Optical Probing of a Fractionally Charged Quasihole in an Incompressible Liquid

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(Received 3 February 2003; published 11 September 2003; publisher error corrected 18 September 2003)

In photoluminescence spectroscopy of a low-mobility two-dimensional electron gas subjected to a quantizing magnetic field, we observe an anomaly around $\nu = \frac{1}{3}$ at a very low temperature (0.1 K) and an intermediate electron density (0.9×10^{11} cm^{-2}). The anomaly is explained as due to perturbation of the incompressible liquid at the Laughlin state due to close proximity of a localized charged exciton which creates a fractionally charged quasihole in the liquid. The anomaly of $\sim$2 meV can be destroyed by applying a small thermal energy of $\sim$0.2 meV that is enough to close the quasihole energy gap.

DOI: 10.1103/PhysRevLett.91.116403 PACS numbers: 71.30.+h, 73.43.Lp, 73.63.Kv

A fractionally charged quasihole in a bulk incompressible liquid state, though elusive to a direct probe as yet, has been an important outcome of Laughlin's celebrated theory of the fractional quantum Hall effect (FQHE) at $\frac{1}{3}$ filling of the lowest Landau level [1–3]. These low-lying charged excitations are a fundamental consequence of the incompressible nature of the ground state—the liquid state proposed by Laughlin. In addition to the ground state energy, the quasihole creation energy for the state proposed by Laughlin is also known very accurately [4]. The energy gap for a well-separated quasiparticle-quasihole pair has been derived from low-temperature measurements [5] and theoretically investigated by many authors [3,6]. A few years ago, several groups reported their successful attempts to detect the existence of fractionally charged objects in the edge states of a two-dimensional electron system (2DES) invoking a chiral Luttinger liquid theory [7]. In this Letter, we report that the lowest-energy charged excitations, the quasiholes, have been probed in an incompressible liquid at $\nu = \frac{1}{3}$ (the Laughlin state) via optical spectroscopy to be described below.

Photoluminescence (PL) experiments have proven to be an important tool for exploring the highly correlated FQHE states [8]. In these experiments, electron-hole pairs are photoexcited by a laser and they may form excitons. The presence of photoexcited holes is one of the striking differences compared to electron transport experiments. The role of the Coulomb interaction between electrons and holes in optical experiments has been explored in recent years, in particular, in experiments on very dilute 2DES, in the density range $\sim 10^{10}$ cm^{-2}. Here, it was found that the ground state is formed by negatively charged excitons, a bound state of two electrons and one hole. In a magnetic field, the two electrons can form either a singlet or a triplet state; the excitons are then called singlet (X_s^-) or triplet (X_t^-) excitons, respectively (see, e.g., [9–16]). For samples with significant disorder, the commonly accepted picture is that at low density the 2DES breaks up into areas with finite density (electron puddles) and completely depleted regions. In the completely depleted regions, neutral excitons (X^0) can be excited. As will be shown below, the effect of the disorder potential is one of the crucial points in our experiments. In experiments at very low temperatures and in this density regime of a 2DES, so called dark triplet excitons were observed [17,18], which at high magnetic fields exhibit a crossing with the X_s^- [19]. On the other hand, at densities in the range $\sim 10^{11}$ cm^{-2}, in samples with very high electron mobility where disorder plays only a minor role the Coulomb interaction between electrons and holes is mostly screened. In this regime, PL experiments revealed a variety of interaction effects of electrons in FQHE states [8]. Naturally, the crossover between these two regimes should reveal interesting interaction related effects. Very recently, we reported the observation of a strong energetic anomaly of the charged excitons in samples with moderate electron mobility ($\mu \sim 10^5$ cm^2/Vs) in what we call an intermediate density range of about 1×10^{11} cm^{-2} [20]. Here we show that in this special parameter range a uniform 2DES, which at filling factor $\nu = \frac{1}{3}$ can form a highly correlated incompressible liquid, and charged excitons coexist. We propose that perturbation of that liquid by a localized charged

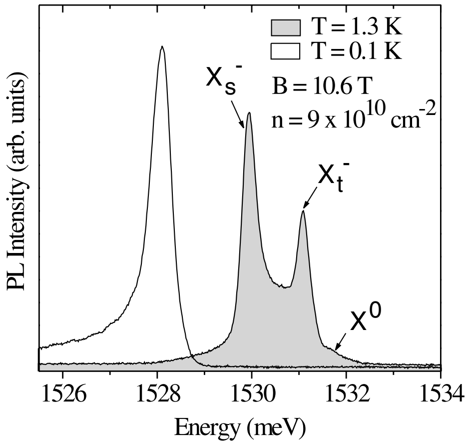

FIG. 1. Left-circularly polarized photoluminescence spectra for a carrier density of 9×10^{10} cm^{-2} and a magnetic field of $B = 10.6$ T, corresponding to $\nu = \frac{1}{3}$, at temperatures 0.1 and 1.3 K.

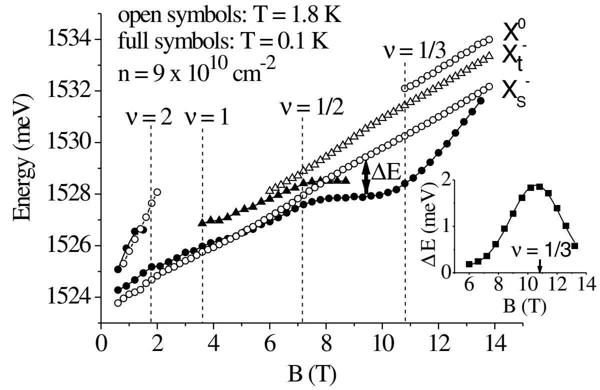

FIG. 2. Positions of left-circularly polarized PL lines versus magnetic field for a density of 0.9×10^{11} cm^{-2} and temperatures 0.1 K (solid symbols) and 1.8 K (open symbols).

exciton leads to the creation of a fractionally charged quasihole in the liquid which can account for the observed anomaly.

The investigated samples are one-sided doped 25 nm-wide GaAs-$Al_{0.3}Ga_{0.7}As$ single quantum wells with carrier densities around 2×10^{11} cm^{-2} under illumination. Via external gates the carrier density can be tuned down to the range $\sim 10^{10}$ cm^{-2}. Experiments are performed via glass fibers in a dilution cryostat at temperatures between $T = 0.1$ K and $T = 1.8$ K resolving circularly polarized light [18,20].

Let us first discuss the salient points of the experimental observations. Figure 1 shows two PL spectra obtained on the same sample at a density of $n = 9 \times 10^{10}$ cm^{-2} and a magnetic field of $B = 10.6$ T, which corresponds roughly to a filling factor of $\nu = \frac{1}{3}$. Note that the only difference between the two spectra is the temperature. For the gray-shaded spectrum in Fig. 1 the temperature was $T = 1.3$ K, while for the other spectrum it was $T = 0.1$ K. At $T = 1.3$ K, one can identify the well-known charged excitons X_s^- and X_t^- and the neutral exciton X^0. Obviously, at very low temperatures there is only a single line which is strongly redshifted [21]. Figure 2 displays the experimentally determined magnetic-field dispersions of the observed PL lines. For $\nu > 2$, i.e., if the lowest Landau level is completely occupied, we find a nearly linear dispersion where Landau level transitions between electrons and holes can be identified. This shows that in this range of filling factors the system behaves like a uniform 2DES where excitonic effects are not well pronounced. On the other hand, for $\nu < 2$ the well-known charged excitons appear at high temperatures ($T = 1.8$ K, open symbols in Fig. 2). Such a crossover from a 2DES to an excitonic system at $\nu = 2$ is well established in the literature [22]. However, at $T = 0.1$ K (solid symbols in Fig. 2), a strong anomaly of the X_s^- occurs in the vicinity of $\nu = \frac{1}{3}$ (cf. also Fig. 1). Further, the triplet exciton X_t^- also seems to show this anomaly for $B = 6$–9 T (solid triangles in Fig. 2). The inset of Fig. 2 shows the experimentally determined anomaly ΔE versus the magnetic field. The most striking result here is that a thermal energy of ~ 2 K (~ 0.2 meV) is sufficient to completely destroy the anomaly which has a strength of about 2 meV. This rules out any trivial localization effect of excitons as also supported by transmission experiments reported earlier [20].

It is clear that the anomaly is closely related to the FQHE states. Variations in PL intensity for the X_s^- and X_t^- states at $\nu = \frac{1}{3}$ and $\frac{1}{5}$ FQHE states were observed earlier [23] and were attributed to a large reduction of electron-hole screening at these filling factors. However, those experiments were reported for very-high-mobility ($> 3 \times 10^6$ cm^2/V s) modulation-doped single heterojunctions, and measurements were performed at a higher temperature ($T = 1.5$ K) and no anomaly was observed in the energy.

In order to explain the anomaly around $\nu = \frac{1}{3}$, we first collect a few relevant facts from the experiment: (i) The anomaly is not seen at higher electron densities where no charged excitons but usual electrons exist, and it is also not seen for lower electron densities where exclusively charged excitons are present [18]. Also for higher mobility samples ($\sim 5 \times 10^6$ cm^2/V s, not shown here) it is not present. Because of the low mobility and relatively low density of the sample, excitons are expected to remain localized. (ii) The anomaly appears near $\frac{1}{3}$, i.e., excitons are near an incompressible liquid [24]. (iii) The most intriguing observation is that a very small thermal energy ($\ll 2$ meV) is required to destroy the anomaly. (iv) The anomaly does not appear near $\nu = 1, 2$ and is therefore an indication that the lowest-energy charged excitations at $\nu = \frac{1}{3}$, the quasiholes (for reasons to be discussed below), are perhaps involved in the process. The quasielectrons are predicted to have higher energies [3].

In our explanation of the observed anomaly, we propose that as a result of potential fluctuations due to impurities in the system, excitons remain localized but they are in close proximity to the incompressible liquid at

$\nu = \frac{1}{3}$. Two of us recently investigated a system where a parabolic quantum dot (QD) [25] is coupled (via the Coulomb force only) to a 2DES which is in a $\nu = \frac{1}{3}$ Laughlin state [26]. Electrons in the dot are confined by a parabolic potential [25], $V_{\rm conf}(x, y) = \frac{1}{2}m^*\omega_0^2(x^2 + y^2)$, where ω_0 is the confinement potential strength and the corresponding oscillator length is $l_{\rm dot} = (\hbar/m^*\omega_0)^{1/2}$. Calculating the low-energy excitations of that dot-liquid system (a QD liquid) we found that in the case of a single electron in the dot the physics is somewhat similar to that of a point impurity in a $\nu = \frac{1}{3}$ liquid state investigated earlier [27]. In this case, the QD emits a fractionally charged quasihole ($e/3$) that orbits around the QD, as evidenced from the charge-density calculations [26,27]. Here we propose that the observed anomaly is related to the QD liquid where the QD contains a charged exciton.

The QD in our model of Ref. [26] plays the role of a localized exciton (charged or neutral) in the present case and perturbs the incompressible fluid due to its close proximity by creating fractionally charged defects. Details on the formal aspects of our theory can be found in Ref. [26]. We model the incompressible state at $\nu = \frac{1}{3}$ filling using the spherical geometry [6] for six electrons. Electrons are treated as spinless particles corresponding to the state described by the Laughlin wave function [1]. We consider the QD size $l_{\rm dot} = 15$ nm and the liquid-dot separation $a = 1.5l_0$. The energy gaps for smaller dots are usually larger than the energy gap of the incompressible liquid and therefore do not have much influence on the liquid. The QD contains either a pair of electron and hole (e, h) (charge-neutral QD), or $2e, h$ (charged QD). We have also considered the case of the QD liquid containing one free quasihole (by adding one flux quantum to the liquid ground state). In Fig. 3, we show the energy spectra (in units of Coulomb energy, $e^2/\epsilon l_0$, where ϵ is the background dielectric constant) for the QD liquid where the QD contains either (e, h) [in Figs. 3(a) and 3(c)] or $(2e, h)$ [in Figs. 3(b) and 3(d)]. In the figures, the energy spectra of isolated dots ($*$), an incompressible liquid at $\nu = \frac{1}{3}$ state ($\diamond$), and the binding energy of the QD to the incompressible liquid ($\bigcirc$) are plotted for comparison. In Figs. 3(c) and 3(d), the QD liquid also contains a free quasihole.

Clearly, for a charge-neutral dot there is no dispersion of the energy as a function of M, and most importantly, the incompressible liquid is not influenced by the dot at all. On the other hand, the energy of the QD liquid is significantly lowered for a charged QD, as compared to the isolated QD or the incompressible liquid without the dot [Fig. 3(b)]. This is in line with the experimental observation where only the charged excitons show the anomaly by lowering the energy. Interestingly, the binding energy of the QD to the liquid increases when the QD liquid contains a free quasihole [Fig. 3(d)]. This might explain the spread of the anomaly near $\nu = \frac{1}{3}$.

In Fig. 4, we plot the electron density distribution in the liquid (L) and in the dot (QD) for the lowest states and for a given angular momentum of the QD-liquid system. The electron (or hole) system in the dot is close to the ground state of an isolated dot, i.e., the influence of the incompressible liquid on it is very small. On the other hand, the low-lying excited states of the QD liquid can be described by the process of ionization as emission of a fractionally charged quasihole: The position of the local minimum at different angular momenta of the charge density correspond to the orbit radius of the quasihole [26,27]. In order to make the connection of quasiholes with the anomaly more direct, we have also evaluated the quasihole creation energy. For the Laughlin state it is 0.0276 $e^2/\epsilon l_0$ [4].

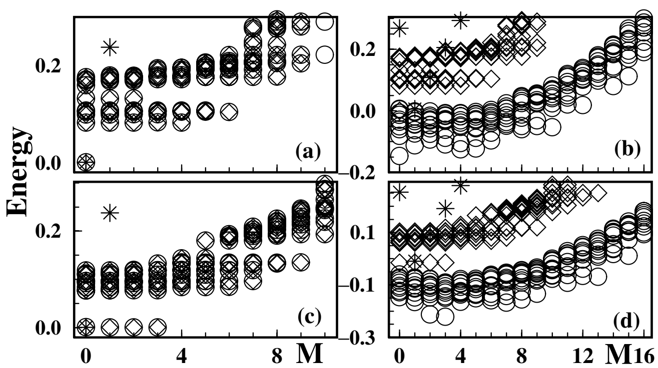

FIG. 3. Energy (in units of Coulomb energy) versus the azimuthal rotational quantum number M for an isolated quantum dot ($*$), a two-dimensional electron liquid ($\diamond$), and a QD liquid ($\bigcirc$). The QD of the QD liquid either contains $(1e, h)$ [in (a) and (c)], or $(2e, h)$ [in (b) and (d)]. In (c) and (d) the QD liquid also contains a free quasihole.

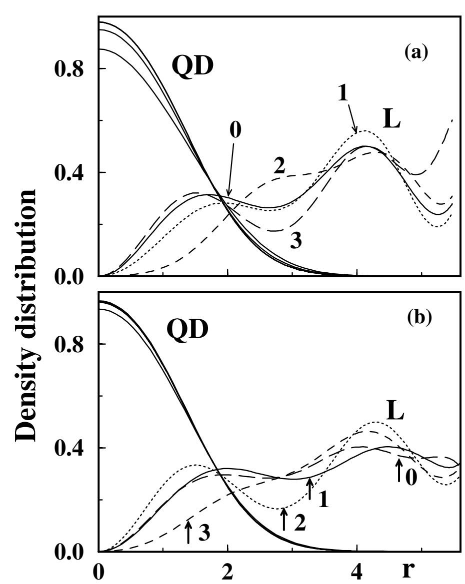

FIG. 4. Charge-density profile of the ground state and low-lying excitations of electrons in the dot (QD) and the liquid (L) of a QD liquid at $\nu = \frac{1}{3}$ (for $M = 0$–3, as indicated in the figure) corresponding to Fig. 3(b). The density distribution in the case where the QD liquid contains a free quasihole [Fig. 3(d)] is shown in (b).

In the spherical geometry the six-electron result of the incompressible state at $\nu = \frac{1}{3}$ is 0.034 $e^2/\epsilon l_0$ [6] (~ 0.5 meV). For the QD liquid, the corresponding value is much lower (0.32 meV) and is expected to decrease a little further with an increasing number of electrons in the system representing the incompressible liquid. This result indicates that the small thermal energy of about 0.2 meV required to destroy the anomaly is, in fact, the quasihole energy gap.

Another interesting possible explanation for our experimental finding would be the binding of one or more Laughlin quasiholes to a nonlocalized charged exciton. This was considered in extensive numerical calculations of the energy spectra of a 2DES in the FQHE state interacting with a valence band hole confined to a parallel 2D layer by Wojs *et al.* [15]. In these calculations, the binding energy of the charged exciton-quasihole complex depends on the ratio d/l_0, where d is the separation of electrons and the hole in the charged exciton. For a stable complex, a ratio $d/l_0 \geq 0.25$ was found in Ref. [15] to achieve a binding energy comparable to our experimental value of the anomaly (≈ 2 meV). By comparing our experimental binding energy of the X_s^- (see Fig. 2) to calculations of Szlufarska *et al.* [28], we find, however, a ratio $d/l_0 < 0.1$ for our situation. So, nonlocalized charged excitons would most likely not explain the observed anomaly. It would be interesting to extend our work at other fundamental filling factors (such as $\nu = \frac{1}{5}, \frac{2}{5}$) which are unfortunately out of our experimental possibilities so far. However this should be considered for future work.

To summarize: PL experiments on a 2DES subjected to a quantizing magnetic field exhibit a significant lowering of exciton energies at and around $\nu = \frac{1}{3}$. This is explained as due to perturbation of the incompressible liquid at $\nu = \frac{1}{3}$ by a localized charged exciton which results in the creation of a fractionally charged quasihole in the liquid. Application of a small thermal energy closes the quasihole gap and therefore the incompressibility of the liquid disappears and so does the anomaly.

We would like to thank Peter Maksym (Leicester, UK) for valuable discussions on the model described here. This work was supported by the Deutsche Forschungsgemeinschaft via SFB 508 (Hamburg) and SFB 348 (Munich), Projects No. Schu1171/1-2 and No. We1630/3-2, and a Heisenberg grant (Schu1171/2-2). Support by the BMBF via Project No. BMBF 01BM918 is gratefully acknowledged.

[1] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983); Surf. Sci. **142**, 163 (1984).
[2] B. I. Halperin, Helv. Phys. Acta **56**, 75 (1983).
[3] T. Chakraborty and P. Pietiläinen, *The Quantum Hall Effects* (Springer, New York, 1995), 2nd ed.; T. Chakraborty, Adv. Phys. **49**, 959 (2000); in *Handbook on Semiconductors*, edited by P. T. Landsberg (Elsevier, New York, 1992), Vol. 1, Chap. 17.
[4] T. Chakraborty, Phys. Rev. B **31**, 4026 (1985).
[5] See, for example, G. S. Boebinger *et al.*, Phys. Rev. Lett. **55**, 1606 (1985); R. G. Clark *et al.*, *ibid.* **62**, 1536 (1989); J. P. Eisenstein *et al.*, *ibid.* **62**, 1540 (1989).
[6] F. D. M. Haldane, Phys. Rev. Lett. **51**, 605 (1983); G. Fano, F. Ortolani, and E. Colombo, Phys. Rev. B **34**, 2670 (1989); R. Morf and B. I. Halperin, Phys. Rev. B **33**, 2221 (1986).
[7] R. de-Picciotto *et al.*, Nature (London) **389**, 162 (1997); L. Saminadayar *et al.*, Phys. Rev. Lett. **79**, 2526 (1997).
[8] See, e.g., A. J. Turberfield *et al.*, Phys. Rev. Lett. **65**, 637 (1990); B. B. Goldberg *et al.*, *ibid.* **65**, 641 (1990); L. Gravier *et al.*, *ibid.* **80**, 3344 (1998); I. V. Kukushkin *et al.*, *ibid.* **82**, 3665 (1999); I. V. Kukushkin *et al.*, *ibid.* **85**, 3688 (2000).
[9] G. Finkelstein *et al.*, Phys. Rev. Lett. **74**, 976 (1995).
[10] A. J. Shields *et al.*, Phys. Rev. B **52**, R5523 (1995).
[11] J. J. Palacios *et al.*, Phys. Rev. B **54**, R2296 (1996).
[12] D. M. Whittaker and A. J. Shields, Phys. Rev. B **56**, 15 185 (1997).
[13] A. Wojs *et al.*, Phys. Rev. B **62**, 4630 (2000).
[14] A. B. Dzyubenko and A. Yu. Sivachenko, Phys. Rev. Lett. **84**, 4429 (2000).
[15] A. Wojs and J. J. Quinn, Phys. Rev. B **63**, 045303 (2000); **63**, 045304 (2000).
[16] C. Riva *et al.*, Phys. Rev. B **63**, 115302 (2001).
[17] G. Yusa *et al.*, Phys. Rev. Lett. **87**, 216402 (2001).
[18] C. Schüller *et al.*, Phys. Rev. B **65**, 081301(R) (2002).
[19] T. Vanhoucke *et al.*, Phys. Rev. B **65**, 233305 (2002).
[20] K.-B. Broocks *et al.*, Phys. Rev. B **66**, 041309(R) (2002).
[21] We note that we consider here left-circularly polarized (σ^-) spectra, only. This is the polarization where the triplet excitons are visible [9,10]. The X_s^- and the X^0 exhibit a Zeeman splitting. The lower energy components of these doublets are visible in the σ^- polarization discussed in this manuscript.
[22] D. Gekhtman *et al.*, Phys. Rev. B **54**, 10 320 (1996); E. I. Rashba and M. D. Sturge, *ibid.* **63**, 045305 (2000).
[23] Y. Kim *et al.*, Phys. Rev. B **61**, 4492 (2000).
[24] Since the mobility of the sample is rather low, we expect that higher-order filling fractions with much smaller energy gaps do not play any significant role. Also the fact that both singlet and triplet excitons show the same anomaly [18] perhaps indicates that electron spins are not involved in the anomaly. Therefore, the influence of $\nu = \frac{2}{5}$ whose ground state and the low-energy excitations involve spin flips [3] on the anomaly can be neglected.
[25] P. A. Maksym and T. Chakraborty, Phys. Rev. Lett. **65**, 108 (1990); T. Chakraborty, Comments Condens. Matter Phys. **16**, 35 (1992); *Quantum Dots* (North-Holland, Amsterdam, 1999).
[26] V. M. Apalkov and T. Chakraborty, Physica (Amsterdam) **14E**, 289 (2002).
[27] E. H. Rezayi and F. D. M. Haldane, Phys. Rev. B **32**, 6924 (1985).
[28] I. Szlufarska *et al.*, Phys. Rev. B **63**, 085305 (2001).