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Forward scattering approximation and bosonization in integer quantum Hall systems

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Abstract

In this work, we present a model and a method to study integer quantum Hall (IQH) systems. Making use of the Landau levels structure we divide these two-dimensional systems into a set of interacting one-dimensional gases, one for each guiding center. We show that the so-called *strong field approximation*, used by Kallin and Halperin and by MacDonald, is equivalent, in first order, to a *forward scattering approximation* and analyze the IQH systems within this approximation. Using an appropriate variation of the Landau level bosonization method we obtain the dispersion relations for the collective excitations and the single-particle spectral functions. For the bulk states, these results evidence a behavior typical of *non-normal* strongly correlated systems, including the spin-charge splitting of the single-particle spectral function. We discuss the origin of this behavior in the light of the Tomonaga–Luttinger model and the bosonization of two-dimensional electron gases.
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1. Introduction

The integer quantum Hall effect (IQHE) [1] appears in two-dimensional electron gases (2DEG) under a strong magnetic field, B, with the electronic Landau level filling factor, ν, equals to an integer number. In this case the non-interacting ground state presents ν completely filled Landau levels and the excitons generated by the electron–electron interaction involve particles in different levels. At stronger magnetic fields the degeneracy, $N_\phi = S/2\pi l^2$ (where S is the area of the 2DEG and $l = \sqrt{c\hbar/(eB)}$ is the magnetic length), of a single Landau level exceeds the number of electrons. In this case many non-interacting ground states can be constructed with all the electrons in the macroscopically degenerate lowest Landau level. In this case the usual perturbative theories, which lead to the Fermi Liquid behavior, are invalid and the effect of the electron–electron interaction turns out to be much more dramatic, giving rise to a new state of the matter and to the fractional quantum Hall effect (FQHE) [2,3].

The study of collective excitations plays an important role in understanding both systems. The existence of magneto-rotons [4,6,5] was verified through inelastic light scattering [7] and phonon spectroscopy [8,9]. However, in the integer quantum Hall systems, at very low electronic densities (less than $10^{-10}\,\mathrm{cm}^{-2}$) multiple magneto-rotons which are not accessible to the usual perturbative theories (possibly because they neglect the mixing of the Landau levels) were observed [10], demonstrating an incomplete understanding of these excitations. Additionally, in the FQHE the coupling between the particle excitations with the magneto-plasmon mode close to the cyclotron frequency, ω_c, seems to be the key for a Hamiltonian theory of these systems [11], and to the origin of most part of the notable properties of their quasi-particles, the *composite fermions* [12,13]. Here we will show that the collective excitations also seem to have a strong influence in the bulk quasi-particles properties even in the IQHE.

In this work, we will explicitly treat the integer quantum Hall systems, although the method we present, together with the Chern–Simons theory [14], also has applications in the fractional case [15]. Assuming a system where the Coulomb energy, $e^2/\varepsilon l$, is much smaller than the cyclotron energy, $\hbar\omega_c = \hbar eB/(mc)$, the so-called *strong field approximation* [4,5] (where the mixing between the Landau levels is neglected) can be used. Under this approximation, the collective magneto-plasma modes were determined by the Green's function method [4] and time-dependent Hartree–Fock theory [5]. In this work, we will see that these modes can also be obtained by a magneto-exciton bosonization method. First, making use of the natural structure of the Landau levels, we divide the 2DEG into a set of N_ϕ one-dimensional interacting channels, one for each guiding center occupied by ν particles. We show that, to first order in $(e^2/\varepsilon l)/\hbar\omega_c$, the *strong field approximation* is equivalent to a *forward scattering approximation* in this model of one-dimensional interacting channels. Thus, we will allow for the transfer of energy and momentum between the different channels mediated by the direct and exchange Coulomb interactions, conserving the net number of particles in each channel. We then use a variation of the *Landau level bosonization* [16] which is ideal for a treatment of the interaction effects in this model.

One of the major advantages of this bosonization method is that, through the *Mattis-Mandelstam* bosonic representation of the fermionic operator [17,18], one is be able to determine the single-particle properties directly from the collective modes, differently from the usual perturbative theory. Another advantage is that this *Mattis-Mandelstam* representation is an identity [18] which, technically, can be used later to extend the model, includ-

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