CYCLOTRON RESONANCE IN AgBr†

G. Ascarelli* and Frederick C. Brown
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 25, 1962)

According to theory, the electron in an ionic crystal has a polaron mass, m^*, which is greater than the band mass, m, in the absence of vibrations or lattice polarization. The ratio of band mass to free-electron mass, m/m_e, enters into the various mobility theories for optical scattering[1-4] as an unknown parameter which, in principle, can be determined by comparison with experiment. When this is done for mobility data on AgBr at 50°K,[5] widely different values of m/m_e are obtained depending upon the theory used (see Table I). The present effort to observe cyclotron resonance in AgBr was undertaken primarily to provide an independent experimental measurement of effective mass. In order to satisfy the stringent requirement for cyclotron resonance, $\omega\tau \gtrsim 1$, the experiment was carried out at a millimeter-wave frequency, $f = 69.9$ kMc/sec. The longitudinal optical-mode frequency of the crystal is about 60 times larger, so presumably the resonance experiment measures the polaron mass, m^*, and not m. A comparison with the values given in Table I should serve as a test of polaron mobility theory.

The results of photoconductivity experiments on AgBr at low temperature indicates that carriers can be released by light absorbed in the band edge at 460 mμ,[6] but high sensitivity is required for detection of a small number of carriers. To aid in this regard, a cylindrical TE_{01n}-mode cavity was chosen and large samples were employed, as shown schematically in Fig. 1. The length of the cavity was adjustable by rotation of a finely threaded piston

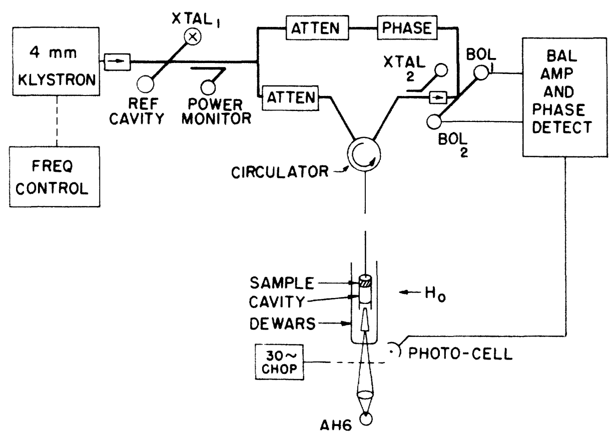

FIG. 1. Outlining the main components of the millimeter-wave cyclotron-resonance apparatus. The magnetic field H_0 was perpendicular to the axis of the sample cavity and could be rotated in the horizontal plane.

Table I. The ratio of band mass to free-electron mass, m/m_e, polaron mass, m^*/m_e, and coupling constant α, determined by comparison of mobility theory[a] and experiment[b] for AgBr.

	Howarth & Sondheimer[c]	Schultz[d]	Low & Pines[e]	Feynman, Hellwarth, Iddings, and Platzman[f]
m/m_e	0.43	0.78	0.30	0.20[g]
m^*/m_e	...	1.4	0.39	0.27
α	2.33	3.15	1.95	1.60

[a] The low-frequency and high-frequency dielectric constants at low temperature are taken as 11.5 and 4.62, respectively. Recent low-temperature Reststrahl measurements[h] yield a value of longitudinal optical frequency of $\omega_l = 2.74 \times 10^{13}$ sec^{-1}.
[b] The observed Hall mobility of electrons in AgBr at 50°K is 1700 ± 200 cm²/volt sec.[i] A similar value of microscopic mobility is assumed at this temperature where the scattering is predominantly by optical vibrations.
[c] See reference 1.
[d] See reference 2.
[e] See reference 3.
[f] See reference 4.
[g] A variational parameter $w = 3$ was chosen corresponding to small coupling constants.
[h] G. O. Jones, D. H. Martin, P. A. Mawer, and C. H. Perry, Proc. Roy. Soc. (London) A26, 10 (1961).
[i] See reference 5.

which served as the lower wall of the cavity. Suppression of the *TM* modes was achieved by a series of grooves turned on the cylindrical wall of the cavity, as well as by providing for a small gap at the ends. Tuning of the cavity was accomplished from outside the Dewars by a mechanical linkage and gear system. Liquid helium was kept out of the cavity and waveguide by a thin-wall glass tube immediately surrounding the cavity. Intermediate temperatures were achieved by applying a small amount of power to a heater and by controlling the pressure of heat-exchange gas in the tube surrounding the cavity.

The AgBr samples, in the form of disks 0.235 in. in diameter and of the order of a millimeter thick, were cut from a zone-refined ingot.[7] They were oriented by means of back-reflection Laue techniques so that the surface of each disk was parallel to the (110) plane. Finally the samples were carefully annealed in the dark in an inert atmosphere. They were located in one of two positions in the cavity, either in the upper end or at the lower end on top of the movable piston. In the first case, the sample was illuminated by light brought into the cavity on the axis through a hole in the piston by a short tapered light pipe. Windows in the bottom of the Dewars permitted illumination from below by intense but well filtered light from a General Electric AH-6 mercury arc. In the second sample position, illumination was accomplished through seven small holes in the piston centered on a circle at the position of maximum electric field. Similar results were obtained for the two geometries and for samples of different thicknesses.

The resonant modes of the cavity were studied, both with and without sample, by tuning through several points, carefully noting the position of the piston. An estimate of dielectric constant can be obtained by observing the amount by which the cavity is shortened when dielectric is present.[8] The dielectric constant of AgBr at 70 kMc/sec and 4.2°K was observed to be 12.5 ± 1.0. It was found to be temperature dependent but increased only slightly on warming to 77°K. Cavity resonances with dielectric present could not be observed at room temperature, apparently because of loss associated with the long wavelength tail of the Reststrahl.

As shown schematically in Fig. 1, microwave power was generated by a 4-mm klystron which was frequency stabilized, either on a reference cavity (crystal 1) or on the sample cavity (crystal 2). Power reflected from the sample cavity was observed at one arm of a symmetrical, three-port circulator constructed as outlined by Thaxter and Heller.[9] The microwave detector consisted of a pair of balanced bolometers biased by microwave power for high sensitivity.[10] Chopped illumination and a lock-in amplifier were employed to drive one axis of an x-y recorder, the other axis of which was fed by a rotating-coil gaussimeter. The records served as a plot of absorbed power versus magnetic field H_0 in the usual manner.[11]

Results at two different temperatures are shown in Fig. 2. Only one peak was observed up to $H_0 = 18$ kilo-oersteds. It did not change appreciably as H_0 was rotated with respect to the crystal axis indicating an isotropic band shape as found for electrons in AgBr.[12] The resonance line was observed to broaden and disappear as the temperature increased above 35°K. The curve marked 27.2°K was obtained with the use of liquid neon as a cryogenic fluid.[13] It corresponds to $\omega\tau < 1$ in agreement with electron-Hall-mobility results at this temperature.[5] Size effects or magnetoplasma phenomena cannot explain the observed resonance line at 18°K which was obtained for different light intensities, sample thicknesses, and sample positions. Actually, polarization effects are minimized for the TE_{01n} mode, since the electric field has only a θ com-

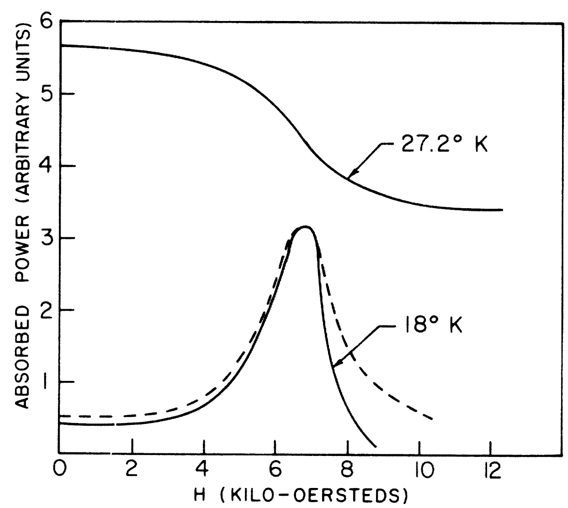

FIG. 2. Cyclotron-resonance absorption in AgBr at 18°K and at a somewhat higher temperature. The single line corresponds to $m^*/m_e = 0.27$. It broadens rapidly with increasing temperature because of the effect of optical-mode scattering. The dotted curve is from a simple theory of line shape for $\omega\tau = 4$.

ponent and is parallel to the flat surfaces of the disk. Although resonance peaks were observed at 4.2°K, the signal-to-noise ratio and reproducibility were poor. This is not entirely explained, but may be related to the fact that serious trapping of carriers occurs below 16°K. At 4.2°K, stronger unfiltered light had to be used. Under these conditions the photo signal may arise mainly because of carriers released near the less perfect surface region of the crystal. In fact, for very strongly absorbed light, absorption constant $\sim 10^4\ cm^{-1}$, the cyclotron orbits tend to intercept the surface. It is hoped that this point can be investigated further, using a vertical solenoidal magnetic field. In addition, higher magnetic fields might permit the observation of holes which seem to have lower mobility and higher effective mass than electrons.

The dashed curve in Fig. 2 is the line shape expected for $\omega\tau = 4$ assuming a constant relaxation time and the sample and field geometry employed in these experiments. The results of this simple theory differ from the usual case, in which the E and H_0 field are perpendicular everywhere, mainly by the addition of a constant term proportional to $1/[1+(\omega\tau)^2]$. An $\omega\tau$ of four corresponds to a mobility of about $5\times10^4\ cm^2$/volt sec at 18°K which is in agreement with other measurements.[13] The observed line shapes are only in approximate agreement with a constant-τ theory. Undoubtedly the situation would be improved by using the Boltzmann equation and treating τ as a function of energy. In fact, the observed rf conductivities are low on the high-field side of resonance, and this is just the effect found in previous work[5] taking the energy dependence of relaxation time into account.

In conclusion, it can be seen that for $f = 69.9$ kMc/sec, the observed resonance at $H = 6.6$ kilo-oersteds corresponds to a polaron mass $m^*/m_e = 0.27$ in good agreement with the recent theory of Feynman et al.[4] Although the agreement may be partly fortuitous, it seems to argue for the Fröhlich model and approximations used by these authors, at least for small coupling constants. The theoretical mobility versus effective-mass curve is such that a 10% error in the experimental mobility gives rise to an uncertainty of about 6% in m/m_e. From the numbers, it appears that the Low-Pines theory can be brought into closer agreement by improving the approximation $m^*/m = 1 + \alpha/6$.

The authors are indebted to many individuals for help in connection with the experiment. Among those are Professor Paul Coleman and the millimeter wave group at the University of Illinois; Mr. Frank Moser of Kodak; Dr. H. S. Jarrett and Dr. R. K. Waring of Du Pont; Dr. J. B. Thaxter, Lincoln Laboratory; and Mr. Bob Watters, Research Laboratory, General Electric Company. The patient assistance of Mr. F. E. L. Witt and Mr. Fred Wise in the Physics Shop at the University of Illinois is gratefully acknowledged.

---

†Work supported in part by the U. S. Air Force Office of Scientific Research.

*Present address: Istituto Superiore di Sanità, Rome, Italy.

[1]D. J. Howarth and E. A. Sondheimer, Proc. Roy. Soc. (London) A219, 53 (1953).
[2]T. D. Schultz, Phys. Rev. 116, 526 (1959).
[3]F. Low and D. Pines, Phys. Rev. 98, 414 (1955).
[4]R. P. Feynman, R. W. Hellwarth, C. K. Iddings, and P. M. Platzman, Phys. Rev. 127, 1004 (1962).
[5]D. C. Burnham, F. C. Brown, and R. S. Knox, Phys. Rev. 119, 1560 (1960).
[6]F. C. Brown, H. H. Tippins, and T. Masumi, J. Phys. Chem. Solids 22, 101 (1961).
[7]F. Moser, D. C. Burnham, and H. H. Tippins, J. Appl. Phys. 32, 48 (1961).
[8]P. P. Penrose, Trans. Faraday Soc. 42A, 108 (1946).
[9]J. B. Thaxter and G. S. Heller, Proc. Inst. Radio Engrs. 48, 110 (1960).
[10]G. Feher, Bell System Tech. J. 36, 449 (1957).
[11]G. Dresselhaus, A. F. Kip, and C. Kittel, Phys. Rev. 98, 368 (1955).
[12]H. H. Tippins (to be published).
[13]Supplied through the courtesy of the Linde Company.