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RECOMBINATION OF FRACTIONALLY CHARGED EXCITONS IN QUANTUM HALL SYSTEMS

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Fractionally charged excitons (FCX's) consist of one or more Laughlin quasiparticles bound to a valence hole or to a negatively charged exciton. They occur when the hole is separated from the layer containing the electrons by a distance of the order of or larger than the magnetic length. The dispersion of FCX's and their importance in photoluminescence is discussed.

Keywords: Fractional quantum Hall effect; magnetoexciton; photoluminescence.

There has been a considerable amount of interest in photoluminescence (PL) in quantum Hall systems for more than a decade.[1–4] Theoretical considerations have revealed[5–9] that in an ideal model with cyclotron energy $\hbar\omega_c$ much larger than Coulomb energy e^2/λ (where λ is the magnetic length) and both electrons (e) and valence holes (h) residing on the same layer, PL gives information about excitons and excitonic complexes but not about correlations in the underlying two-dimensional electron gas (2DEG). Only when the "hidden symmetry"[5,6] resulting from equal magnitudes of e–e and e–h interaction is removed, can PL data be sensitive to these underlying correlations. The simplest way to remove the hidden symmetry is to introduce a finite separation d between the 2D e and h layers. In this case, at the filling factor $\nu \approx \frac{1}{3}$, the hole may bind one or more $e/3$-charged Laughlin quasielectrons (QE's) to form[6,7,10] fractionally charged excitons (FCX's), $h\mathrm{QE}_n$, instead of neutral or negatively charged excitons ($X = e + h$ and $X^- = 2e + h$). Thus far, there has been no experimental confirmation of the existence of FCX's.

We review theoretical ideas on FCX's, the conditions under which they occur, their dispersion, and their effect on PL. We stress which FCX's are most stable and have largest oscillator strength in hope of stimulating experiment. Some of our results were presented before,[9,10] but we arrange them to emphasize particular ideas and to make the manuscript more self-contained and understandable.

Exact numerical diagonalization of an interacting $Ne + h$ system in the Hilbert subspace of the lowest Landau level (LL_0) in Haldane spherical geometry[7,9,11] is by now well-known. The lowest-lying eigenstates of the Ne system can be conveniently pictured using Jain's composite fermion (CF) model,[12] and understood in terms

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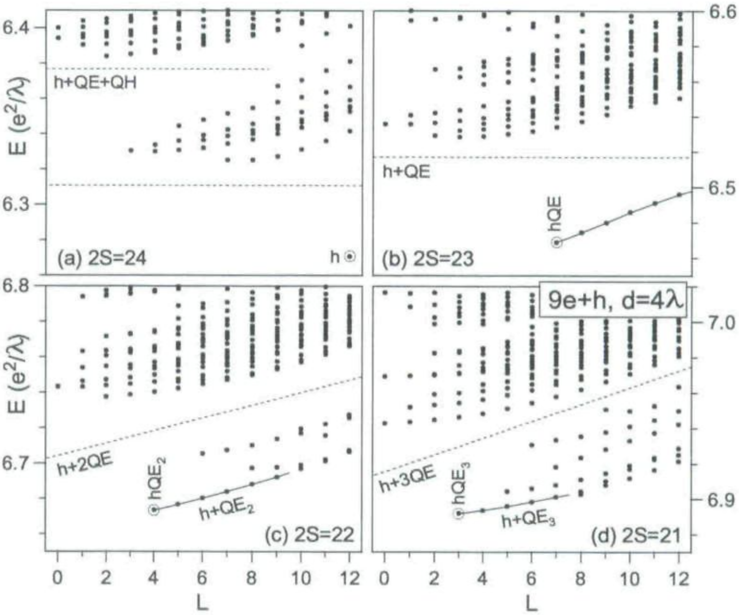

Fig. 1. Energy spectrum of $9e + h$ system at layer separation $d = 4\lambda$ for monopole strengths $2S = 21$ to 24. Lines and open symbols indicate states containing different excitonic complexes.

of the number of Laughlin quasiholes (QH's) or quasielectrons (QE's) and their angular momenta, $l_{\rm QH} = S - (N-1)$ and $l_{\rm QE} = l_{\rm QH} + 1$. $2S$ is the magnetic monopole strength, measured in units of flux quantum hc/e, and e and h angular momenta are $l_e = l_h \equiv l = S$.

When d is small compared to λ, there is no qualitative change in the energy spectrum from that at $d = 0$. Neutral and negatively charged excitons and their properties determine the PL spectrum. For $d \gg \lambda$, the Ne system is only weakly perturbed by the hole. The low-energy eigenvalues fall into simple bands obtained by addition of the hole angular momentum l_h to the angular momenta L_e of different low-energy Ne states. This is illustrated in Fig. 1 for a $9e + h$ hole system with $d = 4\lambda$.[10,7] Label h denotes the hole moving alone in the underlying (locally incompressible) $\nu = \frac{1}{3}$ state, and $h\text{QE}_n$ are FCX bound states of $n = 1$ to 3 QE's attached to the hole. When $d \to \infty$ (and $V_{eh} \to 0$) each band with L_{eh} satisfying $|l_h - L_e| \le L_{eh} \le l_h + L_e$ contains degenerate levels, as was first discussed by Chen and Quinn[7], and by Rashba and Portnoi.[6] Unfortunately, for very large d, the PL intensity is small due to the small e–h overlap. However, between these weak coupling ($d \gg \lambda$) and the strong coupling ($d \ll \lambda$) regimes, there is a region ($d \simeq \lambda$) of intermediate coupling, where V_{eh} is not simply a small perturbation, but it is not so strong that X and X^- form in a dilute ($\nu \ll 1$) electron system. In this intermediate regime, PL should be readily detectable. It should involve FCX's and give information about (Laughlin) e–e correlations in the underlying 2DEG.

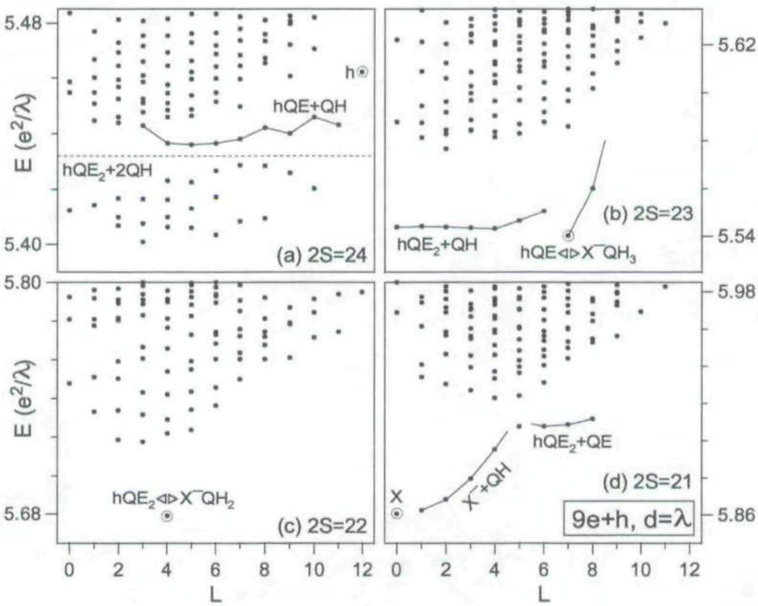

Fig. 2. Energy spectrum of a $9e+h$ system at $d=\lambda$ for monopole strengths $2S=21$ to 24.

In Fig. 2 we display numerical result for the $9e+h$ system at $d=\lambda$ for $2S=21$ to 24.[10] Fig. 2(d) contains an $L=0$ ground state similar to the "multiplicative" state at $d=0$, which consists of a "decoupled" neutral exciton together with a Laughlin state of the remaining $N-1=8$ electrons. There is also a band of states with $L=1$ to 6 which is attributed to a QH of angular momentum $l_{\rm QH}=\frac{7}{2}$ and an X^- of angular momentum $\frac{5}{2}$. These values result from the generalized CF picture,[9] in which $2S_e^*=2S-2(N_e-1)-2N_{X^-}=7$ with $N_e=N-2$ and $N_{X^-}=1$, and $2S_{X^-}^*=2S-2N_e=7$ ($l_{\rm QH}=S_e^*$, $l_{X^-}=S_{X^-}^*-1$). In the case of two electrons and one hole, the X and X^- unbind at $d\simeq\lambda$; however, for larger systems (e.g. $N=9$) interaction with the surrounding unbound electrons can lead to the persistence of these excitonic states beyond the value $d=\lambda$. The X^-QH band in Fig. 2(d), which also appears at $d=0$, seems to cross another low energy band that extends from $L=3$ to 8. This band can be interpreted as three QE's interacting with the hole just as we found in Fig. 1(d) in the weak coupling case. The other weak coupling bands have apparently disappeared into the continuum of higher states. The lowest band in Fig. 2(c) can be interpreted as an X^- interacting with two QH's. The CF picture gives $l_{X^-}^*=3$ and $l_{\rm QH}=4$. The pair of QH's can have $L_{{\rm QH}_2}=7, 5, 3$, and 1, with the value of $L_{{\rm QH}_2}=7$ corresponding to the smallest QH–QH separation. This should produce the most strongly bound FCX with L going from $l_{{\rm QH}_2}-l_{X^-}^*=4$ to $l_{{\rm QH}_2}+l_{X^-}^*=10$. A higher band beginning at $L=2$ might be associated with $L_{{\rm QH}_2}=5$ interacting with the X^-. For $2S=23$, Fig. 2(b) contains two low-lying bands. The first has a hole with $l_h=\frac{23}{2}$ and a QE with $l_{\rm QE}=\frac{9}{2}$, giving a band extending from $L = 7$ to 16 of which only the two lowest states are indicated. The second band beginning at $L = 0$ appears to contain an additional QE–QH pair, whose creation energy is comparable to the energy gained through the interaction.

The numerical diagonalization gives both eigenvalues and eigenfunctions. We have discussed the interpretation of the low energy initial states $|i\rangle$ for different monopole strength $2S$. The final states $|f\rangle$ contain $N-1$ electrons and no holes. The recombination rate is proportional to the square of the matrix element of the PL operator $\hat{\mathcal{L}}$.[7] We have evaluated $|\langle f|\hat{\mathcal{L}}|i\rangle|^2$ for all of the low-lying initial states[10] and arrived at the following conclusions: (i) Conservation of total angular momentum L is, at most, very weakly violated through scattering by "spectator electrons" which do not participate in the binding of the FCX. (ii) For $d \ll \lambda$, the $X^-\mathrm{QH}_2$ state has very small oscillator strength compared to X. (iii) For $d \simeq \lambda$, the $h\mathrm{QE}_2$ and the excited state of hQE (called $h\mathrm{QE}^*$) are the only states with reasonably large oscillator strength. We conclude that at separation $d \simeq \lambda$, the $h\mathrm{QE}_2$ and $h\mathrm{QE}^*$ decays should be observable in PL and encourage experiments to verify this.

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