PHYSICAL REVIEW LETTERS

VOLUME 5 DECEMBER 1, 1960 NUMBER 11

ION RESONANCE IN A MULTICOMPONENT PLASMA

S. J. Buchsbaum
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 19, 1960)

We have performed experiments designed to study the phenomena associated with ion cyclotron resonance in a multicomponent plasma whose charged particle density is sufficiently high that interaction between the various plasma components takes place. We present here a preliminary account of the experimental results.

The transverse oscillations of a uniform, cold plasma in an axial, uniform magnetic field have been studied by a number of authors.[1-4] In Fig. 1 are shown the resonant frequencies of a hydrogen plasma which, for the sake of an example, is assumed to contain the ions H_1^+, H_2^+, and H_3^+ in relative concentrations of 5%, 50%, and 45%, respectively. These frequencies were calculated[3,4] assuming no collisions by finding the roots of the equation $k_x(\omega)=\infty$, where k_x is the propagation constant of an extraordinary wave propagating at right angles to the magnetic field. Equations (2) and (7) of reference 4 are examples of the results of such calculations. The curve marked A in Fig. 1 is given by

$$\omega^2=\omega_b^{\,2}+\omega_p^{\,2}, \tag{1}$$

where $\omega_b=eB/m$ is the electron cyclotron frequency and $\omega_p=(ne^2/m\epsilon_0)^{1/2}$ is the electron plasma frequency. This resonance (included for completeness) is of no concern in this experiment as it occurs at microwave frequencies and depends only upon the motions of electrons. Curves B, C, and D are associated with ion motions and are of interest here. At low plasma densities ("low" to be defined shortly), where sufficient space-charge field to couple the motions of the various plasma components cannot be induced in the plasma, resonance is at the cyclotron frequencies of each ion species. At high plasma densities, curve B tends to the so-called electron-ion hybrid frequency. This limit was studied by Auer et al.[2] and in great detail by Körper,[3] who showed that for a plasma with a single ion species it is given

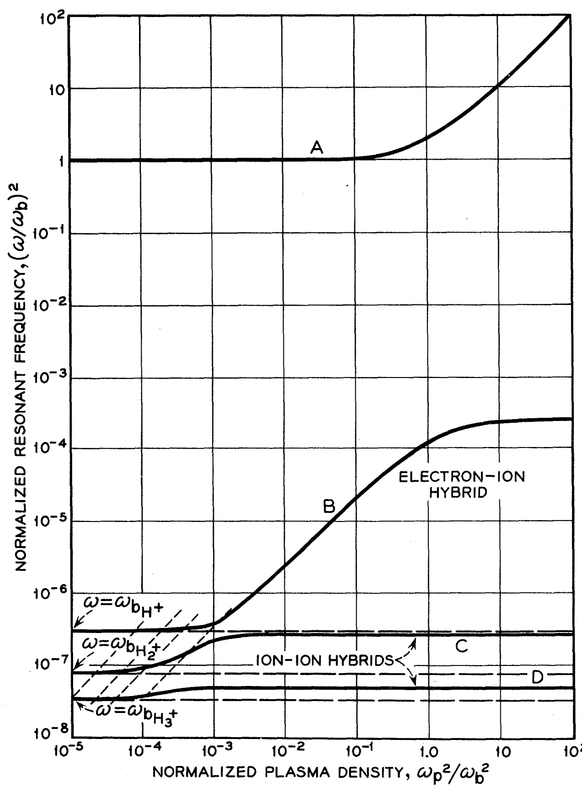

FIG. 1. Calculated resonant frequency of a hydrogen plasma as a function of plasma density and magnetic field. The following ions are assumed present in the indicated concentration: H^+(5%), H_2^+(50%), and H_3^+(45%).

by

$$\omega^2 = \omega_b \omega_{bi}, \qquad (2)$$

where $\omega_{bi} = eB/M_i$ is the ion cyclotron frequency. For a many-component plasma ω_{bi} must be replaced by $\sum_i x_i \omega_{bi}$, where x_i is the relative concentration of the ith ion species. Curves C and D tend to the so-called ion-ion hybrids. It was shown in reference 4 in a three-component plasma that at these resonances the various ion species oscillate out of phase with each other while the electrons remain relatively motionless. The ion-ion hybrid frequencies are then sensibly independent of the electron cyclotron frequency and depend only on ion cyclotron frequencies and on the relative concentrations of the different ion species. For a plasma with more than two ions this dependence is sufficiently involved that the discussion of it must be postponed to a more detailed publication.[5] Here it suffices to say that the solid curves in Fig. 1 never cross the horizontal dashed ones, and that the larger the relative concentration of a particular ion species the closer does its hybrid frequency approach the cyclotron frequency of the next lighter ion. Of importance in these experiments are the "knees" in curves B, C, and D at low plasma densities. They mark the transition from a single-particle behavior to a collective one; "pure" ion cyclotron resonance occurs in the region to the left of the knee. The density at which a knee occurs depends on concentrations of all ions,[5] but pure ion cyclotron resonance generally obtains provided

$$\omega_p^2 \ll \omega_b \omega_{bi}, \qquad (3)$$

where ω_{bi} is the cyclotron frequency of the ion in question. Ion-ion hybrids are attained at densities such that the inequality (3) is reversed, while for the electron ion hybrid one must have $\omega_p^2 \gg \omega_b^2$.

The aim of the experiment was to observe "pure" ion cyclotron resonance and to study the behavior of the resonance with increasing plasma densities. The experiment was performed on the positive column of an arc discharge with a thermionically heated oxide-coated cathode. The tube was connected to a vacuum system, which could be baked out and which could be filled with gas to any desired pressure. The gas used was "spectroscopically pure" hydrogen, helium, or neon provided by the Linde Company. Some, but not great, attention was paid to maintaining the gas purity. The positive column was in an axial magnetic field provided by a Bitter-type solenoid. The large magnetic field (up to 85 kgauss) enables one to perform the experiment at elevated frequencies (6.2, 10.8, 18.18, and 27.3 Mc/sec were used) with a corresponding decrease in linewidths. Also, as (3) reduces to $n \ll [6\times10^7(B \text{ kgauss})^2/(M_i \text{ atomic units})]\ \text{cm}^{-3}$, "pure" cyclotron resonance can be observed at densities which can be obtained in active gas discharges. The central portion of the positive column was surrounded by a resonant structure which, in the absence of a plasma, produced a "twisted" electric potential given by

$$\varphi(r,\theta,z) = \varphi_0 I_m(k_z r)\cos(m\theta \pm k_z z)\cos\omega t; \quad m = 1, 2 \qquad (4)$$

where I_m is the modified Bessel function. The presence of the plasma modifies the argument of I_m which then exhibits the resonances shown in Fig. 1. The twist in the electric potential makes it possible for the rf field to penetrate the plasma more completely,[6] and is given by the axial wave number k_z ($k_z \gg \omega/c$). The static magnetic field was uniform to within 4% over the interaction region. The absorption and dispersion were measured at a constant tube current and a constant gas pressure as a function of the magnetic field by measuring on an rf bridge the changes in the effective admittance of the resonance structure caused by the plasma. This corresponds to motion along the diagonal lines in Fig. 1. No substantial change in the absorption lines was found experimentally when the dipole field [$m = 1$ in Eq. (4)] was replaced by the quadrupole field ($m = 2$).

Figure 2 is an example of "pure" or almost pure ion cyclotron absorption lines in helium with a hydrogen impurity. In Fig. 2(a) the H^+ and H_2^+ lines are at their cyclotron fields while the H_3^+ line is slightly shifted toward lower magnetic field, i.e., toward its hybrid field. There is also evidence for a shifted He^+ line. Figure 2(b) is a dispersion curve.

In Fig. 3 we plot the absorption in relatively pure hydrogen for various plasma densities. At the lowest plasma densities ($I_p = 2.6$ ma) at which the signal-to-noise ratio allowed a reproducible run, the H_3^+ line is at its cyclotron field and the H_2^+ and H^+ lines are broad and already shifted towards lower B fields. As the plasma density increases, all three lines shift towards lower fields in qualitative agreement with Fig. 1. The shift from cyclotron resonance to hybrid resonance requires an increase in density of approximately two orders of magnitude, in agreement

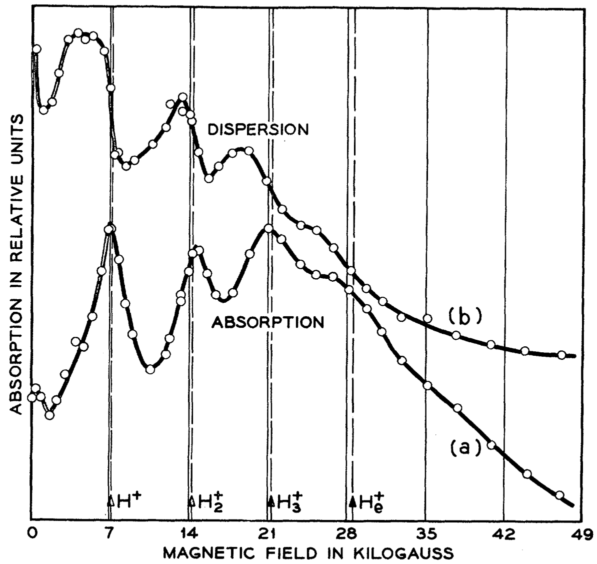

FIG. 2. Absorption and dispersion in a helium plasma with hydrogen impurity. Helium pressure = 100 microns; hydrogen concentration unknown but less than 2%. Quadrupole field, f = 10.82 Mc/sec. Tube current = 8 ma. The arrows indicate the cyclotron fields of the various ions.

with Fig. 1. A quantitative comparison with theory cannot yet be made. We do not know the relative concentrations of the various ions in the plasma which, moreover, are apt to vary as the plasma density is increased. There exists, however, one notable disagreement with Fig. 1. The H_3^+ line definitely crosses the H_2^+ cyclotron field and the H_2^+ line crosses the H^+ field. The reason for this is not yet known, but it is thought to result from the presence of density gradients in the plasma. The behavior of linewidths with increasing density is of interest. The width of the H_3^+ line increases, while that of the H_2^+ line decreases. This is reasonable, however, for the following reasons. In the transition region between cyclotron and hybrid resonances, the frequency (and thus the resonant magnetic field) is density dependent. In a nonuniform plasma one then expects the line to be additionally broadened. Now, in Fig. 3 the H_3^+ line is in the low-density part of the transition region, while the H_2^+ line is in the high-density part of it; it is this fact which, it is now thought, may account for the apparently anomalous behavior of the linewidths.

Results similar to, but not identical with, those shown in Fig. 3 were obtained at other frequencies and pressures and for various other gases.[5]

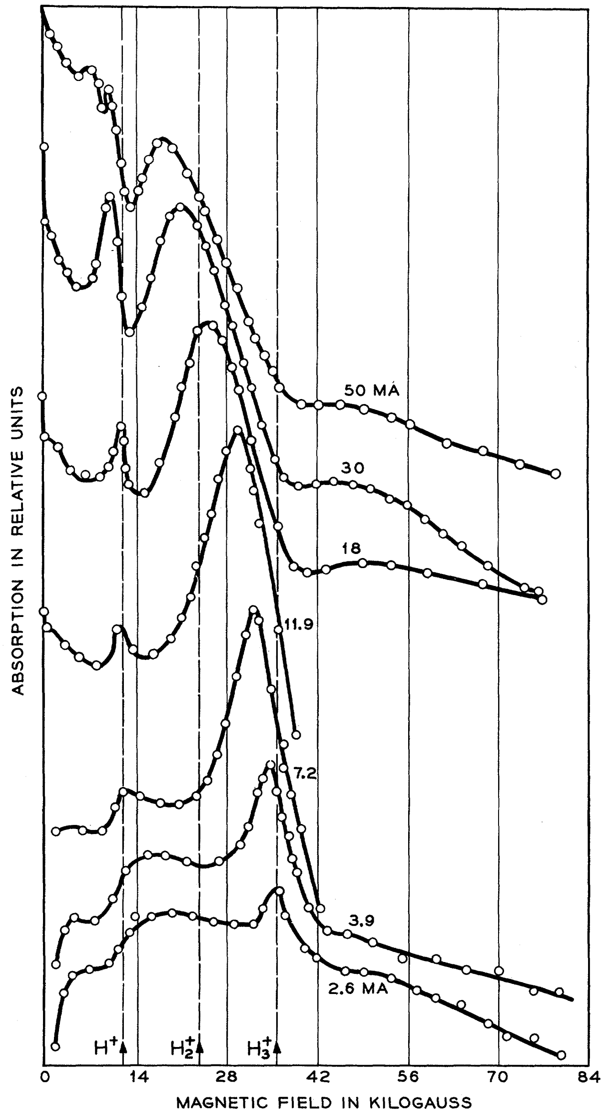

FIG. 3. Absorption in a hydrogen plasma for various plasma densities (tube currents), pressure = 110 microns. Dipole field, f = 18.18 Mc/sec. The arrows indicate the cyclotron fields of the various ions. The origin of the structure in the absorption lines at high magnetic fields is not known.

The author is grateful to H. W. Dail, N. R. Sheeley, and A. S. Wilczek whose aid made this experiment possible. Many stimulating discussions with J. K. Galt are acknowledged.

[1]E. Astrom, Arkiv Fysik 2, 443 (1950).
[2]P. L. Auer, H. Hurwitz, Jr., and R. D. Miller, Phys. Fluids 1, 501 (1958).
[3]K. Körper, Z. Naturforsch. a12, 815 (1957); a12, 220 (1960).
[4]S. J. Buchsbaum, Phys. Fluids 3, 418 (1960).
[5]S. J. Buchsbaum (to be published).
[6]T. H. Stix, Phys. Rev. 106, 1146 (1957); T. H. Stix and R. W. Palladino, Phys. Fluids 1, 446 (1958).