Terahertz conductivity in FeSe$_{0.5}$Te$_{0.5}$ superconducting films

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Abstract. Complex conductivity of FeSe$_{0.5}$Te$_{0.5}$ superconducting films has been investigated using backward-wave-oscillator spectroscopy in the terahertz frequency range. The normal state conductivity corresponds well to the low-frequency limit of a Drude metal. In the superconducting state, the real part of the complex conductivity is not completely suppressed, indicating the existence of a strongly anisotropic gap. Weak features in the conductivity are consistent with the superconducting gap value close to 12 cm$^{-1}$ (1.5 meV). The experimental results are discussed within the framework of a two-gap model based on the $s^\pm$ symmetry of the order parameter.

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1. Introduction

Iron pnictides and chalcogenides represent a new intriguing family of superconducting materials [1–3]. A non-conventional characteristic of the superconductivity of these compounds remains an unresolved puzzle for the superconductivity community. Since the discovery of the superconducting transition [4] in La[O$_{1-x}$F$_x$]FeAs at 26 K, a lot of systematics has been collected experimentally and theoretically. In a simplified picture, the Fermi surface of the new superconductors consists of two cylindrical sheets with the opposite sign of the order parameter ($s^{\pm}$-symmetry). It is certainly not a coincidence but an internal elegance of these materials that the wavevector connecting both parts of the Fermi surface corresponds to a characteristic peak in the spin excitation spectrum. The spin excitation peak disappears in the normal conducting state, clearly revealing its connection to the superconducting mechanism. This connection is made perfect by the fact that the $s^{\pm}$ symmetry of the superconducting order parameter [5] is just what one needs for spin fluctuations to play the binding role in a microscopic mechanism of the superconductivity [6].

Of course, the story and the mechanisms are still not settled and there is a long way to go. Among the actual topics of investigations, there is the problem of the superconducting energy gap [2, 5]. Experimentally two different superconducting gaps are observed [7], which agrees with the $s^{\pm}$ picture. It remains open whether both parts of the gap are anisotropic in momentum space or even contain nodes. Angular resolved photoemission spectroscopy (ARPES) [8] experiments represent the most direct experimental technique to resolve this topic although the sensitivity in the energy region of the smaller gap is limited. Up to now, ARPES experiments in pnictides and chalcogenides are consistent with a fully opened gap at the hole pocket (see [2, 5, 9] for a recent discussion). It should be borne in mind that the ultimate experimental evidence for $s^{\pm}$ symmetry of the superconducting gap is still missing and other scenarios like the $s+i d$ or $d_{xy}$ state cannot be excluded [5].

Among the new superconductors of the iron family, the parent system FeSe is especially appealing due to the relative simplicity of the structure [1]. The superconducting transition temperature of the parent compound [10] can be increased from $T_c = 8$ K to 14 K by, e.g., doping with tellurium [11, 12]. The reports on the symmetry and structure of the gap in the FeSe family remain to a certain extent contradictory, although the results are basically consistent with the $s^{\pm}$ symmetry. The differences in interpretation could at least partly be attributed to specific strengths or weaknesses of experimental techniques. Some experiments point to a
strongly anisotropic s-wave symmetry of the order parameter [13, 14] or even to nodes within the gap [15]. Other reports are consistent with a fully opened gap between 8 cm\(^{-1}\)(1 meV), and 20 cm\(^{-1}\)(2.5 meV), [16–21], which still may be a result of suppressed s\(^\pm\) order parameter within strong disorder [18, 22, 23]. Some characteristic features that correspond to a second gap between 32 cm\(^{-1}\)(4 meV) (tunneling spectroscopy [19]) and 41 cm\(^{-1}\)(5.1 meV) (optical conductivity [20, 24]) have also been observed.

A contribution from optical spectroscopy is an essential part of investigations on novel superconductors. Both a separation of various contributions to the conducting mechanisms and statements about the superconducting gap can be drawn from the optical conductivity. Although the conductivity experiments cannot provide the momentum sensitivity in reciprocal space, the spectral features of the superconducting gap could well be resolved. A first review on the optical results in new superconducting families can be found in [25]. In many optical experiments, features corresponding to a two-gap superconductivity have been detected [24, 26–30]. An important problem to which the optical experiments may contribute significantly is whether conducting states exist below the lower superconducting gap. As a typical example, in reflectivity experiments one would expect perfect reflectance below the gap frequency if the absorption part is suppressed. Indeed, several optical experiments in the new superconducting families revealed a low-temperature and low-frequency reflectance equal to unity, e.g. consistent with the fully opened superconducting gap around 16 cm\(^{-1}\)(2 meV) [31, 32]. In such a case the real part of the complex conductivity is exactly zero below two times the characteristic gap frequency. At the same time, other groups reported a finite low-frequency conductivity in the low-frequency and low-temperature limit [27, 28, 33–39]. The possibility remains that the observed effects are sample and doping dependent and vary from system to system. Of course, within the characteristic frequency range of below about 16 cm\(^{-1}\) the deviations from perfect reflectance are extremely difficult to detect. Other techniques such as transmittance in thin films by e.g. terahertz spectroscopy do provide additional information about the problem [33, 35, 36, 40] but they are also not free from errors and experimental hurdles. For a recent discussion of the optical experiments, see [41].

Experiments on dynamic conductivity in the FeSe family have been until now rather rare [20, 24, 40, 42, 43]. In FeSe\(_{0.5}\)Te\(_{0.5}\) the optical data revealed features corresponding to two superconducting gaps [20, 24] at 20 cm\(^{-1}\)(2.5 meV) and 41 cm\(^{-1}\)(5.1 meV) and the conductivity showed a scaling similar to a dirty Bardeen–Cooper–Schrieffer (BCS) superconductor in the weak coupling limit. In spite of the relatively low in-plane/c-axis anisotropy of less than ten, the out-of-plane response is localized [43] and could be governed by the formation of a pseudogap.

In this work, we present the results of terahertz transmission experiments in superconducting FeSe\(_{0.5}\)Te\(_{0.5}\) films. A non-zero real part of the conductivity in the superconducting state can be interpreted in favor of the existence of nodes in the gap function or a strong gap anisotropy. The experimental results are discussed and analyzed within the concept of the two-gap model of superconductivity.

2. Experimental details

Three thin films with the nominal composition FeSe\(_{0.5}\)Te\(_{0.5}\) and thickness \(d = 100\) nm have been grown by pulsed laser deposition on MgO substrates [44]. The films are epitaxially grown and single phase as revealed by x-ray diffraction (lower inset in figure 1). The c-axis lattice constant deduced from these data is 5.78 Å, which coincides with the FeSe\(_{0.5}\)Te\(_{0.5}\)
Figure 1. Left panels: transmittance (top) and phase shift (bottom, $\varphi/(2\pi \nu)$) of an FeSe$_{0.5}$Te$_{0.5}$ thin film in the normal ($T=20$ K, blue circles) and superconducting ($T=2$ K, red triangles) states. The modulation seen in the spectra is due to Fabry–Pérot interferences within the substrate. Right panels: four-point dc resistivity of the film (top); an electron microscope image of the film surface (middle); x-ray diffraction spectra in $\theta$–2$\theta$ geometry (bottom).

stoichiometry [12, 45]. Electron microscope pictures showed a smooth surface of the films (figure 1). Two samples revealed the superconducting transition temperature of $T_c = 14$ K and one sample revealed $T_c = 10.1$ K as measured by dc resistivity. Although grown in similar conditions, the actual value of the transition temperature often varies from sample to sample. Possible reasons behind such kinds of deviations can be, e.g., the strain effect resulting from the variation of effective films thickness in spite of nominally the same thickness during the preparation. In some cases, the electronic doping level and carrier density of the films can be different in different thin films although their nominal stoichiometries are the same. Such deviations can be due to defects or variations in growing temperatures [12, 44]. Similar phenomena were observed previously in thin films of semiconductors, oxides, etc. In the particular example of iron chalcogenide thin films, reported $T_c$ values vary substantially. For example, the FeSe thin films in [46] are not superconducting at all (with only an indication of a superconducting transition), while the FeSe thin films in [47] show a superconducting transition at about 6 K only.

Transmission experiments at terahertz frequencies ($5 \text{ cm}^{-1} < \nu < 35 \text{ cm}^{-1}$) have been carried out in a Mach–Zehnder interferometer arrangement [48, 49] that allows measurements of the amplitude and phase shift of the electromagnetic radiation in a geometry with controlled
polarization and in external magnetic fields up to 8 T. The full frequency region is achieved using a set of five backward wave oscillators (BWOs) \[48\]. The real and imaginary parts of the terahertz conductivity have been obtained by numerical solution of the Fresnel optical formulae for a two-layer system. Because two independent parameters are available in the experiment, the conductivity is extracted directly, i.e. without application of the Kramers–Kronig analysis. The optical properties of the MgO substrate have been obtained in a separate experiment and they depend only weakly on frequency and temperature. Here relative variations of the refractive index of the substrate are of the order of $10^{-3}$ and the substrate absorption can be neglected.

The actual variations of the substrate refractive index with temperature and frequency are monitored analyzing the positions of the Fabry–Pérot maxima in transmission (figure 1). The electrodynamic properties of the three films were found to be qualitatively similar. Therefore, the results of only one film with $T_c = 14.0$ K (sample no. Fe897) will be presented below.

### 3. Results

Figure 1 shows the transmittance and phase shift spectra of a FeSe$_{0.5}$Te$_{0.5}$ film (sample no. Fe897). The phase shift $\phi$ is given in the normalized presentation $\phi/(2\pi \nu)$, which corresponds to the optical thickness of the sample and is roughly given by $dn$. Here $d \simeq 0.5$ mm and $n \simeq 3.13$ are the substrate thickness and refractive index, respectively. Characteristic oscillations of the spectra with a period of about 3 cm$^{-1}$ are due to Fabry–Pérot-type interferences within the MgO substrate. As is demonstrated in figure 1, on cooling through the superconducting transition temperature both transmittance and phase shift change substantially. This ensures the sensitivity of the experimental technique to the dynamic conductivity at the transition from a metal to a superconductor. After solving the Fresnel equations and obtaining the conductivity, the interference oscillations disappear, which proves the self-consistency of the data analysis.

Figure 2 shows the conductivity spectra of the FeSe$_{0.5}$Te$_{0.5}$ film within the frequency range of our experiment. A gap in the data around 19 cm$^{-1}$ corresponds to a frequency gap between two BWOs. Steps that are seen especially in the imaginary part of the conductivity close to 9 cm$^{-1}$ reflect experimental uncertainties. They are due to variations in calibration and optical path arrangements of different BWOs. In the normally conducting state (black circles), the conductivity corresponds well to the low-frequency limit of the Drude conductivity. In this limit the real part ($\sigma_1(\nu)$, bottom panel) is roughly frequency independent and equals the dc conductivity $\sigma_0$. The imaginary part ($\sigma_2(\nu)$, top panel) reveals a linear frequency dependence which can be approximated by $\sigma_2 \simeq 2\pi \sigma_0 \nu \tau$. Here $\tau$ is the Drude scattering rate and $\nu$ is the frequency. Solid lines represent the Drude fit to the conductivity in the normal state with $\sigma_0 = 5300 \Omega^{-1}$ cm$^{-1}$ and $(2\pi \tau)^{-1} = 200$ cm$^{-1}$.

The inset of figure 2 shows the Faraday rotation angle measured in the normally conducting state (20 K) and at 30 cm$^{-1}$. Within the approximations of the Drude metal in the low-frequency limit and for $2\pi \nu \tau \ll 1$, the Faraday angle is directly proportional \[50, 51\] to the cyclotron frequency $\Omega_c = eB/m^*$. Therefore, together with the conductivity data in zero magnetic fields the Faraday rotation allows to estimate the cyclotron effective mass $m^*$ of the charge carriers in FeSe$_{0.5}$Te$_{0.5}$. From the fit shown in the inset of figure 2, the effective mass can be estimated as $m^* \simeq 11m_e$. This surprisingly high effective mass value correlates with a large mass enhancement in the range 6–20 as recently observed in ARPES experiments \[52\].

The transition to the superconducting state is most clearly seen in the imaginary part of the conductivity: a strong term proportional to $1/\nu$ starts dominating the spectra. This term results
Figure 2. Frequency dependence of the dynamic conductivity $\sigma_1 + i\sigma_2$ in an FeSe$_{0.5}$Te$_{0.5}$ thin film for different temperatures as indicated. Top panel: the imaginary part; bottom panel: the real part. Symbols: experiment; solid line in the normally conducting state: model fit using the Drude conductivity with $\sigma_0 = 5300 \Omega^{-1}\text{cm}^{-1}$ and $(2\pi\tau)^{-1} = 200 \text{ cm}^{-1}$. The solid line for $\sigma_2$ at 8.2 K demonstrates the $1/\nu$ behavior in the superconducting state. The inset shows the Faraday rotation angle in the normally conducting state and at 30 cm$^{-1}$. Symbols: experiment; solid line: model fit within the Drude model.

in the upward curvature of the $\sigma_2$ curves in the superconducting state. The $1/\nu$ term is directly proportional to the spectral weight of the superconducting condensate and corresponds to a terahertz penetration depth of $550 \pm 10 \text{ nm}$ at low temperatures. Just below $T_c$ the real part of the conductivity is suppressed above 20 cm$^{-1}$ and is enhanced at low frequencies (bottom panel of figure 2). This effect may be interpreted as an indication of a coherence peak in this material. Although the width of the superconducting transition is comparable with the data on single crystals [12], it probably cannot be neglected ($\Delta T = 1 \text{ K}$, figure 1). Therefore, the influence of the distribution of the transition temperatures may be important close to $T_c$. Within an effective medium model with distributions of normal and superconducting regions, this could lead to an enhancement of $\sigma_1$ especially at low frequencies.
At temperatures far below \( T_c \), the real part of the conductivity is suppressed up to about 50% of its normal state value. Remarkably, in the terahertz frequency range and at low temperatures, \( \sigma_1 \) remains finite and nearly frequency independent (open circles in figure 2). Such behavior cannot be expected in a conventional BCS superconductor and may be interpreted in favor of nodes or strong anisotropy of the superconducting gap.

If we assume that no nodes exist in the superconducting gap, then a full but small gap \( \Delta \) has to appear at low temperatures. It manifests itself in an optical gap of twice its size in \( \sigma \) (bottom frame of figure 2). Consequently, such a small gap, if it exists, has to be smaller than 1 cm\(^{-1} \) or the superconducting gap has nodes. A possible theoretical explanation to account for the observed behavior will be presented in the next section.

4. Data analysis

The complex conductivity obtained in the present experiment has been analyzed using a two-gap model based on the \( s^\pm \) symmetry [53]. This is a minimum model which takes into account the main characteristic features of the pnictides and chalcogenides [41, 54]. More details of this model can be found in the appendix.

As discussed in the previous section, the imaginary part of the optical conductivity \( \sigma_2(T, \nu) \) in the superconducting state is dominated by a term proportional to \( 1/\nu \) which masks all other contributions. In order to analyze the details of the conductivity spectra in the superconducting state, we will study the product \( \nu \sigma_2(T, \nu) \) instead of \( \sigma_2(T, \nu) \). In particular, the representation \( \nu \sigma_2(T, \nu) \) may reveal more salient features in \( \sigma_2(T, \nu) \) caused by the superconducting gap function or the quasiparticle scattering rate [55]. In addition, we present another important function, the optical scattering rate \( \tau_{op}^{-1}(T, \nu) \), which is calculated from the complex conductivity according to

\[
\tau_{op}^{-1}(T, \nu) = \frac{\Omega_p^2}{4\pi} \text{Re} \left[ \frac{1}{\sigma(T, \nu)} \right] .
\]

Here, \( \Omega_p \) is the plasma frequency.

The comparison between theory and experiment begins with the analysis of the normal state conductivity. In the normal state the optical conductivity is dominated by the elastic impurity scattering and in the THz frequency range the \( \sigma_1(\nu) \), \( \sigma_2(\nu) \) spectra are close to the low-frequency limit of the classical Drude model. Thus, we analyze in a first step the normal state data (\( T = 20 \) K) in order to determine two important material parameters, the plasma frequency \( \Omega_p \) and the normal state quasiparticle scattering rate \( \tau_{qp}^{-1}(T > T_c) \). The latter is found by simultaneous fitting the real and imaginary parts of the optical conductivity calculated via equations (A.1) and (A.8) in the experimental spectra. This gives a preliminary value of \( \tau_{qp}^{-1}(T > T_c) \). We then determine the plasma frequency \( \Omega_p \) using the normal state optical scattering rate \( \tau_{op}^{-1}(T > T_c) = 2\tau_{qp}^{-1}(T > T_c) \) which is energy independent.

In the normal state the experimental \( \tau_{op}^{-1}(T, \nu) \) is nearly frequency independent (figure 4). This allows one to tune the value of \( \tau_{qp}^{-1}(T > T_c) \) in equation (A.8) by improving the qualitative fit to \( \sigma_1 \) and \( \nu \sigma_2 \). This establishes a self-consistent procedure with the help of which we determined \( \tau_{qp}^{-1}(T > T_c) = 63 \) cm\(^{-1} \) and \( \Omega_p = 0.79 \) eV. Within the assumption of the present model, the uncertainties of both values are about 20% and are dominated by errors in the film thickness. The results of the fitting procedure are presented in figures 3 and 4, where the
Figure 3. Comparison between theoretical and experimental conductivity spectra. Top panel: the imaginary part of the conductivity is plotted in the form $\nu \sigma_2$ in order to suppress the $1/\nu$ term in the superconducting state. Bottom panel: the real part of the conductivity. Symbols: experiment; dashed, dotted and dash-dotted lines: the results of the two-gap model described in the appendix. The arrows mark the features in the conductivity which probably correspond to the small superconducting gap (see the text). Gray solid lines indicate the change in slope in the conductivity spectra. The inset represents the temperature dependence of the quasiparticles scattering rate, equation (A.8), which were used to fit the conductivity data.

open black squares indicate the experimental data and the dotted black lines correspond to the theory in the normal state. We note that temperature independence of the plasma frequency and equivalence of the scattering rates for the two channels are the assumptions of the present model. As mentioned above, the present model attempts to explain the experimental conductivity using the minimum number of free parameters.

The results in the superconducting state are then analyzed on the basis of the two-gap model as described in the appendix in order to determine the remaining material parameters, namely (i) $\Delta^{(1)}(0)$, the $T = 0$ K gap amplitude of the extended s-wave symmetric gap function around the $M$-point of the two-dimensional Brillouin zone, (ii) $x$, the amount of s-wave contribution to this gap, (iii) $\Delta^{(2)}(0)$, the amplitude of the isotropic s-wave gap function around the $\Gamma$
Figure 4. Frequency dependence of the quasiparticle scattering rate in FeSe$_{0.5}$Te$_{0.5}$ obtained using equation (1). Symbols: experiment; solid lines: fit results using the two-gap model as described in the text. Arrows correspond to the weak feature in the complex conductivity according to figure 3.

point, (iv) $w_1$ (or $w_2$), the weight of the contribution of the extended s-wave gap function (isotropic s-wave gap function) to the total optical conductivity, and finally, (v) $\tau_{qp}^{-1}(T)$, the temperature-dependent quasiparticle scattering rate in the superconducting state with $\tau_{qp}^{-1}(T < T_c) \leq \tau_{qp}^{-1}(T > T_c)$ [56]. In this analysis, we assume $\Omega_p$ to be temperature independent and that both gap channels are described using identical values for $\tau_{qp}^{-1}(T < T_c)$.

In a next step, the parameters $\Delta_0^{(1)}(0)$, $\Delta_0^{(2)}(0)$, $x$, $w_1$ ($w_2$) and $\tau_{qp}^{-1}(T)$ are determined by a fit to the $T = 2$ K data of the complex optical conductivity. As has already been pointed out in the introduction, in Fe(SeTe) a small superconducting gap [$\Delta_0^{(2)}(0)$] is expected to manifest itself in the frequency range of our experiment. Although the observed spectra do not show any direct gap features, fine details may still provide information about $\Delta_0^{(2)}(0)$. Indeed, as indicated in figures 3 and 4 by arrows and gray solid lines, around 24 cm$^{-1}$ distinct changes in slope may be seen in $\nu\sigma_2$ and $\sigma_1$ spectra. Especially in $\nu\sigma_2$ the features in the spectra are clearly seen and they are above the experimental uncertainties. In the spectra of the real part of the conductivity, the change in slope is more subtle and, therefore, an extrinsic source of this feature cannot be completely excluded. The changes in slope in the conductivity spectra resulted in an estimate of $\Delta_0^{(2)}(0) = 12$ cm$^{-1}$(1.5 meV). On the other hand, as the signature of this gap is rather weak we concluded that the contribution of this gap function to the total conductivity according to equation (A.7) is weak as well. Consequently, we chose $w_2 = 0.3$. The remaining set of parameters, namely $\Delta_0^{(1)}(0)$, $x$ and $\tau_{qp}^{-1}(T = 2$ K), was then determined by the closest possible simultaneous fit to $\nu\sigma_2(T = 2$ K) and $\tau_{qp}^{-1}(T = 2$ K). This resulted in $\Delta_0^{(1)}(0) = 24$ cm$^{-1}$(3 meV), $x = 0.34$ and $\tau_{qp}^{-1}(T = 2$ K) = 57 cm$^{-1}$. The results of this procedure are presented in figures 3 and 4. The $T = 2$ K data are shown by red open diamonds and the theory is shown by red dashed-dotted lines. We see that, in particular, the small features brought about by the gap $\Delta_0^{(2)}(0)$ might be attributed to the above-discussed change in slope in conductivity close to 24 cm$^{-1}$. Keeping this in mind, we conclude that our data are consistent with the small gap around 24 cm$^{-1}$.
In contrast to the conductivity spectra deep in the metallic and superconducting states, the data at intermediate temperatures are not well reproduced by theory. This is, for instance, demonstrated by the spectra at $T = 8.2$ K ((blue) open left triangles in figures 3 and 4). Only $\nu \sigma_2$ can be fitted reasonably well using $\tau_{qp}^{-1} = 60.8$ cm$^{-1}$ as a parameter (upper panel of figure 3, (blue) dashed line). As can be seen in the lower panel of figure 3, the real part of the conductivity at the intermediate temperature substantially deviates from the model predictions. As a consequence, the optical scattering rate at $T = 8.2$ K (figure 4) shows an indication of a non-zero intercept at $\nu = 0$. As we used a minimal theoretical model in the fitting procedure, no further parameters are available to account for the observed difference. A possible hypothesis could be that at intermediate temperatures some parts of the sample remain in the normally conducting state. Via the effective medium model such metallic inclusions would lead to an enhancement of the real part of the conductivity which will be especially strong at low frequencies. The problem of the microwave conductivity in the sample with inhomogeneities has been discussed previously in the context of high-$T_c$ cuprates (see [57] and references therein).

5. Conclusions

In conclusion, using the BWO-type spectroscopy in the terahertz frequency range we investigate the complex conductivity of FeSe$_{0.5}$Te$_{0.5}$ superconducting films. The experimental results are compared with the two-gap model based on the $s^\pm$ symmetry. The normal state conductivity is close to the low-frequency limit of a Drude metal with a scattering rate $(2\pi \tau)^{-1} = 200$ cm$^{-1}$ and an enhanced effective mass of $m^*/m_e = 11$. In the superconducting state, the real part of the complex conductivity remains finite, indicating the existence of a strongly anisotropic gap or even nodes in the gap. Weak features in the conductivity at low temperatures point to a superconducting gap value close to $\Delta_0^{(2)}(0) = 12$ cm$^{-1}(1.5$ meV) for the smaller one of the two gaps.

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Appendix. The two-gap model

The two-gap model used in this work is based on the $s^\pm$-symmetry model proposed for the ferropnictides by Chubukov et al [53]. It consists of the sum of an isotropic s-wave gap function around the $\Gamma$-point (hole pocket) of the two-dimensional Brillouin zone and an extended s-wave gap function centered on the $M$-point (electron pocket). The two-gap functions carry an opposite sign which is of no relevance for the analysis of optical conductivity data. A comparison with the Fermi surface of an Fe$_{1.04}$Te$_{0.56}$Se$_{0.44}$ sample reported by Chen et al [58] reveals that this model is a minimum model also applicable to ferrochalcopybes. We assume, furthermore, that the interband interaction between the two bands is negligible, which is acceptable because we concentrate only on the sub-THz regime of optical conductivity.

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For a superconductor with an anisotropic superconducting gap function $\Delta(v, \phi)$ on a cylindrical Fermi surface with polar angle $\phi$, the optical conductivity $\sigma(T, v)$ for some temperature $T$ and energy $v$ takes the form \cite{54, 59}

$$\sigma(T, v) = \frac{\Omega_p^2 i}{4\pi v} \left( \int_0^\infty d\omega \tanh \left( \frac{\beta \omega}{2} \right) [J(\omega, v) - J(-\omega, v)] \right)_{\phi},$$  \hspace{1cm} (A.1)

where the bracket $\langle \cdots \rangle_{\phi}$ indicates an average over the polar angle $\phi$, $\Omega_p$ is the plasma frequency, $\beta$ is the inverse temperature $(k_B T)^{-1}$ and $k_B$ is the Boltzmann constant. The function $J(\omega, v)$ is given by

$$2J(\omega, v) = 1 - N(\omega, \phi)N(\omega + v, \phi) - P(\omega, \theta)P(\omega + v, \phi)$$

$$+ \frac{1 + N^*(\omega, \phi)N(\omega + v, \phi) + P^*(\omega, \phi)P(\omega + v, \phi)}{E^*(\omega, \phi) - E(\omega + v, \phi)},$$  \hspace{1cm} (A.2)

with * indicating the complex conjugate. Here

$$E(\omega, \phi) = \sqrt{\tilde{\omega}^2(\omega + i 0^+) - \tilde{\Delta}^2(\omega + i 0^+, \phi)},$$  \hspace{1cm} (A.4)

$$N(\omega, \phi) = \tilde{\omega}(\omega + i 0^+)/E(\omega, \phi),$$  \hspace{1cm} (A.5)

$$P(\omega, \phi) = \tilde{\Delta}(\omega + i 0^+, \theta)/E(\omega, \phi).$$  \hspace{1cm} (A.6)

The renormalized frequencies $\tilde{\omega}(\omega + i 0^*)$ and the renormalized gap functions $\tilde{\Delta}(\omega + i 0^+, \phi)$ are understood to be also functions of temperature. Similar to our results, most discussions of the optical conductivity in the superconducting state neglect vertex corrections which are not expected to change our results qualitatively. The vertex corrections can be incorporated through the changes of the scattering rate as introduced below.

The total conductivity of the sample is calculated from the weighted sum

$$\sigma(T, v) = w_1\sigma^{(1)}(T, v) + w_2\sigma^{(2)}(T, v),$$  \hspace{1cm} (A.7)

with $w_1 + w_2 = 1$. Here $\sigma^{(1)}(T, v)$ is the optical conductivity calculated using equation (A.1) for the extended s-wave gap function (around the $M$-point) and $\sigma^{(2)}(T, v)$ is the contribution of the isotropic s-wave gap function (around the $\Gamma$-point).

For an extended s-wave gap, the impurity scattering can change the value of the renormalized gap function $\tilde{\Delta}(\omega + 0^*, \phi)$ as well as the renormalized quasiparticle frequency $\tilde{\omega}(\omega + 0^*) = \omega - \Sigma_{qp}(\omega + 0^*)$ with $\Sigma_{qp}(\omega + 0^*)$ being the quasiparticle self-energy. For the elastic quasiparticle scattering rate $\tau_{qp}^{-1}$ in the Born approximation \cite{60, 61} (with the corresponding optical scattering rate $\tau_{op}^{-1} = 2\tau_{qp}^{-1}$), we have \cite{59}

$$\tilde{\omega}(\omega + i 0^*) = \omega + i \tau_{qp}^{-1}\langle N(\omega, \phi) \rangle_{\phi},$$  \hspace{1cm} (A.8)

$$\tilde{\Delta}(\omega + i 0^*, \phi) = \alpha\Delta_0 + i \tau_{qp}^{-1}\langle P(\omega, \phi) \rangle_{\phi} + \sqrt{1 - \alpha^2\Delta_0^2}\sqrt{2}\cos(2\phi),$$  \hspace{1cm} (A.9)
where $\Delta_0(T)$ is the Fermi surface average of the superconducting gap function at a given temperature $T < T_c$. The temperature dependence of the gap is described by the mean-field temperature dependence of a BCS function. For $\alpha = 1$ equations (A.8) are equivalent to the standard BCS equations of an isotropic $s$-wave superconductor at temperatures $T < T_c$. On the other hand, $\alpha = 0$ reproduces the case of a $d$-wave symmetric superconducting gap. Consequently, $0 < \alpha < 1$ describes the admixture of $s$-wave and $d$-wave symmetric contributions to the gap function thus being a model for an extended $s$-wave symmetric gap function. It is of particular interest that for $\alpha \leq \alpha_c = \sqrt{2/3}$ and $\tau_{qp}^{-1} = 0$ this extended $s$-wave symmetric gap function has nodes. It is also quite interesting to note that for $\tau_{qp}^{-1} > 0$ the nodes vanish already for values $\alpha < \alpha_c$. This behavior is commonly referred to as ‘lifting of the nodes’ [22, 23]. It is, finally, quite convenient to introduce the anisotropy parameter $x = \alpha/(\alpha - \sqrt{1-\alpha^2})$, which gives the percentage of the isotropic $s$-wave component to the extended $s$-wave symmetric gap function.

The optical conductivity in the normal state ($T > T_c$) can be calculated for any value of the quasiparticle scattering rate $\tau_{qp}^{-1}$ using equations (A.1) and (A.8) by setting the renormalized gap function $\tilde{\Delta}(\omega + i0^+, \phi)$ equal to zero.

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