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"Fundamental Interactions and Excitations in Confined Systems"

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Spectroscopy of soft modes and quantum phase transitions in low dimensional electron systems

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Soft excitations and broken symmetries in quantum Hall states of electron double layers

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Soft excitations and broken symmetries in quantum Hall states of electron double layers

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Outline

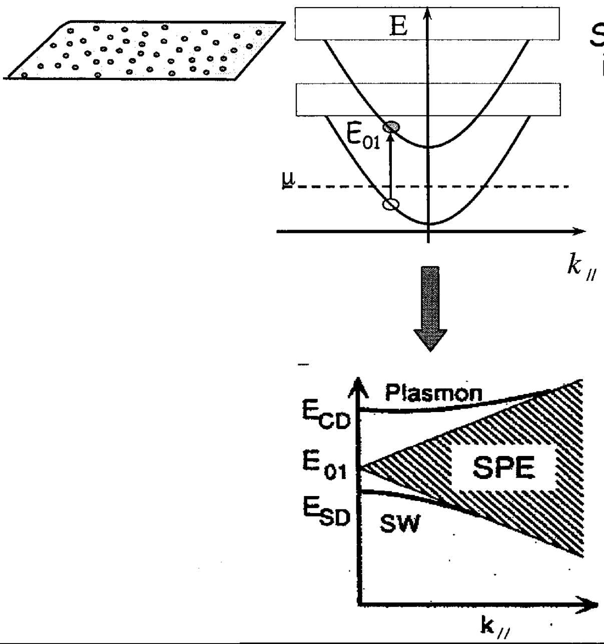
- Collective excitations in the 2DES
- quantum Hall bilayers

- Inelastic light scattering
- breakdown of wavevector conservation

- The bilayer system at ν=2
- Long-wavelength spin-excitation instability

- The bilayer system at ν=1
- Magneto-roton softening and sharpening

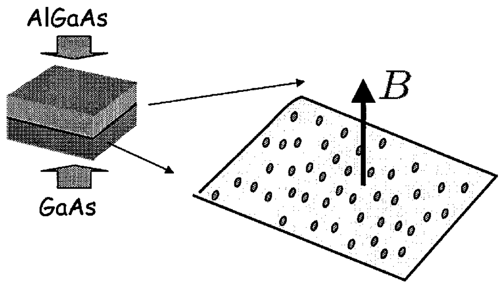
Intersubband excitations: B=0



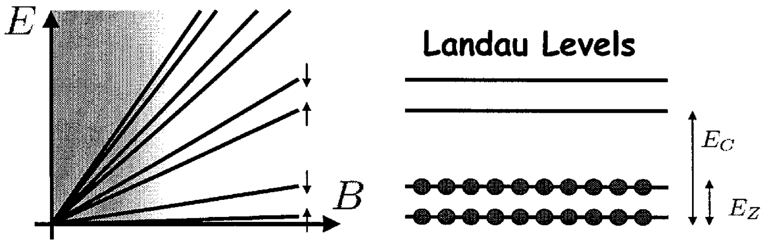
Single-particle intersubband excitations

Many-body effects: excitonic and depolarization terms

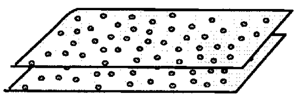
Landau Levels and quantum Hall effects

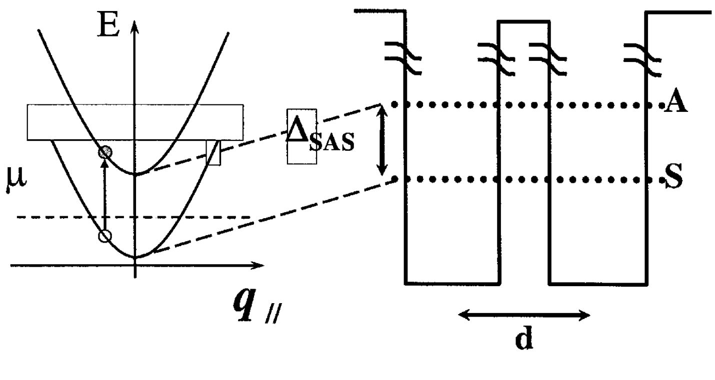


$$E_C = \hbar\omega_C = \frac{\hbar e B_\perp}{m^* c}$$
$$E_Z = -g^* \mu_B B$$
$$N = \frac{e B_\perp}{h}$$
$$\nu = \frac{n}{N}$$

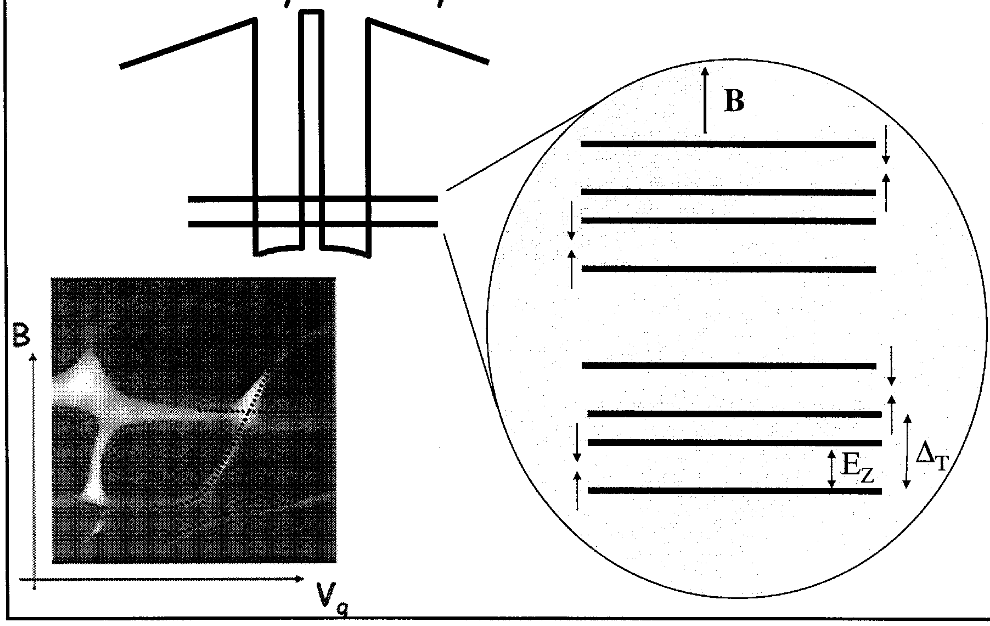


Intersubband excitations in bilayers

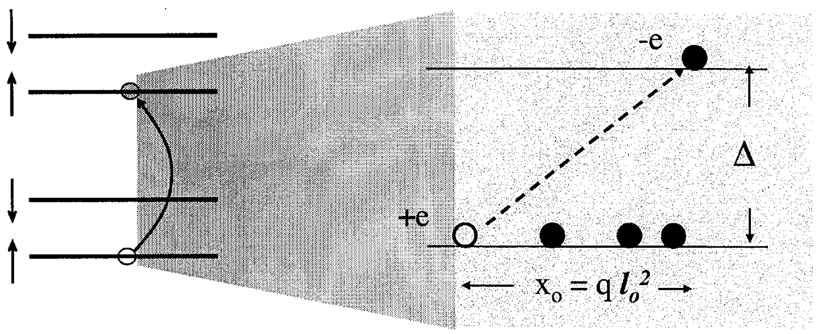




Interplay between spin and pseudospin: new broken-symmetry states

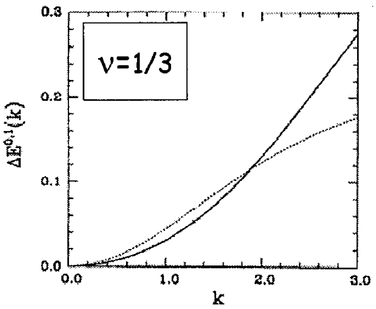


Collective excitations in the quantum Hall regime



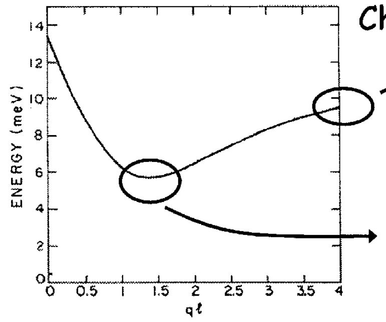
C. Kallin and B.I. Halperin, Phys. Rev. B **30**, 5655 (1984)

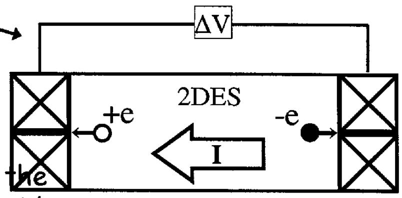
Dispersive spin and charge modes



Spin waves across the Zeeman gap

Charge-density excitations

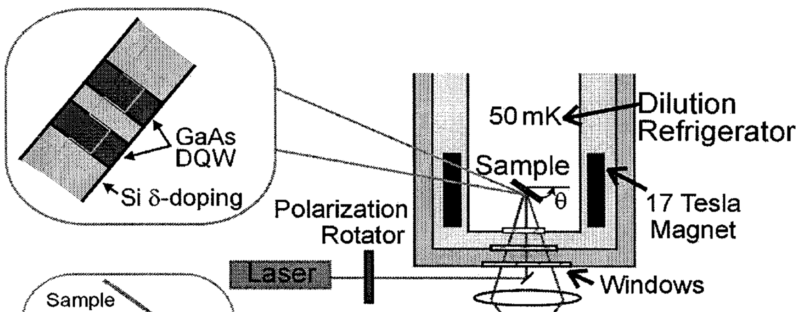


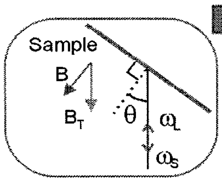


Stability of the electron liquid

Transport probe neutral particle-hole pair at q~∞

Inelastic light scattering



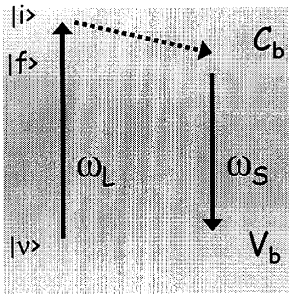


Conservation laws:

$$\omega_L - \omega_S = \omega(q) \qquad q = |\mathbf{k}_{//}|$$

Translational invariance ⇒ $\mathbf{k}_{//} = \mathbf{k}_{L//} - \mathbf{k}_{S//} = (k_I - k_S)\sin\theta < \sim 10^5 \text{cm}^{-1}$

Light-scattering matrix elements and selection rules



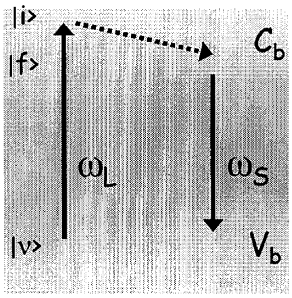
$$M \sim \frac{\langle f|\mathbf{p}\cdot\varepsilon_S|v\rangle H_{if}\langle v|\mathbf{p}\cdot\varepsilon_L|i\rangle}{(E_{iv}-\omega_L)(E_{fv}-\omega_S)}$$

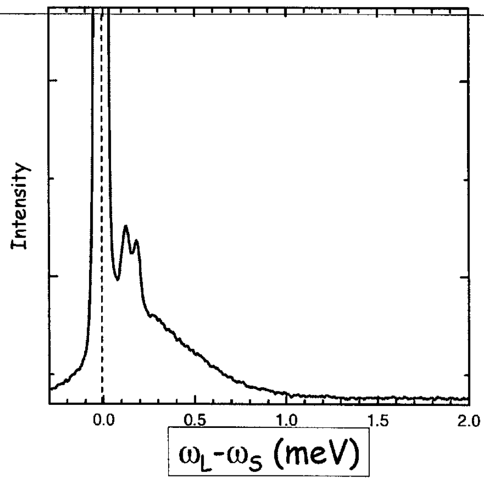
Charge-density modes (CDE)
Polarized spectra

Spin-density modes (SDE)
Depolarized spectra

SDEs light-scattering cross sections are mediated by exchange coulomb interactions with virtual photocreated excitons that are intermediate states in the processes.

Light-scattering matrix elements and selection rules

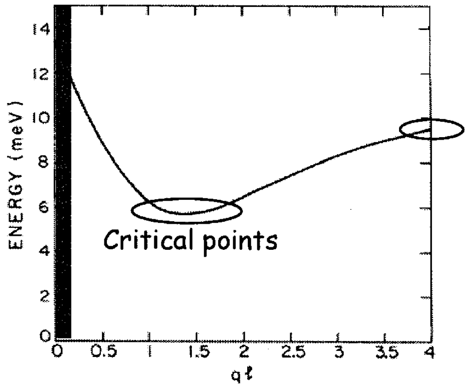




Breakdown of wavevector conservation

magneto-roton minimum located at wavevector ~l_B^{-1} ~10^6cm^{-1}>>~10^5cm^{-1}

Quantum Hall ground state



Conservation laws:

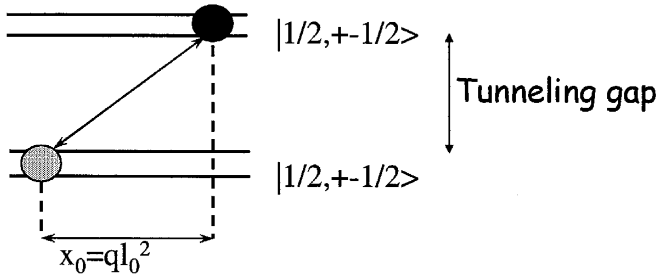
$\omega_L - \omega_S = \omega(q)$ $\quad q = |\mathbf{k}_{//}|$

Translational invariance ⇒ $\mathbf{k}_{//} = \mathbf{k}_{I//} - \mathbf{k}_{S//} = (k_I - k_S)\sin\theta$ <~10^5cm^{-1}

Bilayers at ν=2

VP, A. Pinczuk et al., *Phys. Rev. Lett.* (1997)
VP, A. Pinczuk et al., *Science* (1998)
VP, A. Pinczuk, *Solid State Communications* (2001)
S. Luin, VP et al, *Solid State Communications* (2003)

Neutral particle-hole excitations



STATES

SINGLET — $J=0$, $J_Z=0$ — CHARGE-DENSITY EXCITATIONS (CDE)

◆🗎$_{CDE}$(**q**) = (◆$_{SP}$+♠$_x$)^2+◆🗎$_d$(**q**)-◆$^2{}_b$(**q**)

TRIPLET — $J=1$, $J_Z=-1,0,+1$ — SPIN-DENSITY EXCITATIONS (SDE) AND SPIN-FLIP (SF) MODES

◆🗎$_{SDE}$(**q**) = (◆$_{SP}$+♠$_x$)^2-◆$^2{}_b$(**q**)

ν=2

◆🗎$_{SDE}$(**q**) = (◆$_{SP}$+♠$_x$)^2-◆$^2{}_b$(**q**)

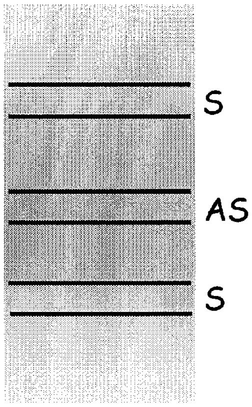
$\omega_{SF} = \omega_{SDE} \pm E_z$

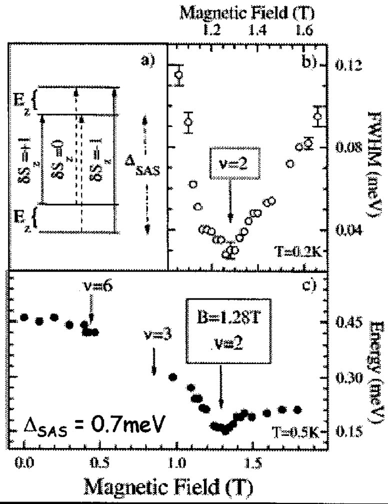
↓ $J_Z=\pm1$ ↘ $J_Z=0$

The impact of excitonic shift

$\blacklozenge_{SDE}(\mathbf{q}) = (\blacklozenge_{SP}+\bullet_x)^2-\blacklozenge^2_b(\mathbf{q})$

Excitonic shift ~ $n_S-n_{AS} = n \cdot(\nu_S-\nu_{AS})/\nu$

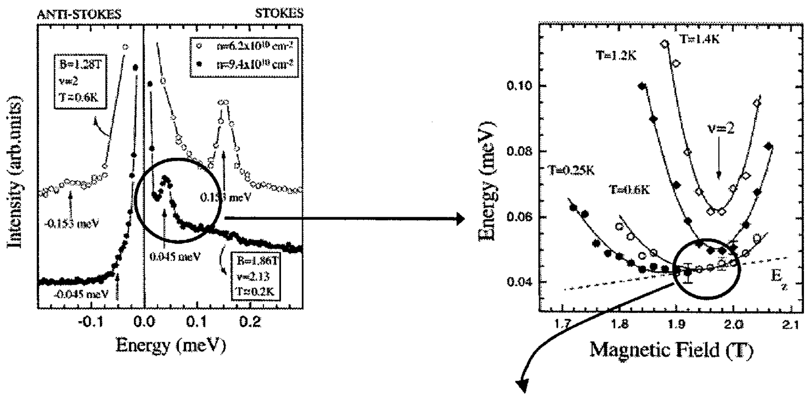




Collapse of spin excitations

Impact of n

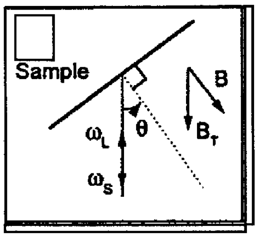
Impact of B

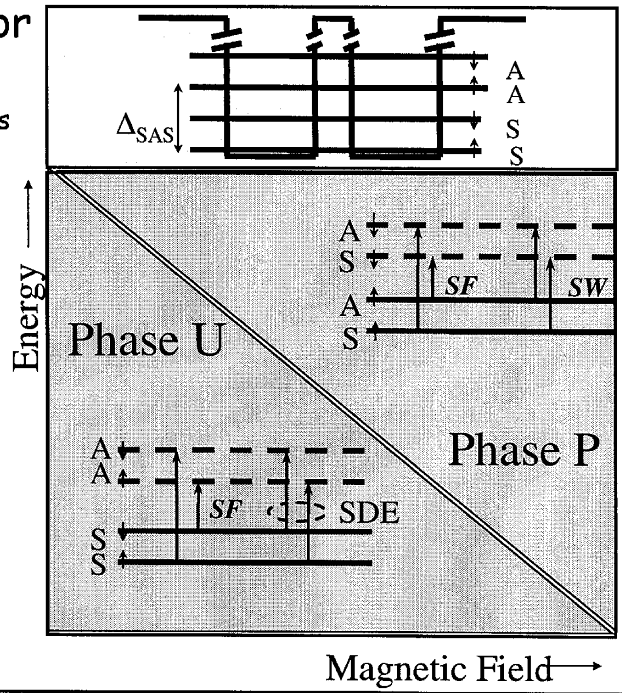


$\omega_{SDE} \rightarrow E_z \Rightarrow \omega^-_{SF} = \omega_{SDE} - E_z \rightarrow 0$

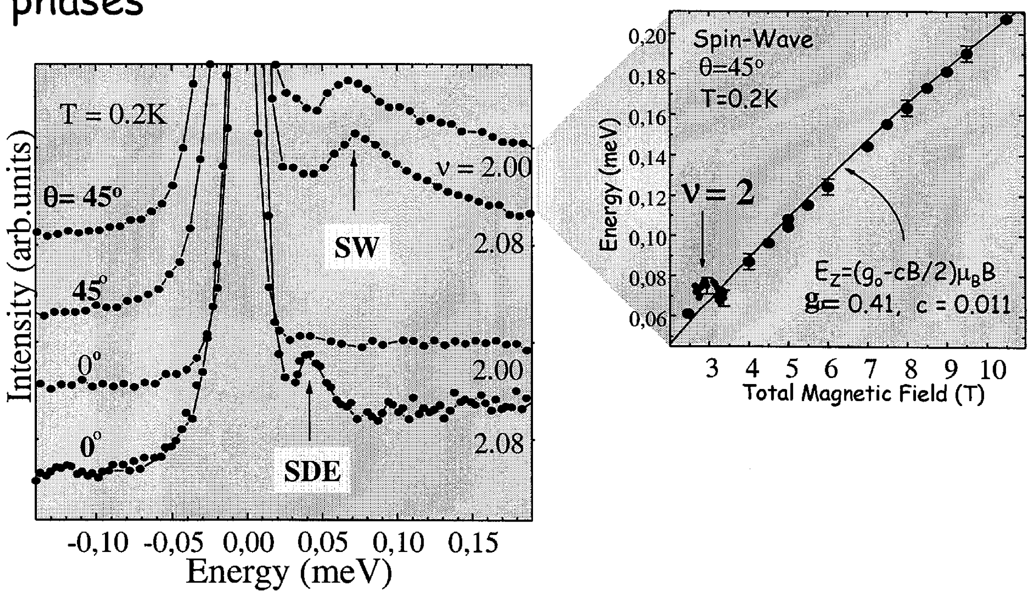
Tilted field behavior

- Tunneling amplitude decreases
- Zeeman energy increases

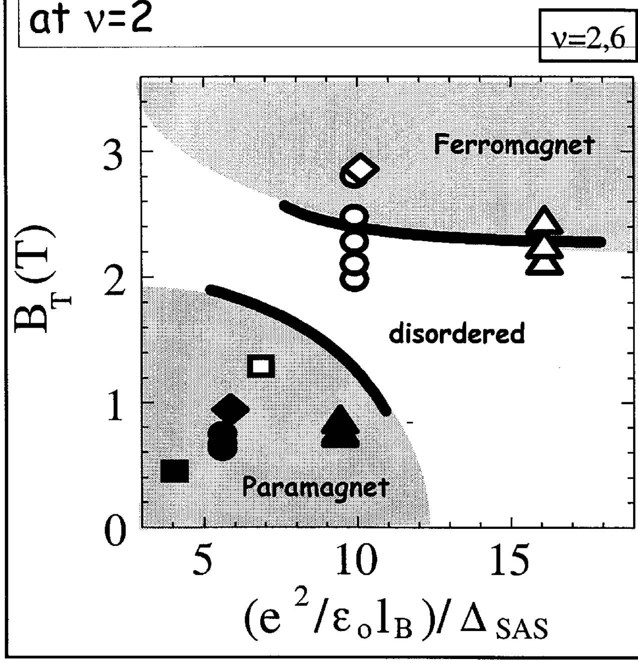




Inelastic light scattering signatures of three spin phases



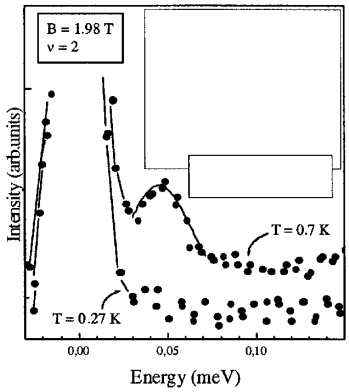
Phase diagram of coupled double quantum well at ν=2

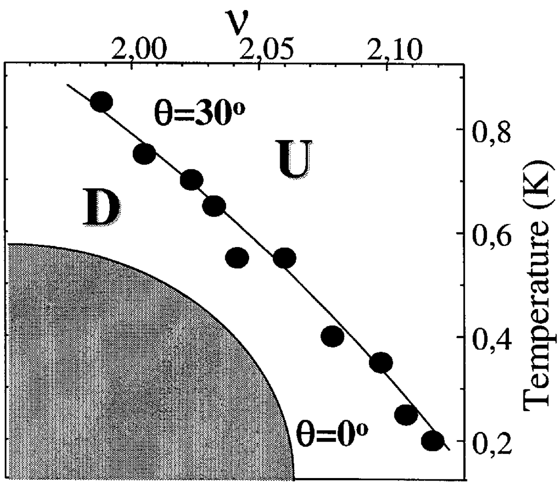


Order parameter:
$\delta S_+ = \delta(S_x - iS_y)$
Broken symmetry
canted antiferromagnetic state

L. Zheng et al. PRL (1997)
S. Das Sarma et al PRL (1997)
J. Schliemann, et al. PRL (2000)

Finite temperature phase transition





S. Das Sarma, S. Sachdev, L. Zheng, PRL (1997)
M. Troyer, S. Sachdev, PRL (1998)

Conclusion ν=2

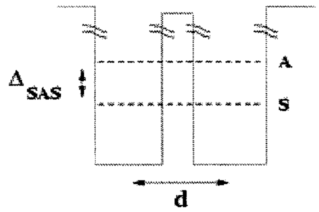
- Collapse of the Spin-density excitations
- Excitonic instability
- Observation of an intermediate "disordered" phase
- The transition appears as a continuous QPT
- Finite-temperature phase transition

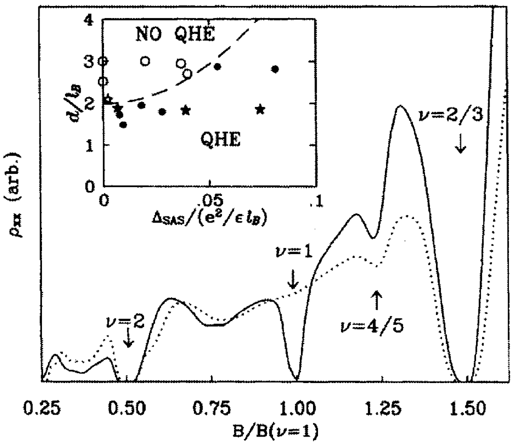
Bilayers at ν=1

S. Luin, VP et al. *Phys. Rev. Lett.* (2003)
S. Luin, VP et al. *Physica E* (in press)
S. Luin, VP et al, *Solid State Communications* (2003)

Inspired by...experiments

Bilayers at ν=1:
phase transition





G. S. Boebinger *et al.*, Phys. Rev. Lett. **64**, 1793 (1990)
S. Q. Murphy, J. P. Eisenstein, *et al.*, Phys. Rev. Lett. **72**, 728 (1994)

Inspired by...HF calculations

H. A. Fertig, Phys. Rev. B **40**, 1087 (1989).

H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. Lett. **65**, 775 (1990)

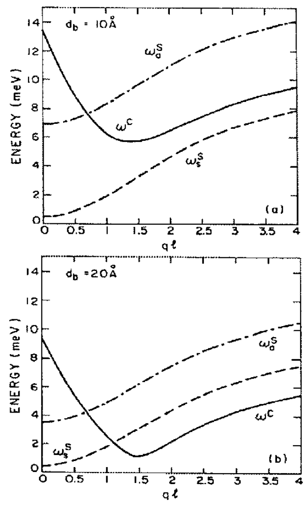
L. Brey, Phys. Rev. Lett. **65**, 903 (1990)

X.M. Chen and J.J. Quinn, Phys. Rev. Lett. **67**, 2113 (1991)

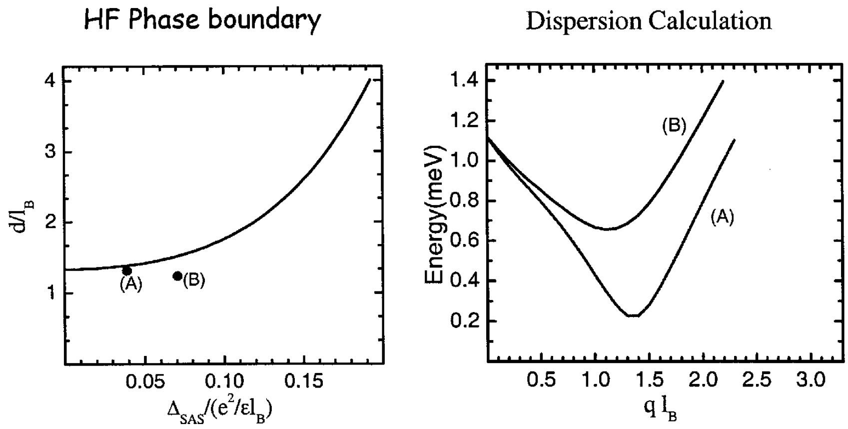
R. Côté and H.A. Fertig, Phys. Rev. B **65**, 085321 (2002)

Y. N. Joglekar, A. H. MacDonald, Phys. Rev. B **65**, 235319 (2002)

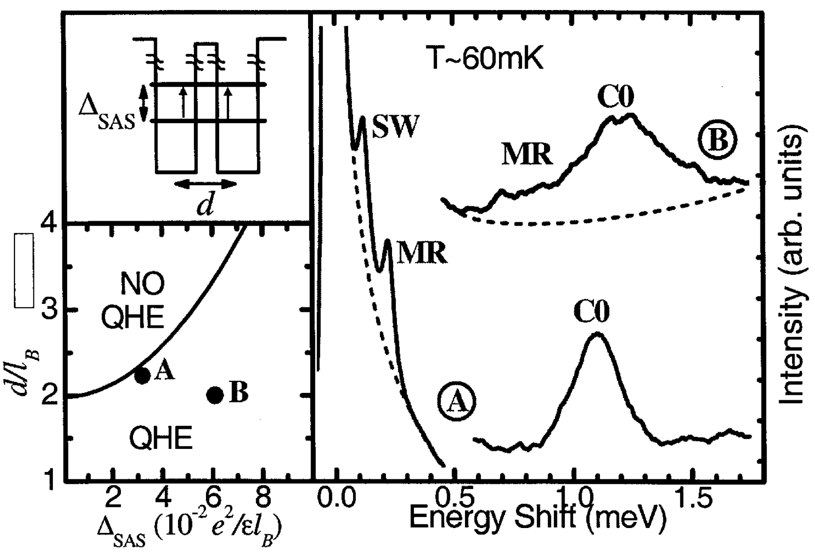
..and many others....



Time dependent Hartree-Fock Theory

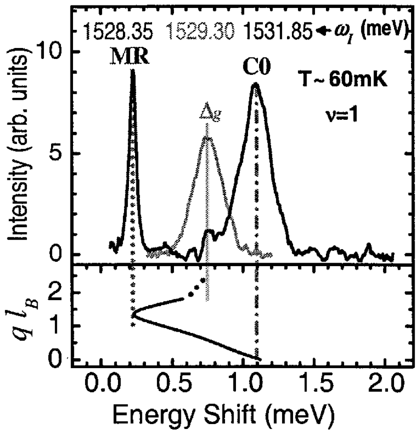


Observation of roton minimum at ν=1

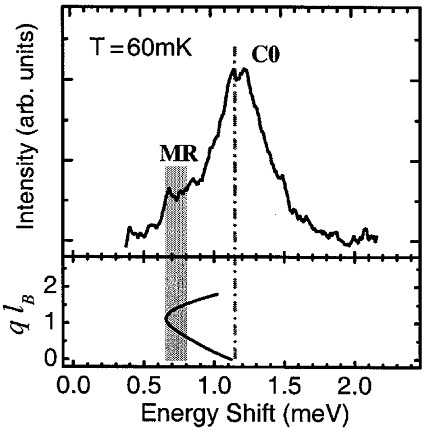


Magneto-roton softening

Close to phase transition



Far from phase transition

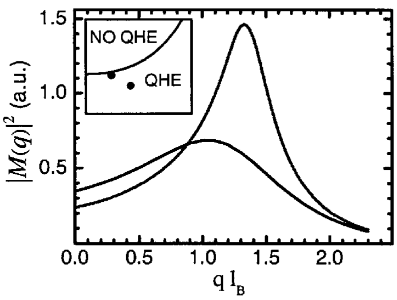


Magnetorotons soften and sharpen approaching the phase boundary

Sharpening of magnetoroton

Oscillator strength

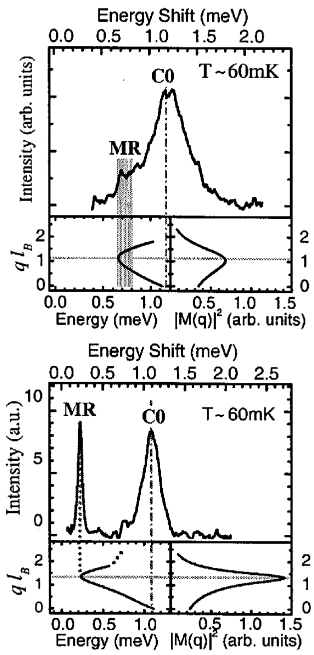
$$I(\omega) \leftarrow S(q,\omega) \propto |M(q)|^2 \frac{\omega_C(q)\omega\Gamma}{[\omega^2 - \omega_C^2(q)]^2 + \omega^2\Gamma^2}$$



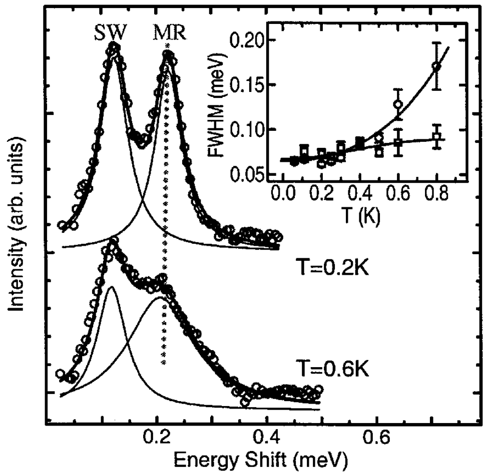
$$I(\omega) \sim \int S(q',\omega) f(q';\alpha,q)\, dq'$$

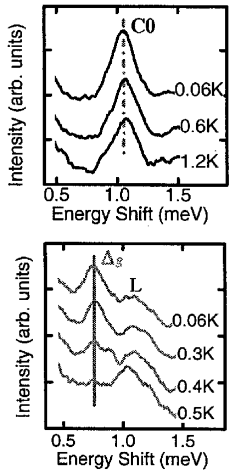
I. K. Marmorkos and S. Das Sarma, Phys. Rev. B **45**, 13396 (1992)

$$G(r) \leftrightarrow \iint S(q,\omega)\, d\omega\, e^{-iqr}\, dq \sim \int |M(q)|^2 e^{-iqr}\, dq$$



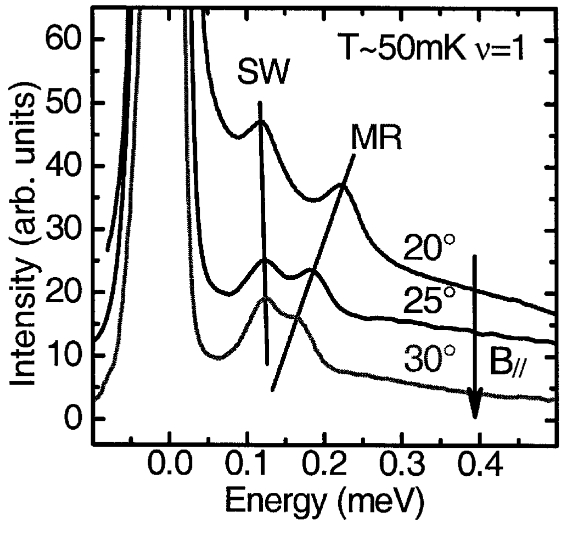
Temperature dependence





Temperature fluctuations destroy the structure in the QH liquid

Tilted fields: on-going work



Conclusion ν=1

- Observation of magneto-rotons
- Softening and sharpening of rotons
- HF accounts semi-quantitatively for the experimental results
- Lineshapes and temperature-dependence suggest the role of correlations: evidence for a broken-symmetry state