Quantized $\nu = 5/2$ state in a Two-Subband Quantum Hall System

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Currently, there is a strong interest in the even-denominator fractional quantum Hall state at filling factor $\nu = 5/2$, partially because of its potential relevance for topological quantum computation resulting from the non-Abelian statistics its quasi-particle excitations are predicted to obey. The 5/2 state is usually studied in GaAs/AlGaAs-heterostructures with a single heterointerface or relatively narrow quantum wells where electrons occupy only the first subband. By widening the quantum well, the accessible density range is large enough to substantially populate the second subband. This adds an additional degree of freedom.

Here, we report that the two-dimensional system formed by the bottom subband may condense in the 5/2 fractional quantum Hall state even when the second subband becomes occupied. The 5/2 state continues to exist as an incompressible fluid over a wide range of fillings of the second subband. This is different from previous reports on two-subband systems, where quantum Hall features follow the *total* filling factor. We attribute this difference to the increased quantum well width in our samples resulting in a larger spatial separation of the charge distributions of the two subbands. This suppresses intersubband scattering and increases the Coulomb energy involved when transferring charge between the two subbands.

The magnetotransport experiments were carried out on single sided modulation doped GaAs/AlGaAs heterostructures containing an 80, 60 or 50 nm wide quantum well. An in-situ grown doped quantum well, located below the two-dimensional electron system, served as a backgate to tune the electron density. Resistance measurements were performed in a dilution refrigerator with a base temperature below 20 mK.

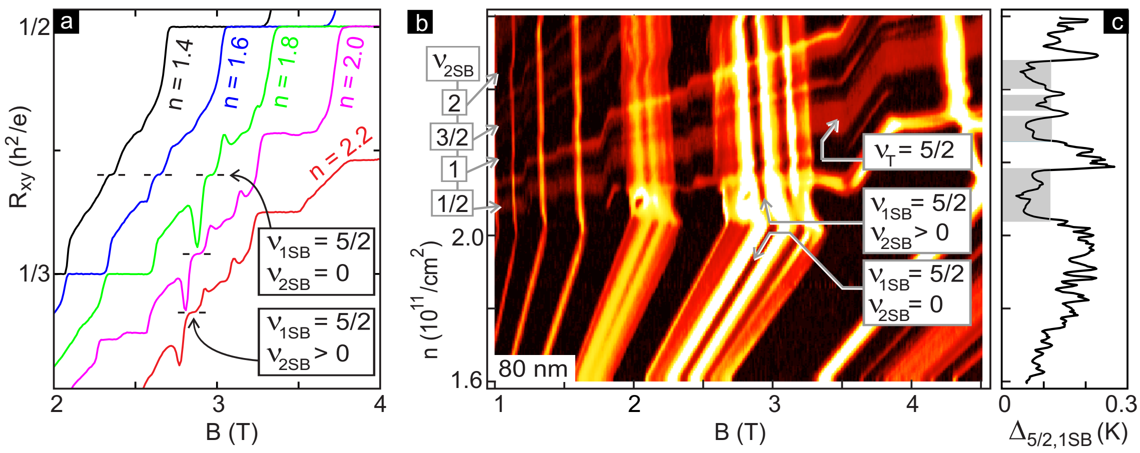

Figure 1: Transport data of a two-dimensional electron system residing in a 80 nm wide quantum well. An in-situ grown backgate allows a variation of the electron density. (a) Hall resistance for selected densities (given in $10^{11}/\mathrm{cm}^2$). (b) Longitudinal resistance (see Fig. 2(b) for a colorbar). Upon occupation of the second subband its electrons show integer and fractional quantum Hall states (examples indicated on the left). Meanwhile, the 5/2 state of the lower subband continues to exist. Its quantization is apparent from a plateau in R_{xy}, indicated in panel (a), and from vanishing R_{xx} as seen in panel (b). The $\nu_\mathrm{T} = 5/2$-state of the total density looses its quantization. (c) Activation energy of the lower subband 5/2 state. Regions where it is influenced by second subband features are shaded.

Figure 1b shows the longitudinal resistance in the density versus magnetic field plane measured on the 80 nm quantum well sample. Panel a shows the Hall resistance for selected densities. At lower densities electrons occupy only the first subband (1SB) and a 5/2 quantized Hall state is observed. At higher density when also the second subband (2SB) is populated, the $\nu_\mathrm{T} = 5/2$ state for the *total* electron density looses its quantization. The longitudinal resistance no longer vanishes and the Hall plateau disappears. The 5/2 state of the first subband, however, persists as an incompressible quantum Hall state over a wide range of fillings of the second subband: the longitudinal resistance still vanishes and the Hall resistance still shows a plateau at filling factors ($\nu_\mathrm{1SB} = 5/2$, $\nu_\mathrm{2SB} > 0$). Yet, the plateau is found at progressively lower R_{xy} as is expected when the total density increases. Meanwhile the second subband electrons go through a series of integer and fractional quantum Hall states as indicated in panel b. Lines marking a fixed filling factor of the first or second subband would follow a zigzag or sawtooth course. This can be understood as a consequence of intersubband charge transfer.

Hence, we have realized a compound system in which a two-dimensional electron system condensing in a quantized 5/2 state coexists with a second two-dimensional electron system whose density we can vary between $0 < \nu_{2\mathrm{SB}} \lesssim 1$. Even though the 5/2 state is known to be very fragile, we find it surprisingly undisturbed by the presence of the partially populated second subband. Figure 1c displays the activation energy (obtained from temperature dependent measurements) along the line of constant filling factor $\nu_{1\mathrm{SB}} = 5/2$ as a function of the total density. When the second subband is populated the activation energy $\Delta_{\nu_{1\mathrm{SB}}=5/2}$ can only be determined where the electrons in the second subband condense into an incompressible state and thus do not contribute to the longitudinal resistance (other regions are shaded in gray). There, $\Delta_{\nu_{1\mathrm{SB}}=5/2}$ remains independent of the second subband filling within the experimental uncertainty. This underlines that the only weakly changing density of the first subband determines this state, while the influence from the second subband is small.

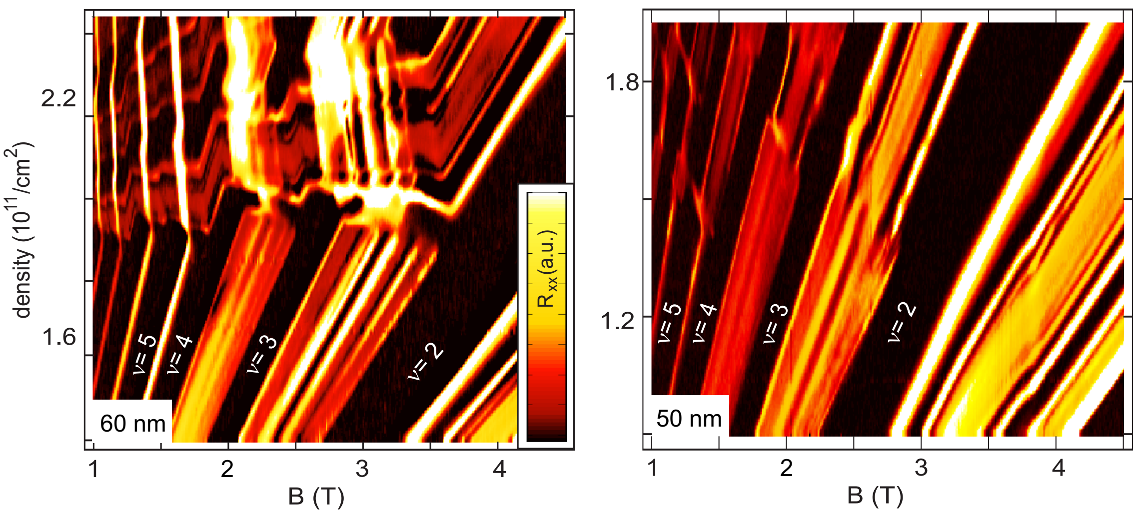

Figure 2: Longitudinal resistance. (a) In the 60 nm sample, when two subbands are populated their quantum Hall features coexist. In particular, a quantized 5/2 state of the lower subband is observed even when the second subband is populated. (b) In the 50 nm sample the quantum Hall features follow the total density.

Our observation of a 5/2 state in the first subband at a non-integer filling of the second subband implies that the topmost occupied Landau levels of both subbands are pinned at the same energy. Otherwise, it would be energetically favorable to transfer electrons from one subband to the other, filling up the lower of the partially populated levels. But such intersubband charge transfer quickly aligns the topmost partially filled subband levels due to the additional capacitive energy involved. Charge transfer then stops until one of the Landau levels is completely filled. This energy depends strongly on the quantum well width.

The quantum well width dependence is illustrated in Fig. 2. We observe the ($\nu_{1\mathrm{SB}} = 5/2$, $\nu_{2\mathrm{SB}} > 0$) state also in a 60 nm quantum well in panel a. However, the behavior in a 50 nm quantum well (panel b) is different. In contrast to the wider quantum wells, no quantum Hall features associated with only the first or second subband show up once the second subband is populated. Rather, nearly all features follow the *total* filling factor. The 5/2 quantized Hall state disappears once the second subband gets populated. Our calculations indicate that the capacitive energy for intersubband charge transfer is smaller than in the wider quantum wells, but not negligible, and regions of coexisting fractional SB filling factors should be observed. We conjecture that their absence is related to a larger overlap between the charge or probability densities $|\psi_{1\mathrm{SB}}|^2$ and $|\psi_{1\mathrm{SB}}|^2$ of the two subbands. This overlap enhances the probability for intersubband scattering. It promotes level mixing which can result in an avoided level crossing so that an energy gap prevents the coexistence of a partially filled Landau level in both SBs. This would explain the observation that quantum Hall features are determined by the total density even when the second subband is populated.

An in-plane magnetic field has a similar effect: It mixes the otherwise orthogonal first and second subband wavefunctions, provided that the probability densities associated with these wavefunctions overlap in space. Indeed, we observe in tilted field experiments that in the 80 nm quantum well a co-existence of partially filled Landau levels in both subbands is maintained even up to a tilt angle of 70°. In a 60 nm quantum well already at 10° tilt angle, all single subband quantum Hall states have vanished once the second subband becomes occupied. Hence, these tilted field measurements support the conjecture that a larger spatial overlap between the subband probability densities is responsible for the lack of single subband quantum Hall features once the second subband becomes occupied in narrower quantum wells such as our 50 nm sample.

References:

[1] *Nuebler, J., B. Friess, V. Umansky, B. Rosenow, M. Heiblum, K. von Klitzing and J.H. Smet.* Physical Review Letters **108**, 046804 (2012).

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