6 and Li^7, and the stated error is the error only in the ratio $\Delta\nu_7/\Delta\nu_6$. The inclusion of the factor $(m_{r6}/m_{r7})^3$ is made by analogy with the corresponding case of the hydrogens, since in each case the problem is one involving a single s electron. No rigorous justification of the inclusion of this factor has been made. The neglect of this factor increases the ratio g_7/g_6 obtained from the $\Delta\nu$'s to 2.64072 ± 0.00005. The discrepancy between the observed value of g_7/g_6 and that calculated from (3) is then 0.00033 ± 0.00007. It seems probable that this discrepancy can be explained in a manner similar to that used in the treatment of H and D. This awaits a more detailed calculation of the effect of the nuclear structure of Li on the h.f.s.

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[13] H. Taub and P. Kusch, Phys. Rev. **75**, 1481 (1949).
[14] E. Fermi, Zeits. f. Physik **60**, 320 (1930).