

Ground State of 2D Electrons in High Magnetic Field - A DMRG study -

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The density matrix renormalization group (DMRG) method is a kind of variational method combined with the real space renormalization group method. We extend the DMRG method to 2D quantum systems in magnetic field and study the ground state of 2D electrons in quantum Hall systems. In this method we use the eigenstates of free electrons in Landau gauge as initial one-particle basis states and iteratively extend the size of system by adding one-particle states with restricting the number of many-body basis states. The restriction of many-body basis states is controlled by the density matrix calculated from the ground state wave function. The truncation error in the ground state wave function is estimated from the eigenvalues of the density matrix, and it is typically 10^{-4} for systems with 25 electrons with keeping 180 states in each block.

The low energy excitations and pair correlation functions in Landau levels of $N = 0, 1, 2$ are systematically calculated for a wide range of fillings. The obtained results for systems with up to 25 electrons confirm the existence of various electronic states including incompressible liquid states, compressible liquid states, charge density waves called 'stripe', 'bubble' and Wigner crystal.

Phase diagram for the lowest Landau level

In the lowest Landau level, the existence of compressible liquid at $\nu = 1/2$, incompressible liquid at $\nu = 5/11, 4/9, 3/7, 2/5, 1/3$ and $1/5$, and Wigner crystal below $\nu \sim 1/7$ is confirmed. The vanishing of the excitation gap at $\nu = 1/2$ is shown in the size dependence of the excitation gap, and circularly symmetric pair correlation functions at $\nu = 1/$

confirmed, where ν_N is the filling factor of the Landau level of index N . At $\nu_N = 1/2$, we calculate low energy spectrum and pair correlation functions for various Haldane's pseudo-potential V_1 . The obtained results show that the ground state is different from neither stripe state in higher Landau levels nor compressible liquid state in the lowest Landau level. The pair correlation function is consistent with the pairing formation. Between $\nu_N \sim 0.47$ and 0.37 stripe ground state is obtained. The correlation function is similar to that observed in higher Landau levels, but the amplitude of the stripes is 50% smaller and the period is 30% shorter than those observed in $N = 2$ Landau level. Below $\nu_N \sim 0.37$, the ground state correlation functions become similar to that in the lowest Landau level and weak stripe correlation with oscillations along the stripes is observed. At $\nu_N=1/3$ the ground state correlation function seems to be quite different from that of Laughlin state in the lowest Landau level. Although the ground state continuously connects to Laughlin state, the excitation gap is very small and the short range pair correlation function is enhanced. This is due to the large reduction of the short range repulsion V_1 in the second lowest Landau level. On the other hand, the ground state at $\nu_N = 1/5$ is almost identical to that in the lowest Landau level, because V_3 of the Coulomb interaction projected onto $N = 1$ Landau level is slightly increased from that of the lowest Landau level. The ground state at low fillings is almost the same to that in the lowest Landau level, and the first order transition to Wigner crystal is expected at $\nu_N \sim 1/7$.

Phase diagram for the third lowest Landau level

In the third lowest Landau level $N = 2$, CDW states called stripe and bubble are obtained. From $\nu_N = 1/2$ to 0.42 the stripe state is the ground state. Compared with the stripes in the second lowest Landau level, the amplitude is much larger and the period is longer. Between $\nu_N=0.42$ and 0.24 the two-electron bubble state is found. Since the correlation functions sharply change at the transition, the transition between the stripe state and the bubble state is expected to be first order. With further decreasing ν_N , the bubble state becomes unstable and different ground state characterized by Wigner crystal is realized. The three-electron bubbles expected in Hartree-Fock calculations are missing in the DMRG calculation, which is consistent with recent experiments where only one reentrant integer quantum Hall effect state is observed between $\nu_N = 0$ and $1/2$.

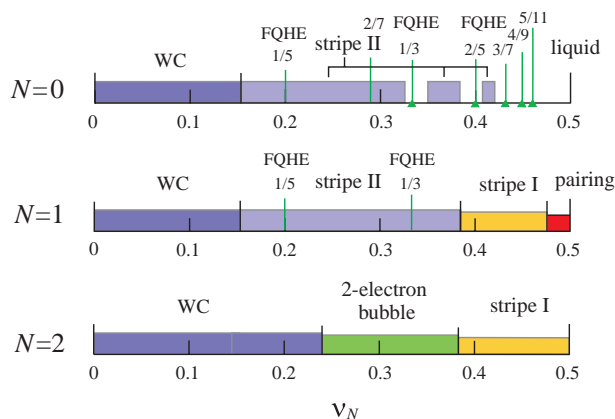


Figure 1: The ground state of 2D electrons in N -th Landau level determined by the DMRG.