714 (1968).
[3]D. N. Lyon, D. B. McWhan, and A. L. Stevens, Rev. Sci. Instr. 38, 1234 (1967).
[4]D. B. McWhan, T. M. Rice, and P. H. Schmidt, to be published.
[5]Purchased from the Linde Company, Speedway, Ind.
[6]The transition was determined in as many ways as possible with reproducible results, i.e., temperature cycling at constant pressure, pressure cycling while cooling and warming, and recycling after releasing pressure to ≈5 kbar. Also, two crystals were mounted in the same cell with different crystallographic orientations with respect to the axis of applied load in the girdle die. The transitions in the two samples were within 1 kbar even though the initial stress coefficients of T_0 along the [11.0], [10.0], and [00.1] axes are −6.8, −4.1, and −0.5 K/kbar, respectively [J. Feinlieb and W. Paul, Phys. Rev. 155, 841 (1967); I. G. Austin, Phil. Mag. 7, 961 (1962)].
[7]Feinlieb and Paul, and Austin, Ref. 6
[8]M. Foex, J. Jaffray, S. Goldsytaub, R. Tyand, R. Wey, and J. Wucher, J. Rech. Centre Nat. Rech. Sci. Lab. Bellevue (Paris) 21, 237 (1952).
[9]The unit cell volume at 77°K given by E. P. Warekois, J. Appl. Phys. 31, 3465 (1960), does not agree with that given in S. Minomura and H. Nagaraki [J. Phys. Soc. Japan 19, 131 (1964)] and one estimates that $\Delta V/V<1\%$.
[10]Minomura and Nagaraki, Ref. 9.
[11]C. T. Anderson, J. Am. Chem. Soc. 58, 564 (1936).
[12]X-ray diffraction measurements using a camera described in W. Bond and D. B. McWhan, Rev. Sci. Instr. 35, 626 (1964), give $d\ln a/d\ln V\approx\frac{2}{3}$ and $d\ln c/d\ln V\approx-\frac{1}{3}$, where a and c refer to the hexagonal unit cell.
[13]O. A. Cook, J. Am. Chem. Soc. 69, 331 (1947).
[14]The bulk modulus was estimated to be 3100 kbar from L. Knopoff, Phys. Rev. 138, A1445 (1965).
[15]G. K. White and S. B. Woods, Phil. Trans. Roy. Soc. (London), Ser. A 251, 273 (1959).
[16]D. Adler and H. Brooks, Phys. Rev. 155, 826 (1967).
[17]D. Adler, J. Feinlieb, H. Brooks, and W. Paul, Phys. Rev. 155, 851 (1967).
[18]N. F. Mott, Rev. Mod. Phys. 40, 677 (1968).
[19]It has been shown that at least two bands must be considered in metallic VO_2 which also has a metal-semiconductor transition. H. W. Verleur, A. S. Barker, Jr., and C. N. Berglund, Phys. Rev. 172, 788 (1968).
[20]W. Kleiner, Lincoln Laboratory, Massachusetts Institute of Technology, Solid State Research Report No. 3, 1967 (unpublished), quoted in J. M. Honig and T. B. Reed, Phys. Rev. 174, 1020 (1968).
[21]For an account of excitonic phase transitions see B. I. Halperin and T. M. Rice, Solid State Phys. 21, 115 (1968) and references therein.
[22]B. I. Halperin and T. M. Rice, Rev. Mod. Phys. 40, 755 (1968).

SUBMILLIMETER CYCLOTRON RESONANCE IN TELLURIUM

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We report cyclotron resonance measurements in high-purity tellurium at submillimeter wavelength confirming that the isoenergetic surfaces involved at low magnetic fields are ellipsoids grouped by pairs symmetrical with respect to the Brillouin-zone corners. We explain the violent perturbation of the Landau levels at high magnetic field by assuming the ellipsoids to coalesce into dumb-bell surfaces, as for the Shubnikov–de Haas effect.

A recent band-structure calculation[1] for tellurium predicts near the corner M of the Brillouin zone a valence band of the shape depicted in Fig. 1(a). Near the maximum of the valence band the isoenergetic surfaces are ellipsoids, of revolution around the trigonal axis c, centered in N and N' symmetrical with respect to M [surfaces S_{E_1} in Fig. 1(b)]. When the energy increases up to E_S these ellipsoids coalesce into a "dumb-bell" shaped surface (surface S_{E_2}). Such a model, with the assumption of a constant quadratic dependence of E with $k\perp c$, allowed the interpretation of Shubnikov–de Haas results.[2,3] Previous cyclotron resonance experiments at magnetic fields lower than ours[4-6] showed ellipsoidal isoenergetic surfaces

$$E(k)=\hbar^2\left[\frac{k_x^{\,2}+k_y^{\,2}}{2m_1}+\frac{k_z^{\,2}}{2m_3}\right],$$

with

$$m_1=(0.119\pm0.006)m_0,\quad m_3=(0.25\pm0.01)m_0$$

(Ref. 4);

$$m_1=(0.109\pm0.003)m_0,\quad m_3=(0.264\pm0.008)m_0$$

(Ref. 5).

Our experiment has been realized with high-

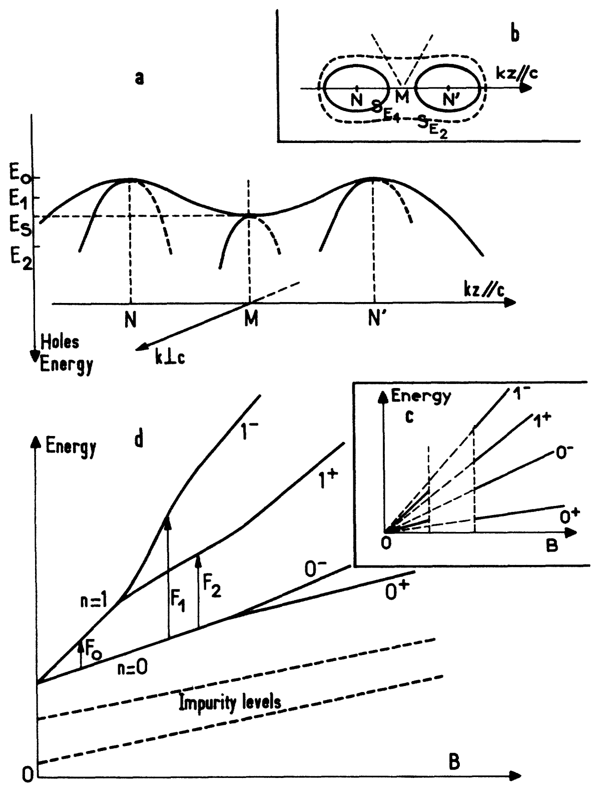

FIG. 1. (a) Shape of the valence band near the Brillouin-zone corner. The maximum E_0 of the valence band is shifted from the trihedral vertex along the side edge of the prism. (b) Section of the isoenergetic surfaces cut by a plane parallel to the c axis. S_{E_1} corresponds to E_1 close to E_0; S_{E_2} to $E_2 > E_S$. (c) Scheme of the Landau levels at low and high magnetic field deduced from a Bohr-Sommerfeld argument. (d) Scheme of the Landau levels deduced from a quantum calculation.

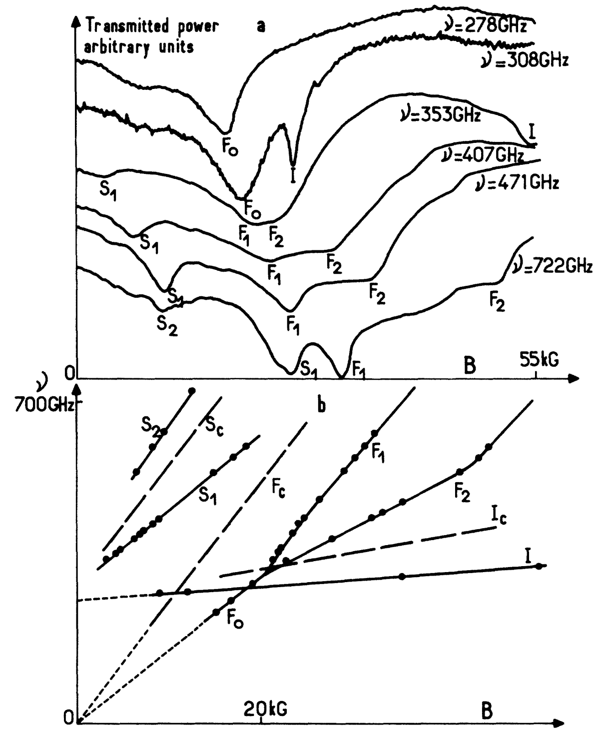

FIG. 2. (a) $\vec{B} \perp c$: Experimental recordings (at various frequencies) of the transmitted microwave power as a function of the magnetic field. The main absorption line F_0 (cyclotron resonance) splits into F_1 and F_2 at $B \sim 20$ kG, $\nu \sim 320$ GHz. The secondary lines are labeled I, S_1, S_2. (b) Plot of the frequency versus magnetic field for the absorption lines. Solid lines, $\vec{B} \perp c$; dashed lines, $\vec{B} \parallel c$.

purity p-type samples[7] $n_p \sim 10^{13}$ carriers/cm^3, $\mu \sim 100\,000$ cm^2/V sec at $T \sim 4°$. For our experimental frequencies $\nu > 300$ GHz, we have $\omega\tau > 10$ and $\omega/\omega_p > 4$. Working at $\omega > \omega_p$ allows the use of a transmission technique.[4]

The frequency band 280-740 GHz is covered by five CSF carcinotrons. The microwaves are transmitted through oversized waveguides. An Allen-Bradley bolometer is used to measure the transmitted power. The direction of the magnetic field $\vec{B}$ is either parallel or perpendicular to the trigonal axis c of the crystal.

$\vec{B} \parallel c$. —The cyclotron resonance is an intense absorption line (F_c) for which the relation between frequency and magnetic field is linear up to $B = 28$ kG. Some other absorption lines show up at these high frequencies, probably related to the existence of impurity levels: (i) A doublet of sharp lines I_c shows up with a small magnetic field dependence (it disappears when the microwave is exactly polarized with its electric field perpendicular to $\vec{B}$). (ii) A secondary line S_c appears for $\nu > 300$ GHz; in an $\omega(B)$ diagram the corresponding experimental points fall on a straight line which extrapolates to ($B = 0$, $\nu = 300$ GHz).

$\vec{B} \perp c$. —At the lower frequencies $\nu \sim 300$ GHz the cyclotron resonance shows up on the recording [Fig. 2(a)] as a broad, intense absorption line F_0 at a magnetic field proportional to ω [Fig. 2(b)]. At higher frequencies $\nu > 330$ GHz the cyclotron resonance line F_0 splits into two lines F_1 and F_2 behaving differently with the increase of the frequency. Also, some new secondary absorption lines show up which will be related to the existence of impurity levels: (i) A sharp absorption peak I at a frequency depending weakly on the magnetic field. (ii) Two secondary lines S_1S_2 appear at low B. The position of S_1 in the $\omega(B)$ diagram can be extrapolated to $B = 0$, $\nu = 300$ GHz.

For decreasing values of the angle between $\vec{B}$ and c, F_0 transforms itself continuously into F_c, S_1 into S_{1c}, and I into I_c.

Discussion.—The tellurium sample used in these experiments is nondegenerate and at $\nu = 300$ GHz, $\hbar\omega_c \sim 1.24$ meV, $\hbar\omega_c \gg kT$ for $T = 1.8$°K. Hence the sample is in the extreme quantum limit. We first treat the fundamental cyclotron absorption lines F_0, F_1, F_2, and F_c.

(i) At low field, the carriers stay around points N or N' in the Brillouin zone. Where the energy has the usual quadratic k dependence, they occupy normal Landau levels with energies $E_n = (n + \frac{1}{2})\hbar\omega_c$, ω_c proportional to B. The observed transition between $n = 0$ and $n = 1$ gives the ellipsoid effective masses

$$m_1 = (0.109 \pm 0.001)m_0, \quad m_3 = (0.29 \pm 0.02)m_0.$$

(ii) At high field the behavior depends on the magnetic field direction. For $\vec{B} \parallel c$, the energy is still quadratic in $k_\perp$ and leads to a normal Landau quantization. The absorption frequency ν is proportional to B. For $\vec{B} \perp c$, the $E(k)$ relation becomes more complicated and the previous Landau scheme is no longer valid. A qualitative discussion can be based on semiclassical arguments. The carrier orbits in reciprocal space should enclose quantized areas A_n given by the Bohr-Sommerfeld condition,

$$\partial A_n = A(E_{n+1}) - A(E_n) = 2\pi eH/\hbar c. \qquad (1)$$

At low fields (1) involves the elliptic sections of the isoenergetic surfaces S_{E_1} (Fig. 1) and leads to the Landau levels of case (i). At higher field the orbit dimensions must increase and the orbits now belong to the type S_{E_2} surfaces which result from the coalescence of two S_{E_1} ellipsoids. Hence an energy difference $E_{n+1} - E_n$ roughly twice smaller than for case (i) is now large enough to meet condition (1) [Fig. 1(c)].

As a result, the energy level quantization will be deeply modified from case (i) to case (ii), and the transition between these two regimes can be described only through a more detailed quantum mechanical calculation (for instance, in the effective-mass approximation). One can show[8] that each low-field Landau level splits into two levels, $n = 0 \to 0^+$, 0^-; $n = 1 \to 1^+$, 1^- [Fig. 1(d)]; the splitting occurs when the level energy comes close to E_S. This scheme accounts for the observed fundamental absorption curves F_0 ($n = 0 \to n = 1$) giving rise to F_1 ($0 \to 1^-$) and F_2 ($0 \to 1^+$), when the $n = 1$ level diverges at $\nu \sim 320$ GHz (the fields used here are not high enough to reveal the $n = 0 \to 0^+$, 0^- splitting). One gets for E_S at $\nu_c \sim 320$ GHz, $E_S \sim \frac{3}{2}\hbar\omega_c \sim 2$ meV.

The secondary lines S_1, S_2, S_c, I, I_c can be related to transitions involving impurity states.[9] A transition between two impurity levels can account for the sharp lines I and I_c. The S_c and S_1 lines occur for frequencies which for a given B are very nearly those of the fundamental absorption plus a constant (~300 GHz). They can be ascribed to transitions from an impurity level (1.8 meV beneath the first Landau level $n = 0$) towards the second ($n = 1$) Landau level. S_2 might be a harmonic of S_1 corresponding to a final level $n = 2$. The precise study of impurity levels[10] is presently in progress.

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[1]M. Picard and M. Hulin, Phys. Status Solidi 23, 563 (1967).

[2]C. Guthmann and J. M. Thuillier, Solid State Commun. 6, 835 (1968).

[3]P. S. Dubinskaya, V. A. Noskin, I. G. Tagiev, I. I. Farbshtein, and S. S. Shalyt, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 8, 79 (1968) [translation: JETP Letters 8, 47 (1968)].

[4]J. H. Mendum and R. N. Dexter, Bull. Am. Phys. Soc. 9, 632 (1964).

[5]J. C. Picard and D. L. Carter, J. Phys. Soc. Japan Suppl. No. 21, 380 (1966).

[6]J. C. Picard, thèse d'état (unpublished).

[7]I. I. Farbshtein, A. M. Pogarskii, and S. S. Shalyt, Fiz. Tverd. Tela 7, 2383 (1965) [translation: Soviet Phys.—Solid State 7, 1925 (1966)].

[8]O. Betbeder and M. Hulin, to be published.

[9]R. Kaplan, J. Phys. Soc. Japan Suppl. No. 21, 249 (1966).

[10]To the difference of the preceding study (Ref. 9) the calculation of the energy levels of the hydrogenic atoms must here apply to the case $\hbar\omega_c/2\mathrm{Ry}^+ \sim 1$ (where Ry^+ is the effective Rydberg).