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Photoluminescence Detected Doublet Structure in the Integer and Fractional Quantum Hall Regime

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We present here the results of polarized magneto-photoluminescence measurements on a high mobility single-heterojunction. The presence of a doublet structure over a large magnetic field range ($2>\nu>1/6$) is interpreted as possible evidence for the existence of a magneto-roton minima of the charged density waves. This is understood as an indication of strong electronic correlation even in the case of the IQHE limit.

The use of magneto-photoluminescence (MPL) spectroscopy to study the integer (IQHE) and fractional quantum Hall effects (FQHE) has attracted considerable interest in recent years. In the case of the IQHE, the appearance of the gap in the spectrum at the Fermi energy is caused by the quantization of the magnetic Landau levels or the quantization of the spin energy levels and is essentially a single particle phenomenon. In the case of FQHE, the appearance of the gap is understood as a result of condensation of the 2 DEG into an incompressible quantum liquid (IQL)[1] due to strong electron-electron correlations which takes place at fractional filling factors ν=p/q<1.

One of the most significant phenomenon that occurs in the FQHE regime is the emergence of low-lying charge-density (CD) waves that display characteristic magneto-roton (MR) minima at a wave vector close to the inverse magnetic length. At large wave vector, neutral CD waves excitations consist of pairs of fractionally charge quasiparticles that are associated with the energy gaps of the IQL. More recently, it was suggested that the strong correlations between electrons are important in explaining the structure observed in photoluminescence at ν=1 and this state is considered to be a strongly correlated state,[2] similar to the incompressible states at fractional filling factors. It was shown that the system always has a gap, even when the single-particle gap vanishes (i.e. when g=0), as a result of electron-electron repulsion. It has also been shown[3] that, in that case when the electron Zeeman energy is large, the low energy states at ν=1 are the excitonic states in which the spin-$\uparrow$ lowest Landau level is filled and the valence band hole binds with a single spin-$\downarrow$ electron to form an exciton. In analyzing the PL spectra obtained from a 2 DEG in the FQHE regime, the appearance of a doublet structure in the photoluminescence (PL) spectrum[4–7] around ν=2/3 was interpreted by Apalkov and Rashba[8] as an evidence for the appearance of an indirect, single MR transition from an extensive area in k space for $k\ell_B \cong 1$ (where ℓ_B is the magnetic length). The formation of the rotons is due to the reduction, at large wave vectors, of the excitonic binding energy between the electron and the hole.[9–11] The MR minimum is a precursor to the gap collapse associated with the Wigner crystal instability[12] and is connected with the excitonic attraction between fractionally charged quasiparticles. The calculations[8] reported for the case of the filling factor ν=1/3 showed that the dispersion of the excitons is strongly suppressed by their coupling to the IQL and the lowest branch of the exciton spectrum passes completely below the MR spectrum. Another important result of note is the fact that, even if its theoretical prediction is based on calculations performed in the case of fractional filling factor ν=1/3, the existence of the MR peak was observed in the MPL, also at filling factors that do not involve the FQHE.[4–7] In addition, evidence of excitonic binding and roton minima formation was found by Pinczuk *et.al.* for the filling factors $\nu>1$[13] and ν=1/3[14] from inelastic light scattering studies performed on the 2DEG formed in high-mobility GaAs structures. Karrai *et.al.*[15] analyzed the magneto-transmission spectra obtained from a quasi-three-dimensional electron system subjected to a parallel magnetic field and found evidence for the existence of a MR excitation for a wide range of magnetic fields.

In this report, we present the results of MPL measurements of a MBE grown high quality GaAs/$Al_{0.3}Ga_{0.7}As$ single heterojunction (SHJ) with a dark electron density of $1.2\times10^{11}cm^{-2}$ and a mobility higher than $3\times10^{6}cm^{2}/Vs$. In these experiments, during constant laser illumination, the 2DEG density increased to $2.1\times10^{11}cm^{-2}$. The experimental layout for the PL measurements has been described previously.[16] Using a quasi-continuous magnet, the field was varied from 0 to 60 T, while the temperature was changed from 1.5K to 450mK. The polarized spectra that we obtained showed the appearance of a doublet at filling factors $\nu>3/2$ and the persistence of this effect to the highest magnetic fields utilized. In Fig. 1 we show the unpolarized spectra obtained at a temperature of 1.5K at the filling factor ν=2, 3/2 and 1. The E0-hh peak that appears at ν=5 (B=1.82T)

shows a splitting for $2>\nu>1$ and this is clearly shown in the spectra at $\nu=3/2$. This splitting, once formed, is present for the whole range of magnetic fields examined. We believe that the lower energy peak of the doublet is associated with neutral exciton (X) transition, while the higher energy peak may be evidence of a MR transition. The difference in the energies (Δ) between these two peaks as a function of magnetic field is shown in the inset of the Fig.1. It can be seen that Δ has a sudden increase in the region of $\nu=1/2$ (16-19T) and then saturates for fields higher than 30T, a behavior similar to that reported by Heiman *et.al.*[4,5] in their MR studies. The value of the separation (0.4-1.2 meV) is close to the FQHE quasiparticle-quasihole separation gap energy (about 1 meV). It does not scale as the magnetic energy ($B^{1/2}$) but rather follows an almost linear behavior in the range $1>\nu>1/3$.

Cooper and Chklovskii[3] noted that in the situation where the valence-band hole is close to the electron gas compared with the electron-electron spacing, the most important initial states are the excitonic states, in which the Landau level of spin-$\uparrow$ electrons is fully occupied, and the valence-band hole binds with a spin-$\downarrow$ electron to form an exciton. The excitonic states will compete for the initial ground state of the system with the "free-hole" states in which the photoexcited electron fills the vacant spin-$\uparrow$ state and the hole occupies the lowest Landau level single particle state. As the filling factor is swept from $\nu>1$ to $\nu<1$, the form of the initial state contributing to the PL signal is believed to undergo a transition from an excitonic state to a "free-hole" state and a red shift in the luminescence line should be expected. The fact that in the case of our sample, there is no discontinuity in the energy line is an indication that there is no change in the nature of the initial excitonic state. The lack of the transition to a "free-hole" state in our case is also confirmed by the absence of the additional peak in the LCP polarization as observed by Plentz *et.al.*.[17]

The evolution of the intensities of the two peaks is shown in Fig. 2. The excitonic line shows distinctive minima at $\nu=1, 2/3, 5/9, 4/11, 1/3$. Similar behavior has been reported by Turberfield *et.al.*[6] and can be related to the localization of the electrons in these states concomitant with a reduction of the screening factor. The intensity behavior of the line labeled MR shows a deep minimum at $\nu=8/11$ and local maxima at $\nu=2/5$ and 1/3 (1/3 fractional hierarchy). A similar transfer of intensity from the lower energy line to the higher energy one at $\nu=1/3$ was previously reported by Heiman *et.al.*[4,5] and may be caused by an enhancement of the CD wave as a result of a reduction of screening.

Fig. 3 shows the right circularly polarized (RCP) spectra at the same temperature of 1.5K at low and high magnetic fields. It can be seen that the spectra taken at low magnetic fields show a decrease of the intensity of the lower energy peak with magnetic field as a result of depopulation of the spin-$\downarrow$ electronic level, a behavior that is expected in the case of the neutral exciton. At large magnetic fields, the intensities of the two peaks are almost the same as a result of low filling factor. Fig. 4 shows the ratios of the intensities of the MR and excitonic peaks for the right (RCP) and left (LCP) circular polarizations. In the LCP case this ratio is less than one as a result of a higher intensity of the excitonic peak compared to the RCP case. The difference in the energies (not shown) of the two peaks as a function of magnetic field is almost the same for both polarizations; like the unpolarized data, this difference does not scale as $B^{1/2}$ as may be expected.[8] Haldane and Rezay[8] estimated a separation value $\Delta=0.075e^2/\epsilon\ell_B$ (where $\epsilon=12.8$ for GaAs) which is larger than the value that we measured for the magnetic fields in excess of 15T ($\nu=0.6$). The evolution of the energies with the magnetic field in both polarizations at the filling factor $\nu=1$ does not show any significant blue or red shift.

In the case of narrow quantum wells it has been shown, both theoretically and experimentally, that the correlation hole of the hole term is the primary mechanism that generates the blue shifted energy associated with the IQHE.[19] In the case of wider quantum wells, a red shift in energy at $\nu=1$ indicates that the screening is reduced and the electron-hole Coulomb interaction (vertex correction) is enhanced.[19] The fact that no significant energy shift is seen in both RCP and LCP spectra at filling factor $\nu=1$ seems to indicate that the cancellation of the screened exchange and Coulomb hole terms for the electrons is close to exact, while the vertex correction term and correlation hole of the hole term cancel each other to a very good degree. This can be interpreted as an evidence of an incomplete cancellation of screening for this filling factor. Because of the finite temperatures, we expect that some of the low energy excited states will also be populated. These states will consist of both finite momentum exciton states and of long wavelength spin wave excitations of the system. They will be seen as fluctuations in the overall polarization of the system and will lead to a mixing between the two circular polarizations. For this reason, a degree of uncertainty in the measured ratio of the intensities is possible. For the LCP spectra, the doublet is resolved at magnetic fields higher than in the RCP spectra. We believe that this may be caused by a broadening of the excitonic transition line as a result of the presence of the spin waves in the LCP spectra. This appears as a result of the recombination of one of the valence-band holes with a spin-$\uparrow$ electron, a process that leaves a spin reversal in the final state.

Fig. 5 a and b show the MPL spectra in both LCP and RCP polarizations for two temperatures (1.5K and 450mK) at two filling factors $\nu=1/5$ and 1/3. All the intensities are normalized with respect to the zero field spectra. It can be seen that, by decreasing the temperature, the higher energy peak is the one that becomes stronger, ruling out the possibility of it being generated by the changes in the population of electrons and photo-excited holes. A similar behavior was reported by Heiman*et.al.*[4] and was explained by Apalkov and

Rashba[8] as being due to the proximity between the electron and hole confinement planes. This proximity can also be explained by a process similar to the one described by Kim *et.al.*[20], namely the reduction in screening between electrons, and is the main reason for the existence of the excitonic states at ν=1. In Fig. 4a the intensity of the excitonic peak in the LCP spectra is clearly larger than that observed in the RCP spectra. The poorer resolution of the two peaks in the LCP spectra compared to the RCP spectra can be explained by the broadening of the excitonic transition line as a result of the presence of the spin waves in the LCP spectra.

In conclusion, MPL measurements have been performed on a high quality GaAs/AlGaAs SHJ. The spectra showed a doublet structure over a large range of the magnetic field ($2>\nu>1/6$) that we believe to be evidence for the coexistence of the E0 excitonic excitations and MR minima of the CD waves. Their presence over such a wide field range and filling factor is understood as a confirmation of the strong correlation effects among electrons in the integer and quantum Hall regime.

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FIG. 1. Unpolarized MPL spectra at 1.5K for three different filling factors. The appearance of the doublet structure is resolved at $\nu=3/2$. The inset shows the difference (Δ) between the magneto-roton (MR) and the exciton (X) energies as a function of magnetic field to 58T.

FIG. 2. The evolution of the integrated intensities of the magneto-roton (MR) and exciton (X) peaks with magnetic field at 1.5K. The excitonic line (X) shows distinctive minima at ν=1, 2/3, 5/9, 4/11, 1/3. The intensity behavior of the MR line shows a deep minimum at $\nu=8/11$ and local maxima at $\nu=2/5$ and 1/3.

FIG. 3. Right circularly polarized (RCP) spectra at 1.5K at low and high magnetic fields. The spectra taken at low magnetic fields show a decrease of the intensity of the lower energy peak with magnetic field as a result of depopulation of the spin-$\downarrow$ electronic level. At high magnetic field, the intensities of the two lines are almost the same.

FIG. 4. The ratio of the magneto-roton (MR) and exciton (X) intensities for right (RCP) and left (LCP) circularly polarized spectra as a function of magnetic field.

FIG. 5. Right (RCP) and left (LCP) circularly polarized spectra taken at two different temperatures, 1.5K and 450 mK, for filling factors (a) $\nu=1/5$ and (b) $\nu=1/3$. All the intensities have been normalized with respect to the zero field spectra.

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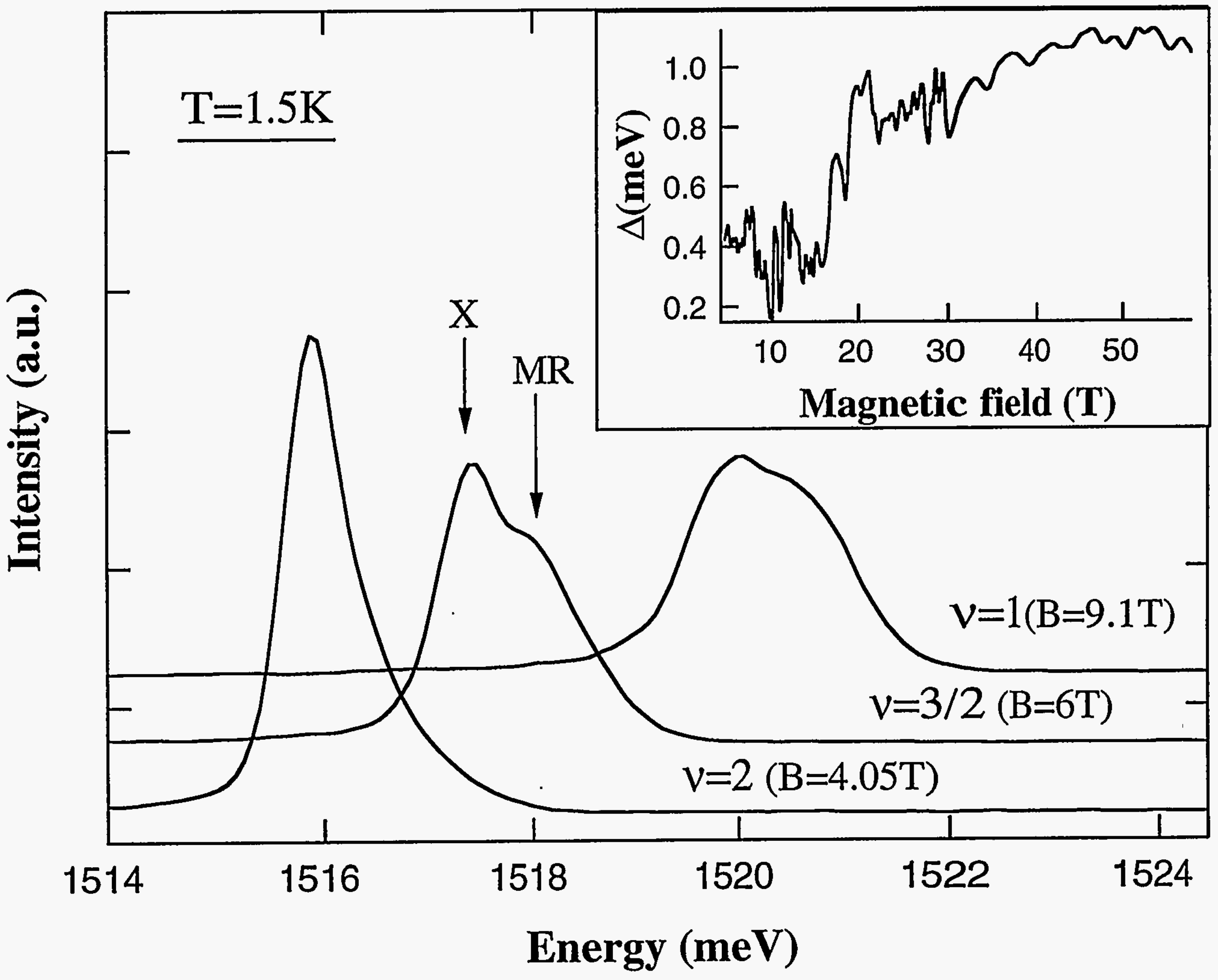
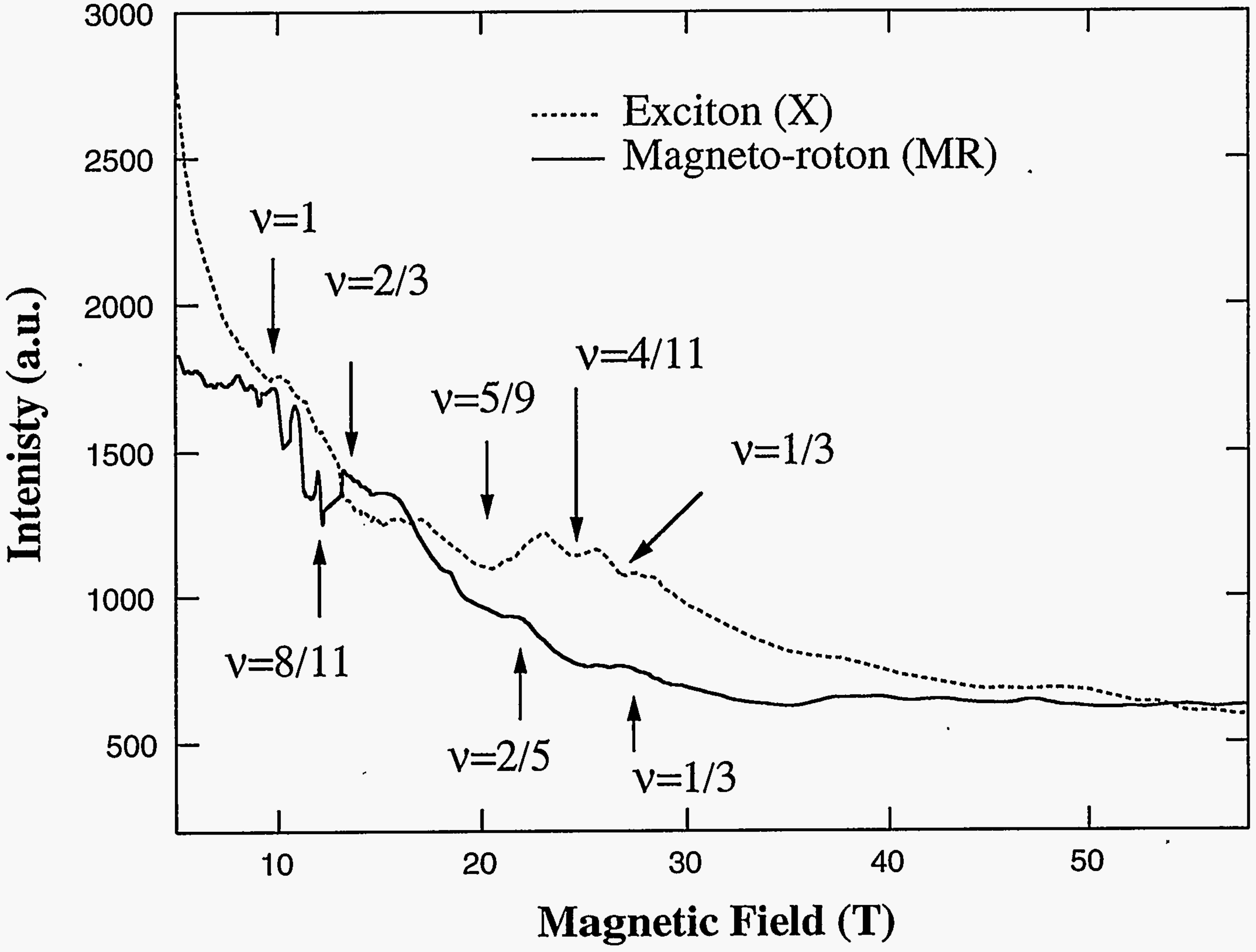


Munteanu et. al., Fig. 1



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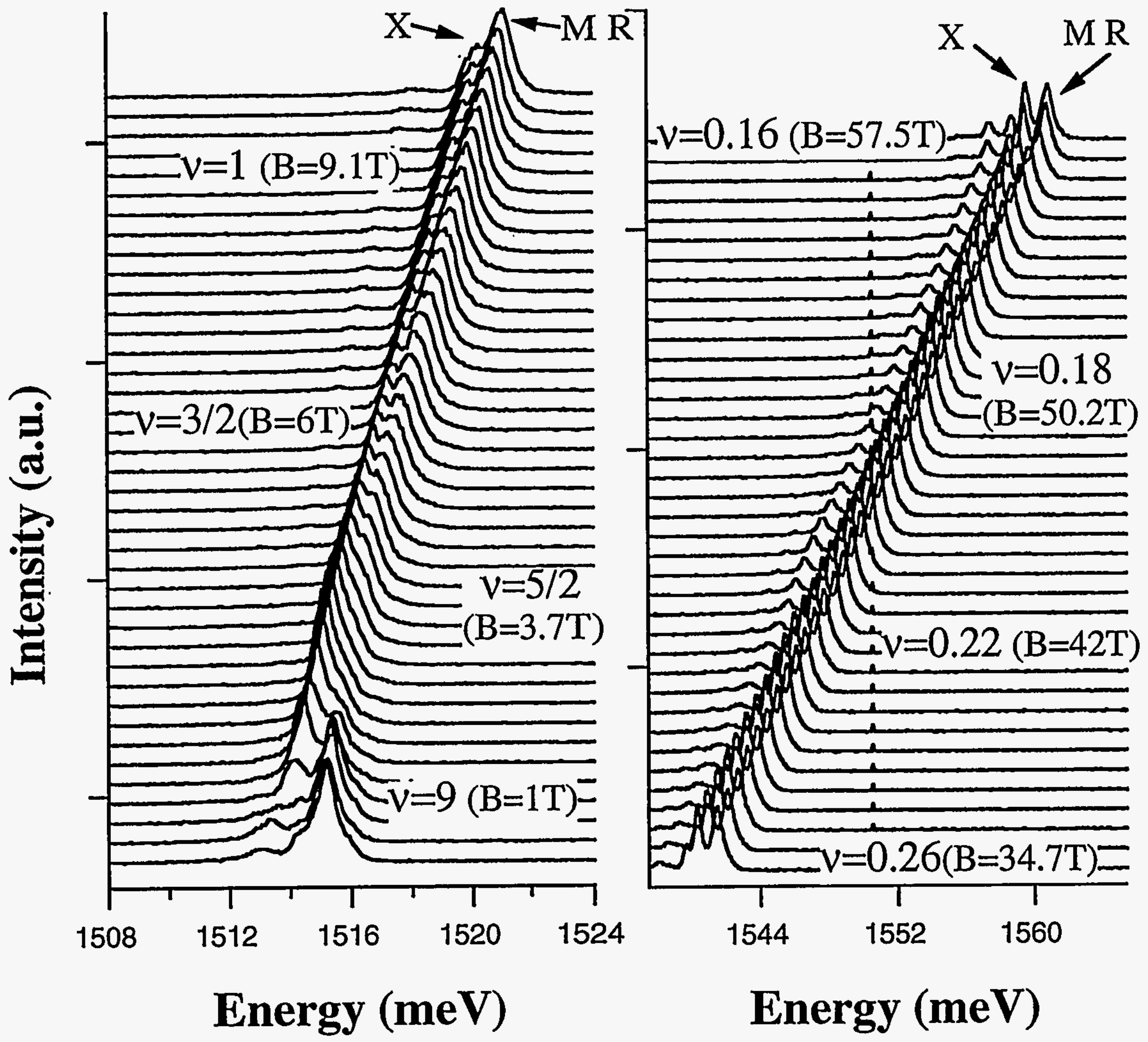

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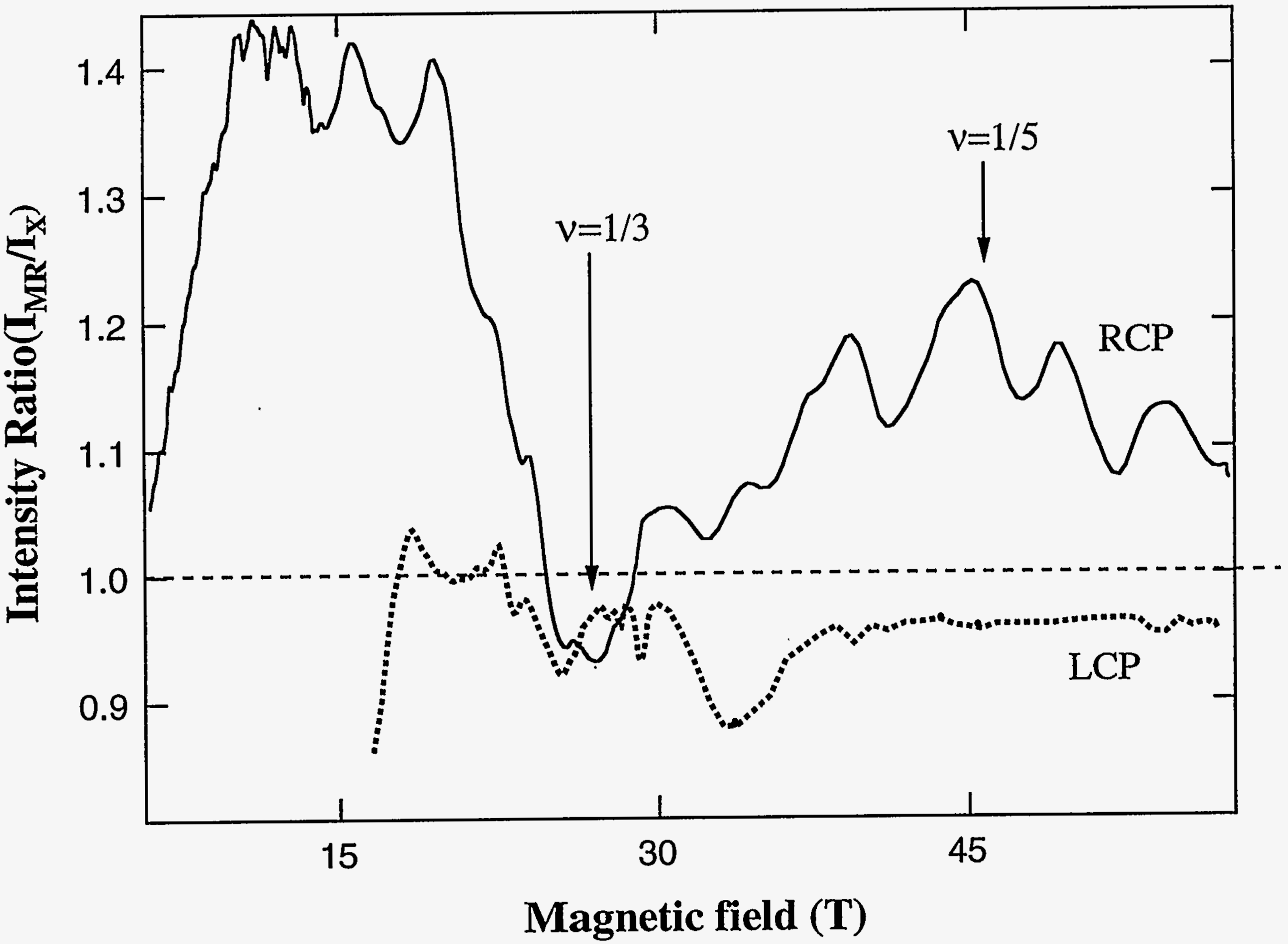

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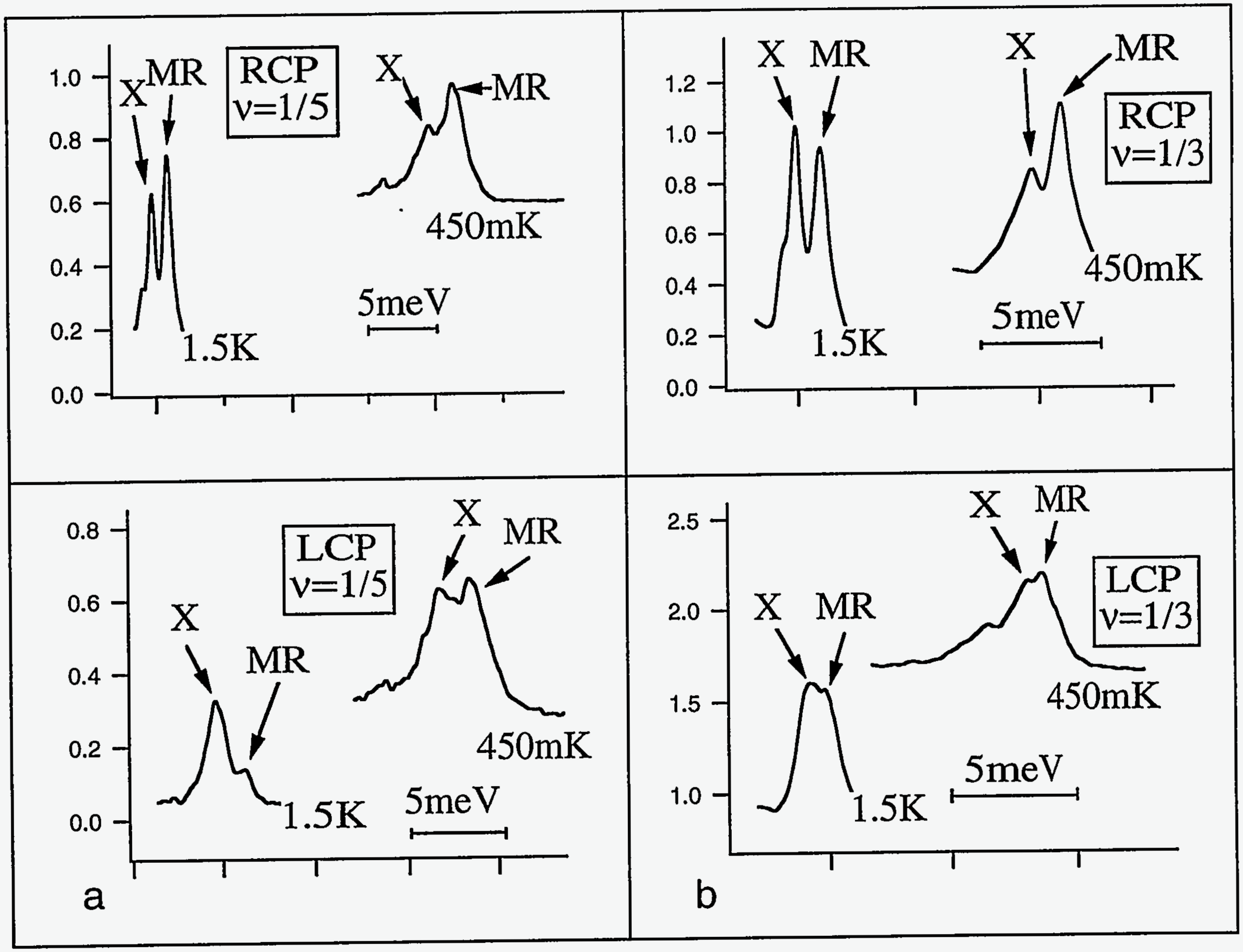

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