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Interlayer Correlations versus Intralayer Correlations in a Quantum Hall Bilayer at Total Filling One

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Abstract

In Quantum Hall bilayers, at total filling factor one, a transition from a compressible phase with weak interlayer correlations to an incompressible phase with strong interlayer correlations is observed as the distance between the two layers is reduced. The transition between these two regimes can be understood using a trial wavefunction approach based on the composite particle picture.

The quantum Hall effect is observed in two-dimensional electron gases in strong perpendicular magnetic field at very low temperatures. The controlling parameter for these systems is the filling factor ν, the ratio of electron-density to the areal degeneracy of single-particle eigenstates with a given kinetic energy quantum number (i.e., the density of states in a particular "Landau-level"). At low temperatures and filling-factors smaller than unity, the dynamics of the system are confined to the lowest Landau-level (LLL), and the properties of the quantum state are governed entirely by electron interactions. In bilayer quantum Hall systems, where the layer index provides a supplementary degree of freedom, at filling fraction $\nu = \frac{1}{2} + \frac{1}{2}$ at least two different quantum states are known to occur, depending on the spacing d between the layers [1]. For large enough spacing, the two layers interact very weakly and must be essentially independent $\nu = \frac{1}{2}$ states, that may be thought of as compressible composite fermion (CF) Fermi seas [2] with strong intralayer correlations but very weak interlayer correlations. On the other hand, at small enough values of d the groundstate is expected to be the interlayer coherent "111 state", which we can think of as a composite boson (CB) condensate, with strong interlayer correlations and intralayer correlations which are weaker than those of the composite fermion Fermi sea [1]. Experimentally, numerous features of a phase transition between the above two phases are observed [3], but the precise nature of this transition remains unclear. Here we outline how the idea of composite particles is useful in understanding this transition.

At fractional fillings $\nu < 1$ in a single layer, exponentially many equivalent configurations of the system would exist in absence of particle interactions (since there are far more LLL orbitals than electrons). Yet, at some values of the filling factor such as $\nu = \frac{p}{2p\pm1}$, one observes incompressible states. I.e., there exists a single ground state that is separated by a well-defined gap from the rest of the spectrum — an effect entirely due to interactions. It is impossible to tackle this problem in perturbation theory, due to the giant initial degeneracy of the relevant Hilbert space. Instead, another approach has proven to be very successful: guessing the exact wavefunction! For example, for the above mentioned fractions one may obtain highly accurate trial wavefunctions by assuming that the system is effectively described by CFs — bound states of an electron and two vortices (zeros of the wavefunction) or “flux quanta”. These CFs then experience a reduced magnetic field, since the bound flux has (effectively) already been taken into account. Attaching vortices has the effect of keeping the electrons far from each other, and this turns out to be an extremely efficient way of optimizing the interaction energy. In the end what justifies this approach is its empirical success: numerically, the wavefunctions obtained with this prescription have close to perfect overlap with the exact solution of the problem when tested on small system sizes. The case of $\nu = \frac{1}{2}$ is particularly interesting in that the CFs experience a vanishing effective magnetic field [2], and behave very similarly to free electrons: they fill a Fermi sea. The $\nu = \frac{1}{2}$ trial wavefunction is

$$\Psi^{CF} = \mathcal{P}_{LLL} \prod_{k<p} (z_p - z_k)^2 \det \left[e^{i\mathbf{k}_i \cdot \mathbf{r}_j} \right] \tag{1}$$

with $\mathcal{P}_{LLL}$ the projection to the LLL. If two layers of $\nu = 1/2$ systems are placed far from each other ($d \to \infty$), the wavefunction will be two noninteracting copies of this CF Fermi sea. However, if instead we place two such layers close together ($d = 0$), something very different happens. We know that attaching vortices to the particles lowers the energy, since it enhances the average inter-particle distance. But now, we need to make particles avoid each other in opposing layers as well as in the same layer. Since we still have two vortices per particle available (corresponding to $\nu = 1/2$) a good way to allocate the vortices is given by the “111-state”:

$$\Psi_{111} = \prod_{i<j} (z_i - z_j)(w_i - w_j) \prod_{i,j} (z_i - w_j) \tag{2}$$

Again, we see this wavefunction as being built of composite objects (known as composite bosons or CBs) consisting of electrons with one vortex attached in each layer. Whereas the CFs in wavefunction (1) are associated to a set of distinct quantum numbers $\mathbf{k}_i$, there is no need for such distinction in the case of CBs: just attaching vortices yields a proper antisymmetric wavefunction. In other words, all the CBs may populate the same state and condense into a (incompressible) ground state, as represented by (2).

Since the concept of composite particles successfully describes the system at $d = 0$ and $d \to \infty$, one may expect that it is also helpful for understanding the intermediate regime. We propose a state with coexistence of CBs and CFs, with the number of CBs decreasing at larger d. The balance between CBs and CFs results from the trade-off in intra-layer and inter-layer interaction energy. It was previously shown [4], that the wavefunctions deduced from this heuristic picture give good trial wavefunctions in the intermediate regime. Unfortunately, these calculations were restricted to very small model systems and further imposed a fixed number of CB and CF in the system. The latter assumption did not allow certain scattering processes that exchange vortices and can turn a pair of CBs into a pair of CFs. In upcoming works [5], we construct trial wavefunctions that overcome these shortcomings: they can be examined for system sizes of up to 80 electrons and more, they treat these previously neglected scattering processes, and we find an extremely good agreement with exact diagonalizations for small system sizes.

References

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