# Robust even denominator Fractional Quantum Hall State

1. **Robust fractional quantum Hall states and continuous quantum phase transitions in a half-filled bilayer graphene Landau level**

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2. **Even denominator fractional quantum Hall state in bilayer graphene**

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The even denominator fractional quantum Hall (FQH) state observed near filling 5/2 has attracted a great deal of attention since its discovery thirty years ago. [1]. The current consensus is that this state is described by the Pfaffian state proposed by Moore and Read [2] (or its particle-hole conjugate, called anti-Pfaffian [3, 4]). This state is best understood as p wave pairing of composite Fermions and is of special interest because the quasi-particles are expected to obey non-abelian statistics, i.e. the exchange of particles leads to a new state in the Hilbert space, rather than just a phase change. The idea that manipulating non-abelian objects can lead to fault-tolerant quantum computer has launched the major enterprise of topological quantum computing. [5,6] Unfortunately, the 5/2 filling state observed in GaAs quantum wells have proven to be rather fragile. It has a small energy gap of about 0.5K and is easily destroyed by disorder. As a result, various proposals (for example, [7,8] ) to detect the non-abelian nature of the quasi-particles have not been successfully carried out. In recent years, the search for non-abelian physics have shifted to Majorana bound states in man-made proximity induced superconducting structures, (see [9]). While a great deal of progress is being made, one should still keep an eye on the half-filled Landau level system. Thus the recent advances made by Zibrov et al. and Li et al. in creating a robust Pfaffian state is of great interest in that it may re-open the window into this fascinating quantum state with potentially far-reaching consequences.

The even denominator FQH state has been reported in three systems: GaAs quantum wells, ZnO [10] and suspended bi-layer graphene [11]. The gap in ZnO is even smaller at 90mK while the transport activation gap observed up to now in graphene is about 600mK, comparable to GaAs. Thus it is significant that Zibrov et al reported a thermodynamic gap of 4K and a transport activation gap of 1.8K in their specially constructed bilayer graphene structures. The larger gap is in line with theoretical expectation, because the size of the gap is determined by Coulomb repulsion which should be stronger in graphene because it does not have the larger background dielectric constant of GaAs. Indeed a variety of FQH states have been predicted in the graphene systems. [12,13] The smaller gap observed earlier is presumably due to disorder. The bi-layer graphene is a complicated system in that in addition to the well-known spin and valley degeneracy, the magnetic orbitals N=0 and 1 are nearly degenerate. (The N=1 orbital can be thought of as linear superposition of the conventional zeroth and first Landau levels).The 8-fold degeneracy complicates the interpretation of the original experiment, where the freely suspended bi-layer is gated from below [11]. It has since been shown that by placing insulating BN films and gate electrodes on both top and bottom, the density of the top and bottom layer and be controlled independently and the system is found to be mostly fully polarized in the N=0 or 1 orbital. [14] However, the even denominator fraction was not seen. Zibrov et al discovered that by replacing the gold electrodes with graphite, disorder is greatly reduced and the various fractions, including the even denominator ones, emerge clearly. Most interestingly, they found that when the N=0 orbital state is partially occupied, the standard odd denominator states 1/3, 2/5, 3/7…known as the Jain sequence are clearly seen. On the other hand, when the N=1 orbital state is partially occupied, the filling fraction -½ and -1/3 and -2/3 are the only dominant incompressible states. They measured the thermodynamic gap (the difference in the chemical potential for adding or removing an electron) using the capacitance penetration field technique and obtained the 4K gap mentioned earlier, thus earning the adjective “robust” in their title. Their interpretation is that projection of the Coulomb repulsion to the N=0 and N=1 orbital leads to rather different pseudo-potentials which favor either the conventional Laughlin/Jain states or the Pfaffian states. The paper also contains extensive numerical computations based on the new DMRG method by Mike Zaletel. In addition, the paper shows other phase transitions which are not fully understood, demonstrating the richness of this platform and the many knobs available to the experimentalists to turn.

A more recent paper by Li et al. studies similar duo-gate samples but focuses on transport measurements. They report even denominator states at -1/2, 3/2, -5/2 and 7/2. The largest transport gap of 1.2K is found at -1/2. Altogether, these papers gives a compelling picture that the Pfaffian state is stabilized in bi-layer graphene and offer hope that the next step of demonstrating the exotic nature of this state and its quasi-particles may be possible, perhaps not too far in the future!

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