Quantum Disordering of a Quantum Hall Superfluid

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Abstract. We discuss, in a ground state wave function approach, possible phases in the quantum Hall bilayer at total filling factor one. The picture of the electron system that we arrive at is a mixture of composite boson (CB) and composite fermion (CF) quasiparticles (Simon *et al.*[1]). For small distances between layers CBs prevail in the superfluid state. The inclusion of CFs with increasing distance brings quantum disordering of the superfluid state. The new phases that may come as a result of this are the ones with algebraic off-diagonal long-range order (ODLRO) or no order at all, before the final state with two decoupled layers with CFs and no CBs (Milovanović[2],Papić and Milovanović[3]). Comparisons with experiments are made and the relevance of the bilayer setup as a stage for new topological phases is discussed.

The quantum Hall bilayer effectively consists of two 2D electron gases brought into a close proximity. At the total filling factor $\nu_{tot} = 1$ it exhibits superfluid behavior[4, 5] when the distance between the layers is of the order of the interparticle spacing inside the layers. A good ground state trial wave function in this case is:

$$\Psi_{111}(\{z\},\{w\}) = \prod_{i<j}(z_i - z_j)\prod_{k<l}(w_k - w_l)\prod_{m,n}(z_m - w_n), \tag{1}$$

where z's and w's denote the 2D complex coordinates in two layers and appropriate quasiparticles in the fractional quantum Hall (FQHE) terminology are CBs. What is also confirmed in experiments is: when the layers are far apart i.e. when they are decoupled, each layer is described by the Fermi liquid-like state,

$$\Psi_{1/2}(\{z\}) = \prod_{i<j}(z_i - z_j)^2 \det[e^{i\mathbf{k}_i\mathbf{r}_j}], \tag{2}$$

where det[...] denotes a Slater determinant of free waves and appropriate quasiparticles are CFs.

The question comes what happens at intermediate distance, how the transition proceeds, or might be phrased as, what kind of superfluid disordering can result in two Fermi liquid-like states?

There are two paradigms that we know of regarding the superfluid disordering: (1) Berezinskii-Kosterlitz-Thouless (BKT) disordering via vortex dipole creation and unbinding or 2D XY model, and (2) λ transition disordering via creation and condensation of vortex loops or 3D XY model. The evolution in time of any vortex pair in the first case is static and can be represented as in Fig.1(a), and in the second case there are times

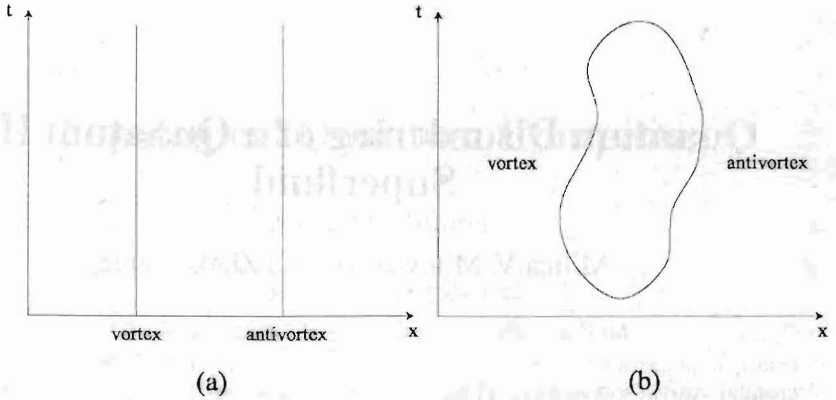

FIGURE 1. Time evolution of a vortex-antivortex pair

when the pair is created and annihilated and the pair evolution in time effectively makes a loop as in Fig.1(b).

To answer the question about the bilayer behavior at intermediate distances, we may propose a trial ground state wave function where, classicaly speaking, we divide electrons into two groups, one that correlates as CBs and the other as CFs with, at the end, the overall antisymmetrization necessary because all the electrons are identical. The intercorrelations between these two groups are also needed and in assigning them we are guided by the requirement that each electron sees so many flux quanta as there are electrons. So if we denote by a line the Laughlin-Jastrow factor between any of the two (sub)groups, A and B, of electrons:

$$\prod_{i,j}(z_{A,i}-z_{B,j}), \tag{3}$$

we have two possibilities as in Fig.2(a),(b). In Fig.2(a) the intercorrelations we choose mimic the intercorrelations of the Ψ_{111} function and in Fig.2(b) we bind exclusively in the same layer like in $\Psi_{1/2}$. Overall, there are four possibilities if we add a possibility of CF pairing denoted by a wriggly line in Fig.2(c),(d).

A simple, phenomenological Chern-Simons (CS) theory[3] can be constructed which will tell us that both in Fig.2(a) and Fig.2(c) we have a superfluid response, in Fig.2(b) a response of a disordered superfluid (algebraic decay of correlations at $T=0$) with compressible behavior and in Fig.2(d) a (completely) disordered superfluid with incompressible behavior. Fig.2(d) represents a totally incompressible state both in charge and pseudospin channel.

It is the absence of the special correlations encoded in Fig.2(d) that can be ascertained in experiments where the transition very likely involves the states in Fig.2(a),(b). Due to the presence of impurities, the quantum fluctuations (Fig.1(b)) of the naively expected $2+1$ dimensional quantum phase transition are frozen out and the transition and dis-

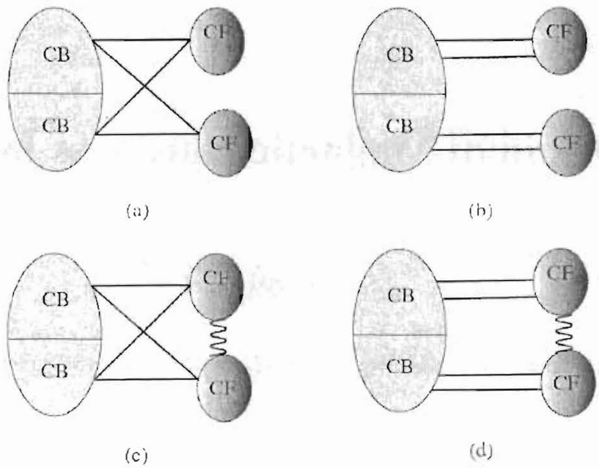

FIGURE 2. Different kinds of CB and CF binding

ordering proceeds in a BKT fashion. In a homogeneous system the loop condensation would lead to a totally incompressible state that we find in Fig.2(d). Its total incompressibility and a creation through loop condensation signals a possibility that the state represents a topological phase[6]. If we extend the quasiparticle content of the superfluid where next to vorticity we have the charge degree of freedom and therefore four kinds of quasiparticles ("merons"[7]), we expect the simplest $U_2(1) \otimes \overline{U_2(1)}$ double CS theory (pseudospin liquid) to describe the topological phase. Just like counterflow setting in the experiments[5], it is invariant under combined layer index exchange and time reversal.

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