the temperature variation of the nucleation limit at high pressure, as we did at low pressure for the cavitation limit.

It seems that, by repeatedly asking naive questions on the effect of high intensity acoustics in both liquid helium and water, on surface tensions and on the way that stable nuclei appear when matter changes state, we have encountered several unsolved problems. We have found a few answers to several questions, but a lot remains to be understood.

About the author

Sebastien Balibar leads a research group at the ENS in Paris. His main achievements concern roughening and other surface porperties of crystals, quantum evaporation, wetting and critical phenomena, nucleation of bubbles and crystals using acoustic waves.
e-mail: balibar@lps.ens.fr
http://www.lps.ens.fr/~balibar/

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Shining light on electron quantum liquids in two dimensions

Vittorio Pellegrini[1] and Aron Pinczuk[2,3]
[1] NEST-INFM and Scuola Normale Superiore, Pisa, Italy;
[2] Dept. of Applied Physics and Applied Mathematics and Dept. of Physics, Columbia University, New York, USA;
[3] Bell laboratories, Lucent Technologies, Murray Hill, New Jersey, USA

The itinerant carriers that play pivotal roles in many of the properties of a solid originate from the valence electrons of constituent atoms. A simple assembly of itinerant electrons at densities of conventional metals behaves as a liquid of fermions that supports well-known electrical transport properties and collective behaviour with excitations such as plasma waves. The early work of E.P. Wigner and F. Bloch created an awareness of the intricate many-electron physics that may emerge when reaching the low-density limit [1]. As the electron density reduces, new highly correlated phases are expected as quantum mechanical interactions dictate key behaviours of the electron assembly. The difficulties in achieving the required low critical values of the density in high quality systems with very long electron relaxation times hinder the manifestation of broken-symmetry phases such as the electron crystal and ferromagnetic state proposed by Wigner and Bloch.

The endeavours linked to the creation, study and manipulation of new collective electron phases are among the most central areas of contemporary condensed-matter science. A key development in these branches of fundamental and applied science, that continues to have a major impact on current research, was the introduction of modulation-doped semiconductor quantum structures at the end of the 70's [2]. This advance in fabrication, by Molecular Beam Epitaxy (MBE) methods [see Figure 1a], enables creation of electron fluids in two dimensions (2D) in which scattering due to imperfections is highly suppressed to levels below those of intrinsic mechanisms (phonons) even at the lowest temperatures. The availability of nearly perfect electron systems in modulation-doped artificial quantum structures has stimulated the phenomenal expansion of studies of low-dimensional systems that continues to the present [3].

The discoveries of the integer and fractional quantum Hall effect are key milestones in condensed matter sciences [4,5]. The search for the elusive electron-crystal state in modulation-doped quantum structures led to the unexpected discovery of fractional quantization of the Hall effect of the two-dimensional electron gas in a perpendicular magnetic field [5]. The transport signatures of the fractional quantum Hall effects are seen as macroscopic manifestations of a quantum fluid in which the highly correlated electron liquid is represented by a quantum state with a single many-particle wave function [6]. Experimental and theoretical studies of quantum Hall electron liquids have uncovered some of the more intriguing many-body behavior in contemporary physics. The multiplicity of quantum Hall states seen in superior quality systems at low temperatures [see Figure 1d] can be regarded as sequences of 'compressible' (metallic) and 'incompressible' (insulating) states that occur as the external

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magnetic field changes. These are quantum phase transitions (QPT) that emerges at constant temperature ($T \rightarrow 0$) and are driven by changes in interactions linked to changes in magnetic field [7].

Quantum Hall liquids have characteristic low-energy collective excitations that represent time- and space-dependent oscillations of the charge or the orientations of spin of the many-electron system. The excitation modes are described by characteristic energy vs. wave-vector dispersions [8]. In continuous QPT's the transformations are linked to softening of low energy excitation modes, because the energy required to cause the change that is associated with the collective mode coordinate vanishes. This softening thus induces an instability in which the 2D electron system changes quantum ground state by incorporating properties associated with the excitation. When the soft mode has vanishingly low energy ($\omega \rightarrow 0$), the spontaneous broken symmetry phase has a continuous order parameter that vanishes at the critical point of the transition [9].

In this article we describe inelastic light scattering methods that explore the collective excitation spectra of remarkable electron fluids in the quantum Hall regimes. Light scattering measurements access spin and charge excitations and offer unique insights on the ground-state configurations of the electron quantum liquids and on the QPT's that link the different states. This introduction is followed by a short overview of quantum Hall liquids and their excitations. We continue with a description of the conceptual framework that applies to light scattering processes in 2D electron layers in semiconductors. We end with a description of recent results from spin-aligned quantum Hall ferromagnets that highlight the physics of electron quantum fluids in two dimensions that is revealed by inelastic light scattering experiments.

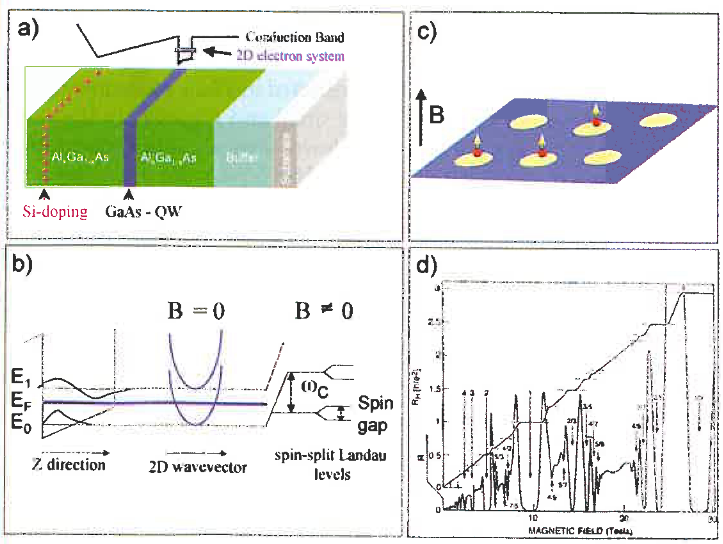
Quantum Hall systems

Figure 1a shows a typical layer sequence of a modulation-doped (Si-doping) quantum well GaAs/$Al_xGa_{1-x}As$ sample. The design of the artificial structure allows fine control of parameters such as density, mobility and level splitting. In the quantum structures designed for optical experiments the aluminium composition is kept at $x \leq 10\%$ to minimize the impact of layer width fluctuations and other disorder [11]. Low-temperature electron mobility above 5×10^6 cm^2/Vs are typical for these samples. Free electron density below 10^9 cm^{-2} was reported [12]. As shown in Fig. 1b, in a magnetic field B perpendicular to the 2D plane the in-plane kinetic energy becomes quantized into discrete macroscopically-degenerate Landau levels (LLs), and coupling of B to electron spin further splits each LL into spin-up and spin-down states separated by the Zeeman energy E_Z (spin gap). Landau level quantization is linked to cyclotron motion of the electrons with orbits of semiclassical radius related to the magnetic length $l_0=(\hbar c/eB)^{1/2}$ as shown in Fig.1c. This orbital motion defines the cyclotron gap $\omega_C=(eB/m_ec)$, where m_e is the electron effective mass, that separates LLs with same spin. The filling factor $\nu=n2\pi(l_0)^2$ defines the number of occupied LLs. For integer or 'magic' fractional values of ν, the longitudinal resistivity ρ_{xx} is vanishingly small and the Hall resistance R_H is quantized with extreme precision at values $h/\nu e^2$ (see Fig.1d). The pioneering experiments by Klaus von Klitzing, Gerhard Dorda and Michael Pepper [4], and by Horst Stormer, Dan Tsui and Art Gossard [5] and the theoretical work done by Robert Laughlin [6] led to Nobel prizes in Physics in 1985 and 1998 for the discoveries and interpretations of the quantum Hall effects.

Figure 1d shows that there is absence of dissipation in quantum Hall states at the lowest temperatures. The longitudinal conductivity in a perpendicular magnetic field

$$\sigma_{xx}=\rho_{xx}/(\rho^2_{xy}+\rho^2_{xx}),$$

shows that the quantum Hall states are also insulating ($\sigma_{xx} \rightarrow 0$), i.e. there is a gap in their excitation spectrum. The gaps in the integer ν states (IQHE) can be understood in terms of cyclotron or spin gaps. In states with fractional ν (FQHE) the gaps are linked to the emergence of 'incompressible' quantum liquids [6] driven by fundamental electron interactions. The quantum liquids emerge in response to the deceptively simple Coulomb repulsion in 2D and the Pauli principle that applies to fermions. In recent years light scattering spectroscopy has evolved into a primary experimental tool for the study of gap excitations in the quantum Hall regimes, and offer direct tests of key predictions of theories of the electron fluids. In studies of the quantum fluids of 2D electron systems in perpendicular magnetic fields light scattering experiments play roles similar to neutron and X-ray scattering studies of elementary excitations in superfluid liquid Helium.



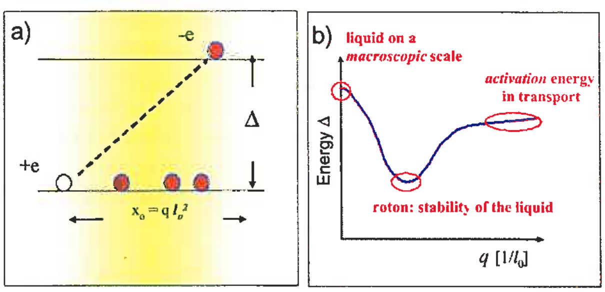
◄ **Fig. 1:** a) Sequence of layers in a typical GaAs/AlGaAs modulation-doped heterostructure grown for light scattering studies. The conduction-band profile along the growth axis is also shown. The high-mobility 2D electron system resides in the GaAs quantum well. Buffer and substrate layers are of GaAs. b) From left to right: schematic of the two lowest quantized energy levels E_0 and E_1 and wave functions along the growth direction; E_F is the Fermi energy. Sketch of the subband dispersion as a function of the in-plane wave-vector at zero magnetic field B. Quantization of the in-plane kinetic energy into Landau levels under the application of B. $\omega_c=eB/m_ec$ ($m_e=0.067m_o$ is the effective electron mass in the GaAs semiconductor with m_o being the free electron mass) is the cyclotron gap. $E_Z=-g\mu_BB$ (g=-0.44 is the effective gyromagnetic factor in the GaAs, μ_B the Bohr magneton) is the Zeeman energy (spin gap). c) Schematic semi-classical representation of electrons with spin moving into cyclotron orbits in a perpendicular magnetic field. The drawing shows occupied and empty states in the lowest Landau level with filling factor $\nu<1$. Vertical arrows identify the orientation of the spin. d) Manifestations of the integer and fractional quantum Hall effects in magneto-transport experiments. The values of the quantized values of ν are also shown (after Ref.[10]).

Collective modes of quantum Hall liquids

Collective excitation modes of quantum Hall states are built from neutral particle-hole pair transitions. In these excitations a quasi-particle is promoted to an empty state and a quasi-hole is created in the ground state as shown schematically in Fig.2a. In excitations of the charge degree of freedom the spins of the particle and hole are identical. In spin excitations there is a spin flip. These pairs are the building block of the collective modes and can be regarded as magnetic-excitons with a dipole length x_0 [3,8], where x_0 represents the displacement between the centers of the two cyclotron orbits (see Fig.2a). From a semiclassical point of view, the balance between the Lorentz and Coulomb forces leads to a center-of-mass velocity of the neutral pair that is inversely proportional to the separation between the particles. The excitonic pairs are thus characterized by the in-plane wavevector **q** that is a quantum number for the excitation with $x_0 = q l_0^2$. The coupling between particle and hole in the neutral pairs gives rise to many-body terms that have a strong q-dependence [3]. The roton (or magneto-roton), a minimum of the dispersion at finite wavevector of the order of $1/l_0$, is the characteristic manifestation of these interactions. It is caused by excitonic terms (called vertex corrections) of the Coulomb interaction that bind particle-hole pairs and greatly reduce their energy. Figure 2b shows the roton in the dispersion of charge excitation modes (CDE) predicted at $\nu=1/3$ [13]. At the roton wavevector there is a peak in the structure factor of the quantum Hall liquid in analogy with that for excitations in superfluid He^4. As the lowest energy excitation of the liquid, the magneto-rotons are barometers of its stability. Roton instabilities have been predicted to trigger transitions from liquid to Wigner crystal states [13,14].

Different Coulomb interaction terms enter in the dispersions of spin and charge modes. In CDE (see caption to Fig.2), the direct term of the Coulomb interaction (depolarization term) adds to the excitonic term mentioned above, and to differences in self-energy contributions. In spin excitations the depolarization shift is absent. In the large-wavevector limit both excitonic and direct terms of Coulomb interactions vanish and the mode energy is given by the self-energy terms summed to additional single particle contributions such as cyclotron gaps. However, in the FQHE regime, the lowest collective CDE are intra-Landau level excitations and the opening of the gap is a purely many-body effect. The large wavevector limit ($q \to \infty$) represents infinitely separated particle-hole pairs. The energies of the lowest charge excitations at $q \to \infty$ are conceptually linked to the gaps measured in temperature-activated magneto-transport.

In the case of spin modes there is also an additional contribution due to the Zeeman gap. There are spin wave excitations in which only spin changes, and spin-flip excitations in which other quantum numbers change too (see caption to Fig.2).



▲ Fig. 2: a) Schematic representation of the particle-hole pairs (magneto-excitons) that enter in the construction of the collective excitations with in-plane wavevector **q**. In the integer quantum Hall regime Δ is the single-particle gap that separates Landau levels with different quantum numbers and /or spin. In the fractional quantum Hall regime Δ is the many-body gap that opens due to electron-electron interactions. The neutral pairs in the collective mode in conduction-band states of GaAs heterostructures can be classified according to a change in the total angular momentum J. Excitations with $\Delta J=0$ are the singlets of charge-density modes (CDE). Excitations with $\Delta J=1$ are triplets in which the spin degree of freedom is changed. Those are spin-density modes without a fluctuating charge density and spin-flip excitations. b) Representative wave-vector dispersion of CDE mode. The dispersion applies, for instance, to the intra-Landau level excitations in the fractional quantum Hall state at filling factor $\nu=1/3$. The three critical points correspond to the long wavelength limit (q=0) conventionally probed in optical experiments, to the lowest energy excitations at the roton minimum and to the long wave-vector limit ($q \gg 1/l_0$) relevant in magneto-transport studies.

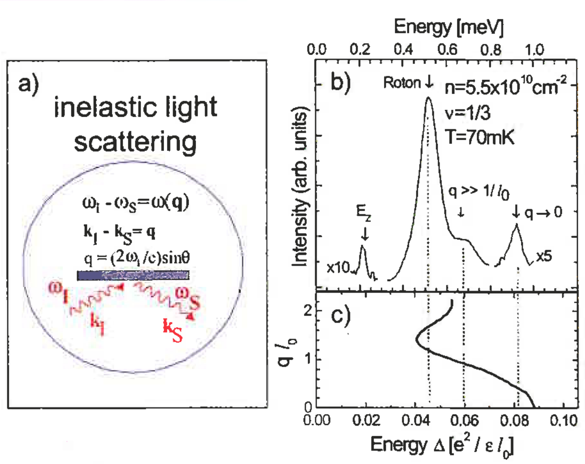
Inelastic light scattering from quantum Hall liquids

This section presents a basic conceptual framework that applies for resonant inelastic light scattering spectroscopy of collective modes of quantum Hall liquids. First we recall that the kinematics of the light scattering process is dictated by conservation of energy and momentum. In a translational invariant system expected in quantum structures in absence of disorder, conservation of momentum implies conservation of wave-vector (see Fig.3a).

Conservation of energy implies that $\omega_I - \omega_S = \pm\omega(\mathbf{q})$ (see Fig.3a) where I and S refer to incident and scattered photons. The ± signs apply to Stokes and anti-Stokes processes respectively and $\omega(\mathbf{q})$ is the collective-mode energy at the in-plane wavevector **q**. Large resonant enhancements, that are required to observe the excitations of 2D electron systems, occur when ω_I and ω_S overlap the energies of optical transitions of the semiconductor quantum structure that hosts the 2D electron system. Within time-dependent perturbation theory the resonant light scattering amplitude includes two virtual intermediate valence-to-conduction band optical transitions. Light scattering by spin excitations with change in the total angular momentum $\Delta J=1$ (see caption to Fig.2) are made possible by spin-orbit coupling in the valence states of the semiconductor. It can be shown that charge- (CDE) and spin-density excitations (SDE) can be separated by specific polarization selection rules. Light scattering by CDE or SDE tends to be stronger when the two polarization vectors of incident and scattered light are parallel or orthogonal, respectively.

An important aspect of resonant inelastic light scattering processes is related to the transferred in-plane component of the wave-vector **q**. This value is small and typically in the range $q \cdot l_0 \leq 0.2$ ($l_0 \approx 10$nm). Breakdown of wavevector conservation, however, can occur in quantum Hall liquids due to the impact of dephasing mechanisms associated either with residual disorder in the insulating phases or thermally activated by temperature. Light scattering processes with breakdown of wavevector conservation, particularly effective under strong resonance conditions, allow probing excitations at the critical points of the mode dispersions such as the ones at the magneto-roton minimum.

Figure 3b shows an example of a rich light scattering spectrum obtained in the FQHE at $\nu=1/3$ under resonant conditions (the incident laser light is close to the fundamental band-gap of the GaAs heterostructure). Figure 3c shows the calculated dispersion of the lowest CDE mode (the FQHE gap excitation). The spectra clearly display the three major excitations associated to the critical points of the dispersive CDE and, in addition, the spin-wave mode E_Z at the Zeeman gap. The observation of the q=0 CDE excitation



▲ **Fig. 3:** a) Kinematics of inelastic light scattering. b) Inelastic light scattering spectrum (Stokes side) in the fractional quantum Hall effect at ν=1/3 of the high mobility 2D electron system in a GaAs quantum structure. The horizontal axis is $\omega_I - \omega_S = \omega(\mathbf{q})$. The three relevant modes associated to the critical points of intra-Landau level dispersive collective CDE mode are clearly resolved. The spin-wave SW mode across the Zeeman gap is also visible (after Ref.[15]). c) Dispersion of the collective mode at ν=1/3 (after Ref. [16]).

is intriguing since the S(q,ω) for charge modes in the FQHE is predicted to vanishes as q^4 for small wavevectors [13]. This observation thus highlights the impact of strong resonance enhancements. It also offers direct experimental tests for possible new interpretation of the character of the long-wavelength CDE such as the one in terms of a two-roton bound state [15]. Inelastic light scattering spectra by low-lying rotons of spin excitations have also been reported in the FQHE at ν=2/5 [17].

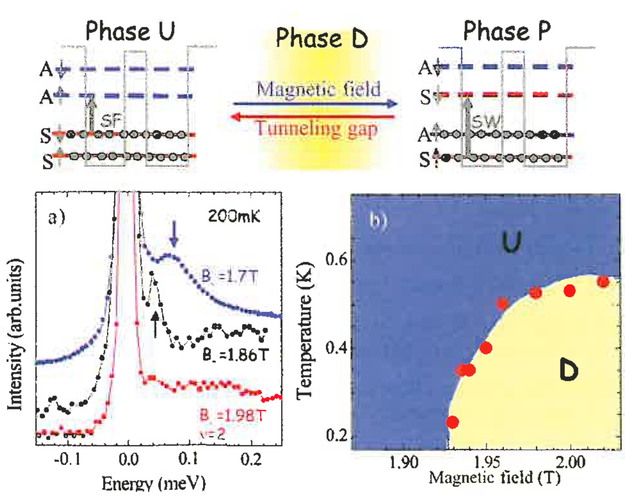
Finally we remark that these light scattering experiments require extreme sensitivity, large stray-light rejection and great spectral resolution. These characteristics are achieved by a combination of single-mode tunable lasers with very small linewidths, double or triple spectrometers and small-pixel CCD detectors. In order to keep the electron temperatures at the ultra-low values required for these studies, typical incident powers are kept below 10^{-3} W\cm^2.

Instabilities in quantum Hall magnets

The observation of spin modes by inelastic light scattering opens research avenues for the study of the spin polarization of quantum Hall liquids. In several cases, the spin properties of such quantum Hall states are highly non-trivial and driven by many-body Coulomb interactions. At ν=1, for example, exchange interaction effects can lead to spontaneous ferromagnetism which in fact can persist even in the limit E_Z=0. The ground state in this configuration is an exceptionally strong itinerant ferromagnet. More exotic ferromagnetic states can be created in bilayer quantum Hall liquids. These systems are composed of two 2D electron layers in close proximity. Here the new degree of freedom associated with layer occupation (described by a *pseudospin* quantum number) creates electron *inter-layer* correlation effects that have no counterpart in the single-layer case. This is the source of novel ground states with peculiar spin and pseudospin properties that are linked through QPTs.

In this section we review our light scattering experiments in bilayer quantum Hall systems that reveal soft (low-energy) excitations at QPTs. These experiments are carried out in modulation-doped double quantum well samples that consist of two identical 18-nm thick GaAs quantum wells separated by an $Al_{0.1}Ga_{0.9}As$ undoped barrier (see Fig.4 upper part, grey lines). One intriguing example of QPT occurs at the total filling factor ν=2. Tunneling between the two layers determines the splitting Δ_{SAS} (bare tunnelling gap) of the lowest symmetric S and antisymmetric A states as sketched in the upper left panel of Fig.4. The spin configuration of the bilayer depends on the interplay between Δ_{SAS} and the bare Zeeman energy E_Z. When $\Delta_{SAS} \gg E_Z$, electrons occupy the lowest spin-split S levels and the electron spin polarization in this phase, called phase U, is zero. This configuration shown in the left upper panel of Fig.4 is a spin-singlet quantum Hall paramagnet.

The lowest energy spin excitations are triplets (ΔJ=1) across the tunnelling gap. These excitations are classified according to the change of angular momentum along the magnetic field. $\Delta J_z = \pm1$ are spin-flip (SF) modes (one of these two modes is shown in the upper left part of Fig.4) while ΔJ_z=0 mode corresponds to the SDE. Within the Hartree-Fock approximation their energies are given by $\omega=\omega_{SDE}\pm E_Z\cdot\Delta J_z$ where ω_{SDE} is the SDE energy. In the opposite limit $\Delta_{SAS} \ll E_Z$ (shown in the right upper panel of Fig.4) the electrons are fully spin polarized (phase P). This quantum Hall ferromagnet supports characteristics spin-wave (SW) modes across the Zeeman gap.



▲ **Fig. 4:** Upper panel: Schematic representation of the potential in the conduction band of the GaAs/AlGaAs double quantum well. The spin-split symmetric (S) and anti-symmetric (A) levels are also shown. Landau level occupations correspond to filling factor ν=2. SF and SW indicate transitions that enter in spin-flip excitations across the tunnelling gap and spin-wave excitations across the Zeeman gap. Phase U is spin unpolarized. Phase P is polarized. An intermediate state with unusual properties, probably linked to disorder, emerges in phase D when the magnetic field increases or the bare tunnelling gap decreases. a) Resonant inelastic light scattering spectra with orthogonal linearly-polarized incident and scattered photons. The peaks labelled with an arrow correspond to the **q**=0 ΔJ_z=0 spin-density excitation (SDE). At ν < 2.13 (B = 1.86T) the SDE disappears from the spectra and signals the transformation from phase U to phase D. The background at positive energies is due to luminescence. b) Finite-temperature phase diagram constructed from light scattering results. The phase boundary shown by the red dots is given by the lowest value of the critical temperature at which the SDE peak reappears in the spectra as a function of the magnetic field.

The q ≈0 SDE is the unstable collective mode discovered in light scattering studies of phase U [18]. Its energy is strongly reduced with respect to the value at zero magnetic field due to excitonic corrections that are maximized at ν=2. The impact of this excitonic correction enhancement is shown in Fig.4a where three representative light scattering spectra are displayed. While the SDE mode at B=0 is found at a energy close to 0.5meV (not shown), at 1.7T the mode energy has already diminished to 0.065meVand at 1.86T it has collapsed to the remarkably low value of 0.045meV, which is equal to the value of the Zeeman gap at that magnetic field.

The sudden disappearance of the SDE mode after a further small increase in magnetic field (see the red spectrum in Fig.4a at 1.98T) is interpreted as a soft-mode instability towards a disordered broken-symmetry intermediate phase D that emerges before phase P occurs at higher magnetic fields [18]. The emergence of phase P is monitored by the appearance of the SW in the light scattering spectra. The light scattering results shown in Fig.4a reveal that phase D occurs when the SDE collapses to E_Z and therefore when the spin-flip mode with ΔJ_z=1, shown in the upper left part of Fig.4, softens to vanishingly low energies ($\omega_{SF} = \omega_{SDE}$-$E_Z \approx 0$).

These experiments thus uncover a link between a QPT in the spin degree of freedom and the collective mode (excitonic) instability [18,19]. Further support for the existence of an intermediate broken-symmetry two-dimensional electron state linked to phase D comes from the analysis as a function of temperature. These studies show that the SDE peak that had disappeared at T=200mK when the electron bilayer is in phase D, recovers at higher temperatures. The abrupt appearance of the SDE excitation at a critical temperature is interpreted as a finite-temperature D→U transition. Figure 4b summarizes the observed critical temperatures (red dots) as a function of B.

Resonant light scattering methods offer... unique venues for investigations of the novel behaviours.

Intriguing soft mode behaviour in the spin and *pseudospin* degree of freedoms have been observed in our most recent light scattering experiments in coupled bilayers at total filling factor ν=1 [20,21]. Here the lowest spin excitations are SF transitions across the tunnelling gap and SW. Within the Hartree-Fock approximation the energy spacing of these excitations at **q**=0 is given by the bare tunnelling gap Δ_{SAS}. The signatures of instabilities are here associated with the marked collapse of the SF mode towards the SW energy as an in-plane component of the magnetic field is applied while keeping the filling factor (i.e. the perpendicular component of B) constant at ν=1. The SF collapse is associated with an abrupt change in the energy and temperature dependence of the SW. Although this work is still in progress these unexpected observations suggest that at the critical in-plane magnetic field an unusual situation emerges due to the suppression of the impact of the bare tunnelling gap on the collective properties of the electron bilayer.

Outlook

More than 70 years after Wigner and Bloch offered a glimpse of the exciting world that emerges from fundamental interactions in many electron systems, research on the infinitely diverse low-dimensional systems is at the frontiers of condensed-matter science. Resonant light scattering methods offer to these fields unique venues for investigations of the novel behaviours. In this article we have briefly touched on quantum Hall liquids in which new collective spin states can be created and manipulated for them to develop unstable excitations linked to quantum phase transitions. Among examples we have considered is the intriguing role of magneto-rotons that soften due to exciton-like interactions to drive phase transformations to exotic quantum liquids of electrons. This is just one of the multiple roles we envision for light scattering in studies of the remarkable fundamental collective behaviour of electrons in low-dimensional structures.

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