

Annealing at 260°C in carbon dioxide reduced R_0 and b ; after annealing, $R_0=0.71$ c.g.s.m. and $b=0.84 \times 10^{-9}$ c.g.s.m./gauss² with mean deviations of 6 and 8 percent, respectively.

Heaps² found $R=+1$ c.g.s.m. for single crystals with H parallel to the trigonal crystal axis. We found no report of Hall coefficient measurements for thin layers of bismuth.

The resistivity ρ was measured at 293 and 77°K. $\rho_{293}=1.09 \times 10^{-4}$ ohm-cm perpendicular to the trigonal crystal axis.

For our samples the temperature coefficient of resistivity was negative. ρ_{77}/ρ_{293} decreased from 3.1 at 0.2 microns to 1.7 at 1.3 microns. This is in contrast to the positive temperature coefficient observed by Kaye³ for single crystals.

Annealing had no appreciable effect on the resistivity.

The influence of a magnetic field on the resistivity was measured at 293°K for fields up to 12 kgauss (H perpendicular to plane of bismuth film). For each sample the resistivity increased with increasing H according to an equation of the form,

$$\rho(H) = \rho_{293} + aH^2, \quad (2)$$

where ρ_{293} is the field free resistivity and a is a constant. The increase in ρ due to a field of 12 kgauss varied from 7 percent for the thinnest sample up to 22 percent for the thickest one. Annealing had no effect on the constant a .

Measurements with H parallel to the plane of the sample indicated that the increase in ρ was about twice as great as with H perpendicular to the sample. This result is in agreement with measurements on single crystals by Kaye,³ assuming that our layers are polycrystalline with the trigonal axis perpendicular to the backing, as found by Lane.⁴

According to a theory by Jones,⁵ R should be independent of H for pure bismuth; i.e., for equal numbers of electrons and holes. Equation (1) corresponds, according to the theory, to bismuth alloyed with tetravalent impurities which act as electron acceptors. A relation of the same type as Eq. (2) holds for pure bismuth and for bismuth alloys, provided the impurity content is small, the temperature is high, and H is sufficiently small.

These arguments, applied to our results, do not necessarily mean that tetravalent impurities are responsible for the observed effects. A relation similar to Eq. (1) would be found if a number of the free electrons were trapped in surface states (this effect may be appreciable for evaporated layers because of the small size of the crystallites). Electron trapping can also account qualitatively for the dependence of ρ on the sample thickness, the negative temperature coefficient of ρ , and the decrease in R_0 and b on annealing.

To check the suggested interpretation, experiments are being carried out on films distilled from spectroscopically pure bismuth.

¹ W. F. Leverton and A. J. Dekker, Phys. Rev. **80**, 735 (1950).

² C. W. Heaps, Phys. Rev. **30**, 61 (1927).

³ G. W. Kaye, Proc. Roy. Soc. **170A**, 561 (1939).

⁴ C. T. Lane, Phys. Rev. **48**, 193 (1935).

⁵ H. Jones, Proc. Roy. Soc. **155A**, 653 (1936).

The Electric Quadrupole Moment of Li⁶

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QUADRUPOLE splitting of the Li⁶ and Li⁷ magnetic resonances has been obtained from a natural single crystal of LiAl(SiO₃)₂ (spodumene). The apparatus used is a recording radio-frequency spectrometer consisting of an r-f oscillator, an untuned r-f amplifier, a detector, an audio amplifier, and a phase-sensitive detector to be described in detail elsewhere.

The crystal, about 40 mm × 9 mm × 10 mm, was placed in the r-f coil of the oscillator tank, the coil itself residing in the gap of a permanent magnet which produces a constant magnetic induction in the neighborhood of 7312 gauss. The Li⁷ resonance occurs near 12.10 Mc sec⁻¹ in this field. The resonance of the Li⁶ nucleus,

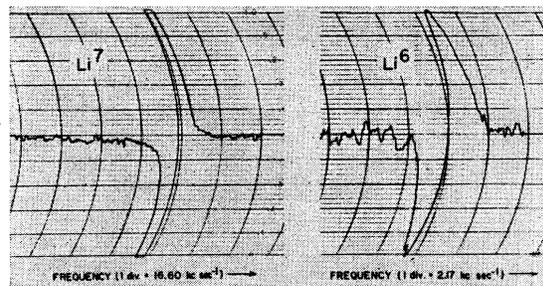


FIG. 1. Lithium nuclear magnetic resonances in a single crystal of LiAl(SiO₃)₂ at a crystal orientation giving essentially zero quadrupole splitting. The center of the Li⁷ resonance occurs at approximately 12.097 Mc sec⁻¹ and the center of the Li⁶ resonance occurs at approximately 4.582 Mc sec⁻¹.

which is presumably present in this crystal in its natural abundance of 7.39 percent, falls near 4.58 Mc sec⁻¹.

The mounting of the crystal permitted it to be turned about its c -axis, and the Li⁷ resonance was observed as a function of crystal orientation in order to find the maximum and minimum (zero) quadrupole splittings. The crystal was then set at one of these orientations and left untouched while both Li⁷ and Li⁶ resonances were recorded. Simply for purposes of comparison, Fig. 1 shows both resonances for the crystal orientation giving minimum splitting. Maximum splittings, which permit experimental evaluation of the magnitude of the ratio of the quadrupole moments, appear in Fig. 2. The Li⁶ resonance in this figure is one of several recorded at this crystal setting.

The nuclear quadrupole interaction splits the magnetic resonance spectrum of a nucleus with spin $I > \frac{1}{2}$ into $2I$ components, which spread over a frequency range¹

$$\Delta\nu = (3eQ/2Ih)(\partial E_z/\partial z)_0, \quad (1)$$

where e is the proton charge, Q is the nuclear quadrupole moment, and $(\partial E_z/\partial z)_0$ is a component of the gradient of the crystalline electric field, evaluated for present purposes at the lattice site of a lithium nucleus. In accordance with Eq. (1), the ratio of the quadrupole moments is

$$|Q_6/Q_7| = \Delta\nu_6 I_6 / \Delta\nu_7 I_7. \quad (2)$$

The spins of Li⁶ and Li⁷ are previously known to be 1 and $\frac{3}{2}$. The number of quadrupole components found for each resonance in Fig. 2 incidentally confirms these values.

The centers of the satellite lines of the Li⁷ resonance in Fig. 2 are separated by 66.4 ± 0.6 kc sec⁻¹ = $\Delta\nu_7$. For the less completely resolved Li⁶ resonances, absorption curves were obtained by direct integration, by means of a planimeter, of the experimentally measured derivative. The result of integrating the Li⁶ derivative of Fig. 2 is shown in Fig. 3. Curves such as this were analyzed by recognizing that the symmetry properties of the two component absorption curves require the midpoint C of the center line AB of the resultant curve to lie on both of the component quadrupole

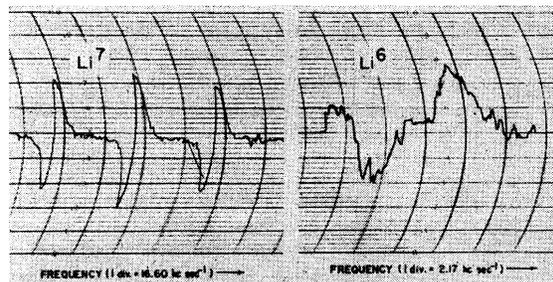


FIG. 2. Lithium nuclear resonances in a single crystal of LiAl(SiO₃)₂ showing the maximum quadrupole splitting obtainable with the crystal c -axis perpendicular to the external magnetic field.

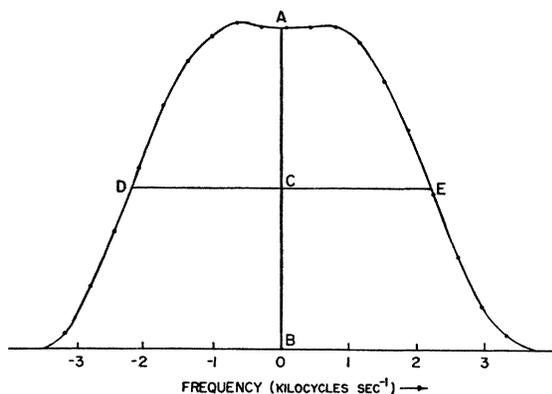


FIG. 3. Li^6 absorption curve obtained by integrating the resonance of Fig. 2, showing construction lines used in arriving at the splitting of the incompletely resolved pair of quadrupole component lines.

curves. Therefore, the midpoints of the segments DC and CE are separated by the frequency $\Delta\nu_6$, once one is satisfied that ordinates at D and E of the resultant curve originate solely from one quadrupole component and are not influenced by a tail of the other component line, and it follows that $DE = 2\Delta\nu_6$. Each of the three Li^6 resonances analyzed in this way gave values which depended to some extent upon whether attempts were made to correct for slight zero-drift of the spectrometer. Averages of these values for each of the three resonances were, respectively, 2.20, 2.35, and 2.34 kc sec^{-1} . All individual determinations of $\Delta\nu_6$ fall within the limits $2.30 \pm 0.15 \text{ kc sec}^{-1}$, which value may be used in Eq. (2) to find $|Q_6/Q_7| = (2.3 \pm 0.2) \times 10^{-2}$. The quoted error is roughly twice the usual statistical probable error, and the ratio is significantly below the upper limit of 4.4×10^{-2} arrived at by Kusch.²

The value of $(\partial E_z/\partial z)_0$ is not known for this crystal; and $Q_7 = 2 \times 10^{-26} \text{ cm}^2$, as obtained by Kusch,³ must be used to evaluate the magnitude of Q_6 . The result, $|Q_6| = 4.6 \times 10^{-28} \text{ cm}^2$, is about one-sixth as large as the quadrupole moment of the deuteron, $2.73 \times 10^{-27} \text{ cm}^2$.

Attempts are being made in this laboratory to improve the accuracy of the ratio $|Q_6/Q_7|$ by utilizing higher frequencies to increase signal-to-noise and by efforts to eliminate possible magnetic field inhomogeneities which may prevent more complete resolution of the Li^6 resonance. Such increased accuracy may be of doubtful value, however, so long as the magnitude of Q_7 is known to but one significant figure.

We wish to thank Mr. Werner G. Zinn for assistance in assembling parts of the spectrometer.

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¹ R. V. Pound, *Phys. Rev.* **79**, 685 (1950).

² P. Kusch, *Phys. Rev.* **75**, 887 (1949).

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Beta-Activity of Potassium

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EARLY measurements on the specific beta-activity of potassium gave values ranging from 20 to 50 betas/sec/gm of ordinary potassium, while later results have tended to converge on a figure near 31 betas/sec/gm. As, however, two recent determinations^{1,2} put the activity as low as 28.3 ± 1.0 betas/sec/gm of potassium, and 318 ± 10 betas/min/gm of KI, (i.e., 22.5 betas/sec/gm of potassium), respectively, the work described below, which favors a larger value, may be of interest.

A G-M tube with a mica end window of thickness 9.6 mg/cm^2 , cathode diameter 2 inches, and an argon-alcohol filling was used for the beta-measurements. Its geometry was determined using a modification of the usual $\text{Ra}(E+F)$ calibration technique. $\text{Ra}(E+F)$ sources were obtained by spontaneous deposition on

nickel from a solution of $\text{Ra}(D+E+F)$ in $N/10$ HCl, and the subsequent growth in the alpha-activity of the $\text{Ra}F$ was measured using Ilford 50 μ nuclear plates, type C2. For a source placed directly in contact with a plate the counting efficiency is 50 percent, since alpha-particle backscattering is negligible. Consequently, by exposing a plate to a source for a suitable time and finding the average number of tracks per microscope field, the absolute activity can be determined knowing merely the diameters of the microscope field ($2.875 \times 10^{-2} \text{ cm}$), and that of the source, (4.50 cm). In practice the exposure time was chosen to give the convenient number of about 15 tracks per field, and varied between 3 and 8 hours. Exposures were made at two-day intervals for at least twenty days, and the growth of the $\text{Ra}F$ thus followed absolutely. The amount of $\text{Ra}E$ present at any time could then be deduced, and from the observed beta-activity the counter geometry found.

The mean of four independent determinations by this method, corrected empirically for window absorption of the $\text{Ra}E$ beta particles, is 35.6 percent. This figure is too large by a factor of about 1.5 on account of beta backscattering; but since nickel of sufficient thickness to give saturation backscattering was used as backing for all sources, both $\text{Ra}E$ and KCl, this factor need not be considered further.

The actual count/sec/gm of KCl, extrapolated to zero thickness was 5.39. Taking into consideration the geometry as found above, the potassium content of KCl, and the window absorption of the K^{40} beta-particles, this corresponds to a figure of 32.0 ± 3 betas/gm of ordinary potassium.

Some counts were also made on KBr of different origin to ensure that no radioactive contamination was present in the KCl.

The only factor uncorrected for in the above calculations appears to be the self-scattering present in the KCl sources, but absent in the almost weightless $\text{Ra}E$ sources. This can,³ under adverse conditions, introduce an error of up to 8 percent; but since with the arrangement used the sources were quite close to the counter window (7.1 mm away), the effect is not likely to be large.

The thickness of aluminum required to reduce the intensity of the K^{40} beta-rays by half was also investigated, and found to be $69.5 \pm 2 \text{ mg/cm}^2$, a logarithmic plot being linear down to 200 mg/cm^2 .

A more detailed account of the work will be published later. The author is indebted to Professor J. H. J. Poole for advice on this problem.

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³ B. P. Burt, *Nucleonics* **5**, 28 (August, 1949).

Remarks on Relativistic Quantum Mechanics

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IN two letters¹ we have described a classical approach to the interaction representation of Tomonaga and Schwinger, based on the classical field dynamics of Weiss.² Unfortunately these letters were of necessity extremely condensed, and they also contained serious errors. The theory has since been developed in detail, and considerably extended;³ but, although the first section is now in the press,⁴ some time must elapse before a complete discussion can be published. It therefore seems pertinent to give a brief summary of the results. The notation has been defined in I and II.

A covariant and formally consistent scheme of quantum field dynamics is obtained by first extending the classical theory of Weiss, and then quantizing it by a generalization of the usual rules. In the Heisenberg picture the operators ξ depend on an arbitrary parametrized space-like surface σ , and vary according to the Eqs. II(1); in the alternative Schrödinger picture the state vector $\Psi[\sigma]$ depends on σ , and varies according to II(4). The interaction representation is a particular case of the general

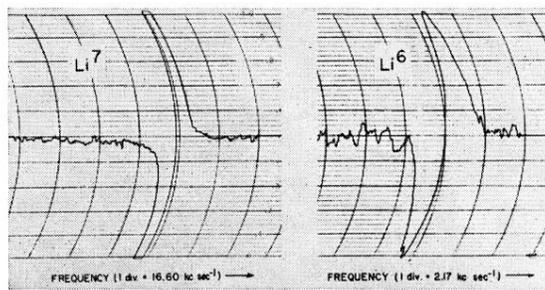


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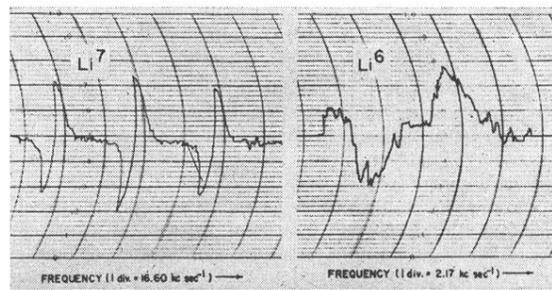


FIG. 2. Lithium nuclear resonances in a single crystal of $\text{LiAl}(\text{SiO}_3)_2$ showing the maximum quadrupole splitting obtainable with the crystal c -axis perpendicular to the external magnetic field.