

representing the interaction of the nuclear magnetic moment with the external magnetic field. The diagonal elements of Eq. (3) can be written

$$(1, m | V | 1, m) = -(2, m | V | 2, m) = Am,$$

where $m = I, I-1, \dots, -I$. This follows from a relation pointed out by Kramers. The wave functions, (1) and (2) then yield

$$(\pm \frac{1}{2}, m | V | \pm \frac{1}{2}, m) = \pm Amg_{11} \cos \theta / g$$

and, for the off-diagonal elements

$$(\pm \frac{1}{2}, m+1 | V | \pm \frac{1}{2}, m) = (g_{\perp} \sin \theta / 2g) B [I(I+1) - m(m+1)]^{\frac{1}{2}}.$$

The eigenvalues are

$$E(\frac{1}{2}, m) = \frac{1}{2} g \mu_B H + [(\frac{1}{2} \Delta \nu_{11} g_{11} / g + \gamma H)^2 \cos^2 \theta + (\frac{1}{2} \Delta \nu_{\perp} g_{\perp} / g + \gamma H)^2 \sin^2 \theta]^{\frac{1}{2}}$$

$$E(-\frac{1}{2}, m) = -\frac{1}{2} g \mu_B H - [(-\frac{1}{2} \Delta \nu_{11} g_{11} / g + \gamma H)^2 \cos^2 \theta + (-\frac{1}{2} \Delta \nu_{\perp} g_{\perp} / g + \gamma H)^2 \sin^2 \theta]^{\frac{1}{2}}.$$

In the above result, $\frac{1}{2} \Delta \nu_{11}$ and $\frac{1}{2} \Delta \nu_{\perp}$ were substituted for A and B , since these quantities can be identified with one-half of the experimentally observed hfs component separation for parallel and perpendicular fields. For allowed transitions, $\Delta m = 0$, and assuming γH is small compared to $\Delta \nu_{11}$ and $\Delta \nu_{\perp}$, the energy separation for levels between which transitions are allowed, then, is

$$E(\frac{1}{2}, m) - E(-\frac{1}{2}, m) = \mu_B g H_m + (m/g) (\Delta \nu_{11}^2 g_{11}^2 \cos^2 \theta + \Delta \nu_{\perp}^2 g_{\perp}^2 \sin^2 \theta)^{\frac{1}{2}}.$$

This gives

$$\mu_B^2 g^4 (\Delta H)^2 = \Delta \nu_{\perp}^2 g_{\perp}^2 + (\Delta \nu_{11}^2 g_{11}^2 - \Delta \nu_{\perp}^2 g_{\perp}^2) \cos^2 \theta,$$

where ΔH is the separation between adjacent hfs components in magnetic field units. A similar relation, in a different form, has been given by Pryce.

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† Permanent address; Michigan State College, East Lansing, Michigan.

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Nuclear Spin Relaxation Times in Single Crystals of LiF

R. V. POUND

Department of Physics, Harvard University, Cambridge, Massachusetts
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THE relaxation times of nuclear spins in crystals are usually of the order of seconds or fractions of a second at room temperatures. Such short times may be caused by paramagnetic impurities,¹ internal lattice jumps,² or by direct spin-lattice interaction through the nuclear electric quadrupole moment.³ In lithium nitrate a relaxation time of the order of an hour has been observed.³ To see whether such a time would be found in sufficiently pure LiF, single crystals of LiF were obtained from the Harshaw Chemical Company and from the Optivac Company. These crystals, $\frac{1}{2}$ " diameter by $\frac{3}{4}$ " long, were used in two associated novel experiments to be reported shortly.^{4,5} As background for these, some preliminary, rather qualitative, results obtained for relaxation times and the effects of x-ray produced color centers are reported here.

The relaxation times were measured by observation of a magnetization curve either after insertion in the 6376-gauss permanent magnet or after r-f saturation. An r-f spectrometer,⁶ held at low level, was set at the frequency of maximum deflection of the recorder for short periods at regular time intervals. The amplitudes of the recorded deflections gave points on the exponential magnetization curve, little net disturbance of the spin system resulting from the sampling.

In the Harshaw crystals the relaxation times were found to be

5 min for Li⁷ and 2 min for F¹⁹. Evidently paramagnetic impurity is still present for otherwise one would expect the F¹⁹ to have the longer relaxation time, having no electric quadrupole moment. The times in the Optivac crystal were 2 min for Li⁷ and 45 sec for F¹⁹, apparently magnetically less pure in spite of a reportedly greater ultraviolet transparency.

It was found possible to remove the crystals from the magnet (residual field of the earth) and return them after a brief interval with only small loss in magnetization. A study of the dependence of the loss of magnetization on the time held out of the field revealed an exponential decay with a time constant of about 15 sec in the Harshaw crystals. The spin system is evidently adiabatically demagnetized to a temperature (about 1°K) determined by the spin-spin interaction, and a relaxation process allows the lattice to heat the spin system with a time constant of 15 sec. In zero field, the F¹⁹ and Li⁷ spin systems are coupled together and thus both showed the same relaxation time. The reasonably large value of this time suggested and made feasible the experiments referred to above.^{4,5}

Two of the Harshaw crystals were irradiated with x-rays. One was irradiated on each of two sides for 30 min, at $\frac{1}{2}$ " from the beryllium window of a molybdenum target, Machlett A-2 tube, run at 40 kv, 20 mamp. The relaxation times were reduced⁷ to $1\frac{1}{2}$ min for Li⁷ and 30 sec for F¹⁹. The other crystal was irradiated on the ends for 40 min each at 5 cm from the target of an AEG-50 tube run at 40 kv, 40 mamp, and on four sides, 10 min each, 3 cm from the target of the tube⁸ run at 40 kv, 50 mamp. The resulting relaxation times were about 30 sec for Li⁷ and 10 sec for F¹⁹. The first crystal showed yellow spots near the x-ray source and the second a uniform yellow coloration about 2 mm deep, presumably F[•] centers. It is suggested that such effects on relaxation times provide a simple means for study of the properties of color centers, using a theory along the lines proposed by Bloembergen, if the paramagnetic relaxation time of the F[•] centers were known. A double resonance experiment involving saturation of the F[•] centers by a microwave signal, while using the nuclear resonance as a thermometer, is planned.

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⁷ The author wishes to thank Professor K. T. Bainbridge for providing this irradiation.

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Hall Coefficient and Resistivity of Evaporated Bismuth Layers

W. F. LEVERTON AND A. J. DEKKER

University of British Columbia, Vancouver, Canada
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FILMS of bismuth 0.2 to 1.3 microns in thickness were prepared by distillation of 99.8 percent pure bismuth in a Vycor glass apparatus similar to the Pyrex apparatus we described recently.¹ During evaporation, the bismuth was heated to 750–850°C, the rate of condensation varied from 30 to 210 $\mu\text{g}/\text{cm}^2/\text{min}$.

The Hall coefficient, R , was measured at 20°C by an ac method.¹ R did not depend on the current density but varied with the magnetic field H according to an equation of the form,

$$R(H) = R_0 - bH^2. \quad (1)$$

Measured values of R for each sample fitted a curve of this type within the experimental error (1 percent) for magnetic fields from 1.5 to 12 kgauss. However, the constants R_0 and b varied from sample to sample; the average values were $R_0 = +0.89$ c.g.s.m. and $b = 1.0 \times 10^{-9}$ c.g.s.m./gauss² with mean deviations of 4 and 10 percent, respectively.