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Possibility of a *s*-wave pairing in heavily Zn-doped $YBa_2Cu_3O_{7-\delta}$ based on magnetic field effect on Andreev reflection spectra

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When the $d_{x^2-y^2}$-wave pairing is suppressed by Zn-doping in $YBa_2Cu_3O_{7-\delta}$ some of the Andreev reflection spectra were found to be similar to the *s*-wave spectra of conventional superconductors. The energy gap is rather reproducible (2.3–3.0 meV). It is suppressed by low magnetic field (H_c^{PC} = 120–270 mT) in great contrast to the *d*-wave spectra (H_c^{PC} > 3 T) with the similar order of gap magnitude. We suppose that the *s*-wave pairing occurs near the Zn impurities.

PACS: 74.72.Bk Y-based cuprates;
74.45.+c Proximity effects; Andreev effect; SN and SNS junctions;
74.20.Rp Pairing symmetries (other than *s* wave);
74.62.Dh Effects of crystal defects, doping and substitution.

Keywords: Y-based cuprates, Andreev reflection, N–S boundary, pairing symmetries, *s* wave, *d* wave, doping and substitution.

The $d_{x^2-y^2}$-wave pairing is widely recognized as a dominant mechanism of superconductivity in the high-temperature superconductors [1]. However, in some cases an additional subdominant order parameter (OP) may better explain the experimental results [2–5]. Theory predicts the appearance of *is*- or id_{xy}-subdominant OP near the (110) surface where the $d_{x^2-y^2}$-wave OP is essentially suppressed due to the change of the order parameter sign along the quasiparticle trajectory [6–8]. The recent tunneling [9] and Andreev reflection [5] experiments are in agreement with the *is*-subdominant OP in $YBa_2Cu_3O_{7-\delta}$ (YBCO). However, the problem is still under debates. We have proposed the new approach here to clarify the question.

The order parameter can be also changed by doping. The Andreev reflection (AR) spectra show the possible transition from $d_{x^2-y^2}$- to *s* (or $d \pm is$)-wave pairing with the oxygen doping change in $Pr_{2-x}Ce_xCuO_4$ [10,11]. It is well known that doping by Zn in YBCO decreases the critical temperature T_c and energy gap [12,13]. The critical temperature in $YBa_2(Cu_{1-x}Zn_x)_3O_{7-\delta}$ falls from about 90 K to about 25 K with the change of x from zero to 0.075 [14]. That is why the heavily Zn-doped YBCO with low T_c is perspective to find out another pairing in YBCO and has been investigated here. We have found the typical for the *s*-wave superconductor Andreev reflection spectra that are very sensitive to low magnetic field in contrast to the *d*-wave spectra.

The first problem is how to distinguish the AR spectra (or the point-contact spectra when there is a barrier at interface) with the different type ($d_{x^2-y^2}$, d_{xy}, s) of OP.

One of the evidence of the *d*-wave pairing is presence of the zero-bias conductance peak (ZBCP) in a tunneling spectrum (except the lobe-direction tunneling and gapless superconductor) [15]. For the point contacts with direct conductivity, ZBCP must be absent if the barrier Z at N/S boundary is zero. However, due to the difference in Fermi velocity in the point-contact electrodes (a normal metal and high-temperature superconductor), Z is always more than zero [16], and ZPCB has been observed in most experiments [12,13,17–19]. Boundary roughness, defects and impurities may decrease the intensity of ZBCP essentially [15].

For the conventional *s*-wave superconductors, the modified Blonder–Tinkham–Klapwijk (BTK) theory [20] discribes an experimental point-contact (PC) spectrum quite well using three fitting parameters: a gap value Δ, Z and relatively small smearing factor Γ, $\Gamma/\Delta \ll 1$. In the case of the *d*-wave superconductor it is not usually possible to do that with the reasonable value of Γ. It is because of the strong gap anisotropy and low-angle resolution for the orifice-like point contacts [21] (~ 90°). However, the channel-like point contacts with rough walls may have the angle resolution close to a tunnel junction. Thus, even for the *d*-wave superconductor, it is possible to register a PC spectrum which is similar to the *s*-wave one. The gap anisotropy effect reduces in this case, and a small number of closely lying gaps forms a PC spectrum, especially if the channel-like point contact in the lobe direction is realized in an experiment. In different point contacts the direction of electron flow is different as a rule, and the gap values extracted may be essentially different for the same T_c in the point-contact region. Taking into account the possible complex configuration of a real point contact (several conducting spots with different shape), analysis only of the PC spectrum form is not reliable method to know the OP type. Nevertheless, the information about gap distribution for the *d*-wave superconductor may be obtained by the proper histogram building [12].

The critical parameters (T_c and H_{c2}) of the *d*-wave superconductor was found to be much higher than that for the conventional *s*-wave one (for $\mathrm{YBa_2Cu_3O_{7-\delta}}$ $T_c \approx 95$ K and $H_c > 100$ T) [22].

Thus, if one will register the PC spectra without ZBCP with low critical parameters and similar gap values for different PCs, pairing is very possible to be of the *s*-wave type.

It was found earlier that doping by Zn decreases T_c without essential change of electron density in $\mathrm{YBa_2(Cu_{1-x}Zn_x)_3O_{7-\delta}}$ [23,24]. At $x \approx 0.1$–0.12, T_c falls to about 10 K. The distribution of energy gaps also goes to zero [12]. At $x \geq 0.05$, some of the PC spectra look like expected for the gapless superconductor [25]. Most likely, the gapless state appears on the part of Fermi surface close to the node lines.

We have investigated the polycrystal $\mathrm{YBa_2(Cu_{1-x}Zn_x)_3O_{7-\delta}}$ sample with the nominal $x = 0.075$. The resistivity measurement shows the wide transition from normal to the superconducting state (from 40 to 10 K). It is in agreement with $T_c \approx 25$ K for $x = 0.075$ obtained in the sample with the steeper resistive transition in Ref. 12. High inhomogeneity in the Zn distribution let us getting the large variety of the PC spectra in the same experiment to study the magnetic field effect.

The standard modulation method [26] was applied to measure dI/dV vs V.

In Fig. 1, two kinds of the PC spectra (with low *Z*) typical for the heavily Zn-doped YBCO ($x \geq 0.05$) are shown. The first (*a*) has the gap-related maximum and relatively narrow ZBCP, the second (*b*) has a wide maximum around $V = 0$. Theory predicts approximately such a form of PC spectrum for the gap- and gapless-superconductor, respectively [27,28].

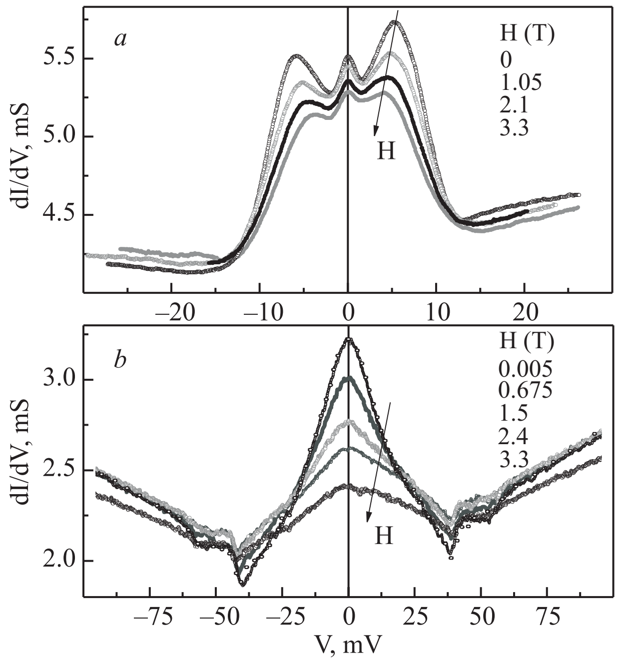

Fig. 1. Magnetic fields dependences of the $d_{x^2-y^2}$-wave Andreev reflection spectra of $\mathrm{YBa_2(Cu_{1-x}Zn_x)_3O_{7-\delta}}$ with $x = 0.075$: (*a*) shows the case of gap-related maximum presence (at $V \approx \pm 6$ mV for $H = 0$). The position of the maximum in zero field may be different for different point contacts (for instance, see the left inset in Fig. 3 and Ref. 12). (*b*) corresponds to the gapless superconductivity case. The bath temperature $T = 4.2$ K.

The magnetic field of about 3 T affects both observed peaks essentially while in the Zn-undoped YBCO, such a field has no any visible effect on our PC spectra (except the ZBCP). In the case (*a*), the magnetic field shifts the gap-related maximum at $V \approx \pm 6$ mV to lower energies like it was found earlier for conventional superconductors [29,30]. The absence of splitting of ZBCP with the field was observed earlier in the tunneling and point-contact experiments too [11,31,32], and one of the possible reasons is that the field is parallel to the N/S interface [33,34]. Our point contacts were made between the rod-shape electrodes (like in Ref. 35) and geometrically the magnetic field was applied parallel to the N/S interface. However, the real situation is difficult to control because of surface roughness.

In the case of gapless regime (*b*), the field suppresses the peak around $V = 0$ without any essential change of its energy location and form. Such a behavior is well known for the conventional gapless superconductors in tunneling experiments [36].

Thus, it seems that there is no any difference in magnetic field effect (except the value of field applied) on the $d_{x^2-y^2}$-wave Zn-doped superconductor YBCO and the

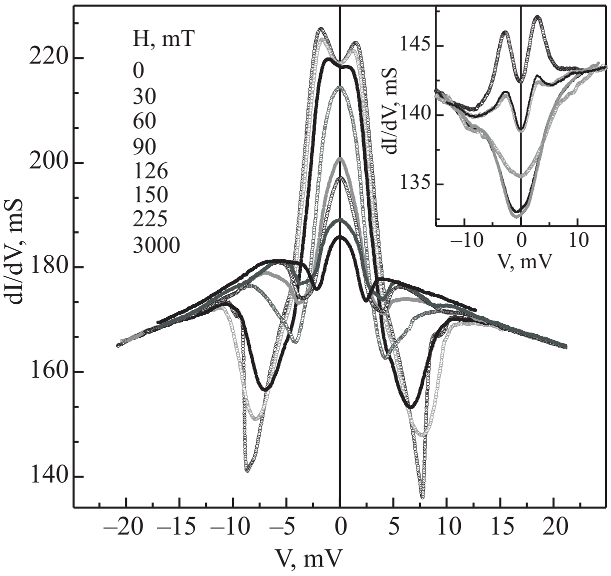

Fig. 2. The *s*-wave type Andreev reflection spectra of $YBa_2(Cu_{1-x}Zn_x)_3O_{7-\delta}$ ($x = 0.075$) with the magnetic field change. $T = 4.2$ K. $H_c^{PC} \approx 225$ mT. Inset shows the case with another character of the background behavior at $H \geq H_c^{PC} \approx 120$ mT: $H = 0, 30, 60, 120, 225, 450, 600$ mT from upper curve.

conventional *s*-wave superconductor assuming that Zn-doping does not change the pairing mechanism.

We have also registered some spectra (Figs. 2 and 3) similar to those found in the numerous studies of the conventional *s*-wave superconductors. They have clear maximum at low energy without any ZBCP. In Fig. 4, the symmetrized experimental curves measured at $H \approx 0$ are compared with the calculated ones. There is a good agreement in the gap-related region (interval about ± 5 mV around zero bias). The structure at ≈ 5–10 mV seen on the curve (*a*) and (*c*) is often observed, but its origin is not clear yet [37–39]. The modified BTK fitting procedure [20] gives the similar values of gap $\Delta = 2.35$–3.0 meV for different point contacts with the small enough smearing factor $\Gamma/\Delta < 0.2$. One shuld to note that the gap value extracted from the point-contact experiment may be different if the bulk gap value depend on pressure. The pressure in the mechanically made point contacts may be rather different, and it may be a reason of the gap value variation found.

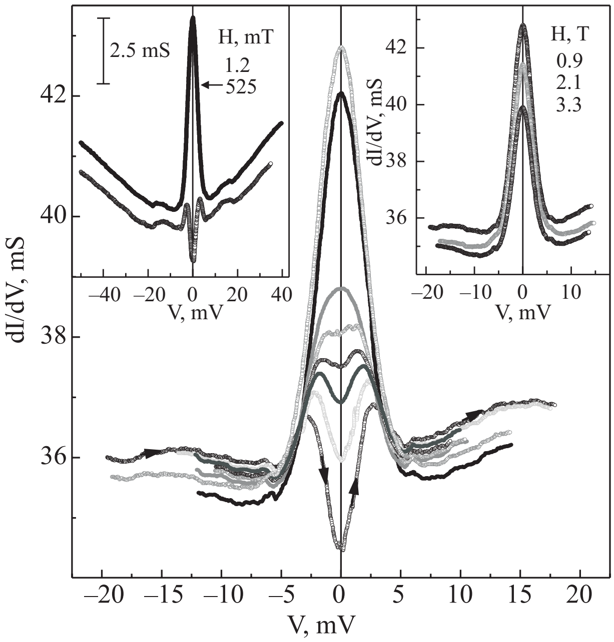

Fig. 3. Unusual transformation of the *s*-wave type spectrum with the magnetic field. $H = 1.2, 105, 150, 180, 225, 270, 600, 900$ mT starting from the bottom at $V = 0$. $T = 4.2$ K. $H_c^{PC} \approx 270$ mT. Right inset shows the high-magnetic field effect. Left inset shows two spectra in the enlarged bias range. The spectrum at $H = 525$ mT is shifted up for clarity.

The most interesting finding is that all the spectra are very sensitive to low magnetic field in great contrast to those shown in Fig. 1. The gap-related maximum goes to zero bias in a way characteristic to the conventional *s*-wave superconductor [29,30]. It is most clear seen for

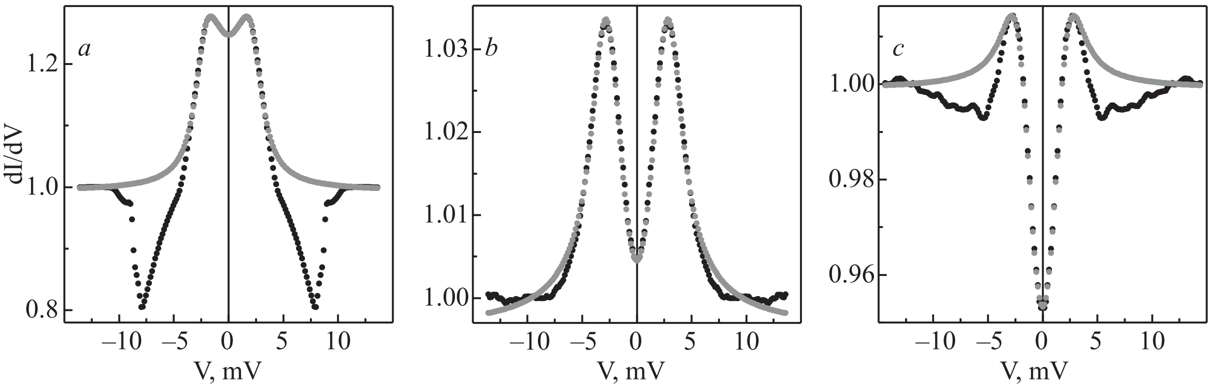

Fig. 4. Comparison of the experimental *s*-wave spectra (dark dots) with the BTK calculations. The experimental curves were previously symmetrized and normalized on value at $V = \pm 15$ mV. The parameters of fitting are as follows: $\Delta = 2.35$ meV, $\Gamma = 0.2$ meV, $Z = 0.30$ (*a*); $\Delta = 3.00$ meV, $\Gamma = 0.4$ meV, $Z = 0.55$ (*b*); $\Delta = 2.40$ meV, $\Gamma = 0.4$ meV, $Z = 1.15$ (*c*).

curves in Fig. 2. The critical magnetic field for the point-contact region H_c^{PC} corresponds to the case when the AR spectrum is entirely suppressed, and for the PC spectra of the *s*-wave type registered here is 120–270 mT. The spectrum in Fig. 3 demonstrates more complex shape and behavior with the increasing magnetic field. It has also the weaker structure at $V = \pm(10\text{–}20$ mV) that is not so changeable with magnetic field (see left inset in Fig. 3) as the low-bias structure (at $V \leq 5$ mV). This high-bias structure is similar to that found in $\mathrm{YBa_2(Cu_{1-x}Zn_x)_3O_{7-\delta}}$ (with $x = 0.025$) gap-related structure [12]. The low-bias double-peak structure transforms into the high ZBCP which then is suppressed in rather high magnetic field in a way similar to the spectrum shown in Fig. 1,*b* (gapless regime). This observation shows that there are different superconducting phases near N/S boundary in this point contact. The different reaction on the magnetic field applied may give such an unusual behavior.

We have also noticed that the *s*-type spectrum is usually registered after the spectrum with the resonance scattering peak similar to that found in Refs. 2 and 40. Because our point contacts were made by the successive mutual shift of electrodes [35], one can suppose that the *s*-type superconductivity locates near a Zn-impurity (or a cluster).

Proximity effect, induced by the $d_{x^2-y^2}$-superconductor, may be a reason of the *s*-wave pairing [41] in a normal electrode, but in Andreev reflection effect the conductance maximum (or a kink) is connected only with the maximum gap along the quasiparticle trajectory [42]. The «proximity gap» is always less than in $d_{x^2-y^2}$-superconductor.

In summary, we have found that some of the Andreev-reflection spectra observed in the heavily Zn-doped $\mathrm{YBa_2Cu_3O_{7-\delta}}$ are similar to the conventional *s*-wave superconductor ones in a shape, gap value reproducibility and sensitivity to low magnetic field. It confirms the possibility of the *s*-wave pairing in $\mathrm{YBa_2Cu_3O_{7-\delta}}$ if the *d*-wave pairing is suppressed.

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