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Vortex core structure in strongly correlated superfluidity

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ABSTRACT

In order to study the vortex core electronic structure in high-T_c superconductors, we examine 1-D Hubbard model with trap potential by using the density matrix renormalization group method. Instead of directly treating the vortex, the approach mimics the carrier density depression inside the vortex core via the trap potential and exactly calculate strong correlation effects on the depressed region. Consequently, we find that the Mott state emerges in the central region and the metallic edge surrounds the Mott region. Furthermore, when adding spin imbalance, the calculations reveal that a local antiferromagnetic order covers the Mott state region, and moreover, the antiferromagnetic order modulates with a long periodicity. We expect that these results closely relate to the vortex core electronic structure while their calculation results can be directly compared with atomic Fermi gases loaded on an optical lattice.

1. Introduction

The vortex core electronic structure in high-T_c superconductors has attracted much attention because the structure is regarded to reflect their anomalous electronic properties. In high-T_c superconductors, the superconducting state occupies a very wide area in the phase diagram, and the anomalous properties are masked by the superconductivity. On the other hand, the superconducting gap is locally suppressed inside the vortex core under the presence of the magnetic field, and the competing orders against the superconductivity are expected to emerge inside the vortex core [1,2]. Such an interesting idea has been intensively studied by experimentalists who mainly operates the scanning tunneling microscope [3], and peculiar spatially modulated structures have been actually observed inside the vortex core. In this paper, we suggest an artificial but fruitful way to theoretically study the peculiar states inside the vortex core. We create a local situation similar to the vortex core and exactly check which kind of orders emerge.

The vortex is a circular object whose center lacks the matter density. This general picture in normal fluids also holds in quantum fluids, and the matter density is actually depressed inside the quantized vortex core. The first microscopic calculation on the matter density depression in the superconducting vortex was made by Hayashi et al. who calculated it by self-consistently solving the Bogoliubov equation for s-wave vortex [4]. Afterwards, since the depression is overestimated by neglecting the Coulomb interaction, the calculation was revised by one of authors (M.M) and Koyama who take into account the Coulomb interaction [5]. In spite of a quantitative difference between these two results, both studies coincide in a conceptual point that the matter density depression inside the vortex core is not negligible in the strong coupling superconductors.

The matter density depression inside the vortex core has recently revived with current intensive studies on the vortex core in atomic Fermi gases [6]. The vortex in the atomic gases is created by giving a kinetic rotation into the condensed gas, and the vortex from strong coupling BEC to weak coupling BCS superfluid is observable in atomic Fermi gases through the Feshbach control. In fact, the experiments demonstrated that the matter density depression inside the vortex core becomes pronounced as one goes to BEC regime. From these facts, the matter density depression is confirmed to be universally non-negligible in strongly coupled superfluidity.

The high-T_c superconductivity emerges by doping hole carriers. Thus, the depressed matter inside high-T_c superconducting vortex core corresponds to the hole carrier, and the core region locally approaches the non-doped phase. Such a situation can be similarly realized by trapping electrons inside a local region or by locally expelling holes from the region. This is considered to be qualitatively equivalent to a system created by trapping Fermi atoms

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loaded on an optical lattice [7,8] inside a harmonic well or other types of wells. In this paper, we therefore study 1-D optical lattice trapped inside the harmonic well potential by using the density matrix renormalization group (DMRG) method [9]. This is because an exact calculation is possible if one uses DMRG. So far, the vortex core calculation has been limited within approximated treatments [1,2]. The present calculation is the first exact calculation although the model system is artificial one. We employ 1-D repulsive Hubbard model with a harmonic trap potential [7,8], and change the repulsive interaction, the spin polarization ratio, and the number of Fermi particles to examine which type of structures emerge. We also note that the present calculation is directly useful for atomic Fermi gases loaded on 1-D optical lattice.

2. Model and numerical method

In this paper, we examine 1-D Hubbard model with a harmonic trap [7,8] as an alternative model instead of calculating directly the vortex core. We believe that the present study gives an insight on the vortex core structure and provide directly predictable results on atomic Fermi gases.

The employed model Hamiltonian [7,8] is given by

$$H_{\rm Hubbard} = -t\sum_{i,j,\sigma}^{N}(a^{\dagger}_{j\sigma}a_{i\sigma} + H.C.) + U\sum_{i}^{N} n_{i\uparrow}n_{i\downarrow} + V\left(\frac{2}{N-1}\right)^2 \times \sum_{i,\sigma} n_{i\sigma}\left(i - \frac{N+1}{2}\right)^2, \quad (1)$$

where $a^{\dagger}_{i\sigma}$ and $a_{i\sigma}$ are the creation and annihilation operators of an electron (a Fermi atom in atomic Fermi gas) with spin (pseudo spin in atomic Fermi gas) $\sigma = \uparrow$ or $\downarrow$, respectively. The Hamiltonian (1) includes the on-site repulsive interaction $U(>0)$, as well as a harmonic confinement (trap) potential characterized by V. The summation (i,j) in the first term, describing tunneling between lattice sites, is taken over the nearest neighbor sites. N is the total number of lattice sites, and $N_{\rm F}(\equiv \sum_{i,\sigma}^{N} n_{i,\sigma})$ is that of fermion particles. The last term in Eq. (1) describes the trap potential whose magnitude at edge sites is set to be V. The boundary condition is simply open boundary condition throughout this paper. We adjust the total number of electrons and the parameter V in order to change the confined state from the Mott state to the metallic state. As an example, we can separately create both the Mott and the metallic states inside a trapped region. The central region is the Mott state and the metallic edge appear around the central region [7,8].

3. Numerical calculation results

Let us present numerical calculation results. In all cases, we fix the parameter U/t and V/t are 7 and 1, respectively. The repulsive interaction strength is considered to be a proper parameter in studying high-T_c superconductors.

3.1. Mott phase and spin imbalance

Here, we focus on a case, in which the particle density is high enough to keep a Mott phase locally inside the trap. In this situation, the hole is expelled from the central region and the non-doped phase locally appears. This is equivalent to the high-T_c superconducting vortex core in the underdoped regime. An interest in this case is its spin structure, i.e., how the antiferromagnetic order develops inside the central region. Fig. 1a shows spatial distribution profiles for electron density n_σ with spin $\sigma = \uparrow$ or $\downarrow$ in addition to their sum $\sum_\sigma n_\sigma$ and subtraction $n_\uparrow - n_\downarrow$. The population balance is completely even for Fig. 1a, in which $n_{\rm F} = n_\uparrow + n_\downarrow = 48$ and $(n_\uparrow, n_\downarrow) = (24, 24)$, and Fig. 1b and c shows, respectively, the correspondent results for imbalanced cases (26, 22) and (28, 20). In the former balance case, it is found that the Mott state showing $\sum_\sigma n_\sigma \sim 1$ and the metallic state ($\sum_\sigma n_\sigma < 1$) spatially separate [7,8]. In addition, the antiferromagnetic order does not develop at all and neither the charge and the spin modulations are not observable. This is reasonable because any local spin structure should not appear in the finite system according to Lieb–Mattis theorem [10]. Such a result was firstly suggested by Rigol et al. [7] and a novel feature peculiar to the spatial profile was pointed out by the

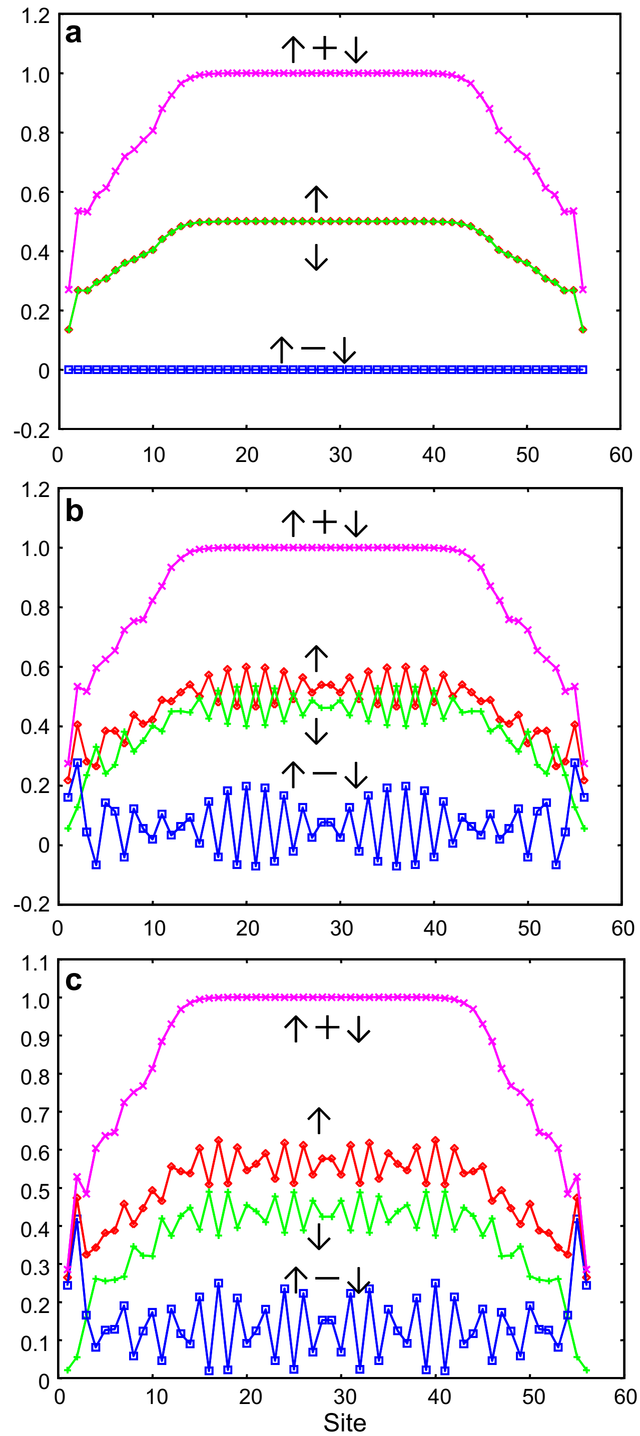

Fig. 1. The DMRG results of the distribution profiles of $\sum_\sigma n_\sigma$, $n_\uparrow$, $n_\downarrow$, and $n_\uparrow - n_\downarrow$ for (a) (24↑, 24↓), (b) (26↑, 22↓), and (c) (28↑, 20↓). In all cases, $U/t = 7$, $V/t = 1$, and $N = 56$.