PHYSICAL REVIEW B VOLUME 48, NUMBER 24 15 DECEMBER 1993-II

Doublet structure of emission spectra from fractional quantum Hall states

Vadim M. Apalkov
L. D. Landau Institute for Theoretical Physics, Moscow 117940, Russia

Emmanuel I. Rashba
*Department of Physics, University of Utah, Salt Lake City, Utah 84112
and L. D. Landau Institute for Theoretical Physics, Moscow 117940, Russia*
(Received 21 July 1993)

A suppression of the exciton dispersion by an incompressible quantum liquid strongly affects the recombination emission spectrum. It comprises two parts; one of them originates from a direct recombination of $k=0$ excitons, and the other from indirect, single magnetoroton, transitions from an extensive area in $\mathbf{k}$ space, $kl \approx 1$, l is the magnetic length. Intensities of the peaks show opposite temperature dependencies. We show that the minimal frequency of magnetorotons may be found from emission spectra by a proper treatment of experimental data.

Magnetoluminescence experiments with two-dimensional (2D) electrons confined in heterojunctions and quantum wells deal with two different recombination processes, the radiative trapping of 2D electrons by neutral acceptors residing outside a confinement layer, and their recombination with free holes. Both groups of spectra show remarkable anomalies when the filling factor ν passes through values where fractional quantum Hall (FQH) states appear. The gaps,[1(a)] and also their temperature dependences,[1(b)] were determined for several FQH states from cusp strengths.[2] The most remarkable feature of intrinsic recombination spectra observed in the vicinity of the fractions is a splitting of the emission band into a well-defined doublet; the intensity distribution between the components strongly depends on the temperature T.[3] This observation was confirmed by more recent experiments,[4–6] and even multiple-peak spectra were observed in the low ν region where the formation of a Wigner solid is anticipated. Some general properties of the emission from FQH states have been established theoretically.[8–10] Nevertheless, to our best knowledge no definite assignment of the doublet components has been proposed yet. We show, that (i) a doublet structure of emission spectra follows, in a straightforward way, from the suppression of the exciton dispersion by a Laughlin incompressible quantum liquid (IQL), and (ii) the energy of magnetorotons[11](MR) in the vicinity of a roton minimum ω_r may be found from the magnitude of the doublet splitting and the temperature dependence of the intensity ratio of the doublet components.

In what follows, we investigate the shape of exciton photoluminescence (PL) spectra, when the background electron density equals exactly $\nu = 1/3$ (processes in the vicinity of fractions, where new recombination channels open,[8,10] need a special consideration). Under such conditions the dispersion of excitons is strongly suppressed by their coupling to an IQL,[8] and the lowest branch of the exciton spectrum $\varepsilon(k)$, where k is the exciton momentum, passes completely below the MR spectrum, $\omega_{\rm MR}(k)$, Fig. 1. The shape of the $\varepsilon(k)$ curve strongly depends on the parameter h/l, where h is a spacing between electron and hole confinement planes (h/l is the charge asymmetry parameter playing an important role in the 2D exciton magnetospectroscopy[8,10]). When h/l increases, the curve $\varepsilon(k)$ first flattens in the area $k \approx l^{-1}$. Then a subsidiary minimum develops on it, and finally, at $h_{\rm cr}/l \approx 0.8$, the subsidiary minimum turns into the lowest one. The position of this minimum is close to that of the roton minimum k_r at the MR dispersion curve. Two facts are of a special importance. (i) There exists an extensive area in $\mathbf{k}$ space where the exciton dispersion is weak, and $\varepsilon(k)$ is small, actually only a few hundredths of $\varepsilon_C = e^2/\kappa l$, a characteristic Coulomb energy. (ii) Only MR-assisted optical transitions are allowed from this area of $\mathbf{k}$ space; the oscillator strengths for these transitions are large, and their frequencies are lower than Ω_0, the frequency of the direct exciton transition from the $\mathbf{k}=\mathbf{0}$ minimum. These facts imply the appearance of a doublet spectrum. For $h < h_{\rm cr}$, the upper (U) peak dominates at $T \to 0$, while the lower (L) peak develops at elevated temperatures. These properties strongly resemble patterns observed by Heiman *et al.*[3] A possible role of MR satellites (shake-up processes) has been discussed in a number of papers,[12,9] primarily as applied to extrinsic

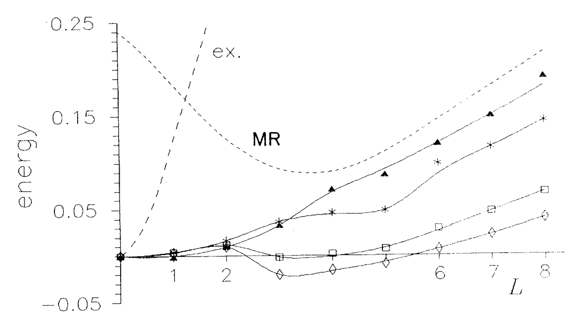

FIG. 1. Dispersion laws for an exciton in the presence of a $\nu = 1/3$ IQL [$h = 0$ ($\triangle$), 0.5 ($*$), 0.83 ($\square$), and 1.0 ($\diamond$)], of an exciton in an empty crystal (ex), and of a MR (mr). Energy in units of $\varepsilon_C = e^2/\epsilon l$, $L \approx 2.5kl$, for exciton spectra $\varepsilon(k=0)$ is chosen as an origin.

emission. It is the shape of the exciton dispersion law that makes intrinsic MR-assisted transitions very specific.

All calculations were performed in the spherical geometry[13] for a system consisting of $N = 5$ electrons and one exciton (electron-hole pair). The size of the sphere was chosen as $2S = 12$, which corresponds to the $\nu = 1/3$ incompressible state for five background electrons. The results are in a qualitative agreement with those obtained for $N = 4$, $2S = 9$. When presenting the results of simulations, we use dimensionless variables, $l = 1, \varepsilon_C = 1$, and restrict ourselves with $h = 0.5$. These data are representative for all the region $h < h_{\rm cr}$.

When T is low, only weakly excited states are populated. Every curve $\varepsilon(k)$ in Fig. 1 designates the bottom of the energy spectrum as a function of k for a fixed h. The emission coming from the lower part of the energy spectrum comprises two contributions. The first comes from direct, zero-MR, transitions from the lowest $\mathbf{k} = \mathbf{0}$ state. The second comes from indirect, single-MR, transitions from the entire $\mathbf{k}$ space; a single MR is left in a crystal after such a transition. To find the latter contribution it is necessary to calculate beforehand a weighted spectral density $f(\varepsilon, k)$, which is a product of a spectral density of states by the oscillator strength for given k and ε. The results for three values of h, and two values of the angular momentum, $L = kS^{1/2}$, are shown in Fig. 2. The curves represented in it were obtained by smearing the histograms, which were calculated for finite-size systems. The main maximum in Fig. 2 originates from the lowest multiplicative state (MS) with a given L.[8] To realize this fact, one should take into account that, for $h = 0$, (i) only transitions from MS's are allowed owing to a hidden symmetry inherent in charge-symmetric systems, (ii) the frequencies of all these transitions are equal exactly Ω_0, and (iii) the lowest branch of MS's repeats exactly the MR dispersion law, and passes above the exciton spectrum bottom (for $k \approx k_r$ closer to it, and for $k < 1$ farther from it[8]). A continuum of MS's exists somewhat above this branch. When h increases, the states which are close to the lowest MS branch acquire from it a considerable oscillator strength for transitions into single-MR states, and form a strong maximum seen in Fig. 2. The maximum broadens when h increases. Aside from the peak broadening, the oscillator strength is also flowing down the spectrum. As a result, transitions from the spectrum bottom become allowed at any k. If $h \gtrsim 0.25$, and $k \approx 1$, a new maximum of $f(\varepsilon, k)$ develops at the spectrum bottom. It seems natural to attribute it to formation of exciton-MR bound states, their existence was established in Ref. 8(a) for $h = 0$, and confirmed by our calculations for $h \neq 0$. The increase in $f(\varepsilon, k)$ near the spectrum bottom, especially for $k \approx 1$, results in the appearance of a narrow and strong MR satellite, hence, in a doublet structure of the emission spectrum. The shape of this spectrum is determined by the function

$$I(\omega) \propto \int d\mathbf{k} \int_{\{\mathbf{k}\}} d\varepsilon\, f(\varepsilon, k) \exp(-\varepsilon/T) \times \delta(\varepsilon - \omega_{\rm MR}(k) - \omega). \qquad (1)$$

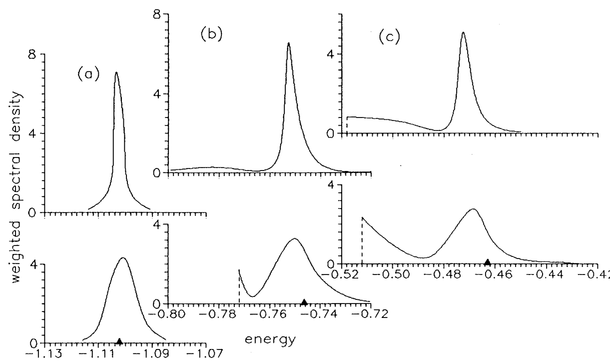

FIG. 2. Weighted spectral density $f(\varepsilon, k)$ near the energy spectrum bottom for different separations of electron and hole confinement planes. When h increases, the main peak in $f(\varepsilon, k)$ becomes broader, and the bottom peak develops. For the upper set $L = 3$, and for the lower set $L = 4$; $h = 0.1$ (a), 0.3 (b), and 0.5 (c). For every h a black triangle marks the frequency of the $L = 0$ zero-MR transition.

The internal integration in (1) is performed over all the quantum states with a given $\mathbf{k}$. The only final states designated in (1) explicitly are those belonging to the MR branch, this is because they make a dominant contribution to the integral. $I(\omega)$ is shown in Fig. 3 for two values of T belonging to the low-T region, where only the contribution of the lowest MS is of importance. The spectra show a pronounced two-peak structure. The L peak in $I(\omega)$ comes from single-MR transitions. An extensive area in $\mathbf{k}$ space, $k \approx 1$, contributes to it. Since $\exp(-\varepsilon/T)$ decreases rapidly with ε for low T, the L peak develops not only when the low-ε peak is seen in $f(\varepsilon, k)$, Fig. 2, but also when $f(\varepsilon, k)$ shows a flat minimum at the spectrum bottom (for $h < 0.25$). The U peak in $I(\omega)$ comes mainly from zero-MR transitions from the $\mathbf{k} = \mathbf{0}$ state. The mechanism originating the doublet structure of the emission spectrum constitutes the main message of this paper.

To discuss experimental data on doublet emission spectra from the above standpoint, it is necessary to describe these spectra in some more detail. L and U peaks must

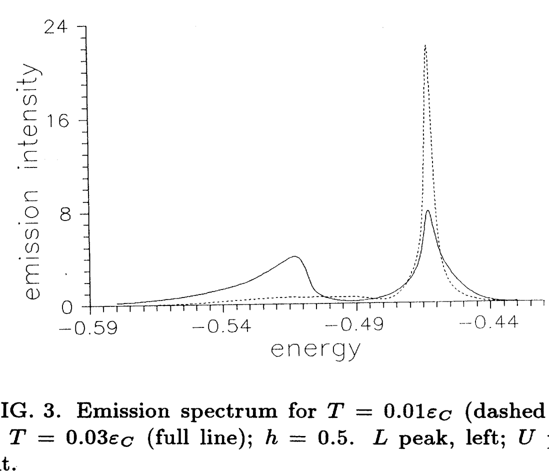

FIG. 3. Emission spectrum for $T = 0.01\varepsilon_C$ (dashed line) and $T = 0.03\varepsilon_C$ (full line); $h = 0.5$. L peak, left; U peak, right.

show different temperature dependences due to redistribution of exciton populations between the $\mathbf{k} = \mathbf{0}$ and $k \approx 1$ areas. The major contribution to the U peak comes from zero-MR transitions, hence, $\Omega_U \approx \Omega_0$. It decreases with T owing to decrease in the population at $\mathbf{k} = \mathbf{0}$. Another contribution to the U peak comes from thermoactivated single-MR transitions from the states forming the main peak in $f(\varepsilon, k)$, Fig. 2. Their frequencies are also close to Ω_0, but the width of this spectrum is larger than that for the major peak, and the intensity of it increases with T. Since the activation energy for MS's is larger than for the bottom states, the full intensity of the U peak decreases with T. The main contribution to the L peak comes from the area in the vicinity of the MR minimum, $k \approx k_r$, since the exciton-MR interaction in this area is strong, and the density of the exciton states is high. Therefore, the activation energy for the L peak, $E_{\rm ac}$, must be close to the spectrum bottom at $k \approx k_r$. The peak width is reduced by the weak exciton dispersion in the same area, and the frequencies of emitted MR's must be close to ω_r. The frequency of the L peak is equal to $\Omega_L = \Omega_0 + E_{\rm ac} - \omega_r$, hence, the doublet splitting equals

$$\delta \equiv \Omega_U - \Omega_L = \omega_r - E_{\rm ac}. \qquad (2)$$

Since ω_r depends on the width of the electron confinement layer, and $E_{\rm ac}$ on h/l, the splitting, δ, depends on both these parameters. Both δ and $E_{\rm ac}$ may be measured experimentally, hence, Eq. (2) allows us to find ω_r. Side by side with the activational contribution to the L peak, there is also a contribution making a low-frequency wing of it, and showing the same T dependence as the major U peak. It comes from single-MR transitions in the vicinity of $\mathbf{k} = \mathbf{0}$. The intensity of the wing is very low at $h \ll l$, and makes up about 1% of the U peak intensity at $h \approx 0.5$.

The above discussion was based on the assumption that $h < h_{\rm cr}$. If $h > h_{\rm cr}$, the doublet structure must survive, but the T dependence of component intensities must change drastically. The L peak must become the low-T component of the doublet, while the U peak becomes its high-T component. We are not aware of any experimental data of this kind. A study of the h/l dependence of the emission spectrum seems promising.

We are now in a position to make a preliminary comparison with experimental data. The doublet structure was described in great detail in Ref. 3 for GaAs-$(\mathrm{Al}_x\mathrm{Ga}_{1-x})$As multiple quantum wells for $\nu = 2/3$. For B=24.5 T the Coulomb energy equals $\varepsilon_C = 250$ K, and $\omega_r = 0.076\varepsilon_C = 19$ K.[11,13] The finite width of the electron confinement layer results in a strong reduction of ω_r;[11] for actual experimental systems this reduction can be as much as a factor of 2.[14] Therefore, one could expect that $\omega_r \approx 9$ K. The observation[3] that "with increasing temperature it is the lower-energy peak that becomes stronger" is in agreement with the above concept, and testifies that $h < h_{\rm cr}$. The observed splitting equals $\delta = 0.5 - 0.7$ meV ≈ 7 K. The activation energy $E_{\rm ac}$, found from the T dependence of the intensity ratio I_L/I_U (see inset in Fig. 4 of Ref. 3), equals $E_{\rm ac} = 0.65$ K. Therefore, it follows from (2) that $\omega_r \approx 8$ K, in reasonable agreement with the expected value. On the contrary, $E_{\rm ac} = 0.65$ K is much less than the value $E_{\rm ac} \approx 0.3\omega_r \approx 3$ K, which is anticipated. This low value of $E_{\rm ac}$ is in conformity with a low value of the gap found from $\rho_{xx}(T)$, $\Delta = 0.88$ K (cf. the anticipated value $\Delta \approx 1.04\varepsilon_C/2 = 13$ K). Therefore, we attribute the low value of $E_{\rm ac}$ to the effect of a random potential. Recently Pinczuk *et al.*[7] have observed a completely resolved L-U doublet, $\delta \approx 0.5$ meV at $\nu = 1/3$, for a high-quality GaAs-$\mathrm{Al}_{0.1}\mathrm{Ga}_{0.9}$As single quantum well. Using their data on $I_L(T)$ and $I_U(T)$ for $0.7 \le T \le 1.3$ K, we have evaluated $E_{\rm ac}$ as $E_{\rm ac} \approx 2.7$ K. This is what one can anticipate for $h/l \approx 0.6 - 0.7$, and results in $\omega_r = \delta + E_{\rm ac} = 9$ K, in complete agreement with the value being expected.[15] In our model the L peak in emission corresponds to transitions to excited, single-MR, states, the energy of which is relatively large, $\omega_r > E_{\rm ac}$. Therefore, the L peak in the PL excitation spectrum should be weak, even when it is strong in emission, and the very fact of its appearance signifies definitely the existence of the bottom peak in $f(\varepsilon, k)$. An L peak in the PL excitation spectrum showing such properties has been observed recently.[16]

In conclusion, we have shown that in the FQH effect regime exciton emission spectra of charge asymmetric systems have a doublet shape, the doublet components being formed by zero-MR and single-MR transitions. It is the weak exciton dispersion in an extensive area of the $\mathbf{k}$ space which gives rise to the specific shape and temperature dependence of the doublet. The theory permits one to find the magnetoroton frequency from emission spectra.

E.I.R. was supported by Subagreement No. KK2004 from QUEST of UCSB, and V.M.A., in part, by a Soros Foundation Grant awarded by the American Physical Society. E.I.R. is grateful to Dr. A. Pinczuk for providing experimental data before publication and useful suggestions, Professor A. L. Efros for a helpful discussion, and Dr. V. G. Burnett for a critical reading of the manuscript.

[1] I. V. Kukushkin *et al.*, (a) Surf. Sci. **263**, 30 (1992); (b) Europhys. Lett. **22**, 287 (1993).

[2] V. M. Apal'kov and E. I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **53**, 420 (1991) [JETP Lett. **53**, 442 (1991)].

[3] D. Heiman, B. B. Goldberg, A. Pinczuk, C. W. Tu, A. C. Gossard, and J. H. English, Phys. Rev. Lett. **61**, 605 (1988).

[4] B. B. Goldberg, D. Heiman, A. Pinczuk, L. Pfeiffer, and K. West, Phys. Rev Lett. **65**, 641 (1990); Surf. Sci. **263**, 30 (1992).

[5] A. J. Turberfield, S. H. Heines, P. A. Wright, R. A. Ford, R. G. Clark, J. F. Ryan, J. J. Harris, and C. T. Foxon, Phys. Rev Lett. **65**, 637 (1990).

[6] E. M. Goldys, S. A. Brown, R. B. Dunford, A. G. Davies, R. Newbury, R. G. Clark, P. E. Simmonds, J. J. Harris, and C. T. Foxon, Phys. Rev. B **46**, 7957 (1992).

[7] A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. West, Phys. Rev. Lett. **70**, 3983 (1993).

[8] V. M. Apal'kov and E. I. Rashba, (a) Pis'ma Zh. Eksp. Teor. Fiz. **54**, 160 (1991) [JETP Lett. **54**, 155 (1991)]; (b) Phys. Rev. B **46**, 1628 (1992).

[9] B.-S. Wang, J. L. Birman, and Z.-B. Su, Phys. Rev. Lett. **68**, 1605 (1992).

[10] A. H. MacDonald, E. H. Rezayi, and D. Keller, Phys. Rev. Lett. **68**, 1939 (1992).

[11] S. M. Girvin, A. H. MacDonald, and P. M. Platzman, Phys. Rev. B **33**, 2481 (1986).

[12] S.-R. E. Yang, Phys. Rev. B **40**, 1836 (1989); Yu. A. Bychkov and E. I. Rashba, Zh. Eksp. Teor. Fiz. **96**, 757 (1989) [Sov. Phys. JETP **69**, 430 (1989)]; V. M. Apal'kov and E. I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **53**, 46 (1991) [JETP Lett. **53**, 49 (1991)]; T. Chakraborty and P. Pietiläinen, Phys. Rev. B **44**, 13 078 (1991).

[13] F. D. M. Haldane, Phys. Rev. Lett. **51**, 605 (1983); G. Fano, F. Ortolani, and E. Colombo, Phys. Rev. B **34**, 2670 (1986).

[14] F. C. Zhang and S. DasSarma, Phys. Rev. B **33**, 2903 (1986).

[15] The frequency of $k = 0$ MR's found in Ref. 7 equals 0.47 of its value for an ideal 2D system, which gives an independent support for the reduction coefficient of MR frequencies, about 0.5, used above.

[16] A. Pinczuk, Bull. Am. Phys. Soc. **37**, 108 (1992).