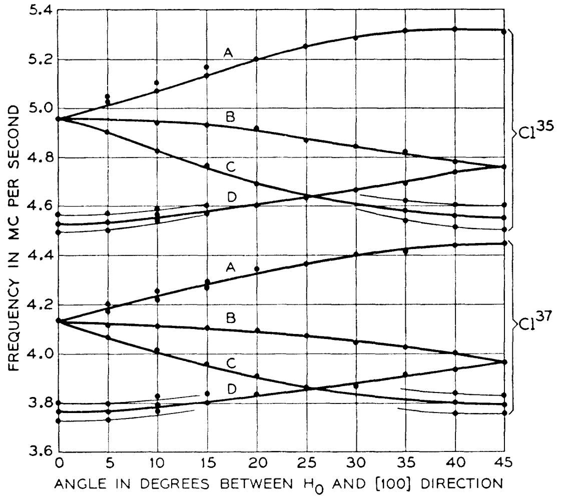

FIG. 2. Variation of the hyperfine and quadrupole splitting with angle between H_0 and the [100] direction, H_0 remaining in the $y-z$ plane. Each level corresponds to a particular chlorine site (see Fig. 3).

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

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

where g_I is the nuclear g factor, β_N = nuclear Bohr magneton, α 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 $[3eQ/4I(2I-1)]\times(\partial^2V/\partial z^2)$, which for $I=\frac{3}{2}$ is just $\frac{1}{4}eQ(\partial^2V/\partial_z{}^2)$. 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 electric field gradient tensor was not axially symmetric. Two of the quadrupole coupling components are:

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

The third component, $(eQ/2h)(\partial^2V/\partial z^2)$, 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.*[2] from their line-width determinations.

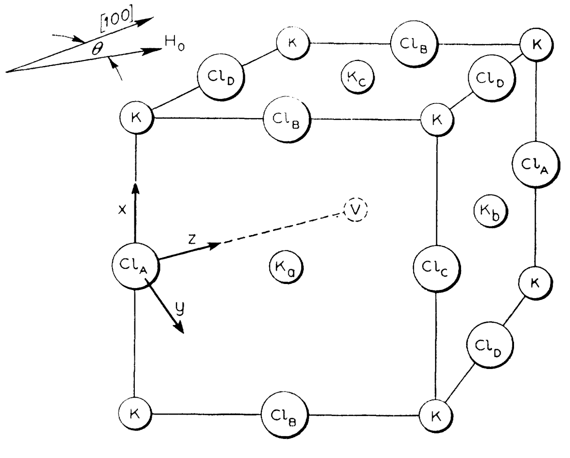

FIG. 3. F center in KCl. The chlorine vacancy is indicated by V.

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.

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Interband Magneto-Optic Effects in Semiconductors

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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[1]

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

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.[2] This effect was attributed to the increase in energy, with magnetic field, of the lowest ($l=0$) magnetic sub-band in the

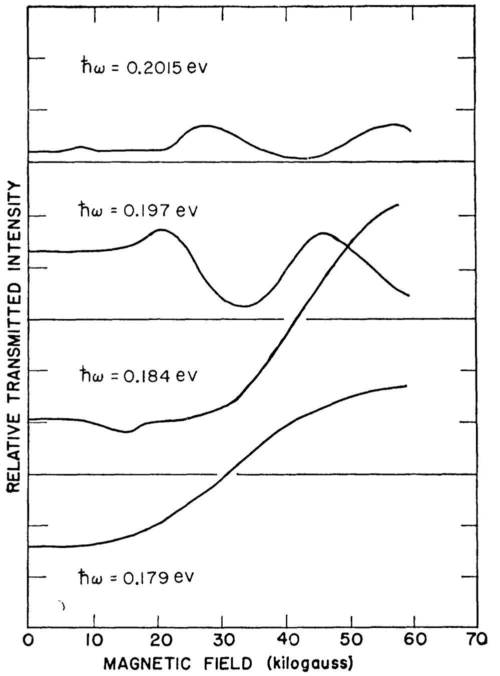

Fig. 1. Intensity of radiation transmitted through an intrinsic specimen of InSb (approximately 10 microns thick) plotted as a function of magnetic field for several photon energies. The magnetic field was parallel to the face of the specimen.

conduction band. These studies have now been extended to higher photon energies using specimens about 10 to 20 microns thick. It is found that for magnetic fields as low as 15 000 gauss, the intrinsic absorption spectrum exhibits several prominent absorption peaks. These absorption peaks are attributed to vertical optical transitions between magnetic sub-bands of the V_2 (light hole) valence band and the magnetic sub-bands of the conduction band.

In Fig. 1, the room temperature transmission of an intrinsic specimen of InSb is plotted as a function of magnetic field at different photon energies. The increase in transmission with magnetic field in the lowest photon energy curve is due to the shift of the absorption edge to higher photon energies. The oscillation in transmission with increasing magnetic field, in the higher photon energy curves, is reminiscent of de Haas-van Alphen effects. In Fig. 2, the relative transmission, $T(H)/T(H=0)$, is plotted as a function of photon energy at several magnetic fields. The curves exhibit three pronounced transmission minima, i.e., absorption peaks, whose positions shift to higher photon energies with increasing magnetic field.

On the basis of available experimental and theoretical information about the free carriers in InSb,[3] it appears that, at the magnetic fields used in these experiments, the condition $\omega_c\tau > 1$ is satisfied for the holes in the V_2 valence band as well as for the electrons in the conduction band, but is not satisfied for the holes in the V_1 (heavy hole) valence band. The levels of both the conduction band and the V_2 valence band are therefore coalesced into well-defined magnetic sub-bands.[4] (See Fig. 3.) It is tentatively suggested that the absorption peak at the lowest photon energy involves transitions from the $l=0$ magnetic sub-band in the valence band to the $l=0$ magnetic sub-band in the conduction band; that the middle absorption peak involves transitions from the $l=1$ valence sub-band to the $l=0$ conduction sub-band; and that the highest photon energy absorption peak involves transitions from the $l=0$ valence sub-band to the $l=1$ conduction sub-band. The separation between the first two peaks is accordingly associated with the separation between the $l=0$ and $l=1$ valence sub-bands, and the separation between the first and third peaks is associated with the separation between the $l=0$ and $l=1$ conduction sub-bands. The absence of other prominent peaks may indicate the existence of a selection rule for Δl. These energy separations indicate a value of $0.044m$ for the effective mass of the light holes. This value is only an upper limit since the coalescence of the valence band levels involves quantum effects arising from the degeneracy of the valence bands. A value of $0.016m$ is obtained for the effective mass of the electrons, in good agreement with

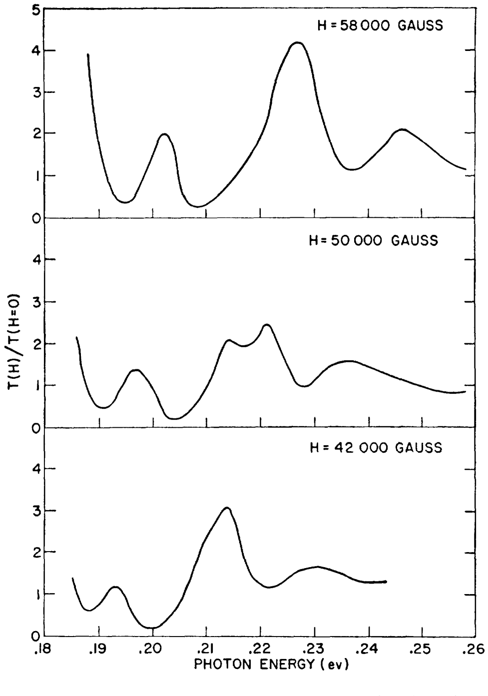

Fig. 2. Relative transmission, $T(H)/T(H=0)$, of InSb at room temperature plotted against photon energy at several magnetic fields. The effective slit width used in the measurements was approximately 0.001 ev. The transmission minimum at 0.217, in the curve for $H=50\,000$ gauss, coincides with an absorption band in the cement used to mount the InSb specimen. The transmitted energy in this region was very low and the indicated band is therefore believed to be spurious.

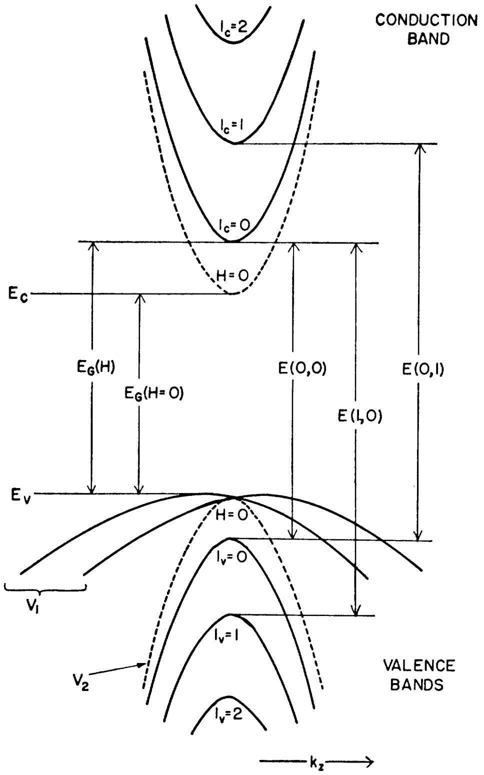

FIG. 3. Schematic energy-momentum diagram of the conduction and valence bands of InSb in the presence of a magnetic field showing the magnetic sub-bands ($l_v=0, 1, 2$) of the V_2 (light hole) valence band and those ($l_c=0, 1, 2$) of the conduction band. The nonparabolic character of the bands and the quantum effects in the valence band have not been taken into account, and it is assumed that the V_1 (heavy hole) valence bands are not appreciably affected by the magnetic field. The V_3 valence band which is split away from the V_1 and V_2 valence bands by spin-orbit interaction is also not shown.

the value of $0.015m$ obtained from infrared cyclotron resonance experiments[5] at comparable magnetic fields.

The effect of magnetic field on optical interband transitions, the interband magneto-optic (IMO) effect, is related to cyclotron resonance in the same way that the Zeeman effect is related to paramagnetic resonance. Both the IMO effect and cyclotron resonance involve the coalescence of energy band levels in a magnetic field. However, the IMO effect involves optical transitions between magnetic sub-bands belonging to different energy bands, whereas cyclotron resonance involves optical transitions between magnetic sub-bands belonging to the same energy band. For intrinsic absorption, the IMO effect does not depend on the presence of free carriers and can therefore be studied under conditions where the free carrier concentration is either too small or too large for cyclotron resonance experiments. Furthermore, the IMO effect should be particularly useful for obtaining information about energy surfaces away from the band edge, as well as about the effective masses of energy bands whose edges occur away from the forbidden energy gap.

We wish to express our appreciation to F. Blatt, E. O. Kane, and R. F. Wallis for valuable discussions. We are also indebted to S. Slawson for preparing the polished thin sections used in the experiments, to A. Mister and R. Anonson for operating the NRL Bitter Magnet, to S. Adler and W. M. Cole for assistance in designing and setting up the optical equipment, and to B. W. Henvis for a number of the calculations.

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[4] The present description is obviously oversimplified, since the coalescence of the valence band levels is complicated by quantum effects arising from the degeneracy of the valence bands. The nature of these quantum effects has not yet been established in detail, so that a more detailed discussion is not possible at present.

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Distribution, Production Rate, and Possible Solar Origin of Natural Tritium*

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LIBBY and co-workers have estimated the production rate of natural tritium as $\bar{Q}=0.14$ T atom/cm^2 of earth surface (cm$_e^2$)-sec, based on their measurements of the tritium content of natural waters.[1,2] $\bar{Q}$ was calculated separately from material balance considerations over (1) the oceans, and (2) the continents, equating the cosmic-ray production rate with the net loss from the oceanic and continental atmospheres by precipitation; the values obtained were, respectively, 0.12 and 0.16, in good agreement.[2] A $\bar{Q}$ value of 0.14, coupled with an average surface ocean concentration (pre-thermonuclear tests) of 0.24 atom T per 10^{18} atoms H (0.24 tritium unit or T.U.), was calculated as indicating uniform mixing of the sea to a depth of about 100 meters, assuming no T to be stored below this depth.[2]

Tritium production by high-energy protons on nitrogen and oxygen has been measured; the cross sections are about 30 mb with excellent agreement between two sets of data.[3,4] From these measurements and considerations of the cosmic-ray primary flux and neutron contribution, $\bar{Q}$ is calculated, independently of observed concentrations, to be approximately[3] 0.2 T atom/cm$_e^2$ sec, and, more precisely,[4] $0.14_{-0.03}^{+0.10}$, in agreement with the rate indicated by the natural concentrations.

However, the tritium production rate must be a good deal higher than the figures quoted above. The average residence time of water below the oceanic thermocline is very probably less than 500 years, and certainly less than 1000 years, as determined by oceanographic measurements,[5,6] data on the heat flux through the ocean floor,[7] and measurements of, and calculations based on, the distribution of radiocarbon in the atmos-