Nuclear Gyromagnetic Ratios II

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By means of super-regenerative oscillator techniques, magnetic resonance absorption peaks have been observed for Be^9, P^{31}, Cl^{35}, Rb^{85}, Cs^{133}, and La^{139}. By simultaneous observation of each of these resonances and of the proton absorption peak in the same magnetic field, the ratio of the resonance frequency ν of each of these nuclei to the proton frequency ν_p in the same applied field has been determined. The experimental results are as follows:

Nucleus	ν/ν_p
Be^9	0.14034 ±0.00007
P^{31}	0.40490 ±0.00011
Cl^{35}	0.09799 ±0.00007
Rb^{85}	0.09661 ±0.00004
Cs^{133}	0.13093 ±0.00014
La^{139}	0.14116 ±0.00014

From these experimental results, the gyromagnetic ratio for each nucleus can be determined in terms of the gyromagnetic ratio of the proton provided suitable corrections for the diamagnetism of the electrons are applied.

THE determination of nuclear gyromagnetic ratios by magnetic resonance absorption measurements in the radio frequency range has been discussed in detail in the recent literature. The present paper is concerned with results obtained for several nuclear species by a method involving a super-regenerative oscillator circuit.[1] This method involves the observation of the change in the amplitude of the output of the oscillator when the Larmor condition $h\nu = (\mu H/I) = gH$ is realized. A tube containing a solution of a salt containing the nuclei of interest is placed in the tank coil of the oscillator, the coil being mounted with its axis at right angles to a strong magnetic field, which can be varied. The Larmor condition is realized by varying the strong magnetic field. The resonance absorption line can be displayed on an oscilloscope by applying a small 60-cycle modulation to the strong magnetic field.

In order to obtain the absolute value of a nuclear gyromagnetic ratio g, the value of the resonance frequency ν and the value of the strong field H must both be determined with high precision. As the precise determination of magnetic fields is a matter of considerable difficulty, a different procedure giving gyromagnetic ratios in terms of the known proton gyromagnetic ratio g_p was adopted.[2] This procedure involved the comparison of the resonance frequency ν of a given nucleus with the resonance frequency ν_p of the proton in the same magnetic field. In order to make this comparison a second oscillator tank circuit containing a proton sample was mounted in the strong magnetic field close to the coil containing the unknown. The outputs of the two oscillators were displayed on the same oscilloscope by means of an electronic switch. The frequency of the second oscillator was varied until the absorption peaks for the proton and the unknown nucleus appeared at the same position on the oscilloscope trace. When the two absorption peaks are properly matched, the gyromagnetic ratio g of the unknown can be determined in terms of the gyromagnetic ratio of the proton g_p from the relations

$$h\nu = gH$$
$$h\nu_p = g_pH. \tag{1}$$

Thus, g is determined in terms of a frequency ratio (ν/ν_p) which is readily determined:

$$g = (\nu/\nu_p)g_p. \tag{2}$$

The frequencies ν and ν_p were determined by zero-beat with a General Radio 805C signal generator calibrated at 100 kc/sec. intervals with a crystal-controlled multivibrator; the 100th harmonic of the multivibrator was adjusted to zero-beat with the 10 Mc/sec. carrier signal from WWV.

The experimental values of the frequency ratios ν/ν_p for Be^9, P^{31}, Cl^{35}, Rb^{85}, Cs^{133}, La^{139} are given in Table I. The observed frequency ratios have been corrected for a small field inhomogeneity; this correction takes account of the fact that the applied field at the proton sample position is slightly different from the field at the unknown-sample position. Each frequency ratio given in the table is the average of ten independent measurements, each of which was made at a different radio frequency. The indicated uncertainty is the average

TABLE I. Experimental results: frequency ratios.

Nucleus	Sample	Resonance frequency/ Resonance frequency of proton
Be^9	$BeCl_2$	0.14034±0.00007
P^{31}	H_3PO_4	0.40498±0.00011
Cl^{35}	$LiCl$	0.09799±0.00007
Rb^{85}	Rb_2CO_3	0.09661±0.00004
Cs^{133}	$CsCl$	0.13093±0.00014
La^{139}	$LaCl_3$	0.14116±0.00014

[1] J. R. Zimmerman and D. Williams, Phys. Rev. (to be published).

[2] Thomas, Driscoll, and Hipple, Phys. Rev. **75**, 902 (1949).

TABLE II. Summary of recent resonance measurements in solids and liquids.

Nucleus	Resonance frequency / Resonance frequency of proton	Calculated from	Ref.
n^1	0.68479 ±0.0004		(a)
	0.685001 ±0.00003		(b)
H^2	0.153506 ±0.000001		(c)
	0.15355 ±0.00005		(d)
	0.1535105±0.000005		(e)
	0.153501 ±0.00007		(f)
H^3	1.066636 ±0.00001		(g)
	1.06666 ±0.00010		(h)
Li^7	0.38862 ±0.00002		(d)
	0.388625 ±0.00004		(i)
Be^9	0.14034 ±0.00007		
B^{10}	0.10745 ±0.00011	$(B^{10}/B^{11})(B^{11}/H^1)$	(i)
B^{11}	0.32085 ±0.00006		(i)
	0.32076 ±0.00009		(d)
C^{13}	0.25143 ±0.00005		(j)
F^{19}	0.94086 ±0.00018		(d)
	0.94077 ±0.0001		(j)
	0.94079 ±0.00010		
Na^{23}	0.26454 ±0.00007		(d)
	0.26450 ±0.00003		(i)
Al^{27}	0.26062 ±0.00007		(d)
	0.26056 ±0.00003		(i)
P^{31}	0.40498 ±0.00011		
	0.40481 ±0.00004		(i)
	0.40495 ±0.0003	$(P^{31}/Na^{23})(Na^{23}/H^1)$*	(k)
Cl^{35}	0.09799 ±0.00007		
	0.09800 ±0.00014	$(Cl^{35}/Na^{23})(Na^{23}/H^1)$	(i)

value of the individual deviations from the mean with the sign of the deviation neglected. In the table the compound used for each nuclear species is indicated; in each case, a saturated solution was used and a small amount of magnetic catalyst was employed.

In general, the values for ν/ν_p given in Table I are in fair agreement with those obtained by other investigators employing different methods of observing the resonances. The only exception is the value for P^{31}; the value obtained for P^{31} is in good agreement with the value reported by Pound[3] but is somewhat larger than the value reported by Bitter.[4] The value for La^{139} has not been determined by other methods. Where a check is available, it is found that the frequency ratios reported here are in some cases slightly higher and in some cases slightly lower than those obtained by other methods; this would seem to indicate that there is no systematic error in the super-regenerative oscillator method.

The uncertainties listed in Table I are somewhat greater than those reported for other nuclei in the earlier paper.[1] As pointed out in the earlier paper, the arrangement for frequency measurement may introduce errors as large as 0.02 percent; the uncertainties listed for the nuclei reported here are somewhat larger than this and are as large as 0.1 percent for Cs^{133} and La^{139}. The primary source of additional error in the work reported here lies in the somewhat ambiguous matching of the proton resonance peak with the resonance peak for the other nucleus. For the six nuclei studied in the present experiment, the resonance signal was weak and broad. The width of the resonance signal was several gauss as compared with about 0.5 gauss for the proton. As the resonance signal was poorly defined, it was difficult to select a resonance "peak" with which to match the proton. The large line widths can be attributed only in part to field inhomogeneities.

From the observed values of ν/ν_p, it would appear that the gyromagnetic ratio g for each nucleus could be determined in terms of the recent measurement of the absolute value[2] of g_p from relation (2). However, it must be recalled that although the resonances are observed in the same *applied* magnetic field, the actual fields at the nuclei are not necessarily the same. The chief correction to be applied is a small correction for the diamagnetism of the electrons. The Lamb correc-

[3] R. V. Pound, Phys. Rev. **73**, 1112 (1948).
[4] F. Bitter, Phys. Rev. **75**, 1326 (1949).

Table II.—*Continued.*

Nucleus	Resonance frequency / Resonance frequency of proton	Calculated from	Ref.
Cu^{63}	0.26515 ±0.00005		(d)
	0.26506 ±0.00005		(i)
	0.26508 ±0.0002	$(Cu^{63}/Na^{23})(Na^{23}/H^1)$*	(l)
Cu^{65}	0.28393 ±0.0004	$(Cu^{65}/Cu^{63})(Cu^{63}/Na^{23})(Na^{23}/H^1)$*	(l)
	0.28391 ±0.00006		(i)
	0.28404 ±0.00009		(d)
Ga^{69}	0.24009 ±0.0008	$(Ga^{69}/Ga^{71})(Ga^{71}/Na^{23})(Na^{23}/H^1)$*	(k)
Ga^{71}	0.30494 ±0.0004	$(Ga^{71}/Na^{23})(Na^{23}/H^1)$*	(k)
Br^{79}	0.25059 ±0.00005		(d)
	0.25054 ±0.0006	$(Br^{79}/Br^{81})(Br^{81}/Na^{23})(Na^{23}/H^1)$*	(m)
Br^{81}	0.27014 ±0.00005		(d)
	0.27003 ±0.00008		(i)
	0.27003 ±0.0003	$(Br^{81}/Na^{23})(Na^{23}/H^1)$*	(m)
Rb^{85}	0.09661 ±0.00004		
	0.09657 ±0.00011		(i)
Rb^{87}	0.32718 ±0.00016		(d)
	0.32718 ±0.00007		(i)
I^{127}	0.20003 ±0.00007		(d)
	0.20013 ±0.0002	$(I^{127}/Na^{23})(Na^{23}/H^1)$*	(k)
Cs^{133}	0.13093 ±0.00014		
	0.13113 ±0.00014	$(Cs^{133}/Li^7)(Li^7/H^1)$	(i)
La^{139}	0.14116 ±0.00014		
Tl^{203}	0.571499 ±0.00005**		(j)
	0.5714 ±0.0001		(n)
Tl^{205}	0.577135 ±0.00005**		(j)
	0.5770 ±0.0001		(n)

* Value for Na^{23}/H^1 taken from 3 for calculation.
** Values for Tl^{203}/H^1 and Tl^{205}/H^1 interchanged.
a W. R. Arnold and A. Roberts, Phys. Rev. **70**, 766 (1946).
b Bloch, Nicodemus, and Staub, Phys. Rev. **74**, 1025 (1948).
c Bloch, Levinthal, and Packard, Phys. Rev. **72**, 1125 (1947).
d See reference 1.
e Bitter, Alpert, Nagle and Poss, Phys. Rev. **72**, 1271 (1947).
f A. Roberts, Phys. Rev. **72**, 979 (1947).
g Bloch, Graves, Packard, and Spence, Phys. Rev. **71**, 551 (1947).
h H. L. Anderson and A. Novick, Phys. Rev. **71**, 372 (1947).
i See reference 3.
j H. L. Poss, Phys. Rev. **75**, 600 (1949).
k See reference 4.
l R. V. Pound, Phys. Rev. **73**, 523 (1948).
m R. V. Pound, Phys. Rev. **72**, 1273 (1947).
n W. G. Proctor, Phys. Rev. **75**, 522 (1949).

tion[5] for diamagnetism has been employed by many investigators but its use for heavier elements is somewhat questionable. Hence, we shall not list values for gyromagnetic ratios; when a reliable diamagnetism correction has been developed, values for nuclear gyromagnetic ratios can be obtained from the observed values of ν/ν_p and the then accepted value of g_p. For purposes of comparison of data obtained by various methods we have assembled the published data and reduced it to frequency ratios ν/ν_p. These values of ν/ν_p are given in Table II. In cases where the original comparison was not made with the proton, the indicated calculation has been made.

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

In connection with the question of internal fields, one might raise questions concerning the effects of small amounts of magnetic catalysts. Thus far, we have not detected any variations in resonance frequency when catalysts are added. However, this problem is receiving further attention.

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