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Effect of impurities and random pinning on the superconducting vortex state

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Abstract

The presence of impurities affects the quasiparticles via potential scattering and pinning of the vortices. We calculate self-consistently the local density of states of an inhomogeneous superconductor in a magnetic field with a random distribution of impurities. The quasiparticles are only significantly affected by the impurities in their vicinity. In contrast, the random distribution of vortices increases the density of states at low energies by filling the gap in the s-wave case and creating a finite value in the d-wave case. The dominant effect on the quasiparticles is due to the vortex scattering.

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Scanning tunneling microscopy (STM) studies of HTSC have revealed a very different quasiparticle structure from that predicted by the pure d-wave BCS single vortex models [1]. In a pure d-wave there are extended gapless states, a fourfold symmetric shape of the LDOS and a zero-bias conductance peak. Experimentally, however, the following are observed: (i) absence of zero-energy peaks, (ii) absence of coherence peaks close to the vortex, (iii) low-energy states with an energy $\sim 5.5\,\mathrm{meV}$ for YBCO and $\sim 7.7\,\mathrm{meV}$ for BSCCO, and (iv) absence of four-fold symmetric star-shaped LDOS. The coherence peaks are recovered about 10 Å from the core center and the core states are localized decaying exponentially with distance (~ 22 Å). Possible reasons for the failure of the pure d-wave theory to explain the experimental results have included a mixed pairing of the type $d_{x^2-y^2} + id_{xy}$ [2], considering that the vortices have

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antiferromagnetic cores such that localized magnetic order coexists with superconductivity or even charge order fluctuations [3].

Recently, a pure d-wave pairing for a vortex lattice has yielded results that are in good qualitative agreement with experiments [4]. Indeed a calculation of the local density of states shows that close to the vortex position the coherence peaks disappear, there are significant low-energy peaks and there is no zero-energy enhancement of the density of states [4]. However, if the vortex distribution is random due to pinning, then the zero-energy density of states is enhanced (becomes finite [4]), still displaying low-energy peaks and no coherence peaks [1]. Away from the vortex core the density of states is qualitatively the same as for the vortex lattice case [4]. The low-energy states, even though strongly peaked near the vortex cores, do not appear to be localized. An approximate scaling of the density of states was found at low energies [4]. For both pairing symmetries either the presence of disorder or increasing the density of vortices enhances the low-energy density of states. In the s-wave case, the gap is filled and the density of states at low energies is a power law, $\rho(\varepsilon) \sim |\varepsilon|^{\alpha}$. In the d-wave case, the density of states has the form $\rho(\varepsilon) \sim \rho_0 + |\varepsilon|^{\alpha}$. The density of states remains finite at zero energy and it rises linearly at very low energies in the Dirac isotropic case, $\alpha_{\rm D} = t/\Delta_0 = 1$ (t is the hopping integral and Δ_0 is the amplitude of the order parameter). For slightly higher energies the density of states crosses over to a quadratic behavior. As the Dirac anisotropy increases (as Δ_0 decreases with respect to the hopping term t) the linear region decreases in width. Neglecting this small region the expression of the density of states is

$$\rho(\varepsilon) \sim \rho_0 + \alpha_{\rm D}^{-1}\left|\frac{\varepsilon}{\Delta_0}\right|^{1+\alpha_{\rm D}^{-1/2}}. \tag{1}$$

It interpolates between quadratic in the isotropic case $\alpha_{\rm D} = 1$ and back to linear as $\alpha_{\rm D}$ increases. Actually, $\alpha_{\rm D} \gg 1$ for the cuprates.

In most systems, disorder is present in the form of impurities. We model the disorder using the binary alloy model [5] where the impurities are distributed randomly over the lattice sites. The vortices are placed on the center of plaquettes of a square lattice. At each impurity site it costs an energy U to place an electron (it acts as a local shift on the chemical potential). It is favorable that a vortex is located in the vicinity of an impurity. At the same time, there is a repulsive interaction between the vortices which is not significantly screened since the penetration length is very large. The actual vortex distribution is obtained by balancing the effective attractive vortex–impurity interaction and the vortices mutual repulsion.

We calculate self-consistently the density of states (DOS) and the local density of states (LDOS) of a d-wave superconductor in a perpendicular magnetic field. We solve numerically the Bogoliubov–de Gennes equations obtaining the quasiparticle spectrum and wavefunctions as a function of position in a two-dimensional lattice. The BdG equations are defined by $\mathscr{H}(\mathbf{r})\Psi_n(\mathbf{r}) = \varepsilon_n\Psi_n(\mathbf{r})$, where $\Psi_n^\dagger(\mathbf{r}) = (u_n^*(\mathbf{r}), v_n^*(\mathbf{r}))$ and where the matrix Hamiltonian is given by

$$\mathscr{H} = \begin{pmatrix} \hat{h} & \hat{\Delta} \\ \hat{\Delta}^\dagger & -\hat{h}^\dagger \end{pmatrix} \tag{2}$$

with [2,4]

$$\hat{h} = -t\sum_{\boldsymbol{\delta}} {\rm e}^{-({\rm i}e/\hbar c)\int_{\mathbf{r}}^{\mathbf{r}+\boldsymbol{\delta}} \mathbf{A}(\mathbf{r})\cdot {\rm d}\mathbf{l}}\,\hat{s}_{\boldsymbol{\delta}} - \varepsilon_F + \mathscr{U}(\mathbf{r})$$

and

$$\hat{\Delta} = \sum_{\boldsymbol{\delta}} {\rm e}^{({\rm i}/2)\phi(\mathbf{r})}\Delta(\mathbf{r},\mathbf{r}+\boldsymbol{\delta})\,{\rm e}^{({\rm i}/2)\phi(\mathbf{r}+\boldsymbol{\delta})}\hat{\eta}_{\boldsymbol{\delta}}.$$

The sums are over nearest neighbors ($\boldsymbol{\delta} = \pm\mathbf{x}, \pm\mathbf{y}$ on the square lattice) and the operator $\hat{s}_{\boldsymbol{\delta}}$ is defined through its action on space-dependent functions, $\hat{s}_{\boldsymbol{\delta}}u(\mathbf{r}) = u(\mathbf{r}+\boldsymbol{\delta})$. The energy $\mathscr{U}(\mathbf{r})$ is the impurity potential which takes the value $U > 0$ at the sites $\{\mathbf{r}_i^p\}_{i=1,N_p}$ hosting an impurity and zero elsewhere. $\mathbf{A}(\mathbf{r})$ is the vector potential associated with the uniform external magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$. The local magnetic flux $\phi(\mathbf{r})$ created by the vortices is defined by $\nabla \times \nabla\phi(\mathbf{r}) = 2\pi\mathbf{z}\sum_i \delta(\mathbf{r}-\mathbf{r}_i^v)$, where $\mathbf{z}$ denotes the direction orthogonal to the two-dimensional lattice. The operator $\hat{\eta}_{\boldsymbol{\delta}} = {\rm e}^{{\rm i}\pi\delta_y}\hat{s}_{\boldsymbol{\delta}}$ carries the symmetry of the d-wave order parameter. The quasiparticles moving through such a random environment not only experience a

Doppler shift caused by the moving supercurrents, but also feel a quantum Berry-like term due to the half-flux Aharonov–Bohm scattering off the vortices.

A detailed information about the scattering of the quasiparticles is obtained by calculating the LDOS for a given impurity/vortex configuration. (i) At a site in the bulk the band-structure profiles are somewhat similar to the case of a vortex lattice [4]. The coherence peaks are evident, the zero energy density of states is very small (but not strictly zero), and the low-energy peaks are smeared out. (ii) At an impurity site (and no vortex nearby) the same structure is apparent except that since the impurity potential is repulsive, the density of states at the impurity site is considerably depleted at low energy (for instance in the very large U limit the density of states is virtually zero at the impurity site; note that we are not considering the $\varepsilon_F = 0$ symmetric case). (iii) In the vicinity of a vortex site (but far from any impurity) the structure is very similar to the case obtained before [4] with no coherence peaks close to the vortex and an enhanced zero-energy density of states near the vortex. (iv) Finally, the interesting case of a location where a vortex is bound to an impurity reveals that the coherence peaks are recovered very close to the vortex. Also, the low-energy density of states at the impurity site is increased with respect to the impurity case, due to the vortex nearby. However, the density of states is considerably smaller than for the case of a vortex far from any impurity. Details of the calculation procedure will be presented in a separate publication [6].

These results agree qualitatively with experimental results considering that most vortices are pinned at the impurities. Also, the results show that the dominant effect on the quasiparticle DOS is due to the vortex scattering.

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