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Reentrant superconductivity on a triangular lattice: application to cobalt oxide superconductor

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Abstract

It is possible that a triplet pairing is responsible for superconductivity in the recently discovered wet cobalt-based compounds. In such a case, the Zeeman coupling does not put limits on the upper critical field (H_{c2}) and its value is determined solely by the diamagnetic effects. In the absence of the Pauli pair-breaking mechanism *reentrant* superconducting phase may set on. It was shown by Rasolt and Tešanović that the Landau level quantization in isotropic superconductors could enhance superconductivity in a very strong magnetic field. In the present paper, we investigate superconducting phase transition in $Na_xCoO_2 \cdot yH_2O$ in the presence of a strong magnetic field. Special attention is put on a possible occurrence of the *reentrant phase*.

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The similarities between cuprate and the recently discovered cobalt oxide superconductors [1] consist predominantly in dimensionality and strong electronic correlations. The pairing symmetry is presently the subject of intensive investigations. The existing experimental results often contradict each other [2,3] and it is unclear, whether superconductivity originates from singlet or triplet pairing. If singlet pairing actually takes place, the resonating valence bond (RVB) state would be a straightforward explanation of superconductivity in the cobalt oxide [4,5]. However, in addition to singlet superconductivity, there is a region of triplet pairing in the phase diagram proposed in Ref. [4]. Recent density functional calculations predict an itinerant ferromagnetic state that, however, competes with a weaker antiferromagnetic instability [6].

Extrapolation of the experimental data [7,8] suggests that $H_{c2}(T=0)$ is of the order of a few tens of Tesla, that is beyond the Clogston–Chandrasekhar limit. This result strongly supports the hypothesis of a triplet superconductivity, at least

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at high magnetic fields [9]. There also exist reports from resistivity measurements that suggest smaller slope of $H_{c2}(T)$ [10]. The discrepancy between these results is unexplained.

The assumption of triplet pairing opens a possibility of the presence of reentrant superconducting phase in very high fields. Such a possibility was analyzed a few years ago as a result of strong Landau level quantization [11]. Similar behavior has also been predicted in a tight binding approach to a square lattice electron system [12]. Here, we discuss the reentrant superconductivity on a triangular lattice, that is usually used to describe Co-based superconductor [4]. However, there are also claims that Kagomé lattice structure is hidden in CoO_2 layers [13]. We start with the Hamiltonian:

$$H = \sum_{\langle ij \rangle \sigma} t_{ij} e^{i\theta_{ij}} c_{i\sigma}^{\dagger} c_{j\sigma} - \mu \sum_{i,\sigma} c_{i\sigma}^{\dagger} c_{i\sigma} + V \sum_{\langle ij \rangle} \sum_{s_1,s_2=\uparrow\downarrow} \left(\Delta_{ij}^{s_1 s_2} c_{i,s_1}^{\dagger} c_{j,s_2}^{\dagger} + \text{h.c.} \right), \quad (1)$$

where t_{ij} is the hopping integral and θ_{ij} is the Peierls phase factor, responsible for the diamagnetic response of the system: $\theta_{ij} = 2\pi/\Phi_0 \int_i^j \vec{A} \cdot d\vec{l}$, where $\Phi_0 = hc/e$ is the flux quantum. $\Delta_{ij}^{\uparrow\downarrow} = \langle c_{i\uparrow} c_{j\downarrow} + c_{i\downarrow} c_{j\uparrow} \rangle$ and $\Delta_{ij}^{\sigma\sigma} = \langle c_{i\sigma} c_{j\sigma} \rangle$ denote the triplet pairing amplitudes. In the Hamiltonian, we have neglected the Zeeman term, that favors a solution with a parallel spin orientation. However, it does not destroy superconductivity in the equal spin channel and, therefore, can effectively be absorbed in a spin-dependent chemical potential. In order to determine the phase diagram we carry out the following steps: (i) applying a unitary transformation, that diagonalizes the kinetic part of the Hamiltonian, we introduce a new set of fermionic operators—in the case of Landau gauge we end up with the Harper equation for the triangular lattice where its energy spectrum is known as the Hofstadter butterfly; (ii) we rewrite the Hamiltonian in terms of the new operators and (iii) construct the gap equation, that allows us to determine the critical temperature for a given magnetic field.

The resulting equations have been solved numerically for 50×50 cluster with mixed boundary conditions. In the weak field regime, the quasiclassical approach, that neglects the influence of the magnetic field on the density of states (DOS), gives a correct temperature dependence of H_{c2} [15]. Therefore, within the reach of laboratory magnetic fields H_{c2} is a smooth function of temperature as can be inferred from the inset in Fig. 1. On the other hand, in the strong field regime the actual structure of the energy spectrum is crucial for $H_{c2}(T)$. It is explicitly apparent in Fig. 1, where we compare DOS at the Fermi level with $H_{c2}(T)$. For free electron gas reentrant superconductivity originates from the high degeneracy of Landau levels in a strong magnetic field. In the present case, strong magnetic field results in a small number of narrow subbands with strongly peaked DOS (see Fig. 2). Therefore, any time the Fermi energy is in the region of a finite DOS, there is a strong singularity in the Cooper pair susceptibility and T_c is finite.

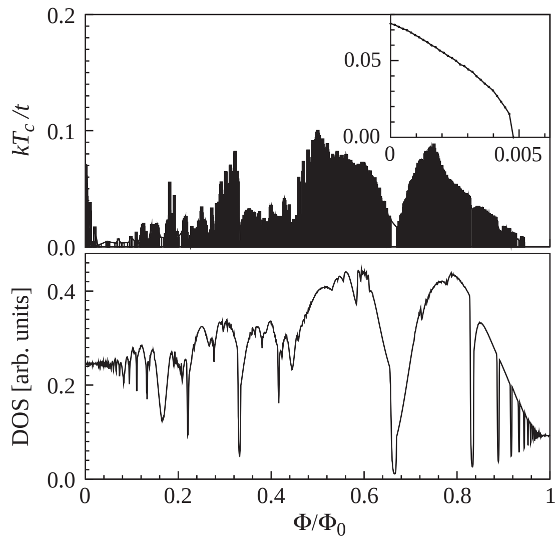

Fig. 1. Shaded area in the upper panel shows the reentrant phase obtained for the occupation number $n = 0.65$ and $V/t = 0.5$. For $t = 0.01$ eV [14] T_c is of the order of a few Kelvins. For comparison we present the density of states at the Fermi level (lower panel). Instead of a magnetic field we present Φ/Φ_0, where Φ is the magnetic flux through the lattice cell ($\Phi/\Phi_0 = 1$ corresponds to $H \sim 10^5$ T). The inset shows $H_{c2}(T)$ in the quasiclassical regime, i.e., for $\Phi/\Phi_0 \ll 1$ when the distance between the energy subbands in the Hofstadter butterfly is much less than $k_B T$.

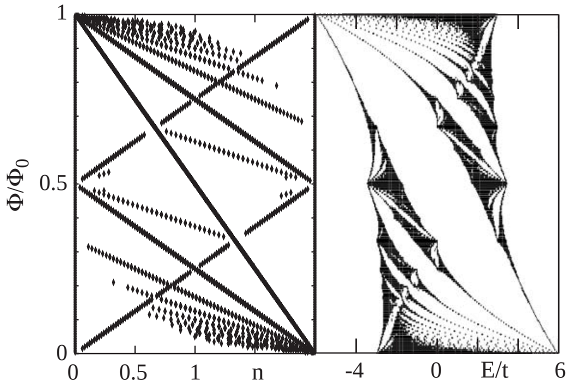

Fig. 2. Right panel shows the energy spectrum (Hofstadter butterfly) for the triangular lattice. The left one shows points where the reentrant phase vanishes.

Despite a complicated fractal structure of the Hofstadter butterfly, one can present a relatively simple phase diagram of the reentrant superconductivity (see the left panel in Fig. 2). Namely, the points of vanishing of the reentrant phase on the (n, H) plane, where n is the occupation number, form a very regular pattern consisting of straight lines only. This amazing result originates from the fact that the number of states below an arbitrary gap in the Hofstadter butterfly depends linearly on the magnetic field.

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