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Vortex cores and vortex motion in superconductors with anisotropic Fermi surfaces

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ABSTRACT

Explaning static and dynamic properties of the vortex lattice in anisotropic superconductors requires a careful characterization of vortex cores. The vortex core contains Andreev bound states whose spatial extension depends on the anisotropy of the electronic band-structure and superconducting gap. This might have an impact on the anisotropy of the superconducting properties and on vortex dynamics. Here we briefly summarize basic concepts to understand anisotropic vortex cores and review vortex core imaging experiments. We further discuss moving vortex lattices and the influence of vortex core shape in vortex motion. We find vortex motion in highly tilted magnetic fields. We associate vortex motion to the vortex entry barrier and the screening currents at the surface. We find preferential vortex motion along the main axis of the vortex lattice. After travelling integers of the intervortex distance, we find that vortices move more slowly due to the washboard potential of the vortex lattice.

1. Superconductors as quantum condensates with a Fermi surface

Kittel's book on Solid State Physics starts the chapter about metals with a quotation to A.R. Mackintosh, who defined a metal as "a solid with a Fermi surface" [1]. The behavior of electrons in metals is characterized by the shape of the Fermi surface and by the bandstructure close to the Fermi level. Both reflect the symmetry of the crystal lattice (which constrains electron motion along directions where electrons are Bragg reflected by the lattice periodicity), the orbital nature of the electrons wavefunctions at the bands crossing the Fermi level and electron interaction effects. The influence of overlapping bands on superconductivity was calculated early on by considering scattering among bands with different orbital character [2]. This is widely taken into account in topical superconductors.

Angle resolved photoemission, quasiparticle scattering or de Haas van Alphen within the superconducting state have been used to measure the superconducting gap over the Fermi surface [3–7]. The drawback of these techniques are, respectively, low resolution in energy, need for impurities that produce scattering and magnetic fields close to H_{c2}. Here we discuss how vortex cores might help in this issue. Vortex cores viewed by Scanning Tunneling Microscopy (STM) at very low temperatures provide a visual account of the anisotropy of the superconducting gap and of the Fermi surface [8–10]. This does not require the introduction of impurities and can be made in a large part of the magnetic phase diagram.

Furthermore, we also show that tilting the magnetic field leads to moving vortex lattices. This might allow studies linking vortex motion and vortex core shape.

2. Fermi surface and superconducting vortex cores

At the core of a superconducting vortex, the density of Cooper pairs drops to zero at a scale of order of the coherence length [14]. Bogoliubov's principle of electron-hole symmetric quasiparticles and Andreev quasiparticle to Cooper pair conversion is quite relevant to understand superconducting vortex cores [11,15]. Let us consider the known Andreev reflection process, following the book of Schmidt [11]. A normal electron travels towards a superconductor. The electron carries charge $-q$ and its energy lies below the superconducting gap value. Upon entering the space where Cooper pairs exist, the superconducting gap gradually increases and the normal electron becomes a superconducting quasiparticle. It acquires thus a mixed electron-hole character and its position moves

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towards the bottom of the dispersion relation, until its energy is equal to the superconducting gap. From that point on, the normal electron becomes a Cooper pair and a quasihole is reflected, moving towards the normal metal with a charge that gradually becomes positive, until the superconducting gap is zero and the particle behaves then as a hole with charge $+q$ in the metal. In a confined geometry of an SNS junction, the process leads to interference effects and level quantization [16,17]. This explains the transport properties of superconducting constrictions [18–21].

In a vortex core, the resulting spatial variation of the dispersion relation is similar, with respect to the momentum at the plane perpendicular to the magnetic field. The quasiparticle dispersion relation crosses zero at the vortex core, where the gap also vanishes. The confined geometry of the vortex core leads to quantized Andreev bound states, as first found by Caroli de Gennes and Matricon [12]. The lowest lying state can be estimated using zero point motion arguments, with a result ($\epsilon_0 \approx \frac{\hbar^2}{p\xi} \approx \frac{\hbar^2\Delta}{m\hbar v_F\xi} \approx \frac{\Delta}{k_F\xi} \approx \frac{\Delta^2}{E_F}$) of order of the result obtained by careful calculation [12].

Several applications of quantized Caroli de Gennes Matricon states have been proposed. The level quantization can be used to control phase-coherent transport through the vortex cores by modifying phase winding in vortices with multiple flux quanta [24] and also that it might lead to tunneling phenomena between Andreev levels [25,26].

Considering that the superconducting gap size varies with temperature and magnetic field, it is found that the length scale for the vortex core size can also vary with temperature and magnetic field [14,27]. For example, Kramer and Pesch took into account the thermal population of Andreev levels and showed that, for low temperatures, only the lowest lying level should be occupied, whereas for higher temperatures, more levels will be occupied [28]. The Andreev levels are spatially distributed, the lowest level being exactly at the center and the rest located at finite radii [12,28]. Thus, decreasing temperature leads to a concentration of states at the core center, which has been termed as vortex core shrinking [27,29].

On the other hand, it is expected that the radial behavior of the dispersion relation depends on the angular dependence of the superconducting gap and the Fermi surface in the plane perpendicular to the magnetic field [30,31].

Actually, the structure of the vortex lattice couples to the superconducting gap as well as to the Fermi surface. The latter was first shown in Ref. by taking into account the non-local relation between the supercurrent density and the vector potential very close to the vortex core. For example, in the nickel borocarbides, the vortex lattice adopts, at high magnetic fields, the square symmetry of the vortex cores through the mentioned non-local relationship [32–35]. The superconductor V_3Si [36] shows also triangular to square vortex lattice transitions as a function of the magnetic field. The orientation of the vortex lattice is in that case strongly linked to the crystal lattice.

The shape of the vortex core shows the angular dependence of the superconducting gap and of the Fermi surface in the plane perpendicular to the magnetic field [30,38]. As highlighted schematically in Fig. 1a, the Andreev levels are influenced by the spatial dependence of the superconducting gap and by the dispersion relation. For example, flat portions on the Fermi surface can provide an increased density of states and lead to an anisotropic vortex core. This might lead to vortex core shapes following the geometry of the Fermi surface (Fig. 1b). In a similar way, a superconducting gap varying as a function of the angle in the plane perpendicular to the magnetic field can lead to anisotropic vortex core shapes [38]. In case of two gap superconductivity, it has been recently shown that the spatial dependence of the order parameter is the same for both bands, leading essentially to a vortex core shape that is very similar than in a one band superconductor [13]. In materials such as 2H-$NbSe_2$, MgB_2 or 2H-NbS_2 available data shows that the magnetic field alters the value of one of both gaps [39–43]. In the Fe pnictides, both gaps remain however rather magnetic field insensitive [44,45].

The orientation of the vortex lattice with respect to the gap and Fermi surface anisotropies can be also discussed in terms of the vortex core shape by making a few simplifying assumptions [37]. The density of states is inversely proportional to the Fermi velocity $N \propto \frac{1}{v_F}$. Then, large N (small v_F) could in principle provide a large superconducting gap Δ. In a superconductor with square gap anisotropy, the minima in the gap would correspond to maxima in v_F. If the gap decreases with temperature or magnetic field, the vortex lattice might then turn, from an orientation determined by the gap minima to an orientation determined by the anisotropy in v_F.

In general, the combined effect of gap structure, non-locality and intervortex repulsion can lock the orientation of the vortex lattice along different crystallographic directions.

3. Vortex cores in 2H-$NbSe_2$, 2H-NbS_2 and β-Bi_2Pd

The vortex lattice of the transition metal dichalcogenide superconductor 2H-$NbSe_2$ is triangular and is oriented with the hexagonal crystalline lattice [23, 47, [48–50]]. The vortex core shows patterns that strongly depend on the bias voltage (Fig. 2). At zero bias, the lowest lying Caroli de Gennes Matricon state gives a zero bias conductance peak, whose spatial dependence provides star shaped vortex cores, with rays extending in between vortex lattice and crystal lattice directions. It is yet unclear if this due to features in the Fermi surface, gap anisotropy, or both. Theoretical calculations mostly use the latter to explain the features observed in 2H-$NbSe_2$ [30] and succeed in explaining the shapes obtained when increasing the bias voltage.

The related material 2H-NbS_2 has a similar T_c, but shows no charge density wave (CDW) transition. In 2H-NbS_2 the lowest level Caroli de Gennes Matricon state of the vortex cores is somewhat more extended spatially, because the coherence length is larger. The vortex lattice is also oriented along the crystalline axis [22]. Nevertheless, there is no in-plane anisotropy of the lowest lying Caroli de Gennes Matricon level. The vortex cores are round. Therefore, the anisotropies causing the star-shape in 2H-$NbSe_2$ are produced by the CDW.

There are open questions concerning the interplay between CDW and superconductivity in 2H-$NbSe_2$. It is controversial whether these coexisting electronic orders compete or cooperate. Moreover, the role of CDW in the in-plane anisotropy of superconducting properties observed in 2H-$NbSe_2$ has to be elucidated. Angular resolved photoemission experiments down to 1K have shown that CDW gap opens in a few localized points at the Fermi surface around K points, leaving most of the Fermi surface free to develop superconductivity [51]. The superconducting gap is smallest at the CDW hot spots and becomes maximun in between. Sixfold in-plane anisotropy of the superconducting gap has been also observed in the Nb derived Fermi surface centred on the Γ point where no signature of CDW has been found. On the other hand, a recent study that combines STM measurements and first principle calculations has proposed that CDW might play a role in the interband coupling between bands with different orbital character and superconducting gap value [52]. Nevertheless, this work does not discuss how this coupling influences the gap value or its in-plane anisotropy. What seems clear is that opening of CDW gap can shape the superconducting gap and also that it reconstructs the Fermi surface leading to anisotropic band structure in the normal phase. Both effects are absent in 2H-NbS_2 where no CDW order appears and the superconducting vortex core are round.