Magnetic pair-breaking in superconducting $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$
investigated by magnetotunneling

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Abstract

The de Gennes and Maki theory of gapless superconductivity for dirty superconductors is used to interpret the tunneling measurements on the strongly type-II high-$T_c$ oxide-superconductor $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ in high magnetic fields up to 30 Tesla. We show that this theory is applicable at all temperatures and in a wide range of magnetic fields starting from 50 percent of the upper critical field $B_{c2}$. In this magnetic field range the measured superconducting density of states (DOS) has the simple energy dependence as predicted by de Gennes from which the temperature dependence of the pair-breaking parameter $\alpha(T)$, or $B_{c2}(T)$, has been obtained. The deduced temperature dependence of $B_{c2}(T)$ follows the Werthamer-Helfand-Hohenberg prediction for classical type-II superconductors in agreement with our previous direct determination. The amplitudes of the deviations in the DOS depend on the magnetic field via the spatially averaged superconducting order parameter which has a square-root dependence on the magnetic field. Finally, the second Ginzburg-Landau parameter $\kappa_2(T)$ has been determined from the experimental data.

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I. INTRODUCTION

The temperature dependence of the upper critical field $B_{c2}$ in several new classes of superconductors attracts much attention as it reveals very unusual behavior. For the conventional type-II superconductors $B_{c2}$ shows a linear increase below $T_c$ and a saturation at the lowest temperatures in agreement with the theoretical predictions of Maki [1] and Werthamer, Helfand and Hohenberg [2]. In the case of certain new superconductors $B_{c2}(T)$ has a positive curvature practically in the whole temperature range. As examples of this anomalous behavior we mention the borocarbides [3], the organic superconductors [4], the high-$T_c$ bismuthates $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ [5], and in the most pronounced way the cuprates [6] where in some cases $B_{c2}(T)$ even diverges at very low temperatures. Several scenarios have been proposed to explain this anomalous behavior. Among others, one can find a bipolaron model [7], an unconventional normal state [8], a strong electron-phonon coupling [9], and the presence of inhomogeneities and magnetic impurities [10].

In the above mentioned cases, magnetotransport or magnetization measurements were employed for the determination of $B_{c2}(T)$. In strongly type-II superconductors a magnetization measurement near $B_{c2}$ can be very difficult because of its extremely small value. Moreover, because depinned vortices in the liquid or solid state cause a finite dissipative resistance before reaching the full transition to the normal state, the complexity of the $B - T$ phase diagram in high-$T_c$'s [11] undermines any direct determination of the upper critical field from magnetotransport data. Recently, the $B_{c2}(T)$ dependencies have been determined for high-$T_c$ superconductors by non-dissipative experimental methods. Carrington et al. [12] have shown, that magneto-specific-heat measurements in the overdoped Tl-2201 cuprates yield in the high temperature region a different curvature of $B_{c2}(T)$ as compared to that determined from ac-susceptibility or from magnetotransport. Blumberg et al. [13] determined the upper critical field from the electronic Raman scattering in the same cuprates and also obtained a conventional temperature dependence with a negative curvature and saturation at low temperatures. In our previous experimental work elastic tunneling was used as a direct tool to infer the upper critical field $B_{c2}(T)$ in the high-$T_c$ oxide $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ [14]. Such a method is based on a measurement of the very fundamental superconducting density of states (DOS), where the superconducting part of the $B - T$ phase diagram is defined from the non-zero value of the superconducting order parameter ($\Delta \neq 0$).

In the present paper the tunneling characteristics measured on $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ in the mixed state at very high magnetic fields are discussed in the frame work of the de Gennes and Maki theory of the gapless superconductivity [15][16]. We show that the theory is applicable at all temperatures below $T_c$ and in a wide range of magnetic fields below the upper critical one. In the experimentally measured tunneling conductances (proportional to the spatially averaged superconducting DOS) at high fields only the amplitude of the deviations from the normal-state tunneling conductance depends on the applied magnetic field. The energy dependence of these deviations is completely controlled by the temperature. The renormalized tunneling-conductance traces reveal a simple scaling behavior. This allows us to determine the temperature dependence of the pair-breaking parameter $\alpha(T)$ and the upper critical field $B_{c2}(T)$. The fitted $B_{c2}(T)$ follows the Werthamer-Helfand-Hohenberg prediction for classical type-II superconductors and is also in agreement with our previous direct determination [14]. The analysis of the amplitude of the tunneling conductance at dif-
ferent magnetic fields enables us to determine the magnetic field dependence of the spatially averaged value $\bar{\Delta}(B)$ of the superconducting order parameter at different temperatures and the temperature dependence of the second Ginzburg-Landau parameter $\kappa_2(T)$.

II. THEORY

The behavior of type-II superconductors in the presence of external magnetic fields has been described on the basis of the phenomenological Ginzburg-Landau (GL) theory \[17\]. Abrikosov \[18\] showed that a type-II superconductor exhibits a mixed (vortex) state, in which the magnetic flux penetrates the sample in the form of quantized flux lines. These results of the GL theory have validity in a restricted temperature region near the transition temperature $T_c$, where the lower and upper critical fields ($B_{c1}(T)$ and $B_{c2}(T)$) are both much smaller than their values $B_{c1}(0)$ and $B_{c2}(0)$ at zero temperature. An important generalization of the GL theory has been made by Maki \[19\] and de Gennes \[20\] in the case of dirty superconductors (where the mean free path $l$ is much smaller than the BCS superconducting coherence length $\xi_0$) extending this theory to arbitrary temperatures when the magnetic field is close to $B_{c2}(T)$. Maki has shown, that Abrikosov’s original theory is applicable at all temperatures in the dirty limit, if in the expressions for the temperature dependencies of critical magnetic field and magnetization two temperature dependent GL parameters $\kappa_i$ are introduced

$$\kappa_1 = \frac{B_{c2}(T)}{\sqrt{2}B_c(T)}, \quad (1)$$

$$-M = \frac{B_{c2} - B}{\mu_0 \beta (2\kappa_2^2 - 1)}, \quad (2)$$

where $M$ is the magnetization and $\beta$ a geometric constant of the vortex lattice. The first GL parameter $\kappa_1(T)$, the ratio of the upper critical field $B_{c2}(T)$ and the thermodynamic critical field $B_c(T)$, is a slowly temperature dependent function with a 20% larger value at 0 K than at $T_c$. The parameter $\kappa_2$ is connected with the slope of the magnetization curve near $B_{c2}$. Caroli et al. \[21\] showed that $\kappa_2(T)$ will be equal to $\kappa_1(T)$ within 2% for a dirty bulk type-II superconductor.

A magnetic field applied to a dirty superconductor breaks the (time-reversal) symmetry of the Cooper pairs and leads to a finite lifetime $\tau_k$ of the condensed paired electrons with the pair breaking parameter $\alpha_k = h/2\tau_k$. This decay process competes with a natural growth of pairs associated with a characteristic lifetime $\tau(T)$ and related parameter $\alpha = h/2\tau$ which is connected with the upper critical field $B_{c2}$ according to

$$B_{c2} = \frac{\alpha \Phi_0}{\pi D \hbar}, \quad (3)$$

where $\Phi_0$ is the flux quantum and $D$ the diffusion constant. Neglecting the effects of spin paramagnetism and spin-orbit scattering the temperature dependence of the pair-breaking parameter $\alpha(T)$ is given by

$$\ln(T_c/T) = \Psi \left( \frac{1}{2} + \frac{\alpha}{2\pi k_B T} \right) - \Psi \left( \frac{1}{2} \right), \quad (4)$$

3
where \( \Psi(z) \) is the digamma function.

Magnetic pair-breaking in superconductors depresses the superconducting order with the occurrence of quasi-particle states inside the otherwise forbidden energy gap. For sufficiently strong pair-breaking, near \( B_{c2} \), a gapless superconducting state exists. Superconductivity with a finite value of the superconducting order parameter (pair potential \( \Delta \)) exists without a minimum excitation energy in the quasi-particle excitation spectrum. This gapless superconducting behavior can be clearly seen in the calculations of Skalski et al. \[22\] for the density of states of the superconducting excitation spectrum in the presence of pair breaking. De Gennes \[20\] has derived a very simple expression for the density of states \( N(E, \mathbf{r}) \) in dirty superconductors in the gapless region for small \( \Delta \) in magnetic fields near \( B_{c2} \), given by

\[
N(E, \mathbf{r}) = N_N(0) \left[ 1 - \frac{\Delta^2(\mathbf{r}, H)}{2} \left( \frac{\alpha^2}{E^2} - \frac{E^2}{(2\Delta)^2} \right) \right],
\]

where \( N_N(0) \) is the DOS at the Fermi surface of the superconductor in the normal state. In the range of validity of Eq. (5), \( \alpha \) does not depend on magnetic field, but is a function of temperature only. Via Eq. (3), the pair-breaking parameter \( \alpha(T) \) is related to \( B_{c2}(T) \). The only magnetic field dependent parameter in Eq. (5) is \( \Delta(\mathbf{r}, H) \). It leads to the important conclusion that the energy dependence of \( N(E, \mathbf{r}) \) is fully controlled by temperature and not by magnetic field or \( \Delta \). Via \( \Delta \), the magnetic field acts just as a scaling parameter for the amplitude of the deviations of \( N(E, \mathbf{r}) \) from \( N_N(0) \).

A direct experimental verification of gapless superconductivity in the presence of a pair-breaking perturbation can be obtained by tunneling spectroscopy \[15,16\]. The differential tunneling conductance measured on a metal-insulator-superconductor (N-I-S) tunnel-junction is directly proportional to the spatially averaged value of the superconducting DOS by

\[
G(V) = \frac{(dI/dV)}{(dI/dV)_N} = \int_{-\infty}^{\infty} N(E) \left[ \frac{\partial f(E + eV)}{\partial(eV)} \right] dE, \tag{6}
\]

where \( G(V) \) represents the tunneling conductance normalized to its normal-state value and the brackets in the integral contain the bias-voltage derivative of the Fermi distribution function. In the case of a gapless DOS the normalized conductance may be transformed into \[23\]

\[
G(V) = 1 + \frac{\Delta^2}{8\pi^2k_B^2T^2} \text{Re} \left\{ \Psi_3 \left( \frac{1}{2} + a - ib \right) \right\}, \tag{7}
\]

where \( a = \alpha/2\pi k_B T, \ b = eV/2\pi k_B T \) and \( \Psi_3 \) is the second derivative of the digamma function. In a geometry with the applied magnetic field perpendicular to the planar surface of the junction barrier, the sample is in the Shubnikov mixed phase with the Abrikosov vortex structure. In a tunneling experiment the spatial average \( \bar{N}(E) \) of the density of states over the sample surface is measured. Therefore, one has to consider in Eq. (5) the spatially averaged order parameter \( \bar{\Delta} \) \[13\].

The magnetic field dependence of \( |\bar{\Delta}| \) in the gapless region of type-II superconductor near \( B_{c2} \) has been calculated by Maki \[19\] yielding
\[ |\tilde{\Delta}|^2 = \frac{4\pi eck_BT(Bc_2 - B)}{1.16\mu_0\sigma(2\kappa_2^2 - 1)\Psi_2(\frac{1}{2} + a)}, \]

where \(\mu_0\) is the vacuum permeability, \(\sigma\) the normal state conductivity and \(\Psi_2\) the first derivative of the digamma function. The linear field dependence of the averaged value of the energy gap squared results in a linearity in the above mentioned scaling of the averaged gapless DOS, or \(G(V)\), with magnetic field. By a simple renormalization of the tunneling conductance to their zero-bias value according to the expression \((G(V) - 1)/(G(0) - 1)\), the field-dependent parameter \(\tilde{\Delta}\) falls out the problem. The in such a way renormalized tunneling conductances at a fixed temperature should collapse on the same curve for different magnetic fields. This behavior can be very useful for the experimental determination of the pair-breaking parameter \(\alpha\) or \(B_{c2}\), and of the order parameter \(\tilde{\Delta}\), or \(\kappa_2\) [15,23]. The region of validity of expressions (5),(7) and (8) in the \(B-T\) diagram is not very well known. They are certainly valid in the high-field region \(B \rightarrow B_{c2}(T)\).

III. EXPERIMENT

The high quality single-crystalline \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) samples were grown by electrochemical crystallisation [24]. The quality of the single crystals was verified by the measurement of the resistance in a four probe contact configuration. In zero magnetic field with decreasing temperature the samples showed metallic temperature dependence which saturates to a residual resistivity \(100 \mu\Omega\text{cm} \) above the superconducting transition with a width \(\Delta T_c \approx 1.2\) K. The ac-susceptibility measurement confirms this transition width. The critical temperature \(T_c = 23\) K has been determined from the midpoint of the zero field transition.

The tunnel junctions were prepared by painting a silver spot on the freshly cleaned surface of the crystal. The interface between the silver and \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) counter electrodes served as a natural barrier forming a planar normal metal-insulator-superconductor (N-I-S) tunnel junction. The tunneling measurements were performed in magnetic fields up to 30 T perpendicular to the planar tunneling junction enabling the formation of the vortex state in the junction area [14].

IV. RESULTS AND DISCUSSION

In Fig. 1 the experimental tunneling data are shown at different magnetic fields increasing from zero to 30 Tesla with a step of 2 Tesla (if not otherwise specified) for three temperatures \(T=1.5, 4.2\) and \(16\) K. For a specific temperature the upper critical field can be directly determined as the field where any trace of the superconducting density of states disappears in the conductance data. In our previous analysis of the tunneling data [14] we deduced the upper critical field from a linear extrapolation of the magnetic field dependence of the zerobias conductance. The obtained temperature dependence of \(B_{c2}\) agreed with the standard WHH theory.
To discuss the validity of the dirty limit \( (l < \xi_0) \) to our system now we have calculated the BCS coherence length \( \xi_0 \approx 49 \, \text{Å} \) from \( B_{c2}(0) = 28 \, \text{T} \) and take the mean free path \( l \approx 33 \, \text{Å} \) from \([23]\). The Ginzburg-Landau coherence length is related to the BCS one via \( \xi_{GL} = 0.855 \sqrt{\xi_0 l} \). The estimated ratio \( l/\xi_0 \) is about \( \sim 0.7 \). One of us (P.W.) has calculated the density of states as a function of \( l/\xi_0 \) \([21]\) and found very small differences for the ratio \( l/\xi_0 \) changing from 0 to 1. Similarly Eilenberger \([27]\) found only small differences for this \( l/\xi_0 \) range when calculating the temperature dependence of the Ginzburg Landau parameters.

Therefore, we believe that the dirty limit model of de Gennes and Maki is applicable in our case. The obtained agreement with experimental data, as discussed further on, seems to justify this approach.

The data sets as shown in Fig. 1 were rewritten in the above mentioned form \((G(V) − 1)/(G(0) − 1)\) and are shown in the right side of the Fig. 1. This simple renormalization of the conductance reveals, that above a certain magnetic field all renormalized conductance curves belonging to the same temperature collapse to the same curve. This is in a full agreement with Eq. (5) for the description of the gapless regime. We have also made the same rescaling procedure for the data sets taken at \( T = 1.5, 3, 4.2, 8, 12, 16 \) and 20 K. At all temperatures an agreement with the de Gennes expression can be found for magnetic fields \( B > 0.5B_{c2}(T) \).

Rewriting Eq. (5) in the form \((N(E) − 1)/(N(0) − 1)\), or \((G(V) − 1)/(G(0) − 1)\), makes that the only unknown quantity is the pair-breaking parameter \( \alpha \). We have made a fit of this renormalized gapless DOS to the experimental data accounting for the thermal smearing as defined in Eq. (6). By this fitting procedure the same \( \alpha \) can be obtained for any tunneling trace at \( B > 0.5B_{c2}(T) \) at a particular temperature.

The experimental values of the upper critical field obtained directly as mentioned above are displayed in the Fig. 2 as a function of temperature together with the temperature dependence of the pair-breaking parameter \( \alpha \) obtained by the fits of the voltage dependence of the conductance. The shown error bars account for the scattering of the \( \alpha \) values as obtained by the fitting to the curves at different fields. Because the amplitude of the normalized superconducting density of states decreases with increasing temperature the error bars increase for increasing temperature. Above 16 K the error bars are of the same order as \( \alpha \) itself. The direct relation between \( \alpha \) and \( B_{c2} \) is defined by Eq. (3), which depends on the diffusion constant \( D \) of the sample. The best agreement between the experimentally determined critical field and pair-breaking parameter is obtained for \( D = 1 \, \text{cm}^2\text{s}^{-1} \). This value is in a perfect agreement with the data of Affronte et al. \([25]\) obtained on a very similar sample made in the same laboratory and also agrees reasonably with the value of Roesler et al. \([28]\) obtained for a thin film, where they found \( D = 0.64 \, \text{cm}^2\text{s}^{-1} \).

In Fig. 3 we show that the zero-field tunneling-conductance trace at 1.5 K can be described by the BCS density of states using the Dynes formula \( N(E) \sim \text{Re}\{E/(E^2 − \Delta^2)^{1/2}\} \) with the complex energy \( E = E' + i\Gamma \) which takes account for a certain sample inhomogeneity via the broadening parameter \( \Gamma \). This formula gives a good description of the tunnel spectra at 1.5 K and zero magnetic field with \( \Delta = 3.9 \pm 0.1 \, \text{meV} \) and \( \Gamma = 0.4 \pm 0.1 \, \text{meV} \), yielding \( 2\Delta/kT_c = 3.9 \pm 0.1 \). This indicates that \( \text{Ba}_{1-x}\text{K}_x\text{BiO}_3 \) is a BCS-like superconductor with a medium coupling strength \([29]\).

In the case of weak-coupling superconductors, the pair-breaking parameter at \( T = 0 \, \text{K} \) is connected with the energy gap \( \Delta(0) \) by the expression \( \alpha = \Delta(0)/2 \). In our BKBO sample at \( T \to 0 \, \text{K} \) the superconductivity is destroyed at \( \alpha \sim 2.85 \, \text{meV} \) which is about 45% higher.
than the expected value $\Delta(0)/2 \sim 2$ meV. A similar discrepancy has been found in tunneling experiments of conventional type-II superconductors in the dirty limit with a finite value of $l/\xi_0$ and with strong-coupling effects \[23\]. In our case with $l/\xi_0$ about $\sim 0.7$ also the strong-coupling plays an important role as shown in ref. \[30\].

In Fig. 3, the normalized tunneling conductances $(dI/dV)/(dI/dV)_N$ at $T = 1.5$ K are also displayed for magnetic fields $B > 10$ T where the scaling in the voltage dependence of the conductance curves holds. These curves are fitted by the de Gennes formula using the previously determined pair-breaking parameter $\alpha = 2.85$ meV. Then the only fitting parameter is the superconducting order parameter $\Delta$. Thus, we obtained the magnetic-field dependence of the superconducting order parameter $\Delta$. The same procedure was repeated for the magnetic-field dependent data sets at different temperatures. The results of $\Delta(B)$ are shown in Fig. 4 for $T = 1.5$, 8, and 16 K. In the inset we display the magnetic field dependence of $\Delta^2$. $\Delta^2(B)$ changes linearly with the applied field not only in the high field region near $B_{c2}$ as predicted by Maki (Eq. (8)) but at least from $B > 0.5B_{c2}(T)$. This finding supports the evaluation of the upper critical field from tunneling spectroscopy as made in our previous work where a linear extrapolation of the zero-bias tunneling conductance $G(0)$ was used to obtain $B_{c2}(T)$ \[14\].

The normalized zero-bias tunneling conductance $G(V = 0, B)_T$ at a certain temperature can be approximated by

$$G(V = 0, B)_T = 1 - P(B)_T(B_{c2} - B),$$

where $P(B)_T$ is the slope of the normalized zero-bias conductance $G(V = 0, B)_T$ versus magnetic field at a fixed temperature with dimension $[T^{-1}]$. With this expression for the zero-bias tunneling conductance substituted into Eq. (7) together with $\Delta$ from Eq. (8) we can derive the second GL parameter $\kappa_2$ as a function of the temperature \[23\]

$$\kappa_2(T) - 0.5 = -\frac{e}{4.64\pi\mu_0 k_B T \sigma P(B)_T} \frac{\Psi_3(\frac{1}{2} + a)}{\Psi_2(\frac{1}{2} + a)}. \quad (10)$$

Here, besides the slope $P(B)_T$ of the zero-bias tunneling conductance and the pair-breaking parameter $\alpha$ the electrical conductance $\sigma$ is an experimental parameter. For $\sigma$ we can take $\sigma = 0.125 \times 10^7 \Omega^{-1}m^{-1}$ from ref. \[25\]. The resulting temperature dependence of $\kappa_2$ is shown in Fig. 5 by open symbols together with the theoretical prediction of Caroli, Cyrot and de Gennes \[21\] for a dirty type-II s-wave superconductors in the mixed state. Despite the fact that the error bars are very big a discrepancy is obvious. As shown by Guyon et al. \[23\] the slope $P(B)_T$ at different temperatures is expected to be constant. In our case it changes at higher temperatures (see inset in Fig. 5). If the slope is kept artificially constant as it was at low temperatures (dotted line in the inset) we derive a much better agreement with the theoretical prediction of Caroli et al. (full symbols in Fig. 5). One possible explanation of this discrepancy between the theoretical predictions of Caroli et al. and our $\kappa_2(T)$ calculation from the real temperature dependent $P(H)_T$ values could result from the local sample inhomogeneity \[14,31\] because at higher temperatures possibly another phase can play a role in the tunneling characteristics. In this case the correct $\kappa_2(T)$ dependence of the major bulk superconducting phase is determined from the constant $P(H)_T$ following the predictions of Caroli et al.. Then, $\kappa_2(T)$ is equal to $\kappa_1(T)$ and it can be used for the
determination of basic superconducting quantities, connected with the GL parameters, like the thermodynamic critical magnetic field or the free energy.

Anyhow, the $\kappa_2(T)$ parameter calculated from our magnetotunneling data reveals a saturation at low temperatures. Its value at higher temperatures is in a qualitative agreement with the earlier published values of the GL parameter $\kappa$ in the BKBO system [32]. The saturating character of $\kappa_2(T)$ in the low temperature region proves a dirty limit and a non $d$-wave character of the superconductivity in the BKBO system. Pure superconductors [27] similarly as $d$-wave superconductors should reveal a characteristic $\kappa_2(T) \sim \ln(1/T)$ dependence [33].

V. CONCLUSIONS

The pair-breaking theory has been applied for analyzing the magnetotunneling results in the BKBO superconductor. It has been shown, that the generalization of the Ginzburg-Landau theory provided by Maki and de Gennes for the dirty type-II superconductors in a field region close to $B_{c2}$ is valid in a much wider interval of magnetic fields. The theory for the gapless superconductors describes the experimental tunneling data for magnetic fields $B > 0.5B_{c2}(T)$ very well. In this region of magnetic fields the tunneling curves can be fitted by the de Gennes formula for the thermally smeared averaged density of states. As a consequence the tunneling curves reveal an universal scaling in the magnetic field dependence for a fixed temperature. This allows us to calculate the temperature dependence of the pair-breaking parameter $\alpha$ (or $B_{c2}$) and the Maki parameter $\kappa_2$ from the tunneling curves. The averaged superconducting order parameter squared $\bar{\Delta}^2$ reveals linearity with the magnetic field in the same range of magnetic fields. This linearity can be applied not only in interpretation of the tunneling measurements but also in the case of many superconducting quantities governed by $\bar{\Delta}^2(H)$ in the high-field limit, like magnetization, magnetic susceptibility, thermal conductivity, etc.. The obtained temperature dependence of the upper critical field is in satisfactory agreement with the theoretical predictions of Maki and Werthamer, Helfand and Hohenberg for classical type-II superconductors.

The wide magnetic field range where the pair-breaking theory has been proved to be valid (far below the real $B_{c2}$) makes this tunneling approach very promising for the high-$T_c$ cuprates where the upper critical field is experimentally not available for reliable estimates of the temperature dependence of $B_{c2}$.

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FIGURE CAPTIONS

Fig. 1: Normalized \((G, \text{left side})\) and renormalized \(((G-1)/(G(0)-1), \text{right side})\) tunneling conductances of the \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\)-Ag tunnel junction in magnetic fields from zero up to 30 T in steps of 2 T (if not mentioned else) at the indicated temperatures. The renormalized curves have been fitted to the de Gennes formula (Eq. (5)) of the DOS (open circles) yielding the indicated pair-breaking parameter \(\alpha\).

Fig. 2: Temperature dependence of the upper critical magnetic field \(B_{c2}\) of \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) determined directly from an extrapolation of the zero-bias tunneling conductance (closed circles, left scale) and of the pair-breaking parameter \(\alpha\) determined from a fit to the de Gennes formula of the DOS for the full voltage-dependence of the conductance (open squares, right scale). The full line shows the prediction of the standard WHH theory.

Fig. 3: Experimentally measured normalized tunneling conductances at \(T = 1.5\) K (closed squares) shifted along the Y-axis as indicated by the high-voltage values at the right side. The lines show the BCS dependence at \(B = 0\) T (dotted line) and the fitting to the de Gennes pair-breaking (PB) formula of the DOS at \(B > 10\) T (full lines).

Fig. 4: Magnetic field dependencies of the averaged value of the energy gap \(\bar{\Delta}\) at different temperatures. The inset shows the squared values \(\bar{\Delta}^2\) as a function of magnetic field.

Fig. 5: Temperature dependence of the second Ginzburg-Landau parameter \(\kappa_2\) calculated from magnetotunneling results (left scale) for the temperature dependent \(P(B)_T\) (open circles) and for a constant \(P(B)_T = 0.0395\) T\(^{-1}\) (closed squares). The full line shows the theoretical prediction of Caroli et al. \[21\]. The inset displays the temperature dependence of the zero-bias slope \(P(B)_T\).
