The effect of magnetic impurities in a two-band superconductor: A point-contact study of Mn-substituted MgB$_2$ single crystals

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We present the first results of directional point-contact measurements in Mg$_{1-x}$Mn$_x$B$_2$ single crystals, with $x$ up to 0.015 and bulk $T_c$ down to 13.3 K. The order parameters $\Delta_\sigma$ and $\Delta_\pi$ were obtained by fitting the conductance curves with the two-band Blonder-Tinkham-Klapwijk (BTK) model. Both $\Delta_\sigma$ and $\Delta_\pi$ decrease with the critical temperature of the junctions $T_{cJ}$, but remain clearly distinct up to the highest Mn content. Once analyzed within the Eliashberg theory, the results indicate that spin-flip scattering is dominant in the $\sigma$ band, as also confirmed by first-principle band structure calculations.

The two-band character of superconductivity in MgB$_2$ has been almost completely understood and explained by now, but the effects of disorder and chemical doping are still in need of some experimental clarification. Several substitutions have been tried, either in the Mg or in the B sites, but only few of them have been successful and none has been able to enhance the critical temperature of the compound. However, their study has proven useful to clarify the role of the different scattering channels and to try to control them selectively. Substitutions with magnetic impurities (Mn, Fe) represent a class of its own because of the spin-flip pair-breaking scattering that is expected to dramatically suppress superconductivity – even though the way it does it in a two-band superconductor has never been studied experimentally. Up to now, only two successful Mn substitution in the Mg site have been reported, one in polycrystalline samples and one in single crystals. Here, we present the first results of point-contact spectroscopy (PCS) measurements in Mn-substituted MgB$_2$ single crystals grown at ETHZ, which allowed us to study the effects of magnetic impurities on the order parameters (OPs) of a two-band superconductor. The amplitudes of the OPs, $\Delta_\sigma$ and $\Delta_\pi$, were determined as a function of the critical temperature. The resulting trend can be explained within the Eliashberg theory as being mainly due to a doping-induced increase in the pair-breaking scattering within the $\sigma$ bands, with minor contributions from the $\pi-\pi$ or the $\sigma-\pi$ channels. This result, apparently in contrast with the Mn position in the lattice, is however confirmed by first-principle calculations of the local effect of a Mn impurity on the bandstructure of MgB$_2$.

The high-quality Mg$_{1-x}$Mn$_x$B$_2$ single crystals used for our measurements were grown by using the same high-pressure, cubic-anvil technique set up for pure MgB$_2$, and by replacing part of the Mg precursor with metallic Mn. The Mn content $x$ of each crystal was measured by EDX through a careful evaluation of the Mn/Mg ratio; the crystals are single-phase and homogeneous within $\pm\delta x$ ($\delta x=0.0010$). The bulk critical temperature $T_c$ was determined by DC magnetization measurements. As reported elsewhere, the dependence of the lattice constants on the Mn content indicates that Mn replaces Mg in the lattice. The magnetic-field dependence of the Curie part $C^*$ of the magnetic moment $M$ clearly indicates that Mn ions are divalent (i.e. Mn$^{2+}$) and in the low-spin state ($S = 1/2$), as also confirmed by our first-principle band-structure calculations. The crystals were used carefully selected among those with the sharpest superconducting transitions and best structural properties, so that secondary phases or other impurities can be excluded. They had different Mn contents $x$ between 0.0037 and 0.0150, corresponding to bulk critical temperatures $T_c$ between 33.9 and 13.3 K, with $\Delta T_c(10 - 90\%)$ increasing with doping from 0.65 K to 5.4 K. The point contacts were made by putting a small drop of silver paint on the flat side surface of the crystal so as to inject the current mainly parallel to the $ab$ planes, which in pure MgB$_2$ is the best configuration for the observation of both the $\sigma$- and $\pi$-band gaps. In most cases, we studied the temperature dependence and the magnetic-field dependence of the conductance curves ($dI/dV$ vs. $V$), so as to determine the critical temperature of the junction (i.e., the “Andreev critical temperature”, $T_{cA}$), and to understand whether one or two OPs were present. The conductance curves were then normalized to the normal state and fitted with the two-band BTK model, as described elsewhere. The fitting function contains the OPs $\Delta_{\sigma,\pi}$, the coefficients $Z_{\sigma,\pi}$ (related to the potential barrier and to the Fermi velocity mismatch at the interface) and the lifetime broadening coefficients $\Gamma_{\sigma,\pi}$ as adjustable parameters, plus the weight $w_{\pi}$ of the $\pi$-band contribution to the conductance. For reliable estimates of the OP amplitudes, whenever possible, we selected contacts with rather high resistance ($R_N \gtrsim 30 \Omega$), and with no dips in the conductance curves, so as to fulfill the requirements...
for ballistic conduction [10].

Fig. 1 reports some normalized conductance curves (symbols) in crystals with different Mn content. From now on, we will label the curves with the corresponding value of $T^\pi_c$ instead of the Mn content or the bulk $T_c$, since PCS is a local, surface-sensitive probe. $T^\pi_c$ can be smaller than $T_c$ if the bulk transition is broad (as for the most-doped crystals) or if proximity effect occurs at the S/N interface (when $\xi \approx a$, being $a$ the actual contact size).

Lines in Fig. 1 represent the two-band BTK fit of experimental curves. In conventional superconductors, spin-flip scattering makes the superconducting gap become ill-defined [11] and, for strong scattering, bands of states within the original energy gap are formed [12, 13]. Strong-coupling calculations for MgB$_2$ [14] have shown that magnetic impurities can give rise to sub-gap states in both the partial $\sigma$- and $\pi$-band DOS, that are not taken into account by the BTK model. However, the sub-gap features in the DOS are by far smaller than the peaks connected to the OPs $\Delta_\pi$ and $\Delta_\sigma$ [14]. At any finite temperature they are further smeared out, so that they would be very difficult to observe experimentally. One can reasonably expect that the same happens in the Andreev-reflection curves. As a matter of fact, all the experimental conductance curves are rather broadened and have smaller amplitude (see Fig. 1) than in pure MgB$_2$ [8], so that even if sub-gap structures exist, they are practically unobservable. Hence, the BTK model can be used as a reasonable, first-order approximation to a more specific model for Andreev reflection in the presence of magnetic impurities on the superconducting side of the contact, which is lacking at the present moment.

Even if the fit of the conductance curves shown in Fig. 1 indicates the existence of two OPs in the Mg$_{1-x}$Mn$_x$B$_2$ system, it is clear that some curves – especially at the highest doping levels – show little or no structures associated to the larger OP. To check in a more convincing way if two-band superconductivity persists up to the highest Mn content, we studied the magnetic-field dependence of the $dI/dV$ curves in the whole range of $T^\pi_c$.

Fig. 2(a) shows the magnetic-field dependence of the conductance curve of a contact with $T^\pi_c=31$ K (circles) with the relevant two-band BTK fit (lines). The zero-field curve shows both the peaks corresponding to $\Delta_\pi$ and the smooth shoulders related to $\Delta_\sigma$. On applying the magnetic field, the small-gap features reduce in amplitude, progressively unveiling the underlying large-gap features. An outward shift of the peaks is observed at some $B = B^*$, when the $\sigma$-band structures become dominant and determine the shape of the conductance curve. Unlike in pure MgB$_2$, here $B^*$ is intense enough
FIG. 3: Symbols: zero-field, low-temperature (T=4.2 K) conductance curve of a contact with $T_c^A = 9.6$ K made on the most-doped crystals ($x = 0.015$). Solid line: best fit given by the two-band BTK model. Dashed line: best fit given by the standard (single-band) BTK model. Arrows indicate the smooth structures related to the two order parameters, which are magnified in the inset for clarity.

(b) shows the field dependence of contacts with much lower critical temperature. For example, Fig. 2(b) reports the field dependence of the normalized conductance curve of a contact with $T_c^A = 18$ K. Here the zero-field conductance does not show clear structures related to $Δ_σ$ but an outward shift of the conductance maxima is observed anyway at $B = B^* \approx 1\,\text{T}$. For higher doping levels, i.e. for $T_c^A < 17$ K, the low-temperature, zero-field conductance curves can be very well fitted with the two-band BTK model (see the bottom curve in Fig. 1), but the critical field is so small and the conductance curves are so broadened that their magnetic-field dependence is not conclusive, at least with our experimental resolution. Moreover, some conductance curves in this region allow a standard (i.e. single-band) BTK fit as well, which gives an OP amplitude $Δ$ that is the “average” of the values given by the two-band fit. However, the single-band fit often fails in reproducing both the position of the peaks and the width of the Andreev-reflection structures in the conductance, as shown in Fig. 4 for a contact with the lowest $T_c^A$. This suggests that two OPs are likely to be present also in the different contacts with the same $T_c^A$ represented by horizontal error bars). For $T_c^A < 17$ K only the results of the two-band BTK fit are shown, based on the preceding discussion and on the regular trend of the OPs for $T_c^A \geq 18$ K. In fact, the presence of a single OP in the low-$T_c^A$ region would imply a sudden change in the slope of the curves around $T_c^A = 17$ K that is not justified by any observed discontinuity in the physical properties of the compound. The persistence of two distinct OPs up to the highest $x$ value indicates that Mn doping does not significantly increase non-spin-flip interband scattering. Actually, this is also suggested by the very low Mn concentration (1.5 % at most) and by the decrease of both the OPs with $T_c^A$ (while interband scattering would increase $Δ_c^A$). This decrease could arise from changes in the DOSs at the Fermi level and in the phonon spectra $α^2F_α(ω)$, but these two effects are certainly negligible here, because Mn is isovalent with Mg and the Mn content is very small. The latter reason also allows assuming the effect of $σ$ and $π$ intraband non-spin-flip scattering to be much smaller than that of pair-breaking scattering in the same channels. This leads to conclude that the main possible cause of the experimental trend of Fig. 4 is an increase in the spin-flip scattering in the $σ-σ$, $π-π$ or $σ-π$ channels.

This simple picture can be made quantitative by solving the Eliashberg equations (EE) in the presence of randomly distributed magnetic impurities, treated within the Born approximation. According to the reasoning above, we used the same phonon spectra, DOS values and Coulomb pseudopotential as in pure MgB$_2$, and neglected all the non-spin-flip scattering rates. We thus took as the only adjustable parameters the spin-flip scattering rates within the bands ($Γ_{σσ}$ and $Γ_{ππ}$) and between bands ($Γ_{σπ}$). We immediately found that $Γ_{σσ}$ is necessary to fit the $T_c^A$ and OP values and that it must be greater than both $Γ_{ππ}$ and $Γ_{σπ}$ – otherwise $Δ_π$ decreases too fast on decreasing $T_c^A$. As for $Γ_{σπ}$, this agrees with the predictions of Ref. 14. For simplicity,
we analyzed separately the two cases: (a) $\Gamma_{\pi\pi} > \Gamma_{\sigma\pi}$, $\Gamma_{\pi\sigma}=0$ and (b) $\Gamma_{\sigma\sigma} > \Gamma_{\pi\pi}, \Gamma_{\pi\sigma}=0$. First of all, we fixed $\Gamma_{\pi\pi}=\Gamma_{\sigma\sigma}=\Gamma_{\pi\sigma}=0$ at $T^A_c=39.4$ K (i.e. $x=0$). Second, we found the values of the parameters that give the experimental values of $\Delta_\sigma$ and $\Delta_\pi$ at $T^A_c=18.0$ K (cases (a) and (b)), by solving the imaginary-axis EE and analytically continuing the solution to the real axis. Once determined the values of $\Gamma_{\pi\pi}$ and $\Gamma_{\sigma\pi}$ in these two points, we searched for the simplest $\Gamma_{\pi\pi}(T^A_c)$ and $\Gamma_{\sigma\pi}(T^A_c)$ curves connecting them and allowing the fit of the experimental values of $T^A_c$ and of the OPs in the whole doping range, with no restrictions on $\Gamma_{\sigma\sigma}$. We found out that these curves are a parabola (for $\Gamma_{\pi\pi}$) and a straight line (for $\Gamma_{\sigma\sigma}$). In both cases, $\Gamma_{\sigma\sigma}$ follows an almost parabolic trend as a function of $T^A_c$ (see Fig.4). The resulting theoretical curves that best fit the OPs are reported in Fig.4 as solid lines (case (a)) and dashed lines (case (b)). The agreement between experimental data and theoretical calculations (especially in case (a)) is striking in the whole range of $T^A_c$. That our simple – but reasonable – model works so well suggests that, up to $x=0.015$, Mg$_{1-x}$Mn$_x$B$_2$ can be treated as a perturbation of the unsubstituted compound, with only the addition of $\sigma$ intraband magnetic scattering and minor contributions from either the $\pi$ intraband or the interband scattering.

The intense Mn pair-breaking in the $\sigma$-$\sigma$ channel has been recently predicted as being due to the hybridization of the $\sigma$ bands of MgB$_2$ with the $d$ orbitals of Mn [17]. To demonstrate that scattering in this channel is much greater than in the $\pi$-$\pi$ and $\sigma$-$\pi$ ones, we performed preliminary calculations of the electronic structure near a Mn substitutional impurity in a $2 \times 2 \times 4$ MgB$_2$ superlattice. The results show that around the Fermi level ($E_F$) there is a spin-down $d_{z^2}$ band, responsible for the Mn magnetic moment, very sensitive to the details of structural parameters [17]. The $\sigma$ and $\pi$ bands behave quite differently near the Mn impurity: while the $\pi$ electron spectral density is depleted around $E_F$ (due to the $\pi$-$d$ interaction), the $\sigma$ bands have a large amplitude. Furthermore, the $\sigma$ bands show a sizeable ($\geq 15$ meV) exchange splitting near $E_F$, larger than the superconducting gap – which is consistent with the experimentally observed complete suppression of superconductivity at about 2% of Mn [17]. On the other hand, the impurity-induced mixing of $\sigma$ and $\pi$ states around Mn (providing a qualitative indication of interband scattering), is present but not very important. These results can explain the quick drop of $T_c$, with the persistence of the two distinct gaps, and a larger scattering within the $\sigma$ band [17].

In conclusion, we have presented the results of the first experimental study of the effects of magnetic impurities on the order parameters $\Delta_\sigma$ and $\Delta_\pi$ of a two-band superconductor. We have shown that, in Mg$_{1-x}$Mn$_x$B$_2$, $\Delta_\sigma$ and $\Delta_\pi$ decrease regularly with the critical temperature but remain clearly distinct down to the lowest $T^A_c$. Within the Eliashberg theory, this is due to an increase in spin-flip scattering in the $\sigma$ bands on increasing the Mn content, with possible minor contributions from the $\sigma$-$\pi$ or the $\pi$-$\pi$ channels. This somehow unexpected conclusion is also supported by first-principle calculations of the bandstructure of MgB$_2$ in the vicinity of a Mn impurity.

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[1] A.Y. Liu, I.I. Mazin and J. Kortus, Phys. Rev. Lett. 87, 87005 (2001); H.J. Choi et al., Nature 418, 758 (2002).
[2] A. Brinkman et al., Phys. Rev. B 65, 180517(R) (2001); A.A. Golubov et al., Phys. Rev. B 66, 054524 (2002).
[3] J.R. Cava, H.W. Zandbergen, K. Inumaru, Physica C 385, 8 (2003).
[4] S.Xu, Y. Moritomo, K. Kato, A. Nakamura, J. Phys. Soc. Jpn. 70, 1889 (2001).
[5] K. Rogacki et al., cond-mat/0510227
[6] R.S. Gonella et al., Phys. Rev. Lett. 89, 247004 (2002).
[7] R.S. Gonella et al., Phys. Rev. B 69, 100504(R) (2004).
[8] G.E. Blonder, M. Tinkham and T.M. Klapwijk, Phys. Rev. B 25, 4515 (1982).
[9] Goutam Sheet, S. Mukhopadhyay, and P. Raychaudhuri, Phys. Rev. B 69, 134507 (2004).
[10] A.M. Duif, A.G.M. Jansen and P. Wyder, J. Phys.: Condens. Matter. 1, 3157 (1989).
[11] A.A. Abrikosov and L.P. Gor’kov, Soviet Phys, JETP 12, 1243 (1961).
[12] H. Shiba, Prog. Theor. Phys. 40, 435 (1968).
[13] E. Schachinger and J.P. Carbotte, Phys. Rev. B 29, 165 (1984).
[14] C.P. Moza and C. Horea, Phys. Rev. B 66, 052501 (2002).
[15] J. Kortus et al., Phys. Rev. Lett. 94, 027005 (2005).
[16] O. V. Dolgov et al., Phys. Rev. B 72, 024504 (2005).
[17] P. Ji Ji Thomas Joseph and Prabhakar P. Singh, Preprint cond-mat/0512675.
[18] F. Bernardini et al., in preparation.