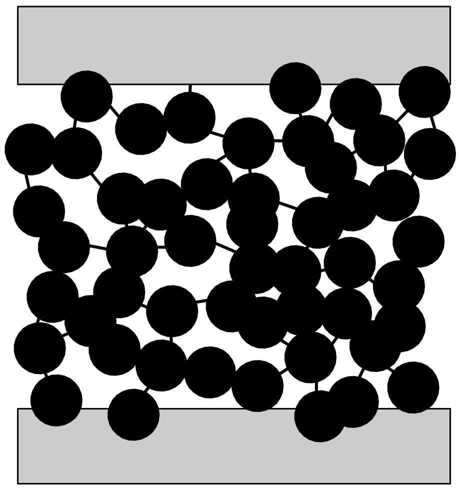

Figure 6. Schematic sketch of the current percolation network through the granular system. The solid line sections represent 'broken' weak links which are connected by 'good' superconducting regions, as indicated by the dotted lines.

as long as the various loops are quantum coherent. It is of interest to note that the relative amplitude of the oscillations (about 10 – 15% of the conductance) does not change for sample lengths between 1000 A and a few µm. For samples longer than 10μm the fluctuation magnitude decays strongly. It seems reasonable, therefore, to speculate that there is a typical coherence length, a few microns in size, which plays a role similar to L_Φ in a normal metal.

A small magnetic field can have two types of influence on the $I-V$ curves. Features which stem from exceeding a supercurrent are expected to be slightly shifted to smaller bias values because of the dependence of I_c on H. In addition, H introduces a phase change in each loop, altering any $I-V$ features associated with quantum interference. Hence our notion that the fluctuations stem from interference effects, while the $I-V$ discontinuities represent destruction of dc superconductivity in links is further supported by the dependence of the $\mathrm{d}V/\mathrm{d}I-V$ curves on the magnetic field as illustrated in Fig. 4. Note that a magnetic field of 300 Oe, while much smaller than H_c of the grains, is larger than the typical field scale for the conductance fluctuations (a few tens of Oe as seen in Fig. 3). Such a field is indeed expected to modify the interference pattern and give rise to a totally different fluctuation trace for both $H = 300$ Oe and $H = -300$ Oe.

5. Conclusion

In summary, we have studied electrical transport properties of mesoscopic granular superconductors. These small structures allow us to focus on the effects of phase fluctuations in the granular system. We observe both discrete stages of the destruction of superconductivity by loss of phase locking between the grains as well as manifestations of superconductive wave-function interference through the disordered film.

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Low-temperature resistivity of underdoped cuprates

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In high-T_c cuprates the metallic state is obtained as a result of hole or electron doping of the parent antiferromagnetic insulator. The nature of this insulator – metal transformation has not been sufficiently understood, mainly because of strong electron correlations which crucially complicate the picture of the normal state [1, 2]. The electron correlations obviously play a dominating role in 'undoped', parent compounds, driving these systems into an insulating state. As the doping increases, and the system deviates essentially from half filling, the importance of electron correlations diminishes, and cuprates are generally believed to evolve towards Fermi liquids in the so-called 'overdoped' range. However, an agreement on how one should treat cuprates at intermediate doping, where the high-T_c superconductivity occurs, has not yet been achieved, in spite of very intense studies of strongly-correlated systems in the last 10 years. The main problem is still that little is known about cuprates in the normal state, because of the superconductivity hiding the normal-state properties over a large part of the phase diagram.

Recent experiments by Ando, Boebinger et al. [3, 4] on $La_{2-x}Sr_xCuO_4$ single crystals utilizing magnetic fields up to 61 T to suppress superconductivity have extended measurements of the normal-state resistivity towards low temperatures for the whole range of hole doping. These measurements have revealed rather unusual behavior for the underlying normal state. For all underdoped compositions ($x < 0.16$) both the in-plane and out-of-plane resistivities at low temperatures demonstrated a similar logarithmic increase whenever the resistivity increased or decreased at high temperatures [3, 4]. This logarithmic increase of the resistivity was considered as evidence of the insulating behavior, and the insulator – metal crossover was suggested to take place far in the superconducting region, somewhere near the optimum doping. If the $\log T$ divergence of the low-temperature resistivity were an inherent property of high-T_c cuprates, this would point to a general peculiarity associated with strong electron correlations implying non-Fermi-liquid behavior [5]. Similar investigations performed on $Bi_2Sr_2CuO_y$ crystals [6] have shown, however, that ρ_{ab} may be temperature independent at low T as well as logarithmically divergent, depending on the sample's purity.

It is also possible that the unusual $\log T$ resistivity behavior observed in [3, 4] may be associated with the effect of the strong magnetic field itself rather than with properties of the normal state underlying high-T_c superconductivity.

Strong magnetic fields may well induce a localization of carriers [7]. Moreover, high-T_c cuprates possess strongly anisotropic electron transport properties, while the influence of a magnetic field on a 2D superconductor is quite specific, resulting in a fundamentally different phase transition into the Bose insulating state with electron pairs localized and field-induced vortices Bose-condensed [8, 9]. It may turn out that in measuring the resistivity of cuprates in a magnetic field one is dealing with peculiar properties of a Bose insulator [9].

A promising way to clarify the situation is to perform resistivity measurements just at the border of the superconducting region and to compare the dependences obtained in a magnetic field with the true normal-state behavior. Moreover it is this strongly underdoped region where one could expect the most pronounced deviation of the behavior of cuprates from that of conventional materials. The $RBa_2Cu_3O_{6+x}$ system (R = Y, rare earth) is an attractive object for such a study, since it allows a simple variation of hole doping by changing the oxygen content x or oxygen order in the chain-layers, see [10 – 12] and references therein. Part of the phase diagram of $RBa_2Cu_3O_{6+x}$ in the vicinity of the superconductor–non-superconductor (SC – NSC) transformation is presented in Fig. 1 as a function of the in-plane conductivity σ_{ab} (280 K), which presumably is roughly proportional to the carrier density in the CuO_2 planes (see [12] for details). Various circles in Fig. 1 indicate the antiferromagnetic and superconducting transition temperatures T_N, T_c measured on one and the same crystal with different oxygen contents (each pair of solid-open circles corresponds to a particular x). Solid circles show the 'quenched' state of the crystal with the oxygen subsystem being disordered by quenching from 120 – 140 °C, open ones — the 'aged' state obtained by room-temperature aging for 5 days, and arrows illustrate the evolution of the crystal's state with oxygen ordering. One can see that a very simple aging procedure allows one to change the density of carriers in CuO_2 planes by up to 20 percent without any change of the stoichiometry [10, 12]. So, while a step-like scanning of the phase diagram may be performed by changing the oxygen content, the well-studied phenomenon of oxygen rearrangement additionally provides a unique possibility to perform a continuous variation of the hole density and to tune the sample gradually through the doping range of special interest.

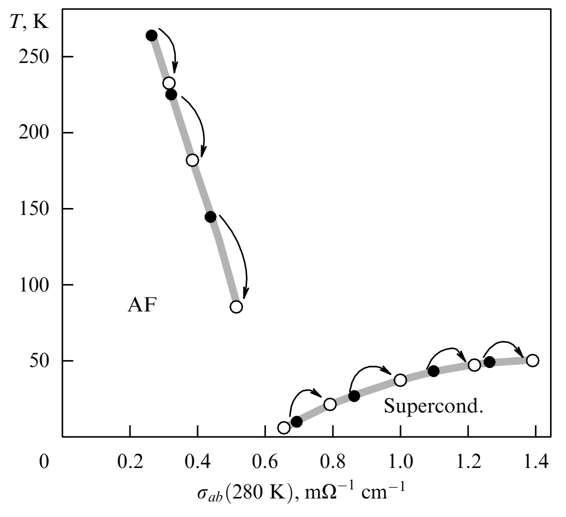

Figure 1. Sketch illustrating the phase diagram of $RBa_2Cu_3O_{6-x}$ as a function of the in-plane conductivity σ_{ab}(280 K), and the influence of oxygen ordering on the sample's state. Solid circles show T_N and T_c for samples quenched in liquid nitrogen (different circles correspond to different oxygen contents x); open circles show the transition temperatures measured after room-temperature aging.

We prepared several $YBa_2Cu_3O_{6+x}$ crystals with $x \approx 0.37$, just at the border of the superconducting region, and measured their resistivity and magnetoresistivity tuning the crystals through the NSC – SC transformation by room-temperature aging [13]. The temperature dependences of the in-plane resistivity ρ_{ab} obtained for the 'aged' and 'quenched' states of one of the $YBa_2Cu_3O_{6+x}$ crystals are presented in Fig. 2. For both states the resistivity passed through a minimum with decreasing temperature. In the room-temperature equilibrium, 'aged' state, the resistivity growth at low temperatures was interrupted by the SC transition, while in the 'quenched' state no signs of the superconducting transition were observed on the $\rho(T)$ curve down to the lowest temperature. It is worth noting that these crystals' states differ only in hole densities in CuO_2 planes. Owing to low T_c the superconducting transition in the 'aged' crystal could be suppressed almost completely by the available magnetic field $H||c$, and the magnetic-field driven SC – NSC transition is illustrated in the inset.

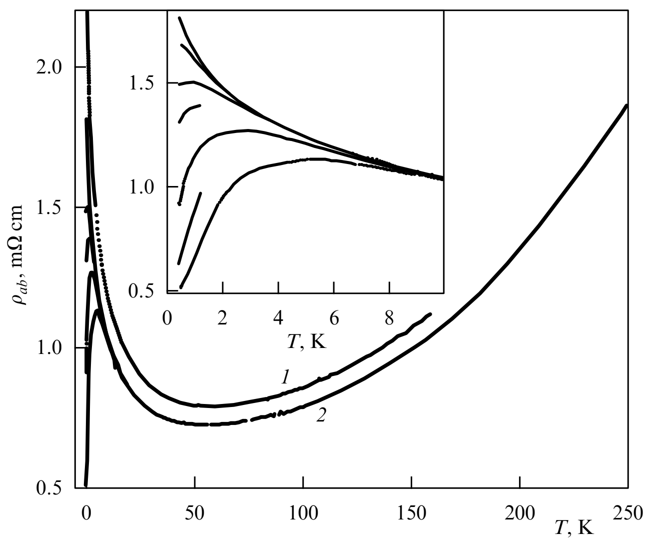

Figure 2. Temperature dependences of the in-plane resistivity ρ_{ab} obtained for $YBa_2Cu_3O_{6-x}$ ($x \approx 0.37$) single crystal in the 'quenched' and 'aged' states. For the 'quenched' state the curves were measured at magnetic fields $H = 0$; 7.7 T are almost indistinguishable in the graph. For the 'aged' state a set of curves measured at various magnetic fields $H||c$ is presented: $H = 0.25$; 0.5; 1; 2; 3; 5; 7.7 T. The inset shows the low temperature region on an enlarged scale.

The resistivity upturn at low temperatures pointed to a possibility that the NSC state corresponded to an insulator. Really, $YBa_2Cu_3O_{6+x}$ crystals are strongly anisotropic and can, probably, be considered as a stack of very weakly bound conducting planes. Therefore, it would not be a surprise if they behave as an insulator, since according to the scaling theory of the metal – insulator transition [14], for a 2D system, no matter how weak the disorder is, there is no true metallic behavior, and the system is expected to become insulating at zero temperature. We however failed to fit the $\rho_{ab}(T)$ data for all crystal states either by exponential ($\rho = \alpha \exp[(\beta/T)^k]$) or by power law ($\rho = \alpha + (\beta/T)^k$) expressions. At the same time, a fit to the logarithmic law $\rho_{ab} = A + B \log T$, Fig. 3, appeared to be rather good. The quenched and intermediate states demonstrated the resistivity which increased logarithmically with decreasing T over almost two orders of magnitude. One could suppose that the state attained by quenching is also a Bose-glass insulator with electron pairs localized by the disorder [8, 9], but the very weak magnetoresistance observed (inset in Fig. 3) gives evidence that this is not the case, and that a true normal state resistivity is observed instead. The principal result obtained is that *quite similar resistivity behavior is characteristic of both the non-superconducting state and the underlying normal state in the SC region.* Observation of the logarithmically increasing resistivity at zero field implies that the role of the magnetic field is nothing more than to uncover the underlying normal state. It can be seen that with increasing magnetic field the resistivity curves for the 'aged' state approach the normal-state resistivity step by step. This behavior is likely to resemble the suppression of superconductivity at the upper critical field in ordinary 3D systems, rather than the 2D SC – I transition picture suggested for the YBCO system [9].

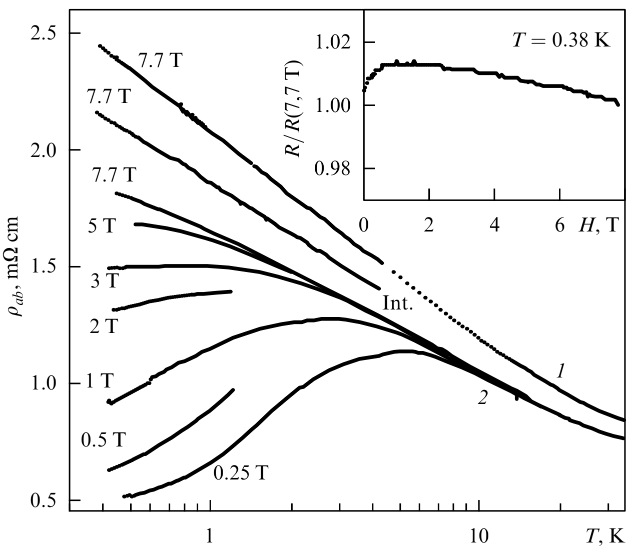

Figure 3. Plots of the resistivity versus logarithm of the temperature for different states of the sample. The values of the applied magnetic field are indicated in the graph. The inset presents the normalized magnetic field dependence of the resistivity obtained at $T = 0.38$ K for the 'quenched' state.

So, the 'logarithmic-like' resistivity turns out to be a rather general property of underdoped cuprates [13, 15], but its origin remains unclear. Values of the resistivity per CuO_2-plane are of the order of the universal quantum resistance $h/4e^2$, which implies that 2D weak localization [14] and interaction effects [16] may be important, and may produce a logarithmic correction to the conductivity at finite temperatures. However, this correction should be small, while at low enough temperatures a crossover from the logarithmic to exponential behavior is expected. In the case of $YBa_2Cu_3O_{6+x}$ crystals [13] as well as those of $La_{2-x}Sr_xCuO_4$ [3, 4] the log T contribution is obviously dominating rather than a correction. Moreover, just the same behavior was observed in [3, 4] for all directions giving additional evidence against the interpretation based on 2D localization effects.

One of the most important questions is whether the resistivity upturns observed are a property inherent to a pure system due to electron correlations, or a manifestation of impurity effects. If the latter, does the superconductivity disappearance correlate with the normal-state resistivity, taking place at some universal value? A comparison of data obtained for several YBCO crystals located just at the border of the superconducting range has shown that low-temperature conductivity does not have a universal value but varies within a rather wide range, for example at $T = 1$ K $\sigma_{ab} = 500 - 2700\,\Omega^{-1}\text{cm}^{-1}$, being higher for purer crystals. These values are to be compared with a lower normal-state conductivity $\sigma_{ab}(1\text{ K}) \approx 300\ \Omega^{-1}\text{cm}^{-1}$ of the $La_{2-x}Sr_xCuO_4$ crystal, $x \approx 0.08$, being still superconducting with a T_c of about 20 K [1]. This dispersion is an indication of the crucial role of impurities and disorder in the low-temperature resistivity and implies that a pure system may be metallic without any resistivity upturn as $T \to 0$. This suggestion correlates well with an observation of both temperature-independent and diverging resistivities in $Bi_2Sr_2CuO_y$ crystals having apparently the same doping level [6].

It is worth noting that a non-universal resistivity at the SC – NSC borderline contradicts the 2D SC – I transition picture, which should be governed by the value of the sheet resistance and take place at the universal threshold value of about $h/4e^2$. Really, it is not sufficiently clear to what extent the theories of 2D electron systems are applicable to bulk, albeit strongly anisotropic, crystals, and it seems likely that the role of interplane interactions in an anisotropic system will be enhanced approaching the localization point. In this case the consideration of cuprates as anisotropic 3D systems may appear to be more appropriate. Evidence in favor of the anisotropic 3D transport in underdoped cuprates was obtained from comparison of the in-plane and out-of-plane resistivities in $La_{2-x}Sr_xCuO_4$ [3, 4] and $YBa_2Cu_3O_{6+x}$ crystals [13], which demonstrated quite similar temperature dependences at low T in spite of very strong anisotropy.

For 3D systems in the close vicinity of the metal – insulator transition one should expect the conductivity to follow the power law [14, 17]: $\sigma = \sigma_0 + \alpha T^n$, $n = 1/2$ or $1/3$, with the parameter σ_0 changing its sign at the transition point. The data from Fig. 3 replotted into a form more conventional for 3D systems, as σ vs. $T^{1/2}$, are shown in Fig. 4. One can see that this presentation is also plausible, though the exponent n is somewhat lower than 1/2. The inset demonstrates that $\sigma(T)$ can be well fitted by the power law without a systematic deviation over the temperature range of almost two orders of magnitude. As can be seen the variation of the charge carrier density due to the oxygen rearrangement results in a uniform shift of the curves towards lower conductivity values, which implies that mainly the value of σ_0 is affected. We notice that for all states of the sample, linear extrapolations (dashed lines in Fig. 4) intersect the zero temperature axis at rather large conductivity levels of $300 - 400\ \Omega^{-1}\text{cm}^{-1}$ (σ_0 even exceeded $2000\ \Omega^{-1}\text{cm}^{-1}$ for another non-SC crystal). So, accepting the anisotropic 3D model one is left with the conclusion that the normal state of YBCO is metallic on both sides of the SC – NSC transition.

While a reliable selection between logarithmic and power-law presentations in Figs 3, 4 can hardly be made, it becomes possible as the system shifts further towards the insulating

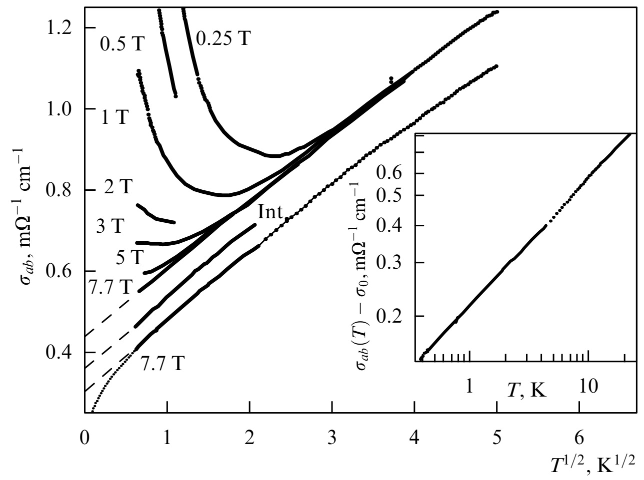

Figure 4. Plots of the conductivity $\sigma_{ab} = 1/\rho_{ab}$ versus $T^{1/2}$. The dotted line depicts, for comparison, the best logarithmic fit, $\rho_{ab} = A + B \log T$, for the 'quenched' state. Inset: temperature dependence of the conductivity on a double-logarithmic scale.

state. Such an analysis performed in [13] for ρ_c has shown that the conductivity continues to follow the power law with $\sigma_0 \to 0$, while the alternative logarithmic representation becomes inappropriate.

Therefore, a description of the normal state in $YBa_2Cu_3O_{6+x}$ as that of a 3D system in the vicinity of the metal – insulator transition seems to be preferable, and the conductivity in close vicinity of the MIT may be described by a scaling temperature dependence. The normal state underlying superconductivity is suggested to be metallic, while the M – I transition is located on the phase diagram at a distance from the SC region. Further studies are obviously highly desirable, and the fact that the normal state appeared to be just the same on both sides of the SC – NSC phase boundary is worth special notice, since it provides a possibility to deal with the problem not complicated by superconductivity.

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Quantum fluctuations and dissipation in thin superconducting wires

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1. Introduction

It is well known that fluctuations wash out the long-range order in low dimensional superconductors [1]. Does this result mean that the resistance of such superconductors always remains finite (or even infinite), or can it drop to zero under certain conditions? A lot is known about the behavior of two-dimensional (2D) superconducting films where the physics is essentially determined by the Kosterlitz – Thouless – Berezinskii (KTB) phase transition [2]. In quasi-1D superconducting wires below the (mean field) critical temperature T_c a nonzero resistivity can be caused by thermally activated phase slips (TAPS) [3]. This effect is of practical importance at temperatures close to T_c where the theoretical predictions have been verified experimentally [4]. However, as the temperature is lowered the number of TAPS decreases exponentially and no measurable resistance is predicted by the theory [3] for T not very close to T_c. Nevertheless, the experiments by Giordano [5] clearly demonstrate a notable resistivity of ultra-thin superconducting wires far below T_c. More recently strong deviations from the TAPS prediction in thin (quasi-)1D wires have been also demonstrated in other experiments [6].

The natural explanation of these observations is in terms of quantum fluctuations which generate quantum phase slips (QPS) in 1D superconducting wires. However, first estimates for the QPS tunneling rate derived from the time-dependent Ginzburg – Landau based theories [7, 8] turned out to be far too small to explain the experimental findings [5] (see [9] for more details).

More recently, the present authors [9] developed a microscopic theory describing the QPS phenomenon and demonstrated that in sufficiently thin wires QPS effects are well within the measurable range and may lead to a nonzero wire resistivity even at $T = 0$. Moreover, the existence of a new superconductor-to-metal (insulator) phase transition as a function of the wire thickness was pointed out in [9].

In the present paper we extend our theory [9] in several important aspects, in particular providing a more detailed discussion of the QPS action in various limits and paying attention to dissipative effects outside the QPS core. We also discuss a possible explanation of the recently observed negative magnetoresistance [10] within the framework of our QPS scenario.

2. The model

Our calculation is based on the effective action approach for a BCS superconductor [11]. The starting point is the partition function Z expressed as an imaginary time path-integral over the electronic fields ψ and the gauge fields $V, \mathbf{A}$, with Euclidean action

$$S = \int \mathrm{d}^3\mathbf{r} \int_0^\beta \mathrm{d}\tau \left\{ \bar{\psi}_\sigma \left[\partial_\tau - \mathrm{i}eV + \xi\left(\nabla - \frac{\mathrm{i}e\mathbf{A}}{c}\right)\right]\psi_\sigma - g\bar{\psi}_\uparrow\bar{\psi}_\downarrow\psi_\downarrow\psi_\uparrow + \mathrm{i}eVn_i + \frac{\mathbf{E}^2 + \mathbf{B}^2}{8\pi} \right\}.$$