Even-denominator fractional quantum Hall physics in ZnO.

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Recommended with a Commentary by Bertrand I. Halperin, Harvard University

In this paper, the authors report results which show the existence of a formidable array of fraction quantized Hall (FQH) plateaus, including even-denominator plateaus, in a recently perfected system: electrons at an interface between ZnO and MnZnO. Furthermore, they argue that the even-denominator fractions have characteristics that compatible with a Moore-Read type state, which would give rise to non-Abelian quasiparticle excitations and localized Majorana modes. Until now, such a candidate state has only been observed in GaAs and, in one experiment, in suspended bilayer graphene.[1]

An important difference between the two-dimensional electron systems (2DES) in ZnO and GaAs arises from the different effective *g*-factors for conduction electrons in the two materials. Because of the small values of the *g*-factor and the electron effective mass in GaAs, the Zeeman energy there is seventy times smaller than the cyclotron energy, for a magnetic field that is perpendicular to the 2DES; by contrast, in ZnO this ratio is closer to unity. This can lead to a reversal in the order in which orbital Landau levels and spin states are filled, at certain filling fractions, after electron-electron interactions are taken into account. Moreover, since the Zeeman energy depends on the total magnetic field, while the cyclotron energy depends only on the component perpendicular to the sample, one can further increase the relative importance of Zeeman energy by tilting the sample relative to the magnetic field. The authors have explored the phase diagram for quantum Hall states in a ZnO structure where the 2DES has a zero-field mobility 550,000 $cm^2 V^{-1} s^{-1}$ and carrier density n= 2.3 x× 10^{11} cm^{-2}, in magnetic fields up to 8 T, with varying tilt angle.

As is well known, even-denominator fractional quantized Hall (FQH) states have been observed in GaAs structures at Landau filling factors ν = 5/2 and 7/2, but generally not at ν = 1/2, 3/2, or 9/2. It is widely believed that the states at 5/2 and 7/2 can be described by the Moore-Read state, which is supposed to be a correct ground state for a spin-polarized system of electrons with Coulomb interactions and one-half electron per flux quantum in the second LL, but not in the first or third LL. The crucial dependence on LL number reflects the differences in the interaction pseudopotentials for electrons in different LLs, which arise, in turn, from the different form factors of the electronic wave functions. The identification of the FQH state at ν = 5/2, in GaAs, with the Moore-Read state also depends on the assumption that the lowest LL is completely filled, while the spin-down states in the second LL are empty and the spin-up states are half full. The filled lowest

LL is inert and is unimportant for the physics. Similarly, at $\nu = 7/2$, it is believed that spin-down states in the second LL are full, while the spin-up states are full and play no role. For $\nu = 1/2$ and $3/2$, all electrons are in the lowest LL, while at $\nu = 9/2$, the second LL is completely full.

In contrast to GaAs, the ZnO sample shows no FQH plateau at $\nu = 5/2$. At $\nu = 3/2$, an FQH plateau was not seen in a perpendicular magnetic field, but a well-established plateau was observed in a tilted field, for tilt angles θ between about 38° and 42°. A clear plateau was observed at $\nu = 7/2$, in a perpendicular magnetic field, and strong indications of a plateau at $\nu = 9/2$ were also observed.

The authors propose that these behaviors can be understood with the following picture. Let us label the orbital LLs by an index $N_e = 0, 1, 2, \ldots$, and the spin states by $\uparrow$ or $\downarrow$. In a perpendicular field ($\theta = 0$), the authors propose that at $\nu = 5/2$, the levels $(0, \uparrow)$ and $(1, \uparrow)$ are completely filled, while $(0, \downarrow)$ is half filled. Since the active electrons have $N_e=0$, there should be no FQH state. At $\nu = 3/2$, the authors propose that level $(0, \uparrow)$ is full while $(1, \uparrow)$ is empty, so the half filled level is again $(0, \downarrow)$, and no FQH plateau should be observed. For $\nu = 7/2$, they propose that the levels $(0, \uparrow)$, $(0, \downarrow)$ and $(1, \uparrow)$ are filled, while $(1, \downarrow)$ is half full, while at $\nu = 9/2$, they propose that the levels $(0, \uparrow)$, $(0, \downarrow)$, $(1, \uparrow)$ and $(2, \uparrow)$ are filled, and $(1, \downarrow)$ is half full. In both cases, one should have an FQH state. The behavior at $\nu = 3/2$, at larger tilt angles, is explained by assuming that for θ greater than a critical value θ_C, there is a change in the configuration, so that now $(0, \uparrow)$ is full and $(0, \downarrow)$ is empty, while $(1, \uparrow)$ is now half full; therefore FQH should appear.

The authors have measured transport properties, at their base temperature (T<20mK) and at T=400 mK, for the full range of tilt angles and filling factors available in their magnetic field range, up to a perpendicular field of 8T. In addition to the even-denominator states, they have observed a large number of odd-denominator FQH states, and have followed their evolution as a function of tilt angle. From the results, they construct a phase diagram for the occupations of the various LL and spin states, which supports their picture of the even-denominator states, described above. Since the transitions between competing spin states are influenced in a complicated way by electron-electron interactions, however, as well as by the Zeeman and cyclotron energies, there are currently no theoretical calculations that can reliably predict the location of these transitions.

Important questions remain about the effects of disorder in this system. The authors find that at large tilt angles, there is a sharp and dramatic rise in the measured longitudinal resistance, by a factor of 10 or more, at a critical angle which depends on the perpendicular magnetic field. They interpret this as due to a change in the screening of impurities, when all the electrons become fully polarized. This resistance is so large, that no FQH states are observed in the high resistance regime. At $\nu = 3/2$, the high resistance state sets in at $\theta = 42°$, and, indeed, no FQH state is observed beyond this tilt angle. On the other hand, as discussed above, the authors' explanation for the quantized Hall state that they see at $\nu = 3/2$, in the range $38° < \theta < 42°$ assumes that the system is already fully polarized in this range of tilt angles. More work is necessary to understand this apparent contradiction.

The authors' discovery of a whole set of even-denominator FQH states in a new material is certainly exciting, particularly if these are of the Moore-Read form, as the authors propose. At this point, however, there is no direct evidence that the observed states are of the Moore-Read form, and the possibility of alternate explanations cannot be completely ruled out. The most prominent alternate form for an FQH state in a Landau level with one-half electron per flux quantum is the so-called (331) state,[2] which assumes there are two distinguishable electron types participating in the correlated state, with one-quarter electron per flux quantum of each type. The (331) state has been advanced as an explanation for FQH states that have been seen in GaAs at total filling $\nu = 1/2$ in double-layer systems and in wide quantum wells.[3-5] Since the 3/2 FQH state in ZnO has been found only in a rather narrow range of tilt angles, close to the transition to full polarization, it is conceivable that the electronic configuration has one-quarter electron per flux quantum in each of the levels $(0, \downarrow)$ and $(1, \uparrow)$, which could lead to a (331) state. If so, this would also be very interesting, as I am not aware of any other instance where a proposed (331) state contains orbital states from two different LLs.

Regardless of explanations, the observation of so many FQH states in a new material is cause for celebration. It will be interesting to see whether sample qualities can be improved even further and what new physics may be found in that case.

References:

[1] D. K. Ki, V. Fal'ko, D. A. Abanin, and A. Morpurgo, Nano Lett. 14, 2135 (2014).

[2] B. I. Halperin, Helv. Phys. Acta 56, 75 (1983).

[3] Y. W. Suen, L. W. Engel, M. B. Santos, M. Shayegan, and D. C. Tsui, Phys. Rev. Lett. 68, 1379 (1992).

[4] J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, K. W. West, and H. Song, Phys. Rev. Lett. 68, 1383 (1992).

[5] Y. Liu, A. L Graninger, S. Hasdemir, M. Shayegan, L. N. Pfeiffer, K. W. West, K. W. Baldwin, and R. Winkler, Phys. Rev. Lett. 112, 046804 (2014).