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# L'EFFET HALL QUANTIQUE FRACTIONNAIRE
## *THE FRACTIONAL QUANTUM HALL EFFECT*

## Foreword

The quantum Hall effect is one of the most beautiful macroscopic manifestations of quantum mechanics in condensed matter. The phenomenon is observed in a two-dimensional electrons gas (2DEG) at low temperature placed in a high perpendicular magnetic field. The Integer Quantum Hall effect discovered more than twenty years ago has provided us with a metrological definition of the resistance based on quantum units. This was followed two years later by the discovery of the Fractional Quantum Hall Effect (FQHE) which is the topic of the present Dossier. FQHE was soon theoretically recognized as fundamentally able to generate fractionally charged excitations. This counter-intuitive prediction, in (only) apparent contradiction with Millikan's experiments on integer charges, has been definitively confirmed by recent shot noise experiments providing a direct detection of the fractional charges. The Fractional Quantum Hall Effect has completely renewed our understanding of quantum fluids. The physics is driven by the cyclotron orbit quantization, the filling factor $\nu = n_s/n_\phi$, which measures the electron density $n_s$ in units of the density $n_\phi$ of flux quantum $h/e$, and the Coulomb interaction. These ingredients are the simplest one can imagine. No interaction with the host material is needed as in the case of superconductivity. However the topology associated with the 2D confinement is a key ingredient and is responsible for completely new kinds of excitations. Topological fractionally charged excitations with fractional anyonic or exclusonic quantum statistics, composite fermions or composite bosons, skyrmions, etc., ..., are the natural elementary excitations required to understand the quantum Hall effect. These concepts go beyond the field of the FQHE and might be useful for the studies of 1D quantum systems, such as carbon nanotubes, anisotropic organic conductors, and the electronic transport in molecules, a field of growing importance. The concept of fractional excitations may also stimulate experiments in the new field of cold atom traps and Bose–Einstein condensates in confined geometries.

The present Dossier only addresses some of the most recent and vivid investigations of the fundamental properties of FQHE. The selected topics are: the fundamental spin polarization and possible elementary excitations called skyrmions, the physics of the edge excitations (Luttinger liquid properties and fractional excitations) and the physics of a bi-layer system with possible connection with Bose–Einstein condensates.

The competition between exchange correlation energy and Zeeman energy makes the physics of the FQHE very rich with a variety of possible quantum phase transitions including spontaneous spin polarization (ferromagnetic state), partially or fully unpolarized states with the possibility of finding new topological excitations, the skyrmions. The first contribution by Melinte et al. (pp. 667–676) addresses these topics. The present understanding of the fundamental spin polarization in FQHE is reviewed. The authors report experimental results on transport and specific heat measurements. Here the weak coupling between electron spins and nuclear spins of the host material allows specific heat to be sensitive to spin excitations and to possible spin phase transitions. Evidence for a transition from skyrmions to single spin-flip excitations around $\nu = 1$ is presented and the polarization of the $4/3$ fractional state is investigated.

The physics of the one-dimensional chiral edge excitations which carry the current at the boundary of a fractional quantum Hall fluid is also an important field of investigations in FQHE. First, the edge excitations are the only known convincing realization of a Luttinger liquid. This is a test bench for probing our theoretical understanding. Improving our knowledge of edge excitations is of crucial importance for further investigation of other possible realizations of Luttinger liquids, provided by 1D molecular conductors such as carbon nanotubes and some anisotropic organic conductors. Second, the shot noise properties of the


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chiral 1D conductors formed at the edges have recently allowed the first experimental observation of fractionally charged carriers. Current correlations measurements should also offer the possibility to probe the fractional statistics of these carriers. Several contributions address these topics. The contribution by Chang (pp. 677–684) definitely establishes a hallmark of the Luttinger liquid: the power law variation of the tunneling conductance with temperature or voltage. While in the FQHE regime the power law exponent is predicted to be a topological number, experiments find deviations related to non-universal experimental features which are discussed. The contribution by Saleur (pp. 685–695) is a review of the recent progresses made in the understanding of the conduction in a Luttinger liquid with an impurity. It is remarkable that quantum integrability based on conformal field theories leads to an exact solution for this difficult problem. This allows the non-perturbative calculation of the non-equilibrium current and the shot noise and this is very useful for comparison with experiments. The solution of this so-called quantum impurity problem has important connections with the physics of dissipative quantum tunneling and also with quantum optics, well beyond FQHE. The contribution by Martin and Safi et al. (pp. 697–707) is about fractional statistics. It is shown theoretically that correlating the current fluctuations originating from the partitioning of fractional excitations between two FQHE edges provides a way to probe the fractional statistics of the carriers. After a clear review of Hanburry–Brown and Twiss experiments with electrons in quantum conductors, the authors present their calculations which predict deviations from Fermi statistics and possible bunching of the fractional quasiparticles.

The article of Pasquier (pp. 709–715) is on the physics of a bilayer electron system. Here, the electronic spin combines with the pseudo-spin associated with the layer index. Raising the interlayer coupling and decreasing the separation allow one to go from two $\nu = 1/2$ gapless states to a single $\nu = 1$ gapped quantum Hall state. This gives interesting phase quantum transitions with unusual excitations. By playing with statistics of the originating particles (electrons or bosonic atoms) the author suggests an interesting connection with the physics of Bose–Einstein condensates in suitable rotating traps where the angular velocity replaces the magnetic field.

The last contribution by Roche et al. (pp. 717–732) gives a review of the most basic properties of the quantum Hall effect so that readers from other fields can have an idea of the physics of the quantum Hall effect. It would have been too long to address all properties and subtleties of the FQHE, and so reading the general review quoted in the bibliography as a further step is recommended. The contribution mainly discusses the edge excitations and the connection with Luttinger liquids. In addition, new experimental results probing electronic transport through an artificial impurity coupling the edges are presented. They are found to compare well with the predictions of the exact solution discussed in the article by Saleur (pp. 685–695). Finally, the physics of the shot noise of the current in this regime is also addressed. A review of the measurements having established the fractional charge of the carriers is given and future developments are discussed.

We hope that the present Dossier, which includes several contributions of leading groups working in this field, will be very stimulating for readers interested by the physics of quantum many body systems and will give an idea of how stimulating and rich the physics of the fractional quantum Hall effect is.

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