

effect. Quantitative interpretation of heavy-ion experiments on reorientation appears possible in view of the following circumstances: (1) excitation of an inner  $s$  electron such as  $5s$  in Pt is not directly harmful, the life of the hole being short; (2) occupation of shells such as  $5p$  and  $5d$ , as well as small overlap of atomic eigenfunctions for different  $n$ , reduces the probability of excitation; (3) removal of an outer electron such as  $6s$  of Pt may even be a simplification; (4) coincidence experiments<sup>2</sup> on ions and gamma rays provide an internal consistency test of the theory; (5) application of magnetic fields<sup>3</sup> to the target, especially along the  $\gamma$ -ray direction, should test for the presence of hfs effects and, barring existence of long-lived atomic states with larger than usual hfs, should eliminate them.

A recoil energy of 9.4 Mev is imparted to Pt<sup>194</sup> by a N<sup>14</sup> ion with energy adjusted to give the distance of closest approach obtained with 5-Mev protons. The corresponding recoil velocity,  $c/98$ , suffices for excitation of outer electrons of Pt in atomic collisions and modifies the hfs effect. This effect is largest for head-on collisions which do not produce a reorientation effect on the distribution of  $\gamma$  rays following Coulomb excitation from  $I=0$  to  $I=2$ .

The sources of error mentioned above operate in addition to the well-known possibility of axis deorientation by inhomogeneous electric fields.

\* This research was supported by the U. S. Atomic Energy Commission and by the Office of Ordnance Research, U. S. Army.

<sup>1</sup> G. Breit and J. P. Lazarus, Phys. Rev. **100**, 942 (1955). In a forthcoming review in the *Reviews of Modern Physics*, K. Alder and A. Winther remark that the above reference appears to contain an extra factor  $49/4$  in the excitation probability estimate. However, since the object of Breit and Lazarus was to estimate the chance of reorientation after the first excitation, it was appropriate to use the relation between the static quadrupole moment and the mean square radius of the nuclear charge distributions. The value used for the moment of the target nucleus was on the upper limit of those indicated by data on nuclear ground states.

<sup>2</sup> Breit, Gluckstern, and Russell, Phys. Rev. **103**, 727 (1956).

<sup>3</sup> G. Goertzel, Phys. Rev. **70**, 897 (1946).

<sup>4</sup> K. Alder, Helv. Phys. Acta **25**, 235 (1952).

## Electronic Structure of $F$ Centers in KCl by the Electron Spin Double-Resonance Technique

G. FEHER

Bell Telephone Laboratories, Incorporated,  
Murray Hill, New Jersey

(Received December 10, 1956)

THE electron spin resonance absorption in  $F$  centers was first observed by Hutchison<sup>1</sup> and investigated in detail by Kip *et al.*<sup>2</sup> They were unable to resolve any hyperfine structure but Kip *et al.*<sup>2</sup> calculated the contact term of the hyperfine interaction from the measured line width. In this letter we wish to report the direct experimental determination of the

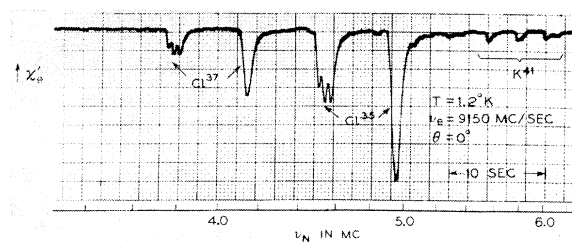


FIG. 1. Interaction of the  $F$  center electron in KCl with its nearest chlorines and K<sup>41</sup>. The magnetic field is parallel to the [100] direction. The additional structure on the chlorine line is the result of quadrupole interaction.

hyperfine and quadrupole interactions of the  $F$  center electron with its nearest neighbors.

The fact that the  $F$  center line is inhomogeneously broadened<sup>3</sup> makes it possible to apply the electron spin double-resonance<sup>4</sup> technique to this problem. In this technique the electron spin resonance line is partially saturated. Upon application of an auxiliary radio-frequency field, whose frequency corresponds to the interaction energy of the  $F$  center electron with one of its neighboring nuclei, the saturation parameter is changed, resulting in a change of the microwave signal. Since the nuclear line width was found to be of the order of 20 kc/sec in comparison to 150 Mc/sec for the electron line width, this technique improved the resolution by about four orders of magnitude.

The  $F$  centers were produced by bombarding KCl with 1-Mev electrons, which resulted in an  $F$  center concentration of  $2 \times 10^{17}$  cm<sup>-3</sup>. The sample was placed in a magnetic field of  $\sim 3000$  oersteds at 1.2°K and partially saturated with a microwave field at  $\sim 9000$  Mc/sec. Figure 1 shows the microwave signal when the auxiliary radio field is swept between 3.4 and 6.2 Mc/sec. This part of the spectrum is due mainly to the interaction of the electron with its nearest chlorines (and partly to the K<sup>41</sup> which are only 7% abundant). This run was made with the magnetic field parallel to the [100] direction of the crystal. When the angle  $\theta$  between  $H_0$  and the [100] direction is changed, the pattern changes as indicated in Fig. 2. This anisotropic part of the hyperfine interaction is a measure of the  $p$  character of the wave function. Each of the lines in Fig. 2 can be associated with a chlorine at a particular lattice site as shown in Fig. 3. The additional splitting of the lines (see Fig. 1) is due to quadrupole interactions of the chlorines ( $I=3/2$ ) and is a measure of the electric field gradient at the respective nuclei. The interaction of the electron with its nearest potassium nuclei was analyzed in a similar fashion.

The experimental results may be conveniently summarized by writing for the part of the Hamiltonian describing the nuclear interaction in a crystal with axial symmetry<sup>5</sup>:

$$\mathcal{H} = a(\mathbf{I} \cdot \mathbf{S}) + b(3I_z S_z - \mathbf{I} \cdot \mathbf{S}) + Q'[I_z^2 - \frac{1}{3}I(I+1)]. \quad (1)$$

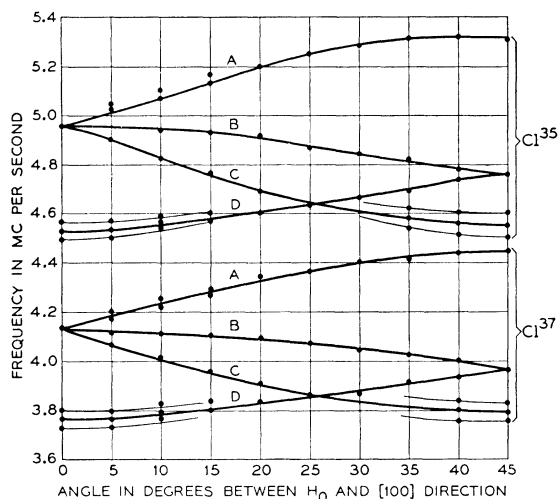


FIG. 2. Variation of the hyperfine and quadrupole splitting with angle between  $H_0$  and the [100] direction,  $H_0$  remaining in the  $y-z$  plane. Each level corresponds to a particular chlorine site (see Fig. 3).

The nuclear transition frequency is then given to first order by:

$$h\nu = \pm g_I \beta_N H_0 + \frac{1}{2} [a + b(3 \cos^2 \alpha - 1)] + Q'(3 \cos^2 \alpha - 1)(m - \frac{1}{2}), \quad (2)$$

where  $g_I$  is the nuclear  $g$  factor,  $\beta_N$  = nuclear Bohr magneton,  $\alpha$  is the angle between  $H_0$  and an assumed axis of symmetry passing through the nucleus in question,  $m$  is the higher value in the  $\Delta m_I = 1$  transition and  $Q'$  is the electric quadrupole interaction  $[3eQ/4I(2I-1)] \times (\partial^2 V / \partial z^2)$ , which for  $I = \frac{3}{2}$  is just  $\frac{1}{4} eQ(\partial^2 V / \partial z^2)$ . By fitting the experimental data to Eq. (2), we find for  $K^{39}$ :  $a/h = 21.6$  Mc/sec;  $b/h = 0.95$  Mc/sec;  $Q'/h = 0.20$  Mc/sec. For  $Cl^{35}$ :  $a/h = 7.0$  Mc/sec;  $b/h = 0.50$  Mc/sec. While we found the hyperfine interaction of the chlorines to have axial symmetry within experimental error, this is not required by the symmetry of the crystal about this point. We did in fact find that the

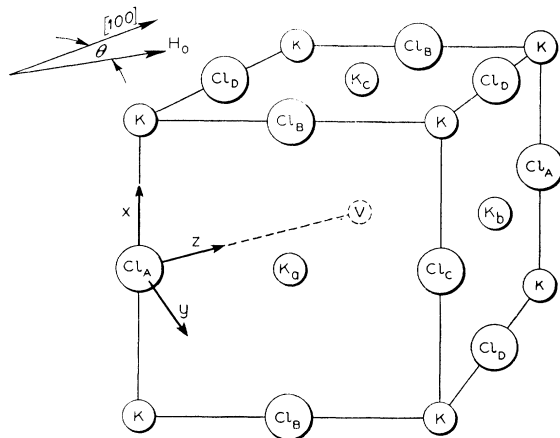


FIG. 3.  $F$  center in KCl. The chlorine vacancy is indicated by  $V$ .

electric field gradient tensor was not axially symmetric. Two of the quadrupole coupling components are:

$$\frac{eQ}{2h} \left( \frac{\partial^2 V}{\partial x^2} \right) = 0.032 \text{ Mc/sec}, \quad \frac{eQ}{2h} \left( \frac{\partial^2 V}{\partial y^2} \right) = 0.045 \text{ Mc/sec}.$$

The third component,  $(eQ/2h)(\partial^2 V / \partial z^2)$ , must by definition be equal to either the sum or the difference of these. Since we could not resolve it experimentally, we believe it to be the difference 0.013 Mc/sec. The values of  $a$  obtained above are in excellent agreement with the values inferred by Kip *et al.*<sup>2</sup> from their line-width determinations.

Many more lines were resolved at frequencies below 4 Mc/sec. They presumably arise from the electronic interaction with next nearest neighbors although the possibility of another center is not excluded. They are being analyzed at present.

I would like to thank Dr. W. L. Brown for bombarding the KCl crystal, Dr. P. W. Anderson for many enlightening discussions, and Mr. E. A. Gere for his assistance in the experiment.

<sup>1</sup> C. A. Hutchison, Phys. Rev. **75**, 1769 (1949).

<sup>2</sup> Kip, Kittel, Levy, and Portis, Phys. Rev. **91**, 1066 (1953).

<sup>3</sup> A. M. Portis, Phys. Rev. **91**, 1071 (1953).

<sup>4</sup> G. Feher, Phys. Rev. **103**, 834 (1956).

<sup>5</sup> A. Abragam and M. H. L. Pryce, Proc. Roy. Soc. (London) **A205**, 135 (1951).

## Interband Magneto-Optic Effects in Semiconductors

E. BURSTEIN AND G. S. PICUS

United States Naval Research Laboratory, Washington, D. C.

(Received December 7, 1956)

IN a magnetic field the quasi-continuous levels of the allowed energy bands of a crystal are coalesced into "one-dimensional" magnetic sub-bands. For simple energy bands, the magnetic sub-bands with  $H$  directed along the  $z$  direction have the form<sup>1</sup>

$$E_l = \frac{\hbar^2 k_z^2}{2m^*} + \hbar\omega_c(l + \frac{1}{2}),$$

where  $\hbar\omega_c = e\hbar H / m^* c$  is the separation between the sub-bands,  $l$  is a positive integer or zero, and the condition for obtaining well-defined sub-bands is  $\omega_c \tau > 1$ . This coalescence of energy band levels into magnetic sub-bands may be expected to have an appreciable effect on optical interband transitions in semiconductors.

Recent studies of the effect of magnetic field on intrinsic absorption in InSb have shown that the magnetic field increases the optical band gap and thus shifts the absorption edge to shorter wavelengths.<sup>2</sup> This effect was attributed to the increase in energy, with magnetic field, of the lowest ( $l=0$ ) magnetic sub-band in the

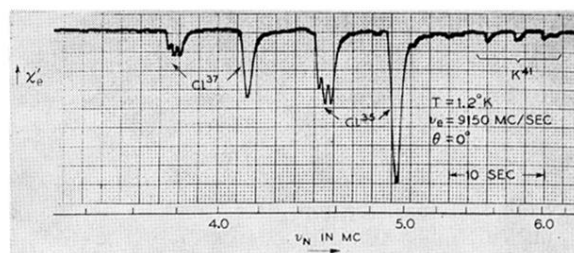


FIG. 1. Interaction of the  $F$  center electron in KCl with its nearest chlorines and  $K^{41}$ . The magnetic field is parallel to the  $[100]$  direction. The additional structure on the chlorine line is the result of quadrupole interaction.