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## Observation of Novel Edge Excitations of a Two-Dimensional Electron Liquid on Helium in a Magnetic Field

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Low-frequency edge excitations in a magnetic field of the two-dimensional electron system on liquid helium are studied. It is found that, in addition to the conventional edge magnetoplasma resonances, novel resonances of smaller amplitude appear at lower frequencies at  $T < 0.9$  K. A comparison of these new modes with the recently predicted acoustic edge excitations is presented. The propagation of boundary oscillations of the electron sheet as well as their coupling to edge magnetoplasmons are also discussed to explain the observed phenomena.

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The observation of edge magnetoplasmons (EMP's) was one of the most unexpected and intriguing discoveries in the physics of the two-dimensional (2D) electron gas [1,2]. In this collective mode the charge density fluctuation  $\delta n$  exists only close to the boundary of the electron sheet within a narrow strip of thickness  $d_B$ , decreasing with the magnetic field  $B$  applied normal to the system. The characteristic property of the EMP is that its frequency *decreases* with increasing magnetic field as  $1/B$  [3,4]. For 2D electron systems in the quantum Hall effect (QHE) regime [5] boundary phenomena are of extreme importance, because all electrical transport is confined to the so-called edge channels [6]. EMP's form the lowest-energy excitations of such 2D systems. Therefore there is considerable current interest in using EMP spectroscopy to investigate fundamental issues regarding the (fractional) QHE [7,8]. Basically, however, EMP's are an entirely classical phenomenon and can be investigated in the nondegenerate two-dimensional electron system on liquid helium [1,2,9].

Recently, several novel types of edge excitations have been predicted theoretically. Some of them are directly related to the quantum edge channels [8,10]; others are classical and exist when the density profile at the edge is smooth [11,12], varying over a length scale  $d$ . The theory of Ref. [12] deals with strong magnetic fields ( $d_B \ll d$ ) and leads to an acoustic spectrum  $\omega_j(q)$

$$\omega_j(q) = s_j q, \quad s_j = 2e^2 n_s / (j \varepsilon m \omega_c), \quad j = 1, 2, \dots, \quad (1)$$

which is lower than the conventional EMP spectrum by a logarithmic factor  $\ln(1/qd)$  ( $n_s$  is the 2D electron density,  $\varepsilon$  the permittivity,  $m$  the electron mass, and  $\omega_c$  the cyclotron frequency). The magnetic field dependence,  $\omega_j \propto 1/B$ , is distinctly different from that of the acoustic modes predicted in the low-magnetic-field limit ( $d_B \gg d$ ) in Ref. [11],  $\omega_j \propto B$ .

In the present Letter, we report the first experimental observations of a new type of edge modes in the 2D electron system on helium at low temperatures at both low and strong magnetic fields. Their resonant frequencies, being significantly lower than EMP frequencies, decrease with  $B$  in the same way as for conventional EMP resonances, which agrees with Eq. (1). But they show this behavior even in low fields ( $d_B \gg d$ ) where the amplitudes are largest, in contrast with the results of Refs. [11] and [12]. Therefore an alternative concept is discussed, which assumes a coupling between edge magnetoplasmons and oscillations of the boundary of the electron pool.

For reasons of convention (though not essential) a rectangular cell as in Ref. [1] was used at low fields and a circular one at high fields. The surface of liquid helium was held between two plates, 3 mm apart, at a distance  $h = 0.5$  mm (rectangular) or 1 mm (circular) from the bottom plate. The electrode geometries of the bottom plate of the rectangular ( $1.5 \times 1$  cm<sup>2</sup>) and cylindrical (diameter 15 mm) cells are shown in the insets of Figs. 1 and 2, respectively. Electrode A (rectangular) or 1 (circular) is excited with an ac voltage at a frequency  $\omega/2\pi$  and amplitude of typically 10 mV. The current induced on electrode C (rectangular) or 5 (circular) was phase-sensitively detected. All other electrodes are grounded and not used further in the present experiments. For practical reasons, phase shifts are measured in the rectangular cell and signal amplitudes in the cylindrical cell.

The results of the measurements using the rectangular cell are presented in Fig. 1 for four different temperatures. At high temperatures ( $T > 1$  K) there is only one resonance attributed to the EMP excitation with smallest wave number  $q = 2\pi/L$ , where  $L$  is the perimeter of the electron pool. A new peak appears when the temperature is decreased below 0.9 K. The position of this peak

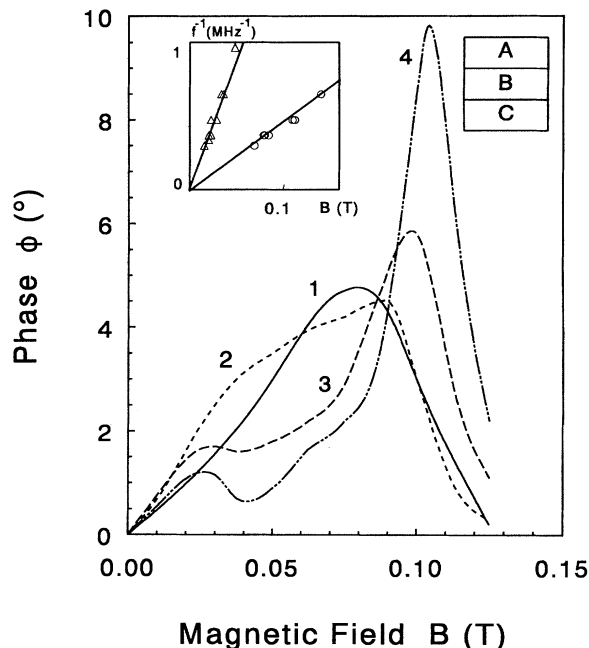


FIG. 1. The phase shift  $\phi$  of the measured current against magnetic field, for a rectangular geometry (see right inset), at temperatures of 0.98 K, (1); 0.88 K, (2); 0.81 K, (3); and 0.51 K, (4) at a frequency of 2 MHz. The electron density was  $4 \times 10^{12} \text{ m}^{-2}$ . Left inset: the inverse frequency  $f^{-1}$  of the EMP resonances ( $\circ$ ) and the new low-frequency resonances ( $\Delta$ ) against magnetic field for the same density of electrons.

increases linearly with electron density, and decreases with  $B$  nearly in the same way as the position of the conventional resonances (see left inset of Fig. 1). Using the definition of  $d_B$  in the transmission line model (see, e.g., Ref. [9]),  $d_B \approx (2\sigma_{xx}/\omega C_s)^{1/2}$ , with  $\sigma_{xx}$  the magnetoconductivity,  $C_s \approx \epsilon/h$ , and using  $d \sim h$ , we obtain  $d_B/d \sim 5$  for these measurements, which corresponds to the case of low fields. Note that the expression for  $d_B$  applicable to our experiments differs from the one in the collisionless regime ( $\omega\tau \gg 1$ ,  $\tau$  electron scattering time) [11].

Data at higher fields are shown in Fig. 3. Typically, the ratio  $d_B/d \sim 0.2$  now. The amplitude of the new resonances, indicated by arrows, is only a few percent of that of the conventional ones. In comparison with the conventional EMP resonances, this new set of resonances is significantly shifted to the lower-frequency domain. From fits to the data shown in Fig. 2, it is found that the frequencies of both the new and the conventional resonances closely follow a  $1/B$  behavior.

The dependence of the amplitude of the new resonances on excitation voltage was found to be linear up to voltages an order of magnitude larger than used normally in the experiments. This means that the new resonances are not subharmonics of conventional resonances. It was verified that the resonances are not of instrumental origin by

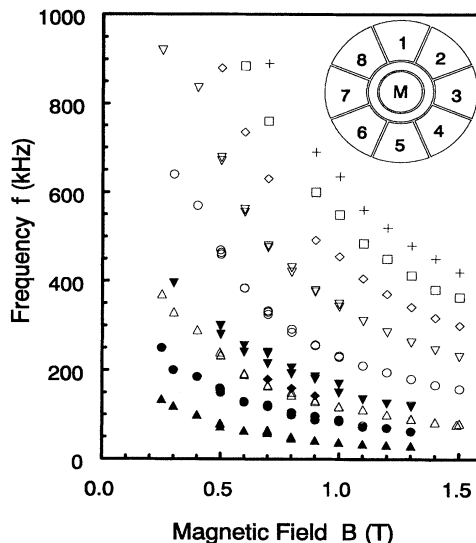


FIG. 2. The first six standing-wave frequencies of EMP's ( $\Delta$ , 1;  $\circ$ , 2;  $\nabla$ , 3;  $\diamond$ , 4;  $\square$ , 5; and  $+$ , 6) and the first four standing-wave frequencies of the low-frequency mode ( $\blacktriangle$ , 1;  $\bullet$ , 2;  $\blacklozenge$ , 3; and  $\blacktriangledown$ , 4) as a function of magnetic field  $B$  (density  $n = 6 \times 10^{11} \text{ m}^{-2}$ ; temperature  $T = 0.5 \text{ K}$ ). The inset shows the bottom plate.

simulating the resonance by an electronic circuit using a quartz crystal, working with signal amplitudes even 3 orders of magnitude above those used in the real experiments. Despite a significant harmonic distortion of the oscillator ( $\sim 3\%$  at the third harmonic), no resonance was

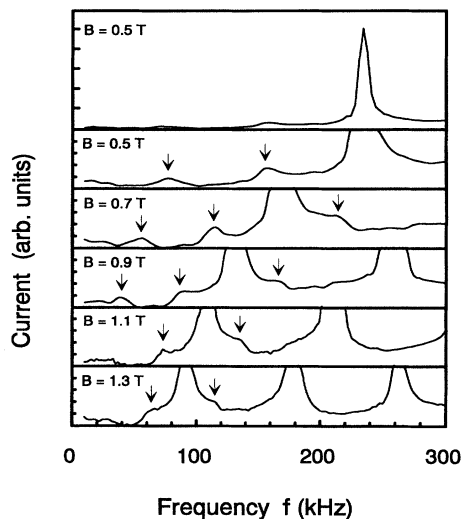


FIG. 3. The amplitude of the measured current as a function of frequency for  $n = 6 \times 10^{11} \text{ m}^{-2}$  and  $T = 0.5 \text{ K}$  for several magnetic field values. The arrows show the location of the low-frequency resonances. The large peaks correspond to the conventional EMP's. The upper panel is the trace at 0.5 T without magnification.

observed in the output of the phase-sensitive detection circuit at subharmonic frequencies, down to the detection level of 0.1%.

The results presented in Figs. 1–3 show that novel low-energy edge excitations of a 2D electron liquid can propagate along the boundary of the electron pool. The dependence of the frequencies of these modes on electron density and magnetic field is the same as for the high-field excitations predicted in Ref. [12] [see Eq. (1)]. The novel modes reported here, however, are most pronounced in the low-field regime, where according to Ref. [11] the low-frequency excitation due to a smooth edge should have the opposite field dependence,  $\omega \propto B$ . We also did not see the resonances with  $j > 1$ . The novel resonances decrease in amplitude at higher magnetic fields and eventually become unobservable. The intensity of the novel resonances is very low in comparison with the conventional resonances. Therefore we should not exclude other possible explanations.

In the following analysis we assume the electrons occupy the half-plane,  $y < 0$ , so that the linear density of the total charge accumulated near the edge,  $Q = \int \delta n dy$ , can be described by a plane wave,  $Q \propto \exp(-i\omega t \pm iqx)$ , propagating along the boundary in the direction dependent on the sign of the  $z$  component of the magnetic field [3,4]. In the acoustic edge mode  $j$  predicted in Ref. [12], the EMP charge density changes its sign  $j$  times in the direction perpendicular to the boundary, which partially screens the electric field perturbation outside the strip and decreases the frequency of the excitations. The analogous effect of screening can be produced by the displacement  $\xi(x, t)$  of the nonrigid boundary of the 2D electron pool from its equilibrium position. In this case the density profile at the edge  $n = n_0(y - \xi)$ . In the simplest model, neglecting screening by the metal plates, the electric potential  $\Phi(y)$  produced by both the density oscillation  $Q$  and the oscillation of the boundary  $\xi$  at large distances,  $|y| \gg d_B$ , and the potential at the edge  $\Phi(0)$  can be written as (see the analogous expressions in Refs. [4] and [13])

$$\begin{aligned}\Phi(y) &\approx 2(Q + en_s\xi)K_0(|qy|), \\ \Phi(0) &\approx 2[Q \ln(1/|q|d_B) + en_s\xi \ln(1/|q|d)],\end{aligned}\quad (2)$$

where  $K_0$  is the modified Bessel function.

The possibility of propagation of boundary oscillations of an electron pool can be understood even from a very simple model of an incompressible 2D electron liquid ( $\text{div}\boldsymbol{\nu} = 0$ , where  $\boldsymbol{\nu}$  is the velocity field). At the boundary, the component of the external electric field parallel to the surface is completely compensated for by the field of the electron pool and therefore cannot give rise to a restoring force. The real restoring force is produced by the perturbation of the electric potential caused by displacements of the boundary [see Eq. (2)]. In this case the Euler equation in the vicinity of the boundary,  $i\omega\nu_x = (e/m)(\partial\Phi/\partial x) + \omega_c\nu_y$ , with the usual boundary

condition  $\nu_y(x, 0) = -i\omega\xi$  gives the dispersion relation

$$\omega_\xi = \frac{1}{2}[(\omega_c^2 + 4\omega_s^2)^{1/2} - \text{sgn}\{B\}\omega_c], \quad (3)$$

where  $\omega_s^2 = eq\Phi(0)/m\xi \approx (2e^2n_sq/m)\ln(1/qd)$ . The frequency of this spectrum is decreasing with  $B$  in the limit of high magnetic fields ( $\omega_c \gg \omega_s$ ),  $\omega_\xi \propto 1/B$ .

The real 2D electron liquid on helium is not incompressible and we should consider the possibility of coupling between EMP's and boundary oscillations. The decrease of the energy of the excitations can be easily seen in a very simple and direct way, by slightly modifying the approach of Ref. [13] to take into account boundary displacements. In this treatment the continuity equation written in the integral form [13], assuming  $\partial\Phi/\partial x \ll \partial\Phi/\partial y$ , and the boundary condition for the normal current,  $j_y(x, 0) = -i\omega en_s\xi$ , give us the following relations:

$$\begin{aligned}i\omega Q + \sigma_{yy} \frac{\partial\Phi}{\partial y} \Big|_{y=0} &= 0, \\ \sigma_{yy} \frac{\partial\Phi}{\partial y} \Big|_{y=0} + \sigma_{yx}iq\Phi(0) &= i\omega en_s\xi.\end{aligned}\quad (4)$$

Here  $\sigma_{yy}$  and  $\sigma_{yx}$  are the diagonal and off-diagonal components, respectively, of the conductivity tensor. Eliminating  $\partial\Phi/\partial y$  in Eq. (4), we can qualitatively show the effect of boundary oscillations by the use of the approximate expression for  $\Phi(0)$  from Eq. (2):

$$\omega = 2\sigma_{yx}q \left[ \ln\left(\frac{1}{qd_B}\right) + \frac{en_s\xi}{Q + en_s\xi} \ln\left(\frac{d_B}{d}\right) \right]. \quad (5)$$

If we assume  $\xi \equiv 0$ , then Eq. (5) gives the spectrum of the conventional EMP,  $\omega_Q \propto 2\sigma_{yx}q \ln(1/qd_B)$ . It should be emphasized that in agreement with Eq. (3) we would have nearly the same spectrum if  $Q \equiv 0$  but  $\xi \neq 0$ :  $\omega_\xi \propto 2\sigma_{yx}q \ln(1/qd)$ .

We can see the effect of coupling by considering the in- and out-of-phase oscillations of  $\xi$  and  $Q$ . The spectrum of in-phase oscillations ( $\text{sgn}\{en_s\xi\} = \text{sgn}\{Q\}$ ) in the limit of strong magnetic fields is independent of the ratio of  $Q$  to  $en_s\xi$ . This mode we attribute to the conventional easily excited resonances, and will still call it the EMP.

In low magnetic fields ( $d_B \gg d$ ) the boundary oscillations are faster ( $\omega_\xi > \omega_Q$ ) by a logarithmic factor, which means that density oscillation might be screened by antiphase motion of the boundary:  $\text{sgn}\{en_s\xi\} = -\text{sgn}\{Q\}$ . This case is sketched in Fig. 4. Of course, the limit of strong screening ( $Q + en_s\xi \rightarrow 0$ ) needs special treatment, but the tendency of the decrease of the frequency of the coupled mode can be seen from Eq. (5). The lower frequency  $\omega_Q$  which exists at  $\xi \equiv 0$  starts to decrease if we increase  $|\xi|$  in antiphase to the density oscillations ( $\text{sgn}\{en_s\xi\} = -\text{sgn}\{Q\}$ ) in the weak field limit [ $\ln(d_B/d) > 0$ ]. Therefore strong screening can substantially reduce the resonant frequency of the coupled mode.

The simplest way to find the spectrum in the limit of strong coupling ( $Q + en_s\xi \rightarrow 0$ ), as well as in the

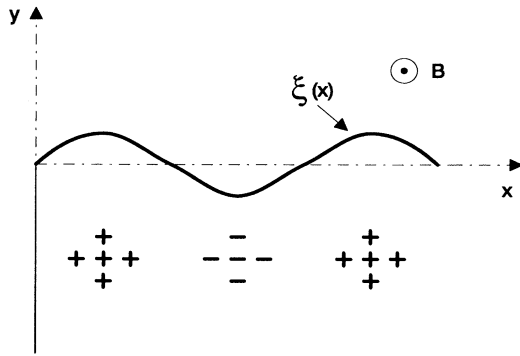


FIG. 4. Sketch of the charge distribution (represented by the distribution of + and - symbols) of an EMP mode, coupled to boundary oscillations [the boundary is represented by the line  $\xi(x)$ ] of the electron sheet for the out-of-phase motion, resulting in a new low-frequency resonance.

case of strong screening by the bottom electrodes, is to consider the electric field perturbations as a pure edge phenomenon in the dynamics of the electron liquid, since they are localized close to the boundary at distances much smaller than their wavelength. In this treatment, field perturbations produce an edge energy per unit length  $\mathcal{E}(\xi)$  and consequently a restoring pressure. In linear approximation the Euler equation with  $\Phi = 0$  at  $y < 0$  and with a new boundary condition for the electron liquid pressure,  $p(x, 0) = \partial\mathcal{E}/\partial\xi$ , gives us the excitation spectrum  $\omega_\xi$ , which has the structure of Eq. (3), but with the new definition of  $\omega_s^2 = \gamma e^2 n_s q/m$ , where  $\gamma$  is a geometrical factor of the order of 1. As expected, this spectrum is lower than the conventional EMP spectrum by the  $q$ -dependent logarithmic factor. To determine the numerical value of  $\gamma$ , more rigorous calculations are needed, taking into account the exact field distribution in the strip and a real density profile at the edge.

Although the theory is not sufficiently developed to allow a numerical fit to the data at present, we would like to emphasize that the determined frequencies of the coupled mode and of the principal resonance in the set observed are of the same order of magnitude and have the same dependence on  $B$  and  $n_s$ .

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