How to Capture a Fractionally-Charged Quasihole?

Christian Schüller[1], **Kay-Birger Broocks**[1], **Patrick Schröter**[1], **Christian Heyn**[1], **Detlef Heitmann**[1], **Vadim Apalkov**[2], **Tapash Chakraborty**[3], **Max Bichler**[4], and **Werner Wegscheider**[5]

[1]Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, 20355 Hamburg, Germany
[2]Physics Department, University of Utah, Salt Lake City, UT 84112-0830, USA
[3]Institute of Mathematical Sciences, Chennai 600113, India
[4]Walter-Schottky-Institut der TU München, Am Coulombwall, D-85748 Garching, Germany
[5]Institut für Experimentelle und Angewandte Physik, Universität Regensburg, D-93040 Regensburg, Germany

In photoluminescence (PL) spectroscopy of a low-mobility two-dimensional electron gas subjected to a quantizing magnetic field, we observe an anomaly around $\nu = 1/3$ at a very low temperature (0.1 K) and an intermediate electron density (0.9 x 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 ≈ 2 meV can be destroyed by applying a small thermal energy of ≈ 0.2 meV that is enough to close the quasihole energy gap.

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 x 10^{11} cm^{-2} under illumination. Via external gates the carrier density can be tuned down to the range ≈ 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 [1,2].

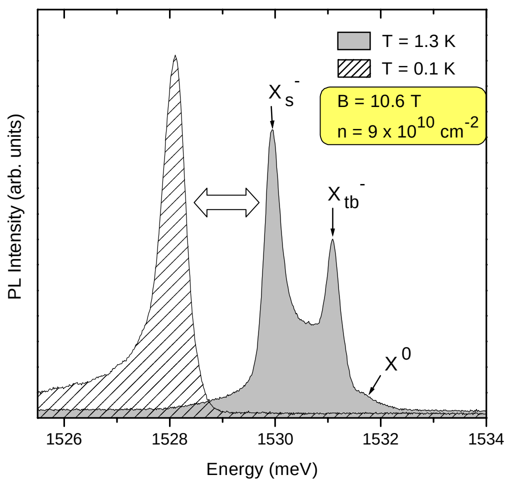

Fig. 1. PL spectra of the same sample at ν = 1/3 for different temperatures.

Figure 1 shows two PL spectra obtained on the same sample around filling factor of $\nu = 1/3$. 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 hatched spectrum it was $T = 0.1$ K. At $T = 1.3$ K, one can identify the well known charged singlet (X_s^-) and triplet (X_{tb}^-) excitons and the neutral exciton X^0. Obviously, at very low temperatures there is only a single line which is strongly redshifted. The most salient features of our experimental results are: (a) The anomaly is not seen at *higher* electron densities where no charged excitons but usual electrons exist, and is also not seen for *lower* electron densities where exclusively charged excitons are present [1]. Also for higher mobility samples it is not present. Because of the low mobility and relatively low density of the sample, excitons are expected to remain localized. (b) The anomaly appears near 1/3, i.e., excitons are near an incompressible liquid. (c) The most intriguing observation is that a *very small thermal energy (<< 2 meV) is required to destroy the anomaly*. (d) The anomaly does not appear near ν =1, 2 and is therefore an indication that the lowest-energy charged excitations, the quasiholes are perhaps involved in the process. The quasielectrons are predicted to have higher energies.

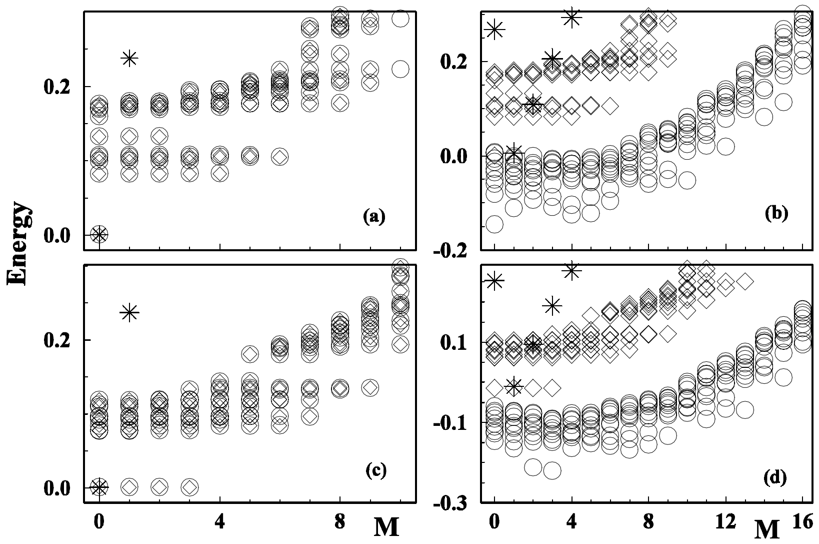

Fig. 2. Energy (in units of Coulomb energy) versus the azimuthal rotational quantum number M for an isolated quantum dot (✱), a two-dimensional electron liquid (◊), and a qd-liquid (○). The QD of the qd-liquid either contains (1e,h) [in (a) and (c)], or (2e,h) [in (b) and (d)]. In (c) and (d) the qd-liquid also contains a free quasihole.

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 ν = 1/3. Two of us recently investigated a system where a parabolic quantum dot is coupled (via the Coulomb force only) to a two-dimensional electron system (2DES) which is in a ν = 1/3 Laughlin state [3]. We call this a quantum-dot liquid (qd-liquid). Calculating the low-energy excitations of that system 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 ν = 1/3 liquid state investigated earlier [4]. In this case, the QD emits a fractionally-charged *quasihole* (e/3) that orbits around the QD, as evidenced from the charge-density calculations [3,4]. 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. [3] 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. We model the incompressible state at ν = 1/3 filling using the spherical geometry for six electrons. 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 ground state). In Fig. 2, we show the energy spectra (in units of Coulomb energy) for the qd-liquid where the QD contains either (e,h) [in (a) and (c)] or (2e,h) [in (b) and (d)]. In the figures, the energy spectra of isolated dots (✱), an incompressible liquid at ν = 1/3 state (◊) and the binding energy of the QD to the incompressible liquid (○) are plotted for comparison. 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. 2 (b)]. This is in line with the experimental observation where only the charged excitons show the anomaly by lowering the energy. 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 $e^2/(\varepsilon l)$. In the spherical geometry, the six-electron result of the incompressible state at ν = 1/3 is 0.034 $e^2/(\varepsilon l)$ (≈ 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 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.

[1] C. Schüller et al., Phys. Rev. B **65**, 081301(R) (2002).
[2] K.-B. Broocks et al., Phys. Rev. B **66**, 041309(R) (2002).
[3] V.M. Apalkov and T. Chakraborty, Physica E **14**, 289 (2002).
[4] E.H. Rezayi and F.D.M. Haldane, Phys. Rev. B **32**, 6924 (1985).