Anomalous Zeeman response of the coexisting superconducting and spin-density-wave phases as a probe of extended s-wave pairing in ferropnictide superconductors

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Anomalous Zeeman response in coexisting phase of superconductivity and spin-density wave as a probe of extended s-wave pairing structure in ferro-pnictide

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In several members of the ferro-pnictides, spin density wave (SDW) order coexists with superconductivity over a range of dopings. In this paper we study the anomalous magnetic Zeeman response of this coexistence state and show that it can be used to confirm the extended s-wave gap structure as well as structure of superconducting (SC) gap in coexisting phase. On increasing the field, a strongly anisotropic reduction of SC gap is found. The anisotropy is directly connected to the gap structure of superconducting phase. The signature of this effect in quasiparticle interference measured by STM, as well as heat transport in magnetic field is discussed. For the compounds with the nodal SC gap we show that the nodes are removed upon formation of SDW. Interestingly the size of the generated gap in the originally nodal areas is anisotropic in the position of the nodes over the Fermi surface in direct connection with the form of SC pairing.

PACS numbers:

I. INTRODUCTION

The discovery of superconductivity at elevated temperatures in a new class of iron based materials (ferro-pnictides)[1] has revived interest in the underlying mechanisms of high temperature superconductivity. Two key question are: what is the relation between antiferromagnetic order and superconductivity and what is the form of the superconducting pairing? These questions are fundamentally connected to one another. A remarkable feature of the ferro-pnictides is that in many cases they exhibit coexistence of superconductivity and antiferromagntism, over a wide range of parameters. As discussed below, studying the coexistence phase can reveal important information regarding both these questions.

A popular theoretical model for superconducting pairing is the extended s-wave ($s_{\pm}$) pairing[2–9], although other pairing symmetries were also discussed[10–14]. In its simplest form, $s_{\pm}$ pairing consists of nodeless singlet pairing but with different signs on different Fermi surface (FS) pockets. Experimental studies on the nature of pairing have not yet reached a unanimous conclusion. Hence new approaches to probing pairing are desirable.

The parent compounds of many of the pnictides are antiferromagnetic metals[15], referred to here as the spin density wave (SDW) state. On doping, the magnetic order is reduced, and superconductivity emerges. Establishing the detailed phase diagram, and whether these two orders occur together, is an important question. In some members of pnictide family e.g. $CeFeAsO_{1-x}F_x$[16] SDW and SC phases have no overlap while in $LaFeAs(O,F)$[17,18] there are conflicting reports on SC and SDW phase coexistence. On the other hand coexistence of SDW and superconductivity in multiple pnictide materials have been reported. For example, in $Ba_{1-x}K_xFe_2As_2$ and $Ba(Fe_{1-x}Co_x)_2As_2$ an extended region of coexistence with $0.2 \leq x < 0.4$ and $0.025 \leq x < 0.06$ with a maximum superconducting transition temperature inside this region of $\sim 28\,K$ and $20\,K$ respectively, are observed[19,20]. Moreover, scanning probe measurements of the latter indicate that the two orders coexist in the same part of the sample[21].

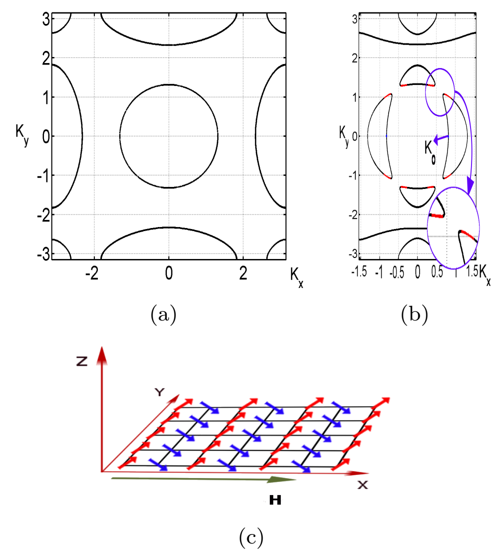


FIG. 1: a) FS in the first Brillouin zone. b) FS in the new Brillouin zone after SDW order forms. SC gap in red regions is robust against Zeeman field. $\mathbf{k}_0$ is the point where the gap closes first. c) SDW in transverse magnetic field $\mathbf{H}$

Theoretical studies of SDW coexisting with superconductivity has a long history (see 22 and references therein). For the pnictides, with extended s-wave gap, the ordering wave vector $\mathbf{Q} = (\pi, 0)$[15] folds the original Brillouin zone (figure 1(a)) and parts of FS with opposite sign gap cross. It might seem that since SC gap changes sign on the new FS it has to have nodes. But the sign change of the gap upon translation by

$\mathbf{Q}$ ($\Delta^{\pm}(\mathbf{q})\Delta^{\pm}(\mathbf{q}+\mathbf{Q}) < 0$) protects the nodeless SC gap[22,23]. One simple way to understand this is that in the clean limit, it is possible to mathematically transform the $s_{\pm}$ SC with SDW problem, into an s wave SC with a charge density wave. Since the latter is an s-wave SC with a time reversal symmetric perturbation, its gap is protected by Anderson's theorem, and no nodes appear. This argument shows the possibility of coexistence of extended s-wave SC gap and SDW but it is not exclusive. Indeed as we show simple s-wave can also coexist with SDW despite the gap size reduces dramatically upon formation of SDW and coexistence is possible for small parameter range[24].

In this paper we study an unusual aspect of the response of the coexisting phase to a magnetic field which is direct evidence of extended s-wave gap structure. The orbital effect of the magnetic field will be to produce vortices as in any type II superconductor. Here, we will focus instead on the *Zeeman* part of the coupling. In a layered superconductor which is appropriate for some of the pnictide materials, a field applied in the plane has a weaker orbital effect[25]. Moreover, the Zeeman coupling is effectively enhanced by the presence of SDW order since those magnetic moments will cant along an applied field. The electron g factor is effectively increased 3 to 4 times over its bare value. The transverse ferromagnetic moment that develops, can decrease the SC gap. We show that this gap reduction occurs in a highly nonuniform fashion. The gap remains robust in some regions of FS (red regions in fig. 1(b)) up to very high fields. In these regions the pairing arises from the interplay of $s_{\pm}$ SC and SDW orders and effectively has a triplet character. So for the first time we show that coexisting phase can exclusively test the extended s-wave SC gap structure. Consequences for STM experiments as well as possible signatures of the Zeeman induced gap closing over parts of the FS in heat transport are analyzed.

In some members of pnictides family, the SC gap has nodes. It is suggested that nodes are result of superposition of simple and extended s-wave pairing[26] i.e. $\Delta_{sc}(\mathbf{k}) = \Delta^0_{sc}(\mathbf{k}) + \Delta^{\pm}_{sc}(\mathbf{k})$ where Δ^0_{sc} is the "simple" s-wave ($\Delta^0_{sc}(\mathbf{k}) = \Delta^0_{sc}(\mathbf{k}+\mathbf{Q})$) and $\Delta^{\pm}_{sc}$ is the extended s-wave ($\Delta^{\pm}_{sc}(\mathbf{k}) = -\Delta^{\pm}_{sc}(\mathbf{k}+\mathbf{Q})$ pairing. The node forms when $\Delta^0_{sc}(\mathbf{k}) = -\Delta^{\pm}_{sc}(\mathbf{k}) \neq 0$. We study the coexistence of nodal pairing with SDW and show that such nodes are gapped out by the SDW. The size of formed gaps are again strongly anisotropic in close connection with form of SC paring.

II. MODEL HAMILTONIAN

The Hamiltonian including the mean field SDW order parameter and the transverse ferromagnetic moment, which is formed in a Zeeman field, as well as Zeeman field coupled with the conduction electrons is:

$$\begin{aligned}\mathbf{H}_{MF} =& \sum_{\mathbf{k}} \Phi^{\dagger}_{\mathbf{k}} \mathbf{h}(\mathbf{k}) \Phi_{\mathbf{k}} \\ &+ \sum_i \Big[\eta\left(e^{\mathbf{Q}\cdot\mathbf{r}_i}\ \mathbf{S}_{AF} + \mathbf{S}_F\right) + \frac{g}{2}\mu_B \mathbf{H}\Big] \cdot \Phi^{\dagger}_i \vec{\sigma} \Phi_i\end{aligned} \tag{1}$$

Here $\Phi^T = (\psi_{\uparrow}, \psi_{\downarrow})$ and ψ_s is the orbital spinor. For simplicity, in the present paper we use a two band model for the pnictides[27,28] which already captures the essential physics. So $\psi^T_s = (d_{xz}, d_{yz})_s$ is the two component spinor corresponding to two d orbitals at the Fermi energy and the kinetic Hamiltonian before formation of SDW is given by[27]:

$$\begin{aligned}\mathbf{h}_k(\mathbf{k}) =& 2t_1(\cos k_x - \cos k_y)\lambda^z + 2(t_2 - t'_2)\sin k_x \sin k_y \lambda^x \\ &+ [2(t_2 + t'_2)\cos k_x \cos k_y + 2t'_1(\cos k_x + \cos k_y) - \mu_f] \cdot \lambda^0\end{aligned} \tag{2}$$

where $t_1(t'_1)$ and $t_2(t'_2)$ represent nearest and next nearest neighbor hoping parameters, μ_f is the chemical potential and λ is the Pauli matrix acting on the orbital space.

Magnetic interactions e.g. $J_1 - J_2$ model[29,30] lead to formation of $\mathbf{Q} = (\pi, 0)$ ordering which we capture in mean-field SDW term. Last term in (1) corresponds to coupling of ordered moments and the Zeeman field ($\mathbf{H}$) with conduction electrons (σ is the Pauli matrix acting on the Physical spin space). $\mathbf{S}_{AF}$ and $\mathbf{S}_F$ are SDW moment and ferromagnetic moment generated by transverse field.

III. ZEEMAN COUPLING STRENGTH

We now estimate the magnitude of the transverse Zeeman coupling ($\Delta_{Ferro} = |\eta\mathbf{S}_F + \frac{g}{2}\mu_B\mathbf{H}|$). Note, the SDW will flop into the plane perpendicular to the field, for sufficiently weak magnetic anisotropy, so the field is transverse to the SDW moment. To estimate the ferromagnetic moment $\mathbf{S}_F = \chi\mathbf{H}$, we use the transverse susceptibility in the non-SC SDW phase of the 1111 compounds: $\chi \sim 0.4 \times 10^{-4}\ emu$[30]. Since η factor in (1) is not known, we can not estimate Δ_{Ferro} directly. The ferromagnetic moment and SDW moment couple to the conduction electrons similarly so we can use the properties of SDW phase to estimate Δ_{Ferro}. The magnitude of SDW moment is $S_{AF} \sim 0.36\ \mu_B$[15] and the SDW gap $\Delta_{SDW} = |\eta\mathbf{S}_{AF}| \sim 0.08\ eV$[31] is measured using optical spectroscopy. The energy scale associated with formation of ferromagnetic moment is $\frac{\Delta_{Ferro}}{\Delta_{SDW}} = |\frac{\mathbf{S}_{Ferro}}{\mathbf{S}_{AF}}| = \frac{\chi|\mathbf{H}|}{|\mathbf{S}_{AF}|}$. The change in electron g factor for transverse field is then $\delta g = \frac{\Delta_{SDW}\chi|\mathbf{H}|/|\mathbf{S}_{AF}|}{\mu_B|\mathbf{H}|/2} = \frac{2\ \chi}{|\mathbf{S}_{AF}|}\frac{\Delta_{SDW}}{\mu_B} \sim 5.5$. The SC gap $\Delta_{sc} \sim 4\ meV$ is measured using ARPES[32]. In a transverse field of $\mathbf{H} \sim 18T$, $\Delta_{Ferro} \sim \Delta_{sc}$. In the layered pnictides, a critical magnetic field of order $50T$ is reported[25] so Zeeman coupling effect might be as relevant as orbital effects.

IV. COEXISTENCE PHASE

To study the coexisting phase we use an extended Hilbert space and consider states at $\mathbf{k}$ and $\mathbf{k}+\mathbf{Q}$ as two component pseudospin: $\Psi_{\mathbf{k}}^T = (\Phi_{\mathbf{k}}, \Phi_{\mathbf{k+Q}})$. With $\mathbf{S}_{AF}||\hat{z}$ and $\mathbf{S}_F||\hat{x}$, $\mathbf{H}_{MF}(1)$ will be:

$$\begin{aligned}\mathbf{H}_{MF}(\mathbf{k}) = &\begin{pmatrix} \mathbf{h}_k(\mathbf{k}) & 0 \\ 0 & \mathbf{h}_k(\mathbf{k+Q}) \end{pmatrix} \sigma^0 \\ &+ \Delta_{SDW}\lambda^0\tau^x\sigma^z + \Delta_{Ferro}\lambda^0\tau^0\sigma^x\end{aligned} \tag{3}$$

τ is the Pauli matrix acting on $(\mathbf{q}, \mathbf{q}{+}\mathbf{Q})^T$ space. Diagonalizing $\mathbf{h}_k(\mathbf{k})$ we get the two bands. At each $\mathbf{k}$ point we project in to the state closer to the Fermi energy which is a two component wave function $\psi_s(\mathbf{k})$. Then $\mathbf{h}_k(\mathbf{k})$ will be replaced by the corresponding energy $\epsilon(\mathbf{k})\lambda^0$. We project the Hamiltonian (3) into the low energy orbital and trace over the two component orbital space (ψ_s) leading to $f(\mathbf{k}) = \sum_s \psi_s^\dagger(\mathbf{k})\psi_s(\mathbf{k}{+}\mathbf{Q})$ in the SDW term that mixes the states at $\mathbf{k}$ and $\mathbf{k}+\mathbf{Q}$ ($f(\mathbf{k})$ is only important in perfect nesting case and is ignored otherwise):

$$\begin{aligned}\mathbf{H}_{MF}^P(\mathbf{k}) = &\left[E^+(\mathbf{k})\tau^0 + E^-(\mathbf{k})\tau^z\right]\sigma^0 \\ &+ \Delta_{SDW} f(\mathbf{k})\tau^x\sigma^z + \Delta_{Ferro}\tau^0\sigma^x\end{aligned} \tag{4}$$

where $E^\pm(\mathbf{k}) = \frac{\epsilon(\mathbf{k})\pm\epsilon(\mathbf{k+Q})}{2}$. Here we use the specific two band model for the pnictides, other Hamiltonians proposed will differ in the form of $E^\pm(\mathbf{k})$. This specific choice does not have qualitative effect on the results presented here. When $\Delta_{Ferro} = 0$ the dispersion is $\varepsilon(\mathbf{k}) = E^+(\mathbf{k}) \pm \sqrt{E^{-2}(\mathbf{k}) + \Delta_{SDW}^2}$. Assuming that the SDW ordering does not change the chemical potential, for the points on the FS we have $\varepsilon(\mathbf{k}) = 0 \Rightarrow E^{+2}(\mathbf{k}) = E^{-2}(\mathbf{k}) + \Delta_{SDW}^2$.

The SC Hamiltonian acting on $\left(\Psi_{\mathbf{k}}, \Psi_{-\mathbf{k}}^\dagger\right)^T$ is:

$$\begin{aligned}\mathbf{H}(\mathbf{k}) = &E^+(\mathbf{k})\tau^0\sigma^0\mu^z + E^-(\mathbf{k})\tau^z\sigma^0\mu^z + \Delta_{sc}^\pm(\mathbf{k})\tau^z\sigma^y\mu^y \\ &+ \Delta_{sc}^0(\mathbf{k})\tau^0\sigma^y\mu^y + \Delta_{SDW}\ f(\mathbf{k})\ \tau^x\sigma^z\mu^z + \Delta_{Ferro}\tau^0\sigma^x\mu^z\end{aligned} \tag{5}$$

where μ is the Pauli matrix acting on SC particle-hole space.

First we consider $\Delta_{Ferro} = 0$ where the Hamiltonian can be diagonalized analytically. Defining $A^2(\mathbf{k}) = 2E^+(\mathbf{k})^2 + \Delta_{sc}^{\pm^2} + \Delta_{sc}^{0^2}$, $E^2(\mathbf{k}) = A^2(\mathbf{k}) - 2\sqrt{\frac{A(\mathbf{k})^4 - (\Delta_{sc}^2 - \Delta_{sc}^{02})^2}{4} - (E^+(\mathbf{k})\Delta_{sc} - E^-(\mathbf{k})\Delta_{sc}^0)^2}$. Many features of coexisting phase could be understood from this dispersion: extended and "simple" s-wave pairing can both coexist with SDW although the gap for "simple" s-wave reduces greatly upon formation of SDW. If the SC gap has nodes as a result of presence of both "simple" and extended s-wave paring[26], upon formation of SDW the nodes are removed, i.e. magnetism enhances the SC properties! In general the gap formed is small[24] but is enhanced if nodes happen to occur close to the nesting regions. In the rest of paper $\Delta_{sc}^0 = 0$ and use $\Delta_{sc} = \Delta_{sc}^\pm$.

V. EFFECT OF MAGNETIC FIELD

Although it seems that all the symmetries of the Hamiltonian (5) are broken by SC and SDW orders, there is a remaining symmetry implemented by the operator $\Sigma = \tau^z\sigma^x\mu^z$ which commutes with the Hamiltonian in (5). Σ has four eigenstates with eigenvalue 1 and four with eigenvalue -1. We can reduce the size of the Hamiltonian in (5) by projecting into the subspaces corresponding to different eigenvalues of Σ.

For zero energy in the characterizing polynomial of (5) we can see that after the ferromagnetic moment is formed, at each $\mathbf{k}$ point the SC gap vanishes when:

$$\Delta_{Ferro}^2 = 2E^-(\mathbf{k})^2\left(1 - \sqrt{1 - \frac{\Delta_{SDW}^2\Delta_{sc}^2}{E^-(\mathbf{k})^4}}\right) + \Delta_{sc}^2 \tag{6}$$

Here one can readily see that the gap vanishes anisotropically, since $E^-(\mathbf{k})$ varies over FS, even though we consider magnitude of Δ_{sc} to be uniform. At the point where the SC gap vanishes first, the low energy excitations dispersion is anisotropic: $\varepsilon(\mathbf{p}) = \frac{\Delta_{SDW}^2\Delta_{sc}}{E^-(\mathbf{k}_0)^3}\left(\alpha|p_x| + \beta p_y^2\right)$. α and β depend on the the band curvatures, $\mathbf{k}_0$ is the position where the gap first closes (fig. 1(b)) and $\mathbf{p}$ denotes deviation from $\mathbf{k}_0$. On the other hand (6) shows that when $|\Delta_{SDW}\Delta_{sc}| > E^-(\mathbf{k})^2$ ferromagnetic moment can not close the gap! More specifically one can look at the point where $E^-(\mathbf{k}) = 0$. We can calculate energies at this point exactly. Defining $\ell^2 = 2\sqrt{\Delta_{SDW}^2\Delta_{Ferro}^2 + \Delta_{sc}^2\Delta_{Ferro}^2 + \Delta_{SDW}^4}$, the energy is $E^2 = \sqrt{\ell^4 + (\Delta_{Ferro}^2 - \Delta_{sc}^2)^2 + 4\Delta_{sc}\Delta_{SDW}} \pm \ell^2 > 0$.

The energies are non-zero as long as both SDW and singlet superconductivity are present, regardless of the ferromagnetic moment. It is important to note that the gap is not SDW gap but it is indeed a SC gap (it vanishes when $\Delta_{sc} = 0$) that is robust against external magnetic field; as we will show it is indeed spin-triplet pairing gap.

Two aspects of these results are particularly puzzling; since the singlet pairing changes sign on the FS, it seems that it should vanish at some points, but our result indicates that nodeless superconductivity coexist with SDW. The other feature is that the coupling with ferromagnetic moment affects the SC gap anisotropically and it can not destroy the gap in some regions. Below we show that the nature of the SC gap can explain these puzzling features.

When $\Delta_{Ferro} = 0$ eigenvalues and eigenstates of the Hamiltonian for the points on the FS could be derived analytically. Interestingly two operators corresponding to the spin-triplet pairing also commute with the Σ. Operator that is important for us is $\Gamma_{Triplet} = \tau^y\sigma^x\mu^y$ which anticommutes with the singlet operator $\Gamma_{Singlet} = \Delta_{sc}\tau^0\sigma^y\mu^y$. The amplitude for any type of pairing is calculated self-consistently using the wave functions of mean field SC Hamiltonian $|\Psi_n\rangle$[33] as $\Delta_p = \Delta_{sc}\sum_{n,E_n<0}\langle\Psi_n|\Gamma_p|\Psi_n\rangle$ where n labels different energy bands of SC Hamiltonian at any momentum:

$$\Delta_S(\mathbf{k}) \propto \sum_n \langle\Psi_n|\Gamma_{Singlet}|\Psi_n\rangle \tag{7}$$

$$= \Delta_{sc} \frac{E^-(\mathbf{k})\left(\sqrt{E^-(\mathbf{k})^2+\Delta_{SDW}^2}-E^-(\mathbf{k})\right)}{\Delta_{SDW}^2 - E^-(\mathbf{k})\left(\sqrt{E^-(\mathbf{k})^2+\Delta_{SDW}^2}-E^-(\mathbf{k})\right)}$$

$$\Delta_T(\mathbf{k}) \propto \sum_n \langle\Psi_n|\Gamma_{Triplet}|\Psi_n\rangle \tag{8}$$

$$= -\Delta_{sc} \frac{\Delta_{SDW}}{\sqrt{\Delta_{SDW}^2 + E^-(\mathbf{k})^2}}$$

$$\Delta_S(\mathbf{k})^2 + \Delta_T(\mathbf{k})^2 = \Delta_{sc}^2 \tag{9}$$

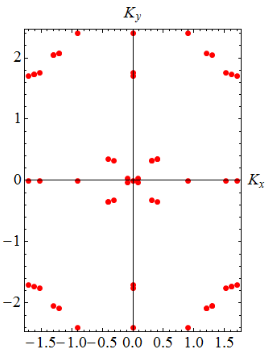
As we expected $\Delta_S(\mathbf{k})$ vanishes where $E^-(\mathbf{k}) = 0$ (it is where singlet pairing changes sign). Around this point $\Delta_S(\mathbf{k}) \approx \Delta_{sc}\frac{E^-(\mathbf{k})}{\Delta_{SDW}}$ so it satisfies the expectation that singlet pairing should change sign between the regions coming from different FSs after zone folding. On the other hand when $E^-(\mathbf{k}) = 0$, $\Delta_T(\mathbf{k}) \approx \Delta_{sc}$ so the pairing is triplet type. In the opposite limit $E^-(\mathbf{k}) \gg \Delta_{SDW}$, $\Delta_S(\mathbf{k}) \approx \Delta_{sc}$ and $\Delta_T(\mathbf{k}) \approx \Delta_{sc}\frac{\Delta_{SDW}}{|E^-(\mathbf{k})|}$ so the pairing is mainly singlet. This even parity triplet pairing is robust against coupling with the ferromagnetic moment i.e. regions with large triplet pairing remain gapped as the ferromagnetic moment forms. Eqn. (9) also shows that singlet and triplet pairings together gap out all of the FS.

A special limit "perfect nesting" (with $t_1' = 0$)[27]. In this limit $E^+(\mathbf{k}) = 0$. It might seems that SDW gaps out all parts of the FS. But here $f(\mathbf{k})$ plays an important role as it vanishes linearly at symmetry protected points on the FS[27]. With superconductivity a full gap opens, which closes at $\mathbf{k}_0$ on increasing the field when $|\Delta_{Ferro}| = |\Delta_{sc}|$. The dispersion then is 'semi-Dirac' like[34] $E(\mathbf{k}_0 + \mathbf{p}) = \sqrt{v_F^2 p_x^2 + \rho p_y^4}$. We do not discuss this case further since it requires fine-tuning to reach.

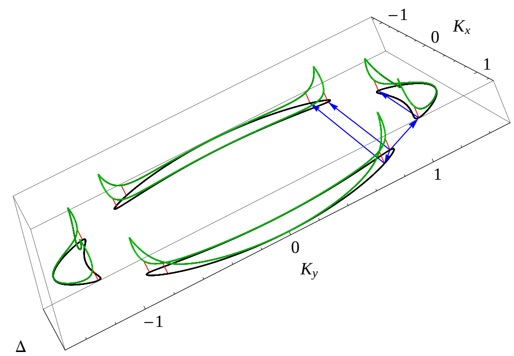
VI. EXPERIMENTAL CONSEQUENCES

So far we have proposed a theoretical picture to understand the coexistence of SC and SDW phase in ferropnictides. We showed transverse Zeeman field reduces the SC gap anisotropically. In the rest of this paper we will discuss the experimental signature of the effect discussed above. The usual experimental tool to map out the dispersion is ARPES which is not suitable in magnetic field.

Another approach which by now is widely used to map the FS (e.g. in cuprate superconductors) is the quasiparticle interferences measurement using STM[35,36]. STM measures the local density of state which is uniform for a normal clean metal. When sources of disorder such as impurities or crystal defects are present, elastic scattering mixes eigenstates that have different momentum but are located on the same contour of constant energy (STM bias voltage). When scattering mixes states $\mathbf{k}_1$ and $\mathbf{k}_2$, an interference pattern with wave vector $\mathbf{q} = \mathbf{k}_1 - \mathbf{k}_2$ appears in local density of states modulations which could be observed by STM as modulations of differential tunneling conductance[37]. The amplitude of the oscillation at momentum $\mathbf{q}$ is proportional to the imaginary part of two convoluted Greens functions and is largest when there is a large joint density of states associated with scattering wave-vector $\mathbf{q}$ i.e. $n(\mathbf{k}+\mathbf{q})n(\mathbf{q})$ where $n(\mathbf{k})$ is the density of state at energy equal to the STM bias voltage and momentum $\mathbf{k}$[37],[38].



(a)



(b)

FIG. 2: a) Fourier transform of the STM observed oscillations in density of states. Red points corresponds to high density. b)Variation of SC gap over parts of the FS in transverse magnetic field. We consider uniform gap size over the fermi surface before turning on the Zeeman field. The lines marked by blue arrows (and symmetry related arrows) connect regions with large density of states at the energy marked by red vertical lines (see[35]). Fourier transform of density modulations have enhanced amplitudes at these momentums.

The Zeeman field will generate the variation of the superconducting gap over the FS. The dispersion along the original FS is very shallow (at list of order $\Delta_{SDW}\Delta_{sc}$) compared to direction perpendicular to the FS. So the density of states at the tips of constant energy curves is larger. The joint density of state for momentums connecting these regions (marked by arrows in figure 2(b)) is increased. These momentums vary continuously as STM bias voltage changes and will give the complete map of dispersion relation. Without external field, there is no gapless excitation. As external field is turned on the gap reduces anisotropically: vanishes in some regions but is not affected where $E^{-}(\mathbf{k})^2 \ll \Delta_{SDW}\Delta_{sc}$.

Recent results on low temperature thermal conductivity of pnictide superconductors[39,40] indicate the presence of a full gap over the FS which is highly sensitive to the external magnetic field. The mechanism presented in this paper also leads to partial destruction of the SC gap in magnetic fields much smaller than the critical field. Based on our estimate presented in section III using a uniform gap magnitude, this field ($\sim 18T$) is still much larger than the range where experiments have been performed. However, an anisotropic gap (as found in some calculations[6]) could lead to much smaller onset fields where the ferromagnetic moment generates nodes in the SC gap. When the gap first vanishes as external field increases, the low energy excitations have anisotropic dispersion $\varepsilon(\mathbf{p}) \propto \alpha|p_x| + \beta p_y^2$ which leads to density of states $N(E) \propto \sqrt{E}$. The signature of such density of states will be seen in temperature dependence of superfluid density $\Delta\rho_s \propto -\sqrt{T}$, as well as field dependence of heat conductivity $\Delta\kappa \propto H^{\frac{1}{4}}$ (this could be understood as the Doppler shift due to superfluid flow around the vortex[41]). Note, in contrast a Dirac node dispersion would have $\Delta\rho_s \propto -T$ and $\Delta\kappa \propto H^{\frac{1}{2}}$.

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