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Current Perspectives

Is the pseudogap a topological state?

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ABSTRACT

We conjecture that the pseudogap is an inhomogeneous condensate above the homogeneous state whose existence is granted by topological stability. We consider the simplest possible order parameter theory that provides this interpretation of the pseudogap and study its angular momentum states. Also we obtain a solution of the Bogomol'nyi self-duality equations and find skyrmions. The normal state gap density, the breaking of the time reversal symmetry and the checkerboard pattern are naturally explained under this view. The pseudogap is a lattice of skyrmions and the inner weak local magnetic field falls below the experimental threshold of observation given by NMR/NQR and μSR experiments.

1. Introduction

The discovery of the high temperature (high T_c) superconductors by Bednorz and Müller (1986) [1] brought new paradigms to the field of condensed matter physics. Three-dimensional superconductivity originates in two-dimensional layers where Cooper pairs are formed and outlive elsewhere. The understanding of any layered compound demands its study at several doping, achieved by changing the number of carriers available in the layers. These properties are best displayed in the so-called temperature versus doping diagram where the critical temperature T_c defines a dome shaped curve whose onset and disappearance take place at critical doping values. In this phase diagram superconductivity is one among many other possible electronic states that involve magnetic, charge and pairing degrees of freedom that either coexist, cooperate or dispute the same spatial locations within the layers. Besides the superconducting and the anti-ferromagnetic state there is another characterized electronic state, the pseudogap state, that lives below a temperature T^* versus doping line in this phase diagram. Interestingly this line approaches the superconducting dome from above by increasing the doping, always with a negative slope and, at some doping value, intersects and crosses the dome, ending at zero temperature, where it defines a so-called quantum critical point. The pseudogap was revealed in 1989, soon after the discovery of Bednorz and Müller, by the observation of a sharp decrease of the nuclear spin susceptibility in the cuprate layer atoms (CuO_2) [2]. This sharp decrease of the NMR Knight shift K indicated the existence of a (above T_c) normal state gap, the pseudogap. The nature of the pseudogap remains so far unknown and a true challenge to the field. It is not clear whether the pseudogap gap line T^* is a thermodynamical or crossover transition [3]. Among the known properties of the pseudogap, are the normal state gap and the spontaneously broken symmetries. The pseudogap state breaks the time reversal symmetry because left-circularly polarized photons give a different photocurrent from right-circularly polarized photons below the line T^*, as shown more than 10 years ago by Kaminski et al. [4]. Recently these results have been confirmed through high precision measurements of polar Kerr effect [5,6], which are also clearly suggestive of a phase transition at T^*, below which arises a finite Kerr rotation [7]. The pseudogap also breaks translational invariance symmetry within the layers and this modulation was first observed through scanning tunneling microscopy, initially coined as the checkerboard pattern, a tetragonal lattice with $4a$ periodicity, where a is the CuO_2 unit cell length. This periodicity was firstly found inside the vortex cores [8] of $Bi_2Sr_2CaCu_2O_{8+x}$, butsoon after incommensurate patterns were also observed in the normal state of this compound [9], below the pseudogap line in the absence of a magnetic field. It is quite remarkable that in the pseudogap phase carriers within the layers arrange themselves into a periodic pattern not necessarily commensurate with the crystallographic

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structure [10]. Nowadays the checkerboard pattern is seen as a consequence a charge density wave [11]. Recent work using resonant elastic x-ray scattering (REXS) correlation done by Ghiringhelli et al. [12] found concrete evidence of this charge-density-wave in the underdoped compound $YBa_2Cu_3O_{6+x}$ with an incommensurate periodicity of nearly 3.2a, both above and below T_c. Thus it is quite clear that a theoretical attempt to explain the pseudogap must take into account the normal state gap and also the broken symmetries. It happens that a magnetic order is expected to arise due to the breaking of the time reversal symmetry. Time reversal symmetry means that a state remains unchanged upon time reversal. We know that the velocity (momentum) and also the magnetic field both reverse sign under a time-reversal operation. Magnetic spins reverse direction when time reverses direction, therefore magnetic order breaks time reversal symmetry and may be the reason for it. The presence of any kind of magnetic order leads to a local magnetic field that must be experimentally accessed by several magnetic probes. Indeed there has been an intense search for this predicted spontaneous local magnetic field inside the high T_c superconductors in the pseudogap phase. Polarized neutron diffraction experiments [13,14] indicate a magnetic order below the pseudogap. NMR/NQR [15,16] and μSR [17,18] experiments set an upper limit to the magnetic field between the layers, which must be smaller than 0.1 Gauss. A proposal of magnetic order with the layers has been put forward by C.M. Varma [13,14,19,20], who claims that microscopic orbital currents cause this order, and consequently, the breaking of the time reversal symmetry.

Recently we have shown that an above the homogeneous (normal) state gap and the broken symmetries can be understood in the context of an order parameter description, and for this reason, suggested this interpretation for the pseudogap [21]. Thus the pseudogap is a gapped topological state made of skyrmions, whose microscopic nature is still controversial. We recall that the description of a condensate through an order parameter was proposed by Ginzburg and Landau much before the BCS unveiled the microscopic mechanism behind superconductivity. According to Gorkov and Volovik [22] a system described by an order parameter that breaks the time reversal symmetry must have an accompanying magnetic order that yields a local magnetic field near to the sample surface even in the absence of an external field. Indeed our description of the pseudogap exactly fits the Gorkov and Volovik scenario with the local magnetic field found around the layers and not just near to the sample surface. This magnetic field originates from spontaneous circulating supercurrents in the layers that give rise to an inhomogeneous excited state which is stable since it is prevented from decaying into the homogeneous ground state by its topological stability. This tetragonal lattice of skyrmions breaks time reversal symmetry and also translational invariance has an energy gap above the homogeneous state that we associate to the pseudogap. We obtain the numerical value of the pseudogap density as a function of the local magnetic field between the layers, which is assumed to fall below the experimental threshold of observation set by NMR/NQR [15,16] and μSR [17,18] experiments. In this paper we provide a detailed study of this order parameter approach to the pseudogap state and derive its angular momentum properties.

2. The theory

We seek here the simplest possible theory able to describe a condensate, the pseudogap, through an order parameter such that it lies above the homogeneous state separated by a gap, hereafter called the normal state gap, and presents broken symmetries. Besides the supercurrents created by its inhomogeneity must be in conformity with the experimental threshold imposed by the maximum observed internal field. Because of its assumed simplicity the present theory does not describe the transition at T^*, as we only try to capture the major qualitative features of the pseudogap. Thus the present description is restricted to temperatures below but near to the T^* line, and above T_c, such that the condensate energy, which regulates the superconducting dome and defines T_c, can be safely ignored. Thermal fluctuations are not included here and so the discussion is restricted to mean field considerations. Even in this simplified context we find that to describe both the pseudogap and the superconducting states there must be at least two components, $\Psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}$. This simplest possible theory is just the sum of the kinetic and the field density energies

$$F = \int \frac{d^3x}{V} \left[\frac{|\vec{D}\Psi|^2}{2m} + \frac{\vec{h}^2}{8\pi} \right], \tag{1}$$

where m and q are the Copper pair mass and charge, respectively. We assume minimal coupling to the field through the covariant derivative $\vec{D} = (\hbar/i)\vec{\nabla} - (q/c)\vec{A}$ and $\vec{h} = \vec{\nabla} \times \vec{A}$. Undoubtedly the lowest free energy state of Eq. (1) is the null homogeneous state $\Psi = 0$, thus with no supercurrents and no resulting local magnetic field, $\vec{h} = 0$ that we identify with the superconducting state restricted to exist under the superconducting dome. Our claim is that above this homogeneous null state lives an inhomogeneous gapped state, topologically stable, conjectured to be the pseudogap. In this paper we give a detailed derivation of the pseudogap from Eq. (1) and obtain its angular momentum properties.

This simple theory has a global $SU(2)$ rotational invariance [23,24] that arises as a natural consequence of the presence of two-components. We believe that this invariance is explicitly broken by extra terms in the free energy, not considered in this simple theory. Even without considering this explicit breaking we find that this naively introduced $SU(2)$ symmetry has possibly only local meaning and is associated to the group of spatial rotations, which turns Ψ into a truly spinorial order parameter. It is not possible to bring the two-component order parameter into a one-component form, $\Psi' = U\Psi$, $\Psi'^T = (\psi' \quad 0)$ by an $SU(2)$ rotation, $UU^\dagger = 1$ in case of an inhomogeneous state. It is only possible to get rid of one of the components in case of an homogeneous solution. For a spatially inhomogeneous solution, $\Psi(\vec{x})$, the rotation to one component form can only be done locally, $U(\vec{x})$. Therefore the free energy of Eq. (1) cannot be reduced to one component in case of an inhomogeneous solution. Under a local rotation $U(\vec{x})$ an extra term appears in the covariant derivative, $\vec{D}' = \vec{D} + U\vec{D}U^{-1}$ so that $F_k = \int d^3x (|\vec{D}'\Psi'|^2/2m)/V$. We consider this a signal of a non-abelian gauge symmetry in the pseudogap phase. This possibility has been considered elsewhere [25,26] but will not be treated here. From the free energy of Eq. (1) we obtain the following variational equations:

$$\frac{\vec{D}^2\Psi}{2m} = 0, \tag{2}$$

$$\vec{\nabla} \times \vec{h} = \frac{4\pi}{c}\vec{J}, \tag{3}$$

where the supercurrent density is given by

$$\vec{J} = \frac{q}{m}\left[\Psi^\dagger\vec{D}\Psi + (\vec{D}\Psi)^\dagger\Psi\right]. \tag{4}$$

The aforementioned weakness of the local magnetic field is a key ingredient for the construction of a perturbation scheme to solve