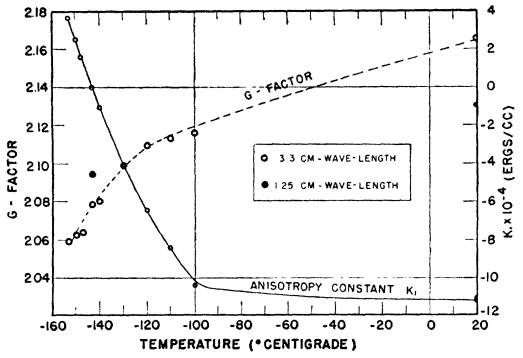

FIG. 1. Anisotropy constant and g-factor for synthetic magnetite single crystal as a function of temperature.

mated to be accurate to within 2 percent, including the probable error in values of magnetization.

Above -143°C the anisotropy constant is negative, indicating that [111] is the direction of easy magnetization, while below -143°, [100] is the direction of easy magnetization. At -143° the resonance magnetic field is independent of orientation, indicating that the material is magnetically isotropic.

The initial permeability of magnetite is known to go through a maximum near -140°C. The effects seems to have been attributed directly to the second-order phase transition which magnetite undergoes in the region of -160°C.[3] The behavior of the magnetic crystal anisotropy makes it seem reasonable that such is not the case. The initial permeability should be high when the crystal anisotropy is low; therefore a maximum in the initial permeability is to be expected near the temperature at which the anisotropy goes through zero. Measurements of the initial permeability of the same natural crystals of magnetite used in the resonance experiments showed the maximum to be at -146°C, which is within a few degrees of the anisotropy point. It is also interesting to note that the anisotropy point occurs at the same temperature for both natural and synthetic crystals, whereas the transition occurs 10°C higher for the synthetic crystal than for the natural.

Published results of the measurement of magnetite's anisotropy constant by other methods are not abundant. The room temperature value obtained from the resonance experiments agrees reasonably well with a value of -1×10^5 erg/cc given by Snoek.[4] Li[5] published some torque curves for magnetite at -155°C. He apparently failed to notice that these curves showed the direction of easy magnetization to be different from what it is at room temperature. On the basis of measurements of magnetization in weak fields, Okamura and Ogawa[6] concluded that the direction of easy magnetization changes near -100°C.

The writer has reported[1] previously that the resonance absorption at 3.3 cm wave-length disappears below the transition. It has now been found that at 1.25 cm the resonance appears below the transition, shifted to appreciably lower field strengths. This effect is being studied in detail.

The synthetic single crystals used in these experiments were grown by J. Smiltens and D. H. Fryklund of this laboratory. The mol ratio of FeO to Fe_2O_3 was found by Smiltens to be 1:0.998. Values of saturation magnetization used in the calculations were obtained by C. Domenicali from pendulum magnetometer measurements.

* This work was sponsored jointly by the ONR, the Army Signal Corps, and the Air Force under ONR Contract N5ori-07801.

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[4] Reference 3, page 21.
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On the Sign of the Electric Quadrupole Moment of Li^7

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THIS note presents data which show that the nuclear electric quadrupole moment of Li^7 is positive. The result is entirely unexpected on the basis of all nuclear models which have been proposed and which predict a negative electric quadrupole moment for Li^7.

The present experiments determine the sign of the coupling energy of the quadrupole moment of a nucleus with the gradient of the electric field produced at that nucleus by the electrons and the other nucleus in certain diatomic molecules. The sign of the quadrupole moment is then derived from experimental results by a theoretical calculation of the gradient of the electric field. While exact wave functions for molecules containing Li are not, of course, available, the calculation nevertheless leads to a positive sign for the quadrupole moment of Li^7 without ambiguity.

The lines observed in the molecular beam magnetic resonance method which result from the re-orientation of the nucleus within a diatomic molecule in an applied magnetic field are complex spectra consisting of a large number of closely spaced lines arising in the rotational states J, m_J. From an observation of the structure of the pattern it is possible[1] in some cases, to determine the magnitude of the interaction energy of the nuclear electric quadrupole moment with the gradient of the electric field at the nucleus. If the nuclear spin is $\frac{3}{2}$, the line $\Delta m_I=\pm1$ exhibits three maxima corresponding to the three possible transitions. At sufficiently high magnetic fields the central maxima $(1/2, -1/2)$ occurs at the frequency $g_I\mu_0H/h$ and the two satellite maxima $(3/2, 1/2)$ and $(-1/2, -3/2)$, are symmetrically disposed about the central line. The frequency interval between the two extreme maxima is $1/2e^2qQ/h$. The general details of the spectrum are the same[2] in heteronuclear and homonuclear molecules.

It is not possible from an observation of the spectrum alone to identify the two satellite maxima in terms of the quantum numbers, m_I, of the terminal states. To determine the sign of the quadrupole interaction it is necessary that this identification be made.

The various diatomic molecules in the beam describe different trajectories in the apparatus, depending principally on the magnetic quantum numbers m and m' of the two nuclei. It is, accordingly, possible to interpose in the beam an obstacle which will predominantly remove molecules of positive m or of negative m from the beam which finally reaches the detector. It is possible to achieve a complete separation of states of positive and negative m only if the second nucleus has a very small g value. The extent to which the separation can be achieved in a general case depends on the relative values of g and g'. If the obstacle is interposed into that portion of the beam in which states of positive m preponderate, then the satellite maximum arising from the transition $(3/2, 1/2)$ will have its intensity reduced relative to the other maximum. If the maxima are not resolved from the central peak, the center of gravity of the pattern will shift in the direction of the line $(-1/2, -3/2)$.

The effect of interposing a wire at an appropriate point along the path of the beam has been investigated for the Li^7 line in Li_2 and LiBr. In each of these two cases the high frequency satellite of the central line corresponds to the transition $(-1/2, -3/2)$. For the Na line in Na_2 and in NaI and for the Cl^{35} line in KCl the high frequency satellite corresponds to the transition $(3/2, 1/2)$.

Feld and Lamb[1] give as that portion of the energy of the levels which depends on the m_I of a single nucleus the expression:

$$E=m_Ig_I\mu_0H+[e^2qQ/4J(2J-1)I(2I-1)]\times[3m_J^2-J(J+1)]\times[3m_I^2-I(I+1)].$$

In all cases under consideration the value of g_I is negative since the nuclear magnetic moment is positive. The satellite maxima

occur for small values of m_J so that at the maxima $3m_J^2-J(J+1)$ is negative. The terms in the energy expression which involve m_I for those values of m_J which give rise to lines near the maxima are then:

$$E=m_I g_I \mu_0 H-(\text{const.})(e^2qQ)(m_I^2).$$

If g_I is negative and if w^2qQ is positive, then the high frequency satellite arises from the transition (3/2, 1/2). If e^2qQ is negative, the high frequency satellite arises from the transition $(-1/2, -3/2)$. It follows that qQ for Li^7 in Li_2 and in LiBr is negative while qQ for Na in Na_2 and NaI and for Cl^{35} in KCl is positive.

H. M. Foley[3] has made a calculation of q for the Li_2 molecule using the Bartlett-Furry wave functions. He finds that $q=-0.0062$ atomic units. From this result $Q(Li^7)$ is positive. The actual determination of the magnitude of Q is somewhat more difficult since the observed line shows no evidence of resolution into three peaks. The observed half-widths of the line is 15×10^3 sec.$^{-1}$ and if it is assumed that the two satellite peaks determine the half width of the line, then $Q(Li^7)=+2\times10^{-26}$ cm^2.

I. I. Rabi[4] has proposed a calculation of q from the known force constants of diatomic molecules. He predicts a negative q at each nucleus of a diatomic molecule. The result is in agreement with the results of the present experiments where it has been found that q has the same sign at the Li nucleus in Li_2 and in LiBr and the same sign at the Na nucleus in Na_2 and in NaI. The negative value predicted by Rabi, when applied to the present experimental results also yields a negative value for $Q(Cl^{35})$. The result is in agreement[5] with the known quadrupole moment of Cl^{35}. From these considerations it is found that $Q(Na)$ is negative and that $Q(Li^7)$ is positive.

[1] B. T. Feld and W. E. Lamb, Phys. Rev. **67**, 15 (1945).
[2] H. M. Foley, Phys. Rev. **71**, 747 (1947).
[3] I am indebted to Professor Foley for the results of the calculation made for this purpose. A detailed analysis of the calculation will be published by him.
[4] I am indebted to Professor Rabi for several discussions concerning the calculation of q. The basis of the indicated calculation will be discussed by Professor Rabi in a forthcoming publication.
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Relation of Nuclear Quadrupole Moment to Nuclear Shell Structure

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AS has been pointed out by Mayer,[1] the exceptional stability of nuclei which have proton or neutron numbers of 2, 8, 20, 50, 82, or 126 suggests the existence of shell structures in nuclei. Schemes have been proposed by Nordheim[2] and by Feenberg[3] for assigning orbital quantum numbers to the last odd proton in nuclei. The purpose of the present note is to point out the dependence of the nuclear shape—as evidenced by the nuclear quadrupole moment*—upon the nuclear shell structure. The relationship found provides new evidence for the existence of shell structure in nuclei. Evidence is also given for an inter-relation of the nuclear magnetic moment to the nuclear quadrupole moment, when the nuclei are similar.

Figure 1 is a plot of nuclear quadrupole moment Q as a function of proton number Z. All nuclei with known moments are included except those which are spherically symmetric because they have spins of zero or $\frac{1}{2}$. The available data** suggest the following relationships of quadrupole moment to nuclear shell structure. At the proton numbers 2, 8, 20, 50, and 82 the quadrupole moment is zero or small. When a new shell begins to form the quadrupole moment is negative. As the number of protons in the unfilled shell is increased, Q becomes positive and increases until it reaches a maximum, when the shell is approximately $\frac{2}{3}$ filled. It then decreases to zero and changes to a negative sign*** at the "magic proton numbers."

TABLE I. Relation of quadrupole to nuclear magnetic moments.

X_1 / X_2	μ_1/μ_2	Q_1/Q_2	Sign of Q	$(\mu_1/\mu_2)(Q_1/Q_2)$ when Q is positive or $(\mu_2/\mu_1)(Q_1/Q_2)$ when Q is negative
Cl^{35}/Cl^{37}	1.20	1.28	−	1.07
Cu^{63}/Cu^{65}	0.94	1	−	1.12
Ga^{69}/Ga^{71}	0.79	1.58	+	1.24
Br^{79}/Br^{81}	0.93	1.20	+	1.12
Eu^{151}/Eu^{153}	2.24	0.48	+	1.08
Re^{185}/Re^{187}	0.99	1.08	+	1.07
			Average	1.12

TABLE II. Some estimated quadrupole moments.

	Q in 10^{-24} cm^2
In^{113}	~1.3
Cs^{137}	≤0.2
K^{39}	~−0.03
K^{41}	~−0.02
Rb^{87}	~0.17
Sb^{121}	~−0.9
La^{139}	~0.2

The above mentioned trends are partly masked by the effects of neutron shell structure. The points where a neutron shell is completed are indicated on the chart by arrows. It is seen that there are minima in the curve at these points. The effects of neutron shell structure are shown again in Fig. 2, where absolute magnitude of quadrupole moment is plotted as a function of neutron number. The effect of proton shell structure does not show up in this plot, partly because the data are meager and partly because the negative Q's are plotted as positive.

In an effort to obtain more Q values for comparison I have correlated magnetic moments with quadrupole moments for isotopic pairs having the same spins. The results are shown in Table I. Other things being equal, the magnetic moment appears to decrease in magnitude as the nucleus becomes more elongated along the spin axis—i.e., as its quadrupole moment becomes more positive (or less negative for flattened nuclei). To show this, the quantity $(\mu_1/\mu_2)(Q_1/Q_2)$ when Q_1 and Q_2 are positive, or $(\mu_2/\mu_1)(Q_1/Q_2)$ when Q_1 and Q_2 are negative, has been listed in the last column of Table I. It is seen that this quantity remains approximately constant. Here the subscript 2 refers to the heavier isotope. The fact that there are no marked differences in the mag-

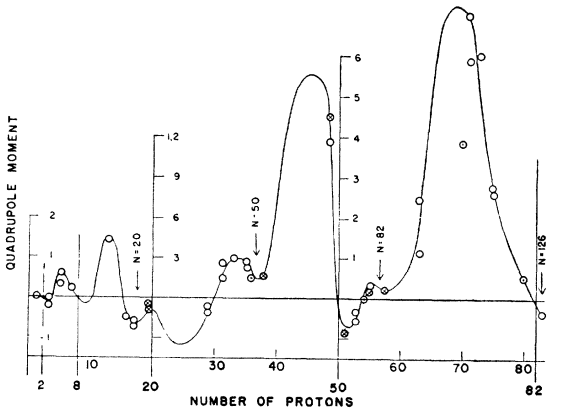

FIG. 1. A plot of nuclear quadrupole moment as a function of the number of protons in the nucleus. Q is in units of 10^{-24} cm^2. O's represent nuclei with an odd proton. ⊙'s represent nuclei with an odd neutron. ⊗'s represent quadrupole moments which have not been measured but have been estimated by the method described here.