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.

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References

Shining light on electron quantum liquids in two dimensions

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magnetic field changes. These are quantum phase transitions (QPT) that emerge at constant temperature ($T \to 0$) 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 ($\omega \to 0$), 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$_x$Ga$_{1-x}$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 $x < 10\%$ to minimize the impact of layer width fluctuations above $5 \times 10^6$ 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 $l_B = (\hbar c/eB)^{1/2}$ as shown in Fig.1c. This orbital motion defines the cyclotron gap $\omega_c = (eB/m_e)$, where $m_e$ is the electronic effective mass, that separates LLs with same spin. The filling factor $v = n_2l_B^2$ defines the number of occupied LLs. For integer or ’magic’ fractional values of $v$, the longitudinal resistivity $\rho_x$ is vanishingly small and the Hall resistance $R_H$ is quantized with extreme precision at values $h/e^2$ (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 ($\sigma_{xx} \to 0$), i.e. there is a gap in their excitation spectrum. The gaps in the integer $v$ states (IQHE) can be understood in terms of cyclotron or spin gaps. In states with fractional $v$ (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.

![Figure 1](attachment:image1.png)
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 by neutral particle-hole pair transitions. In these excitations a quasi-particle is promoted to a state of zero energy.

Collective excitation modes (CDE) predicted at \( v = \frac{1}{3} \) [13]. At the roton minimum of the dispersion at finite wavevector of the order of \( \frac{1}{l_0} \), the lowest energy excitation of the liquid, the magneto-rotons are relevant in magneto-transport studies. Within time-dependent perturbation theory the resonant light scattering amplitude includes two virtual intermediate valence-to-conduction band optical transitions. 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 \( q l_0 \lesssim 0.2 \) (\( l_0 \sim 10 \text{nm} \)). 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 \( v = \frac{1}{3} \) 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 (SDE) can be separated by specific polarization selection rules.
is intriguing since the S(q,ω) for charge modes in the FQHE is predicted to vanish as q→0 for small wavevectors [13]. This observation thus highlights the important role of spin excitations in 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 thus highlights the impact of strong resonance interactions that enter in spin-flip excitations across the tunnelling gap. These excitations are classified according to the spin-split 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 ΔSDE and the bare Zeeman energy Ez. When ΔSDE ≫ Ez, 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 upper left panel of Fig.4 is a spin-singlet quantum Hall paramagnet.

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 v=1, for example, exchange interaction effects can lead to spontaneous ferromagnetism which in fact can persist even in the limit Ez=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.

instabilities in quantum Hall magnets

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 AlAs undoped barrier (see Fig.4 upper part, grey lines). One intriguing example of QPT occurs at the total filling factor v=2. Tunneling between the two layers determines the splitting ΔSDE (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 ΔSDE and the bare Zeeman energy Ez. When ΔSDE ≫ Ez, 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 upper left 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. ΔJz = ±1 are spin-flip (SF) modes (one of these two modes is shown in the upper left part of Fig.4) while ΔJz = 0 mode corresponds to the SDE. Within the Hartree-Fock approximation their energies are given by ω=ωSDE±EzΔJz where ωSDE is the SDE energy. In the opposite limit ΔSDE ≪ Ez (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.

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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 v = 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 an energy close to 0.5meV (not shown), at 1.7T the mode energy has already diminished to 0.065meV and at 1.86T it has collapsed to the remarkably low value of 0.0455meV, 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 Δ_3 = 1, shown in the upper left part of Fig. 4a, softens to vanishingly low energies (ω_{SE} = ω_{SDE} - E_z = 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.

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 v = 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 v = 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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