Chapter 12

dc Josephson Current Between an Isotropic and a d-Wave or Extended s-Wave Partially Gapped Charge Density Wave Superconductor

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1. Introduction

The discovery and further development of superconductivity is extremely interesting because of its pragmatic (practical) and purely academic reasons. At the same time, the superconductivity science is very remarkable as an important object for the study in the framework of the history and methodology of science, since all the details are well documented and well-known to the community because of numerous interviews by participants including main heroes of the research and the fierce race for higher critical temperatures of the superconducting transition, T_c. Moreover, the whole science has well-documented dates, starting from the epoch-making discovery of the superconducting transition by Heike Kamerlingh-Onnes in 1911 [1–7], although minor details of this and, unfortunately, certain subsequent discoveries in the field were obscured [8–11]. As an illustrative example of a senseless dispute on the priority, one can mention the controversy between the recognition of Bardeen-Cooper-Schrieffer (BCS) [12] and Bogoliubov [13] theories.

If one looks beyond superconductivity, it is easy to find quite a number of controversies in different fields of science [14, 15]. Recent attempts [16–18] to contest and discredit the Nobel Committee decision on the discovery of graphene by Andre Geim and Kostya Novoselov [19, 20] are very typical. The reasons of a widespread disagreement concerning various scientific discoveries consist in a continuity of scientific research process and a tense competition between different groups, as happened at liquefying helium and other cryogenic gases [9, 21–24] and was reproduced in the course of studying graphite films [25, 26]. At the same time, the authors and the dates of major discoveries and predictions in the science of superconductivity are indisputable, fortunately to historians and teachers.

Macroscopic manifestations of the superconducting state and diverse properties of the plethora of superconductors are consequences of main fundamental features: (i) zero resistivity found already by Kamerlingh-Onnes (sometimes the existence of persistent currents discovered by him in 1914 is considered more prominent and mysterious [27]), (ii) expulsion of a weak magnetic field (the Meissner effect [28]), and (iii) the Josephson effects [29–37], i.e. the possibility of dc or ac super-currents in circuits, containing thin insulating or normal-metal interlayers between macroscopic superconducting segments. Of course, the indicated properties are interrelated. For instance, a macroscopic superconducting loop with three Josephson junctions can exhibit a superposition of two states with persistent currents of equal magnitudes and opposite polarity [38].

We note that those findings, reflecting a cooperative behavior of conducting electrons (later interpreted in terms of a quantum-mechanical wave function [12, 39–43]), had to be augmented by the observed isotope dependence of T_c [44, 45] in order that the first successful semi-microscopic (it is so, because the declared electron-phonon interaction was, in essence, reduced to the phenomenological four-fermion contact one) BCS theory of superconductivity [12] would come into being. Sometimes various ingenious versions of the BCS theory, explicitly taking into account the momentum and energy dependences of interaction matrix elements, as well as the renormalization of relevant normal-state properties by the superconducting reconstruction of the electron spectrum [46–50], are called "the BCS theory". Nevertheless, such extensions of the initial concept, explicitly related to Ref. [12] and results obtained therein, are inappropriate. This circumstance testifies that one should be extremely accurate with scientific terms, since otherwise it may lead to reprehensible misunderstandings [51].

Whatever be a theory referred to as "the BCS one" or as "the theory of superconductivity" [52], we still lack a true consistent microscopic picture scenario (scenarios?) of superconducting pairing in different various classes of superconductors. As a consequence, all existing superconducting criteria [53–72] are empirical rather than microscopic, although based on various relatively well-developed theoretical considerations. Hence, materials scientists must rely on their intuition to find new promising superconductors [73–78], although bearing also in mind a deep qualitative theoretical reasoning [43, 79–83].

It is no wonder that unusual transport properties of superconductors together with their magnetic-field sensibility led to a number of practically important applications. Namely, features (i) and (ii) indicated above made it possible to manufacture large-scale power cables, fly-wheel energy storage devices, bearings, high field magnets, fault current limiters, superconductor-based transformers, levitated trains, motors and power generators [84–93]. At the same time, the Josephson (weak-coupling) feature (iii) became the basis of small-scale superconducting electronics [88, 94–98], which also uses the emergence of half-integer magnetic flux quantization in circuits with superconducting currents [99, 100]. Smartly designed SQUID devices with several Josephson junctions and a quantized flux serve as sensible detectors of magnetic field and electromagnetic waves, which, in their turn, are utilized in industry, research, and medicine [95–98, 101]. Recently oscillatory effects inherent to superfluid ^{3}He [102–104] and ^{4}He [103–105], which are similar to the Josephson one, were used to construct superfluid helium quantum interference devices (SHeQUIDs) [106].

High-T_c oxide superconductors found in 1986 [107] and including large families of materials with $T_c \leq 138$ K [108–112] extended the application domain of superconductivity, because, first, liquid-nitrogen temperatures were achieved and, second, the predominant $d_{x^2-y^2}$- order parameter symmetry (at least in hole-doped oxides) made possible applications in electronics and quantum computation more diverse [37, 113–122].

While studying high-T_c cuprates, superconductivity was shown to compete with charge density waves (CDWs), so that the observed properties in the superconducting state must be modified by CDWs [123–128]. It should concern Josephson currents phenomenon too [129–134], although this topic has not been properly developed so far.

Of course, other superconducting materials found after the discovery of high-T_c oxide materials are also very remarkable, because of their non-trivial electron spectra, so that Josephson currents through junctions involving those materials should possess interesting features. We mean, in particular, MgB_2 with $T_c \leq 40$ K [135] and a multiple energy-gap structure [136, 137], as well as Fe-based pnictides and chalcogenides with $T_c \leq 56$ K and concomitant spin density waves (SDWs) suspected to have deep relations with superconductivity in those materials [78].

In this paper, we present our theoretical studies of dc Josephson currents between conventional superconductors and partially CDW-gapped materials with an emphasis on cuprates, although the gross features of the model can be applied to other CDW superconductors as well. The next Section 2 contains the justification of the approach and the formulation of the problem, whereas numerical results of calculations, as well as the detailed discussion, are presented in Section 3. Section 4 contains some general conclusions concerning dc Josephson currents across junctions involving partially gapped CDW superconductors.

A more involved case of Josephson junctions between two CDW superconductors with various symmetries of superconducting pairing will be treated elsewhere.

2. Theoretical approach

2.1. d-wave versus s-wave order parameter symmetry

Coherent properties of Fermi liquids in the paired state are revealed by measurements of dc or ac Josephson tunnel currents between two electrodes possessing such properties. The currents depend on the phase difference between superconducting order parameters of the electrodes involved [30, 31, 119]. Manifestations of the coherent pair tunneling are more complex for superconductors with anisotropic order parameters than for those with an isotropic energy gap. In particular, it is true for d-wave superconductors, where the order parameter changes its sign on the Fermi surface (FS) [119, 138–143]. As was indicated above, high-T_c oxides are usually considered as such materials, where the $d_{x^2-y^2}$ pairing is usually assumed at least as a dominating one [117, 144–152]. However, conventional s-wave contributions were also detected in electron tunneling experiments [153–160] and, probably, in nuclear magnetic resonance (NMR) and nuclear quadrupole resonance measurements [161]. Therefore, only a minority of researchers prefer to accept the isotropic s-wave (or extended s-wave) nature of superconductivity in cuprates [162–175]. Notwithstanding the existing fundamental controversies, the d-wave specificity of high-T_c oxide superconductivity has already been used in technical devices [95, 116, 118–120, 122].

2.2. Pseudogaps as a manifestation of non-superconducting gapping

In addition to the complex character of superconducting order parameter, cuprates reveal another intricacy of their electron spectrum. Namely, the pseudogap is observed both below and above T_c [176–180]. Here, various phenomena manifesting themselves in resistive, magnetic, optical, photoemission (ARPES), and tunnel (STM and break-junction) measurements are considered as a consequence of the "pseudogap"-induced depletion in the electron density of states, in analogy to what is observed in quasi-one-dimensional compounds above the mean-field phase-transition temperature [181, 182].

Notwithstanding large theoretical and experimental efforts, the pseudogap nature still remains unknown [126–128, 133, 178, 183–201]. Namely, some researchers associate them with precursor order parameter fluctuations, which might be either of a superconducting or some other competing (CDWs, SDWs, etc.) origin. Another viewpoint consists in relating pseudogaps to those competing orderings, but treating them, on the equal footing with superconductivity, as well-developed states that can be made allowance for in the mean field approximation, fluctuation effects being non-crucial. We believe that the available observations support the latter viewpoint (see, e.g., recent experimental evidences of CDW formation in various cuprates [202–205]). Moreover, although undoped cuprates are antiferromagnetic insulators [206], the CDW seems to be a more suitable candidate responsible for the pseudogap phenomena, which competes with Cooper pairing in doped high-T_c oxide samples [123–127], contrary to what is the most probable for iron-based pnictides and chalcogenides [78, 207]. Nevertheless, the type of order parameter competing with Cooper pairing in cuprates is not known with certainty. For instance, neutron diffraction studies of a number of various high-T_c oxides revealed a nonhomogeneous magnetic ordering (usually associated with SDWs) in the pseudogap state [208, 209].

2.3. Superconducting order parameter symmetry scenarios

Bearing in mind all the aforesaid, we present here the following scenarios of dc Josephson tunneling between a non-conventional partially gapped CDW superconductor and an ordinary s-wave one. The Fermi surface (FS) of the former is considered two-dimensional with a $d_{x^2-y^2}$-, d_{xy}- or extended s-wave (with a constant order parameter sign) four-lobe symmetry of superconducting order parameter and a CDW-related doping-dependent dielectric order parameter. The CDWs constitute a system with a four-fold symmetry emerging inside the superconducting lobes in their antinodal directions for cuprates (the $d_{x^2-y^2}$-geometry of the superconducting order parameter, see Figure 1) or in the nodal directions for another possible configuration allowed by symmetry (the d_{xy}-geometry of the superconducting order parameter). (Below, for the sake of brevity, when considering the extended s-wave geometries for the superconducting order parameter, we use the corresponding mnemonic notations $s^{\text{ext}}_{x^2-y^2}$ and s^{ext}_{xy}.) Thus, the CDW order parameter Σ competes with its superconducting counterpart Δ over the whole area of their coexistence, which gives rise to an interesting phenomena of temperature- (T-) reentrant Σ [126–128, 210, 211]. In this paper, the main objective of studies are the angular dependences, which might be observed in the framework of the adopted model. Of course, any admixture of Cooper pairing with a symmetry different from $d_{x^2-y^2}$-one [148, 154, 160, 212, 213] may alter the results. Moreover, the superconducting order parameter symmetry might be doping-dependent [214]. To obtain some insight into such more cumbersome situations, we treat here the pure isotropic s-wave case as well. Other possibilities for predominantly d-wave superconductivity coexisting with CDWs lie somewhere between those pure s- and d- extremes.

2.4. Formulation of the problem

The dc Josephson critical current through a tunnel junction between two superconductors, whatever their origin, is given by the general equation [30, 35]

$$I_c(T) = 4eT\sum_{\mathbf{pq}} \left|\widetilde{T}_{\mathbf{pq}}\right|^2 \sum_{\omega_n} \mathsf{F}^{+}_{\mathrm{HTSC}}(\mathbf{p};\omega_n)\mathsf{F}_{\mathrm{OS}}(\mathbf{q};-\omega_n), \tag{1}$$

Here, $\widetilde{T}_{\mathbf{pq}}$ are matrix elements of the tunnel Hamiltonian corresponding to various combinations of FS sections for superconductors taken on different sides of tunnel junction, $\mathbf{p}$ and $\mathbf{q}$ are the transferred momenta, $e > 0$ is the elementary electrical charge, $\mathsf{F}_{\mathrm{HTSC}}(\mathbf{p};\omega_n)$ and $\mathsf{F}_{\mathrm{OS}}(\mathbf{q};-\omega_n)$ are Gor'kov Green's functions for d-wave (CDW gapped!) and ordinary s-wave superconductor, respectively, and the internal summation is carried out over the discrete fermionic "frequencies" $\omega_n = (2n+1)\,\pi T$, $n = 0, \pm 1, \pm 2, \ldots$. The external summation should take into account both the anisotropy of electron spectrum $\xi(\mathbf{p})$ in a superconductor in the manner suggested long time ago for all kinds of anisotropic superconductors [215], the directionality of tunneling [216–220], and the concomitant dielectric (CDW) gapping of the nested FS sections [129].

Hereafter, we shall assume that the ordinary superconductor has the isotropic order parameter $\Delta^*(T)$. At the same time, the superconducting order parameter of the high-T_c CDW superconductor has the properly rotated (see Figure 1) pure d-wave form $\Delta(T)\cos\left[2\left(\theta-\gamma\right)\right]$, the angle θ being reckoned from the normal $\mathbf{n}$ to the junction plane and γ is a tilt angle between $\mathbf{n}$ and the bisectrix of the nearest positive lobe. Note that, for the s^{ext}-symmetry, the gap profile is the same as in the d-case, but the signs of all lobes are identical rather than alternating (for definiteness, let this sign be positive).

The dielectric order parameter $\Sigma(T)$ corresponds to the checkerboard system of mutually perpendicular CDWs (observed in various high-T_c oxides [221–223]). In the adopted model, it is nonzero inside four sectors, each of the width 2α, with their bisectrices rotated by the angle β with respect to the bisectrices of superconducting order parameter lobes [126–128, 210, 211]. Actually, we shall assume β to be either 0 or $\pi/4$. Since the nesting vectors are directed along the $\mathbf{k}_x$- and $\mathbf{k}_y$-axes in the momentum space [126, 224], the adopted choice corresponds to the choice between $d_{x^2-y^2}$- and d_{xy}-symmetry. Another possible, unidirectional CDW geometry is often observed in cuprates as well [225–227]. It can be treated in a similar way, but we shall not consider it in this work.

Note also that, in agreement with previous studies [216–220, 228], the tunnel matrix elements $\widetilde{T}_{\mathbf{pq}}$ in Eq. (1) should make allowance for the tunnel directionality (the angle-dependent probability of penetration through the barrier) [140, 229, 230]. We factorize the corresponding directionality coefficient $w\left(\theta\right)$. The weight factor $w\left(\theta\right)$ effectively disables the FS outside a certain given sector around $\mathbf{n}$, thus governing the magnitude and the sign of the Josephson

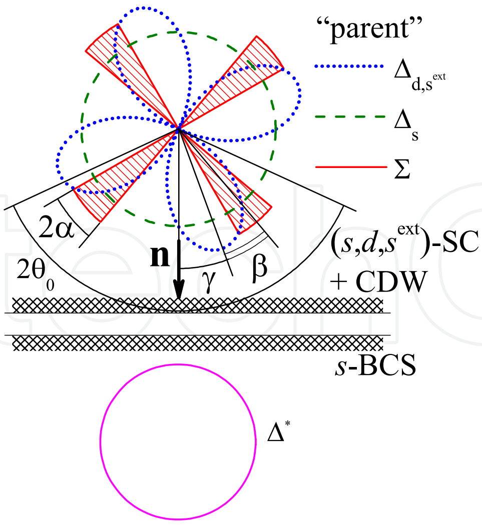

Figure 1. Geometry of the junction between a conventional s-wave superconductor (s-BCS) and a d-, s-extended (s^{ext}) or s-superconductor partially gapped by charge density waves (CDWs, induced by dielectric, i.e. electron-hole, pairing). The angle α denotes the half-width of each of four angular sectors at the Fermi surface, where the CDW gap appears. The gap profiles for the parent CDW insulator (Σ), s- (Δ_s), d- (Δ_d), and s-extended ($\Delta_{s^{\text{ext}}}$) superconductors, and conventional superconductor (Δ^*) are shown. β is a misorientation angle between the nearest superconducting lobe and CDW-gapped sector, γ is a tilt angle of superconducting lobe with respect to the junction plane determined by the normal $\mathbf{n}$, θ_0 is a measure of tunneling directionality (see explanations in the text).

tunnel current. Specifically, we used the following model for $w(\theta)$:

$$w(\theta) = \exp\left[-\left(\frac{\tan\theta}{\tan\theta_0}\right)^2\right], \tag{2}$$

where θ_0 is an angle describing the effective width of the directionality sector. We emphasize that, for tunneling between two anisotropic superconductors, two different coefficients $w(\theta)$ associated with $\mathbf{p}$- and $\mathbf{q}$-distributions in the corresponding electrodes come into effect [216].

In accordance with the previous treatment of partially gapped s-wave CDW superconductors [123–125, 129, 130, 132, 231–234] and its generalization to their d-wave counterparts [126–128, 210, 211, 235] and in line with the basic theoretical framework for unconventional superconductors [236, 237], the anomalous Gor'kov Green's functions for high-T_c oxides are assumed to be different for angular sectors with coexisting CDWs and superconductivity (d sections of the FS) and the "purely superconducting" rest of the FS (nd sections)

$$\mathsf{F}_{\text{HTSC,nd}}(\mathbf{p};\omega_n) = \frac{\Delta(T)\cos[2(\theta-\gamma)]}{\omega_n^2 + \Delta^2(T)\cos^2[2(\theta-\gamma)] + \xi_{nd}^2(\mathbf{p})}, \tag{3}$$

$$\mathsf{F}_{\text{HTSC,d}}(\mathbf{p};\omega_n) = \frac{\Delta(T)\cos[2(\theta-\gamma)]}{\omega_n^2 + \Delta^2(T)\cos^2[2(\theta-\gamma)] + \Sigma^2(T) + \xi_d^2(\mathbf{p})}. \tag{4}$$

Here, we explicitly took into account a possible angle deviation γ of the Δ-lobe direction, which is governed by the crystal lattice geometry, from the normal $\mathbf{n}$ to the junction plane; the latter is created artificially and, generally speaking, can be not coinciding with a crystal facet. The concomitant rotation of the CDW sectors is made allowance for implicitly. The quasiparticle spectra $\xi_d(\mathbf{p})$ and $\xi_{nd}(\mathbf{p})$ correspond to "hot" and "cold" spots of the cuprate FS, respectively (see, e.g., Refs. [176, 238–240]).

Substituting Eqs. (2), (3), and (4) into Eq. (1) and carrying out standard transformations [30, 35], we obtain

$$I_c(T) = \frac{\Delta(0)\,\Delta^*(0)}{2eR_N} i_c(T), \tag{5}$$

$$\begin{aligned} i_c(T) = {} & \frac{1}{2\pi}\int_{\theta_d} w(\theta)\cos\left[2\left(\theta-\gamma\right)\right] P\left[\Delta^*(T), \sqrt{\Sigma^2+\Delta^2(T)\cos^2\left[2\left(\theta-\gamma\right)\right]}\right] d\theta \\ & + \frac{1}{2\pi}\int_{\theta_{nd}} w(\theta)\cos\left[2\left(\theta-\gamma\right)\right] P\left[\Delta^*\left(T\right), \left|\Delta(T)\cos 2\left(\theta-\gamma\right)\right|\right] d\theta. \end{aligned} \tag{6}$$

Here, R_N is the normal-state resistance of the tunnel junction, determined by $\left|\widetilde{T}_{\mathbf{pq}}\right|^2$ without the factorized multiplier $w\left(\theta\right)$, the integration is carried out over the CDW-gapped and CDW-free FS sections (the FS-arcs θ_d and θ_{nd}, respectively, in the two-dimensional problem geometry), $\Delta^*(T)$ is the order parameter of the ordinary isotropic superconductor, whereas the function $P\left(\Delta_1, \Delta_2\right)$ is given by the expression [129, 215]

$$P(\Delta_1, \Delta_2) = \int_{\min\{\Delta_1,\Delta_2\}}^{\max\{\Delta_1,\Delta_2\}} \frac{dx\,\tanh\frac{x}{2T}}{\sqrt{\left(x^2-\Delta_1^2\right)\left(\Delta_2^2-x^2\right)}}. \tag{7}$$

Modified Eqs. (3)-(6) turn out valid for the calculation of dc Josephson current through a tunnel junction between an ordinary *s*-wave superconductor and a partially gapped CDW superconductor with an extended *s*-symmetry of superconducting order parameter [142, 241]. For this purpose, it is enough to substitute the cosine functions in Eqs. (3)-(6) by their absolute values.

At $w\left(\theta\right) \equiv 1$ (the absence of tunnel directionality), $\Sigma \equiv 0$ (the absence of CDW-gapping), and putting $\cos 2\left(\theta-\gamma\right) \equiv 1$ (actually, it is a substitution of an isotropic *s*-superconductor for the *d*-wave one), Eq. (6) expectedly reproduces the famous Ambegaokar–Baratoff result for tunneling between *s*-wave superconductors [30, 31, 35, 242].

Note that, in Eq. (6), the directionality is made allowance for only by introducing the angular function $w\left(\theta\right)$ reflecting the angle-dependent tunnel-barrier transparency. On the other hand, the tunneling process, in principle, should also take into account the factors $\left|\mathbf{v}_{g,nd}\cdot\mathbf{n}\right|$ and $\left|\mathbf{v}_{g,d}\cdot\mathbf{n}\right|$, responsible for extra directionality [140, 219, 230], where $\mathbf{v}_{g,nd} = \nabla\xi_{nd}$ and $\mathbf{v}_{g,d} = \nabla\xi_d$ are the quasiparticle group velocities for proper FS sections. Those factors can be considered as proportional to a number of electron attempts to penetrate the barrier [139]. They were introduced decades ago in the framework of general problem dealing with tunneling in heterostructures [243–245]. Nevertheless, we omitted here the group-velocity-dependent multiplier, since it requires that the FS shape should be specified, thus going beyond the applied semi-phenomenological scheme, as well as beyond similar semi-phenomenological approaches of other groups [138, 139, 141, 236, 246]. We shall take the additional directionality factor into account in subsequent publications, still being fully aware of the phenomenological nature of both $\left|\mathbf{v}_g \cdot \mathbf{n}\right|$ and $w(\theta)$ functions.

It is well known [143] that, in the absence of directionality, the Josephson tunneling between d- and s-wave superconductors is weighted-averaged over the FS, with the cosine multiplier in Eq. (6) playing the role of weight function. In this case, the Josephson current has to be strictly equal to zero. However, it was found experimentally that the dc Josephson current between $Bi_2Sr_2CaCu_2O_{8+\delta}$ and Pb [155], $Bi_2Sr_2CaCu_2O_{8+\delta}$ and Nb [247], $YBa_2Cu_3O_{7-\delta}$ and PbIn [248], $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ and Pb [153] differ from zero. Hence, either a subdominant s-wave component of the superconducting order parameter does exist in cuprate materials, as was discussed above, or the introduction of directionality is inevitable to reconcile any theory dealing with tunneling of quasiparticles from (to) high-T_c oxides and the experiment.

We restrict ourselves mostly to the case $T = 0$, when formula (7) is reduced to elliptic functions [30, 249], although some calculations will be performed for $T \neq 0$ as well. The reason consists in the smallness of T_c for conventional s-wave superconductors (in our case, it is Nb, see below) as compared to T_c of anisotropic d-wave oxides. Hence, all effects concerning T-dependent interplay between Δ and Σ including possible reentrance of $\Sigma(T)$ [126–128, 210, 211, 235] become insignificant in the relevant T-range cut off by the s-wave-electrode order parameter. On the contrary, in the symmetrical case, when one studies tunneling between different high-T_c-oxide grains, T-dependences of the Josephson current are expected to be very interesting. This more involved situation will be investigated elsewhere.

3. Results and discussion

3.1. Total currents

In what follows, we shall consider in parallel the dc Josephson currents between a more or less conventional (weak-coupling BCS s-wave) Nb with a zero-T energy gap $\Delta^*(0) = 1.4$ meV and $T_c = 9.2$ K [247] and either a $d_{x^2-y^2}$- or a d_{xy}- superconductor ($\beta = 0$ and $\pi/4$, respectively). The latter is also possible from the symmetry viewpoint, but have not yet been found among existing classes of CDW superconductors.

The dependences of the dimensionless current $i_c(T = 0)$ on the tilt angle γ are shown in Figure 2(a) for $\alpha = 15^\circ$ and various values of the parameter θ_0 describing the degree of directionality. Since $T = 0$, there is no need to solve the equation set for $\Sigma(T)$ and $\Delta(T)$ for partially CDW-gapped s-wave [233] or d-wave [128] superconductors self-consistently. Instead, for definiteness, we chose the experimental values $\Sigma(0) = 36.3$ meV and $\Delta(0) = 28.3$ meV appropriate to slightly overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples [250] as input parameters. The half-width α of each of the four CDW sectors was *rather arbitrarily* chosen as 15°. In fact, it is heavily dependent on the doping extent and cannot be unambiguously extracted even from the most precise angle-resolved photoemission spectra (ARPES) [200, 251, 252]. Thus, hereafter we consider the parameter of dielectric FS gapping α as a *phenomenological* one on the same footing as the tunneling directionality parameter θ_0.

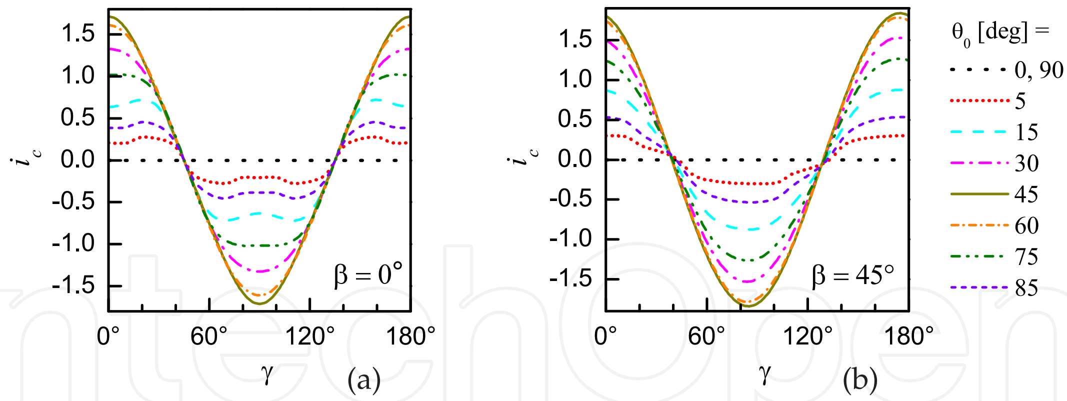

Figure 2. (a) Zero-temperature ($T = 0$) dependences on γ of the dimensionless dc Josephson current i_c for the tunnel junction between an s-wave superconductor and a CDW $d_{x^2-y^2}$-wave one ($\beta = 0°$) for various θ_0's. The specific gap values for electrodes correspond to the experimental data for Nb ($\Delta^*(T = 0) = 1.4$ meV) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ ($\Sigma(T = 0) = 36.3$ meV and $\Delta(T = 0) = 28.3$ meV). The calculation parameter $\alpha = 15°$. See further explanations in the text. (b) The same as in panel (a), but for a CDW d_{xy}-superconductor ($\beta = 45°$).

It is evident that, if the sector θ_0 of effective tunneling equals zero, the Josephson current vanishes. It is also natural that, in the case of d-wave pairing and the absence of tunneling directionality ($\theta_0 = 90°$), the Josephson current disappears due to the exactly mutually compensating contributions from superconducting order parameter lobes with different signs [119, 138, 143]. Intermediate θ_0's correspond to non-zero Josephson tunnel current of either sign (conventional 0- and π-junctions [120, 122, 253]) except at the tilt angle $\gamma = 45°$, when $i_c = 0$. In this connection, one should recognize that the energy minimum *for non-conventional anisotropic superconductors* can occur, in principle, at any value of the order parameter phase [254]. As is seen from Figure 2(a), the existence of CDWs in cuprates ($\alpha \neq 0$, $\Sigma \neq 0$) influences the γ-dependences of i_c, which become non-monotonic for θ_0 close to α demonstrating a peculiar resonance between two junction characteristics. The effect appears owing to the actual $d_{x^2-y^2}$- pattern with the coinciding bisectrices of CDW sectors and superconducting lobes ($\beta = 0°$). This circumstance may ensure the finding of CDWs (pseudogaps) by a set of relatively simple transport measurements.

At the same time, for the hypothetical d_{xy} order parameter symmetry ($\beta = 45°$, Figure 2(b)), when hot spots lie in the nodal regions, the dependences $i_c(\gamma)$ become asymmetrical relative to $\gamma = 90°$ and remain monotonic as for CDW-free d-wave superconductors.

The role of superconducting-lobe and CDW (governed by the crystalline structure) orientation with respect to the junction plane (the angle γ) is most clearly seen for varying α, which is shown in Figure 3. The indicated above "resonance" between θ_0 and α is readily seen in Figure 3(a). One also sees that the Josephson current amplitude is expectedly reduced with the increasing α, since CDWs suppress superconductivity [123–127, 255]. For $\beta = 45°$ (Figure 3(b)), the curves $i_c(\gamma)$ are non-symmetrical, and their form is distorted by CDWs relative to the case of "pure" superconducting d-wave electrode.

The dependence of i_c on the CDW-sector width, i.e. the degree of dielectric FS gapping, is a rapidly dropping one, which is demonstrated in Figures 4(a) (for $\beta = 0°$, i.e. for $d_{x^2-y^2}$ or $s^{ext}_{x^2-y^2}$ symmetries) and 4(b) (for $\beta = 45°$, i.e. for d_{xy} or s^{ext}_{xy} symmetries) calculated for

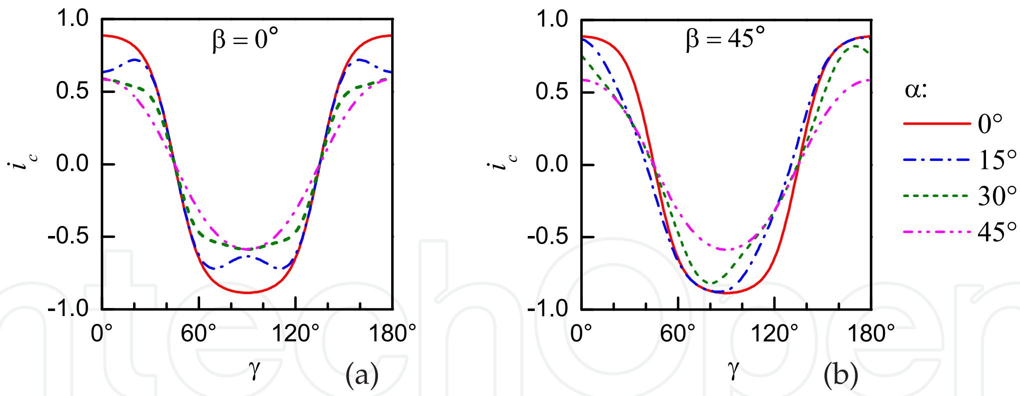

Figure 3. The same as in Figure 2, but for $\theta_0 = 15°$ and various α's.

$\gamma = 0°$ and $\theta_0 = 15°$. Indeed, for cuprates, where the directions of superconducting lobes and CDW sectors coincide, an extending CDW-induced gap reduces the electron density of states available to superconducting pairing until α becomes equal to θ_0 (see Figure 4(a)). A further increase of the pseudogapped FS arc has no influence on i_c, since it falls outside the effective tunneling sector. We note that the α-dependence of i_c for cuprates can be, in principle, non-linearly mapped onto the doping dependence of the pseudogap [200, 251, 252]. It is remarkable that, qualitatively, the results are the same for the extended s-symmetry (denoted as s^{ext}) of the superconducting order parameter and are very similar to those for the assumed s-wave order parameter (curves marked by s).

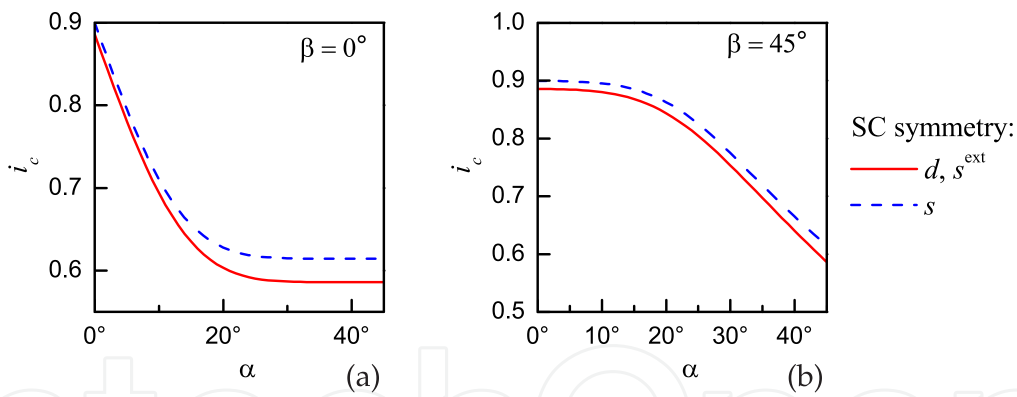

Figure 4. Dependences $i_c(\alpha)$ for $\gamma = 0°$ and $\theta_0 = 15°$ for d-, s-extended, and s-symmetries of superconducting order parameter.

At the same time, if the CDW sectors are rotated in the momentum space by 45° with respect to the superconducting lobes and/or the directional-tunneling θ_0-cone (see Figure 4(b)), the dependences $i_c(\alpha)$ are very weak at small α and become steep for $\alpha > \theta_0$. This result is true for the d_{xy}-, rotated extended s-, and isotropic s-symmetries of the superconducting order parameter coexisting with its dielectric counterpart.

One sees from Figure 4 that, for small $\theta_0 = 15°$, the d- and extended s-order parameters result in the same $i_c(\alpha)$. Of course, it is no longer true for larger θ_0, when contributions from different lobes into the total Josephson current start to compensate each other for d-wave superconductivity, whereas no compensation occurs for the extended s-wave scenario. To make sure that this assertion is valid, we calculated the dependences $i_c(\theta_0)$ for $\gamma = 0°$, $\alpha = 15°$, and $\beta = 0°$ and $45°$. The results are presented in Figure 5. Indeed, for $\theta_0 \geq 30°$, the curves corresponding to d-wave and extended s-wave superconductors come apart, as it has to be. Thus, Josephson currents between isotropic and CDW d-wave superconductors, similarly to the CDW-free case, are non-zero only because the tunneling is non-isotropic.

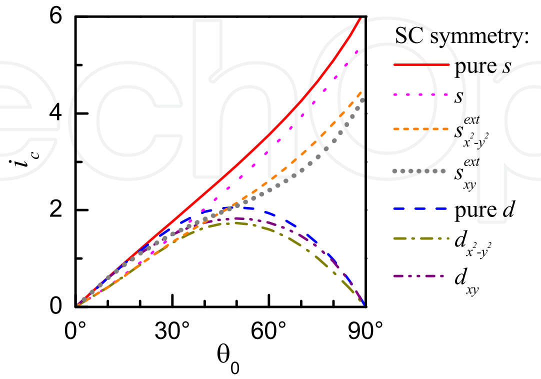

Figure 5. Dependences $i_c(\theta_0)$ for $\gamma = 0°$, $\beta = 0°$, and $\alpha_0 = 15°$ for various symmetries of superconducting order parameter.

It is instructive to compare the tilt-angle-γ dependences of the Josephson currents i_c for possible superconducting order parameter symmetries, which are considered, in particular, for cuprates. The results of calculations are displayed in Figure 7 for $\alpha = \theta_0 = 15°$. For an s-wave CDW-free superconductor, $i_c(\gamma) = \text{const}$. The reference curve $i_c(\gamma)$ for a CDW-free $d_{x^2-y^2}$-wave superconductor (Figure 7(a)) is periodic and alternating. CDWs distort both curves. Namely, the CDW $d_{x^2-y^2}$-wave superconductor demonstrates a non-monotonic behavior of $i_c(\gamma)$, as was indicated above, whereas $i_c(\gamma)$ for the s-wave CDW superconductor becomes a periodic dependence of a constant sign. The curve $i_c(\gamma)$ for the extended s-wave CDW superconductor has a different form than in the s-wave case, although being qualitatively similar. The presented data demonstrate that CDWs can significantly alter angle dependences often considered as a smoking gun,when determining the actual order parameter symmetry for cuprates or other like materials.

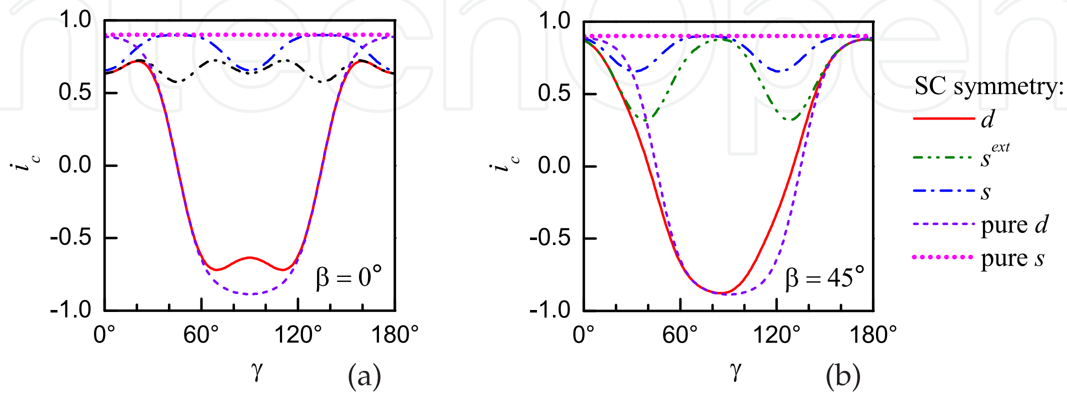

Figure 6. The same as in Figure 2, but for $\theta_0 = 15°$ and various symmetries of superconducting order parameter.

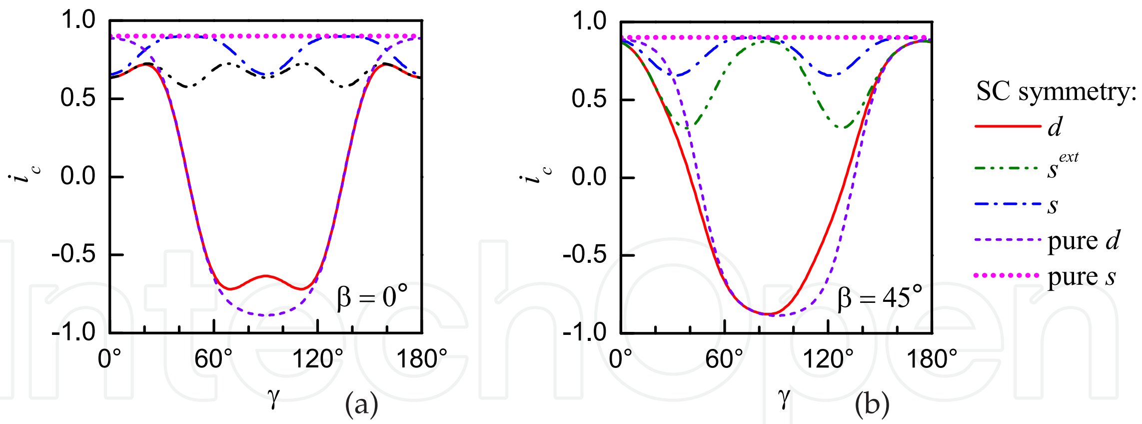

Figure 7. The same as in Figure 2, but for $\theta_0 = 15°$ and various symmetries of superconducting order parameter.

The results for $\beta = 45°$ (Figure 7(b)) differ quantitatively from their counterparts found for $\beta = 0°$, but qualitative conclusions remain the same.

As was indicated above, the temperature behavior of i_c between ordinary superconductors and cuprates is determined by the order parameter dependence $\Delta^*(T)$ for the material with much lower T_c, Nb in our case. This is demonstrated in Figure 8 for *d*-, extended *s*- and *s*-wave CDW high-T_c superconductors. One sees that all curves $i_c(T)$ are similar, differing only in magnitudes.

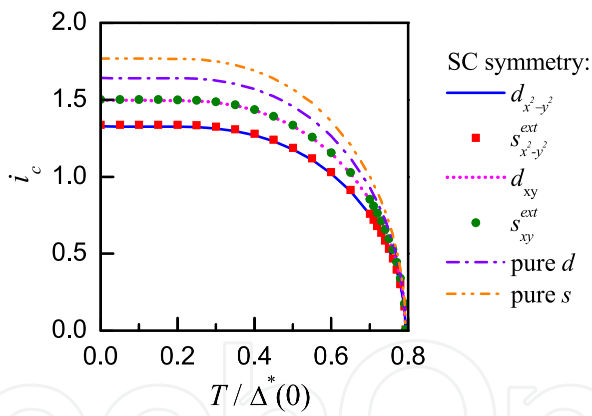

Figure 8. Dependences $i_c(T)$ for $\gamma = 0°$, $\theta_0 = 30°$, $\alpha_0 = 15°$ and various symmetries of superconducting order parameter.

3.2. Analysis of current components

In Figure 9, the dependences $i_c(\gamma)$ resolved into d and nd components are shown for CDW *d*-wave superconductors with $\beta = 0°$, $\alpha = 15°$, and various θ_0's. Note that the order parameter *amplitudes* at $T = 0$ are the same throughout the paper! It comes about that, for a narrow directionality cone θ_0, the contribution of the nested (d) FS sections has quite a different tilt (γ) angle behavior as compared to their nd counterparts. All that gives rise to a non-monotonic pattern seen, e.g., in Figure 2(a).

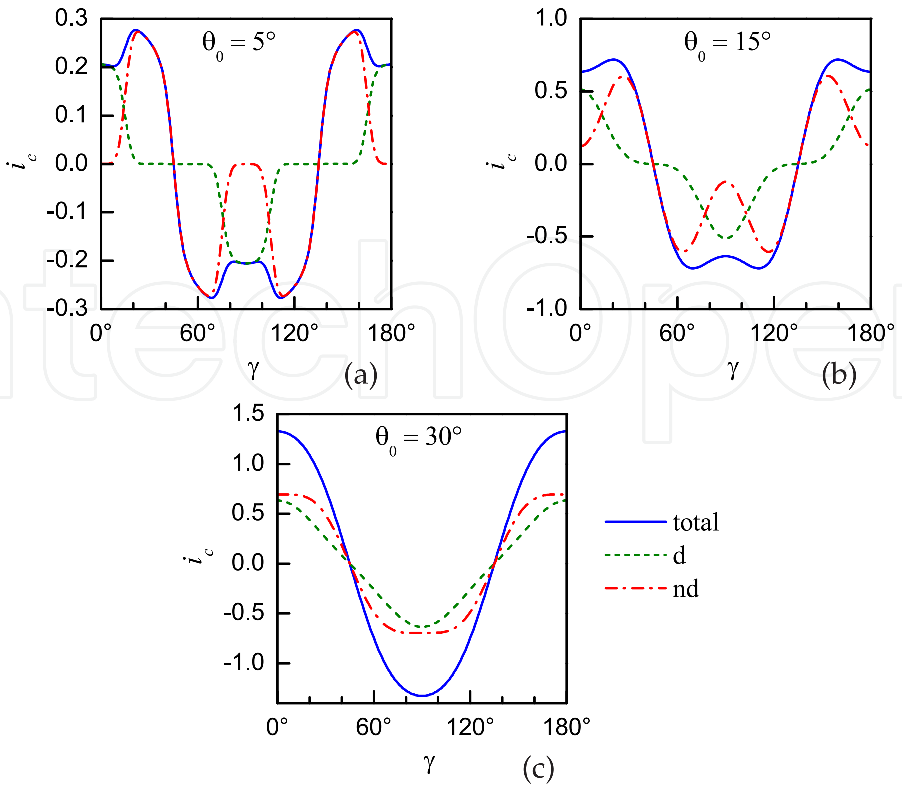

Figure 9. Dependences of i_c and its d and nd components on γ for $d_{x^2-y^2}$ order parameter symmetry, $\alpha_0 = 15°$, and various θ_0's (panel a to c).

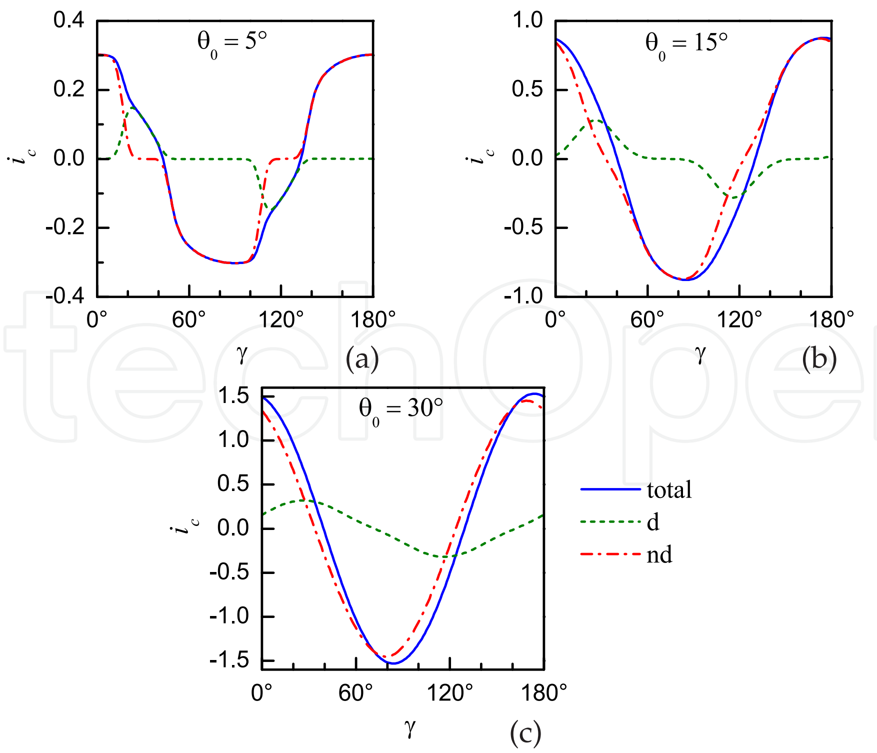

Figure 10. The same as in Figure 9, but for d_{xy} order parameter symmetry.

In Figure 10, the same dependences as in Figure 9 are shown, but for $\beta = 45°$. One sees that, whatever complex is the γ-angle behavior of d contribution to the overall tunnel currents between a d_{xy}-superconductor and Nb, the CDW influence is much weaker in governing the dependences $i_c(\gamma)$.

It is illustrative to carry out the same analysis in the scenario, when the high-T_c CDW superconductor is assumed to be an extended s-wave one, i.e. when the sign of superconducting order parameter is the same for all lobes. In the case $\beta = 0°$, the corresponding results can be seen in Figure 11, where the γ-dependences of d and nd components of i_c, as well as the total $i_c(\gamma)$ dependences, are depicted for the same parameter set as in Figure 9. We see that the d and nd contributions oscillate with the varying γ almost in antiphase, remaining, nevertheless, positive. For large $\theta_0 = 30°$ (Figure 11(c)), oscillations largely compensate each other making the curve $i_c(\gamma)$ almost flat, which mimics the behavior appropriate to CDW-free isotropic s-wave superconductors. However, we emphasize that this, at the first glance, dull result obtained for a relatively wide CDW sector is actually a consequence of a peculiar superposition involving the periodic dependences of d and nd components on γ with rapidly varying amplitudes.

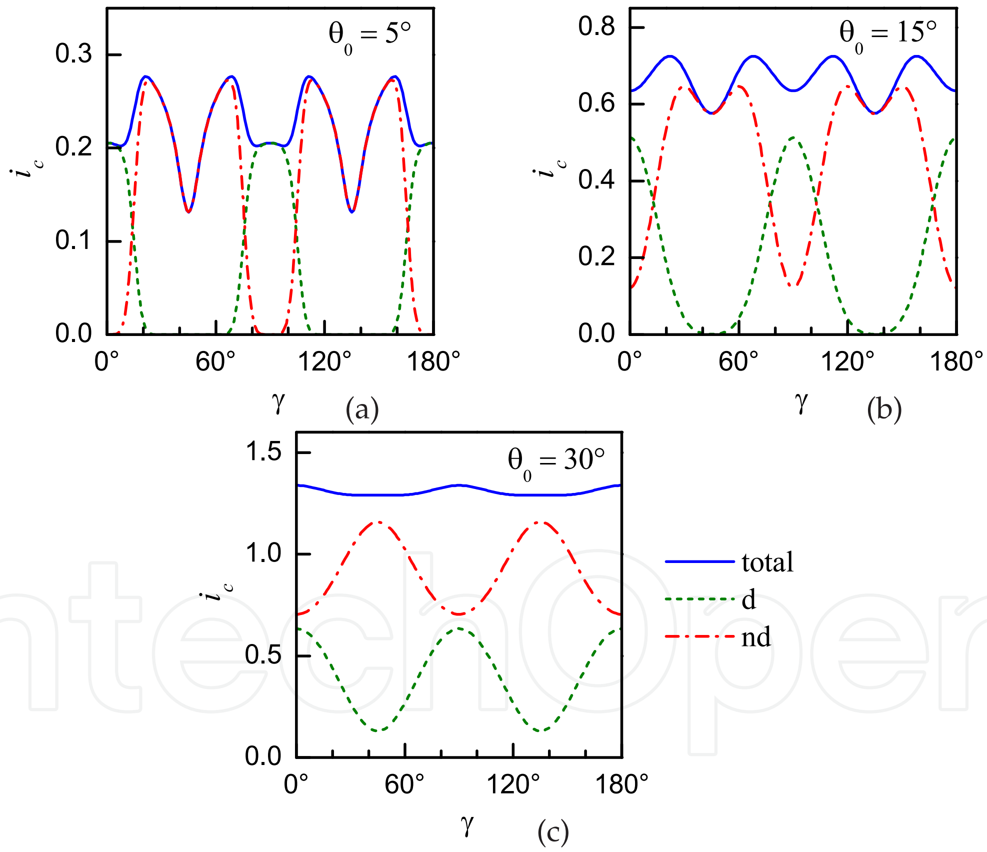

Figure 11. The same as in Figure 9, but for $s^{ext}_{x^2-y^2}$ order parameter symmetry.

The same plots as in Figure 11 were calculated for $\beta = 45°$ and depicted, in Figure 12. Here, the directionality angle θ_0 is the main factor determining the amplitude of i_c, the role of CDWs being much weaker than in the case $\beta = 0°$. It is natural, because now CDW-gapping is concentrated in the nodal regions.

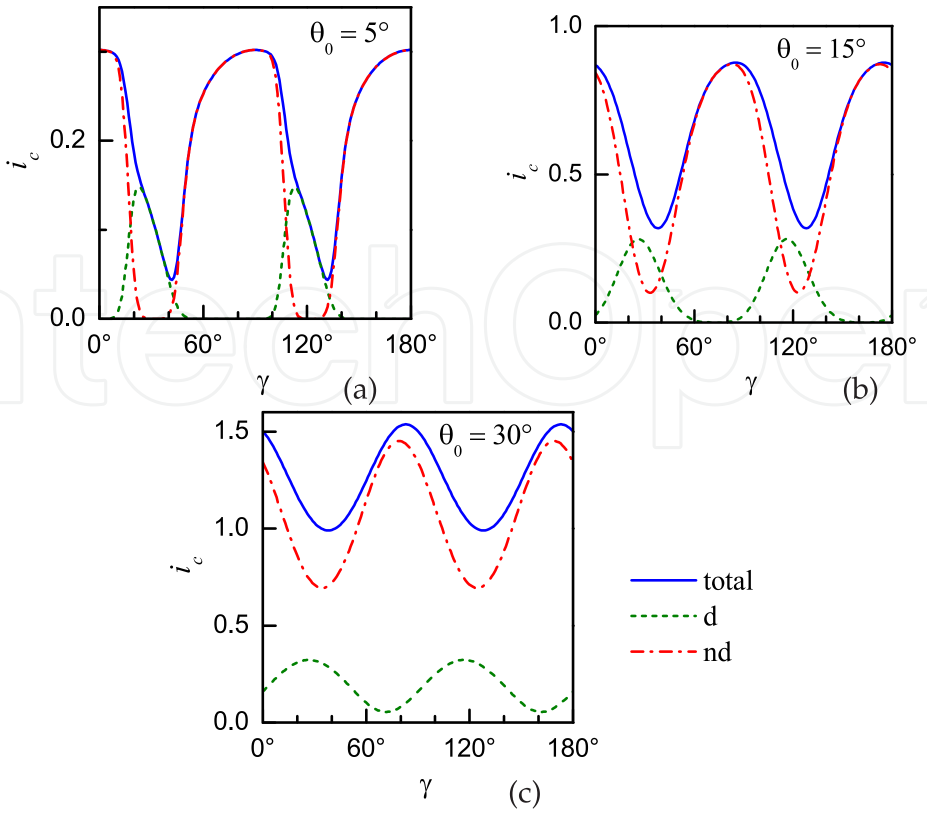

Figure 12. The same as in Figure 11, but for s_{xy}^{ext} order parameter symmetry.

4. Conclusions

The results obtained confirm that the dc Josephson current, probing coherent superconducting properties [30, 31, 33, 37, 119, 256–258], is always suppressed by the electron-hole CDW pairing, which, in agreement with the totality of experimental data, is assumed here to compete with its superconducting electron-electron (Cooper) counterpart [129, 130, 132, 259–262]. We emphasize that, as concerns the quasiparticle current, the results are more ambiguous. In particular, the states on the FS around the nodes of the *d*-wave superconducting order parameter are engaged into CDW gapping [126–128, 210, 211, 235, 263], so that the ARPES or tunnel spectroscopy feels the overall energy gaps being larger than their superconducting constituent.

Our examination demonstrates that the emerging CDWs should distort the dependences $i_c(\gamma)$, whatever is the symmetry of superconducting order parameter. It is easily seen that, for equal (or almost equal) θ_0 and α, CDWs make the $i_c(\gamma)$ curves non-monotonic and quantitatively different from their CDW-free counterparts. In particular, i_c values are conspicuously smaller for $\Sigma \neq 0$. The required resonance between θ_0 and α can be ensured by the proper doping, i.e. a series of samples and respective tunnel junctions should be prepared with attested tilt angles γ, and the Josephson current should be measured for them. Of course, such measurements could be very cumbersome, although they may turn out quite realistic to be performed.

At the same time, when an *s*-wave contribution to the actual order parameter in a cuprate sample is dominant up to the complete disappearance of the *d*-wave component, the $i_c(\gamma)$ dependences for junctions involving CDW superconductors are no longer constant as in the CDW-free case. This prediction can be verified for CDW superconductors with *a fortiori* *s*-wave order parameters (such materials are quite numerous [123–128]).

In this paper, our approach was purely theoretical. We did not discuss unavoidable experimental difficulties to face with in fabricating Josephson junctions necessary to check the results obtained here. We are fully aware that the emerging problems can be solved on the basis of already accumulated knowledge concerning the nature of grain boundaries in high-T_c oxides [37, 115–119, 122, 264–268]. Note that required junctions can be created at random in an uncontrollable fashion using the break-junction technique [250]. This method allows to comparatively easily detect CDW (pseudogap) influence on the tilt-angle dependences.

To summarize, measurements of the Josephson current between an ordinary superconductor and a *d*-wave or extended *s*-wave one (e.g., a high-T_c oxide) would be useful to detect a possible CDW influence on the electron spectrum of the latter. Similar studies of iron-based superconductors with doping-dependent spin density waves (SDWs) would also be of benefit (see, e.g., recent Reviews [78, 269–275]), since CDW and SDW superconductors have similar, although not identical, properties [123–125].

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5. References

[1] Kamerlingh-Onnes H (1911) Further experiments with liquid helium. C. On the change of electric resistance of pure metals at very low temperatures etc. IV. The resistance of pure mercury at helium temperatures. Communs Phys. Lab. Univ. Leiden. 120: 3–5.
[2] Editorial (2011) The super century. Nature Mater. 10: 253.
[3] Editorial (2011) A very cool birthday. Nature Phys. 7: 271.
[4] Cho A (2011) Superconductivity's smorgasbord of insights: A movable feast. Science 332: 190–192.
[5] Larbalestier D, Canfield PC (2011) Superconductivity at 100 – Where we've been and where we're going. Mater. Res. Soc. Bull. 36: 590–593.

[6] van der Marel D, Golden M (2011) Heike's heritage. Nature Phys. 7: 378–379.
[7] Grant PM (April 2011) Down the path of least resistance. Phys. World 24: 18–22.
[8] de Nobel J (September 1996) The discovery of superconductivity. Phys. Today 49: 40–42.
[9] van Delft D (2007) Freezing Physics. Heike Kamerlingh-Onnes and the Quest for Cold. Amsterdam: Koninklijke Nederlandse Akademie van Wetenschappen.
[10] van Delft D, Kes P (September 2010) The discovery of superconductivity. Phys. Today 63: 38–43.
[11] van Delft D, Kes P (2011) The discovery of superconductivity. Europhys. News 42: 21–25.
[12] Bardeen J, Cooper LN, Schrieffer JR (1957) Theory of superconductivity. Phys. Rev. 108: 1175–1204.
[13] Bogoliubov NN (1958) On the new method in the theory of superconductivity. Zh. Éksp. Teor. Fiz. 34: 58–65.
[14] Burgin MS, Gabovich AM (March-April 1997) Why the discovery has not been made? Visn. Nats. Akad. Nauk Ukrainy: 55–60.
[15] Hudson RG (2001) Discoveries, when and by whom? Brit. J. Phil. Sci. 52: 75–93.
[16] de Heer WA (2011) Epitaxial graphene: A new electronic material for the 21st century. Mater. Res. Soc. Bull. 36: 632–639.
[17] de Heer WA, Berger C, Ruan M, Sprinkle M, Li X, Hu Y, Zhang B, Hankinson J, Conrad E (2011) Large area and structured epitaxial graphene produced by confinement controlled sublimation of silicon carbide. Proc. Nat. Acad. Sci. USA 108: 16900–16905.
[18] de Heer WA (2012) The invention of graphene electronics and the physics of epitaxial graphene on silicon carbide. Phys. Scripta T146: 014004.
[19] Geim AK (2011) Nobel Lecture: Graphene: Random walk to graphene. Rev. Mod. Phys. 83: 851–862.
[20] Novoselov KS (2011) Nobel Lecture: Graphene: Materials in the Flatland. Rev. Mod. Phys. 83: 837–849.
[21] Soulen RJ Jr (March 1996) James Dewar, his flask and other achievements. Phys. Today 49: 32–38.
[22] Reif-Acherman S (2004) Heike Kamerlingh-Onnes: Master of experimental technique and quantitative research. Phys. Perspect. 6: 197–223.
[23] van Delft D (March 2008) Little cup of helium, big science. Phys. Today 61: 36–42.
[24] Kubbinga H (2010) A tribute to Wróblewski and Olszewski. Europhys. News 41: 21–24.
[25] Dresselhaus MS (2012) Fifty years in studying carbon-based materials. Phys. Scripta T146: 014002.
[26] Geim AK (2012) Graphene prehistory. Phys. Scripta T146: 014003.
[27] Kitazawa K (2012) Superconductivity: 100th anniversary of its discovery and its future. Jpn. J. Appl. Phys. 51: 010001.
[28] Meissner W, Ochsenfeld R (1933) Ein neuer Effekt bei Eintritt der Supraleitfähigkeit. Naturwiss. 33: 787–788.
[29] Josephson BD (1962) Possible new effects in superconductive tunneling. Phys. Lett. 1: 251–253.
[30] Kulik IO, Yanson IK (1972) Josephson Effect in Superconducting Tunnel Structures. Jerusalem: Israel Program for Scientific Translation.

[31] Waldram JR (1976) The Josephson effects in weakly coupled superconductors. Rep. Prog. Phys. 39: 751–821.
[32] Kulik IO, Omel'yanchuk AN (1978) Josephson effect in superconducting bridges: microscopic theory. Fiz. Nizk. Temp. 4: 296–311.
[33] Rogovin D, Scully M (1976) Superconductivity and macroscopic quantum phenomena. Phys. Rep. 25: 175–291.
[34] Likharev KK (1979) Superconducting weak links. Rev. Mod. Phys. 51: 101–159.
[35] Barone A, Paterno G (1982) The Physics and Applications of the Josephson Effect. New York: John Wiley and Sons.
[36] Likharev KK (1985) Introduction into Dynamics of Josephson Junctions. Moscow: Nauka. in Russian.
[37] Golubov AA, Kupriyanov M Yu, Il'ichev E (2004) The current-phase relation in Josephson junctions. Rev. Mod. Phys. 76: 411–469.
[38] van der Wal CH, ter Haar ACJ, Wilhelm FK, Schouten RN, Harmans CJPM, Orlando TP, Lloyd S, Mooij JE (2000) Quantum superposition of macroscopic persistent-current states. Science 290: 773–777.
[39] Rickayzen G (1971) Superconductivity and long-range order. Essays Phys. 3: 1–33.
[40] Eggington MA, Leggett AJ (1975) Is ODLRO a necessary condition for superfluidity? Collect. Phenom. 2: 81–87.
[41] Svidzinsky AV (1982) Spatially-Nonhomogeneous Problems of the Superconductivity Theory. Moscow: Nauka. in Russian.
[42] Pitaevskii L (2008) Phenomenology and microscopic theory: Theoretical foundations. In: Bennemann KH, Ketterson JB, editors. Superconductivity. Vol. 1: Conventional and Unconventional Superconductors. Berlin: Springer Verlag. pp. 27–71.
[43] Leggett AJ (2011) The ubiquity of superconductivity. Annu. Rev. Condens. Matter Phys. 2: 11–30.
[44] Maxwell E (1950) Isotope effect in the superconductivity of mercury. Phys. Rev. 78: 477.
[45] Reynolds CA, Serin B, Wright WH, Nesbitt LB (1950) Superconductivity of isotopes of mercury. Phys. Rev. 78: 487.
[46] Eliashberg GM (1960) Interaction of electrons with lattice vibrations in a superconductor. Zh. Éksp. Teor. Fiz. 38: 966–976.
[47] Eliashberg GM (1960) Temperature Green's functions of electrons in a superconductor. Zh. Éksp. Teor. Fiz. 39: 1437–1441.
[48] Kirzhnits DA, Maksimov EG, Khomskii DI (1973) The description of superconductivity in terms of dielectric response function. J. Low Temp. Phys. 10: 79–93.
[49] Carbotte JP (1990) Properties of boson-exchange superconductors. Rev. Mod. Phys. 62: 1027–1157.
[50] Carbotte JP, Marsiglio F (2003) Electron-phonon superconductivity. In: Bennemann KH, Ketterson JB, editors. The Physics of Superconductors. Vol. 1: Conventional and High-T_c superconductors. Berlin: Springer Verlag. pp. 233–345.
[51] Kuznetsov VI (1997) Concept and Its Strutures. Methodological Analysis. Kiev: Institute of Philosophy. in Russian.
[52] Anderson PW (1997) The Theory of Superconductivity in the High-T_c Cuprates. Princeton: Princeton Univeristy Press.

[53] Matthias BT (1955) Empirical relation between superconductivity and the number of valence electrons per atom. Phys. Rev. 97: 74–76.
[54] Kulik IO (1964) On the superconductivity criterion. Zh. Éksp. Teor. Fiz. 47: 2159–2167.
[55] Matthias BT (1973) Criteria for superconducting transition temperatures. Physica 69: 54–56.
[56] Stern H (1973) Trends in superconductivity in the periodic table. Phys. Rev. B 8: 5109–5121.
[57] Kulik IO (1974) Superconductivity and macroscopic stability criteria for electron-phonon systems. Zh. Éksp. Teor. Fiz. 66: 2224–2239.
[58] Stern H (1975) Superconductivity in transition metals and compounds. Phys. Rev. B 12: 951–960.
[59] Gualtieri DM (1975) The correlation between the superconducting critical temperature and the number of stable isotopes among superconducting elements. Solid State Commun. 16: 917–918.
[60] Kulik IO (1976) Spin fluctuations and superconductivity (properties of Pd–H solutions). Fiz. Nizk. Temp. 2: 486–499.
[61] Gabovich AM (1977) On the criterion of superconductivity of metals. Ukr. Fiz. Zh. 22: 2072–2074.
[62] Gabovich AM, Moiseev DP (1978) Superconductivity of metals with the allowance for ion core repulsion. Fiz. Nizk. Temp. 4: 1115–1124.
[63] Gabovich AM (1980) About superconductivity of polar semiconductors. Fiz. Tverd. Tela 22: 3231–3235.
[64] Gabovich AM, Moiseev DP (1981) Isotope effect in jellium and Brout models. Fiz. Tverd. Tela 23: 1511–1514.
[65] Chapnik IM (1984) Regularities in the occurrence of superconductivity. J. Phys. F 14: 1919–1921.
[66] Carbotte JP (1987) On criteria for superconductivity. Sci. Progr. 71: 327–350.
[67] Luo Q-G, Wang R-Y (1987) Electronegativity and superconductivity. J. Phys. Chem. Sol. 48: 425–430.
[68] Jou CJ, Washburn J (1991) Relationship between T_c and electronegativity differences in compound superconductors. Appl. Phys. A 53: 87–93.
[69] Hirsch JE (1997) Correlations between normal-state properties and superconductivity. Phys. Rev. B 55: 9007–9024.
[70] Buzea C, Robbie K (2005) Assembling the puzzle of superconducting elements: a review. Supercond. Sci. Technol. 18: R1–R8.
[71] Koroleva L, Khapaeva TM (2009) Superconductivity, antiferromagnetism and ferromagnetism in periodic table of D.I. Mendeleev. J. Phys.: Conf. Ser. 153: 012057.
[72] Taylor BJ, Maple MB (2009) Formula for the critical temperature of superconductors based on the electronic density of states and the effective mass. Phys. Rev. Lett. 102: 137003.
[73] Pickett WE (2008) The next breakthrough in phonon-mediated superconductivity. Physica C 468: 126–135.
[74] Blase X (2011) Superconductivity in doped clathrates, diamond and silicon. C. R. Physique 12: 584–590.
[75] Canfield PC (2011) Still alluring and hard to predict at 100. Nature Mater. 10: 259–261.

[76] Forgan T (April 2011) Resistance is futile. Phys. World 24: 33–38.
[77] Greene LH (April 2011) Taming serendipity. Phys. World 24: 41–43.
[78] Stewart GR (2011) Superconductivity in iron compounds. Rev. Mod. Phys. 83: 1589–1652.
[79] Geballe TH (2006) The never-ending search for high-temperature superconductivity. J. Supercond. 19: 261–276.
[80] Cohen ML (2006) Electron–phonon-induced superconductivity. J. Supercond. 19: 283–290.
[81] Pickett WE (2006) Design for a room-temperature superconductor. J. Supercond. 19: 291–297.
[82] Leggett AJ (2006) What DO we know about high T_c? Nature Phys. 2: 134–136.
[83] Maksimov EG, Dolgov OV (2007) A note on the possible mechanisms of high-temperature superconductivity. Usp. Fiz. Nauk 177: 983–988.
[84] Hassenzahl WV, Hazelton DW, Johnson BK, Komarek P, Noe M, Reis CT (2004) Electric power applications of superconductivity. Proc. IEEE 92: 1655–1674.
[85] Gourlay SA, Sabbi G, Kircher F, Martovetsky N, Ketchen D (2004) Superconducting magnets and their applications. Proc. IEEE 92: 1675–1687.
[86] Hull JR, Murakami M (2004) Applications of bulk high-temperature superconductors. Proc. IEEE 92: 1705–1718.
[87] Tsukamoto O (2004) Ways for power applications of high temperature superconductors to go into the real world. Supercond. Sci. Technol. 17: S185–S190.
[88] Malozemoff AP, Mannhart J, Scalapino D (April 2005) High-temperature cuprate superconductors get to work. Phys. Today 58: 41–47.
[89] Hassenzahl WV, Eckroad SEC, Grant PM, Gregory B, Nilsson S (2009) A high-power superconducting DC cable. IEEE Trans. Appl. Supercond. 19: 1756–1761.
[90] Shiohara Y, Fujiwara N, Hayashi H, Nagaya S, Izumi T, Yoshizumi M (2009) Japanese efforts on coated conductor processing and its power applications: New 5 year project for materials and power applications of coated conductors (M-PACC). Physica C 469: 863–867.
[91] Maguire JF, Yuan J (2009) Status of high temperature superconductor cable and fault current limiter projects at American Superconductor. Physica C 469: 874–880.
[92] Editorial (April 2011) Fantastic five. Phys. World 24: 23–25.
[93] Malozemoff AP (2011) Electric power grid application requirements for superconductors. Mater. Res. Soc. Bull. 36: 601–607.
[94] Mannhart J (1996) High-T_c transistors. Supercond. Sci. Technol. 9: 49–67.
[95] Koelle D, Kleiner R, Ludwig F, Dantsker E, Clarke J (1999) High-transition-temperature superconducting quantum interference devices. Rev. Mod. Phys. 71: 631–686.
[96] Winkler D (2003) Superconducting analogue electronics for research and industry. Supercond. Sci. Technol. 16: 1583–1590.
[97] Yang H-C, Chen J-C, Chen K-L, Wu C-H, Horng H-E, Yang SY (2008) High-T_c superconducting quantum interference devices: Status and perspectives. J. Appl. Phys. 104: 011101.
[98] Anders S, Blamire MG, Buchholz F-Im, Crete D-G, Cristiano R, Febvre P, Fritzsch L, Herr A, Il'ichev E, Kohlmann J, Kunert J, Meyer H-G, Niemeyer J, Ortlepp T, Rogalla H, Schurig T, Siegel M, Stolz R, Tarte E, ter Brake HJM, Toepfer H, Villegier J-C, Zagoskin

AM, Zorin AB (2010) European roadmap on superconductive electronics – status and perspectives. Physica C 470: 2079–2126.

[99] Deaver BS Jr, Fairbank WM (1961) Experimental evidence for quantized flux in superconducting cylinders. Phys. Rev. Lett. 7: 43–46.

[100] Doll R, Näbauer M (1961) Experimental proof of magnetic flux quantization in a superconducting ring. Phys. Rev. Lett. 7: 51–52.

[101] Foley CP, Hilgenkamp H (2009) Why NanoSQUIDs are important: an introduction to the focus issue. Supercond. Sci. Technol. 22: 064001.

[102] Borovik-Romanov AS, Bun'kov YuM, de Vaard A, Dmitriev VV, Makrotsieva V, Mukharskii YuM, Sergatskov DA (1988) Observation of a spin-current analog of the Josephson effect. Pis'ma Zh. Éksp. Teor. Fiz. 47: 400–403.

[103] Packard RE (1998) The role of the Josephson-Anderson equation in suprefluid helium. Rev. Mod. Phys. 70: 641–651.

[104] Varoquaux E (2001) Superfluid helium interferometry: an introduction. C. R. Acad. Sci. Paris 2: 531–544.

[105] Sukhatme K, Mukharsky Yu, Chui T, Pearson D (2001) Observation of the ideal Josephson effect in superfluid ^{4}He. Nature 411: 280–283.

[106] Sato Y, Packard RE (2012) Superfluid helium quantum interference devices: physics and applications. Rep. Prog. Phys. 75: 016401.

[107] Bednorz JG, Müller KA (1986) Possible high T_c superconductivity in the Ba-La-Cu-O system. Z. Phys. 64: 189–193.

[108] Hauck J, Mika K (1995) Classification of superconducting oxide structures. Supercond. Sci. Technol. 8: 374–381.

[109] Fisk Z, Sarrao JL (1997) The new generation high temperature superconductors. Annu. Rev. Mat. Sci. 27: 35–67.

[110] Hauck J, Mika K (1998) Structure families of superconducting oxides and intersitial alloys. Supercond. Sci. Technol. 11: 614–630.

[111] Cava RJ (2000) Oxide superconductors. J. Am. Ceram. Soc. 83: 5–28.

[112] Ott HR (2008) High-T_c superconductivity. In: Bennemann KH, Ketterson JB, editors. Superconductivity. Vol. 2: Novel Superconductors. Berlin: Springer Verlag. pp. 765–831.

[113] Mannhart J, Hilgenkamp H (1997) Wavefunction symmetry and its influence on superconducting devices. Supercond. Sci. Technol. 10: 880–883.

[114] Schulz RR, Chesca B, Goetz B, Schneider CW, Schmehl A, Bielefeldt H, Hilgenkamp H, Mannhart J, Tsuei CC (2000) Design and realization of an all d-wave dc π-superconducting quantum interference device. Appl. Phys. Lett. 76: 912–914.

[115] Schneider CW, Bielefeldt H, Goetz B, Hammerl G, Schmehl A, Schulz RR, Hilgenkamp H, Mannhart J (2001) Interfaces in high-T_c superconductors: fundamental insights and possible implications. Curr. Appl. Phys. 1: 349–353.

[116] Mannhart J, Chaudhari P (November 2001) High-T_c bicrystal grain boundaries. Phys. Today 54: 48–53.

[117] Hilgenkamp H, Mannhart J (2002) Grain boundaries in high-T_c superconductors. Rev. Mod. Phys. 74: 485–549.

[118] Tafuri F, Kirtley JR, Lombardi F, Medaglia PG, Orgiani P, Balestrino G (2004) Advances in high-T_c grain boundary junctions. Fiz. Nizk. Temp. 30: 785–794.

[119] Tafuri F, Kirtley JR (2005) Weak links in high critical temperature superconductors. Rep. Prog. Phys. 68: 2573–2663.
[120] Hilgenkamp H (2008) Pi-phase shift Josephson structures. Supercond. Sci. Technol. 21: 034011.
[121] Loder F, Kampf AP, Kopp T, Mannhart J (2009) Flux periodicities in loops of nodal superconductors. New J. Phys. 11: 075005.
[122] Kirtley JR (2010) Fundamental studies of superconductors using scanning magnetic imaging. Rep. Prog. Phys. 73: 126501.
[123] Gabovich AM, Voitenko AI (2000) Superconductors with charge- and spin-density waves: theory and experiment (Review). Fiz. Nizk. Temp. 26: 419–452.
[124] Gabovich AM, Voitenko AI, Annett JF, Ausloos M (2001) Charge- and spin-density-wave superconductors. Supercond. Sci. Technol. 14: R1–R27.
[125] Gabovich AM, Voitenko AI, Ausloos M (2002) Charge-density waves and spin-density waves in existing superconductors: competition between Cooper pairing and Peierls or excitonic instabilities. Phys. Rep. 367: 583–709.
[126] Gabovich AM, Voitenko AI, Ekino T, Li MS, Szymczak H, Pękała M (2010) Competition of superconductivity and charge density waves in cuprates: Recent evidence and interpretation. Adv. Condens. Matter Phys. 2010: 681070.
[127] Ekino T, Gabovich AM, Li MS, Pękała M, Szymczak H, Voitenko AI (2011) d-wave superconductivity and s-wave charge density waves: Coexistence between order parameters of different origin and symmetry. Symmetry 3: 699–749.
[128] Ekino T, Gabovich AM, Li MS, Pękała M, Szymczak H, Voitenko AI (2011) The phase diagram for coexisting d-wave superconductivity and charge-density waves: cuprates and beyond. J. Phys.: Condens. Matter 23: 385701.
[129] Gabovich AM, Moiseev DP, Shpigel AS, Voitenko AI (1990) Josephson tunneling critical current between superconductors with charge- or spin-density waves. Phys. Status Solidi B 161: 293–302.
[130] Gabovich AM (1992) Josephson and quasiparticle tunneling in superconductors with charge density waves. Fiz. Nizk. Temp. 18: 693–704.
[131] Gabovich AM, Voitenko AI (1997) Non-stationary Josephson effect for superconductors with charge-density waves: $NbSe_3$. Europhys. Lett. 38: 371–376.
[132] Gabovich AM, Voitenko AI (1997) Nonstationary Josephson effect for superconductors with charge-density waves. Phys. Rev. B 55: 1081–1099.
[133] Gabovich AM, Voitenko AI (1997) Josephson tunnelling involving superconductors with charge-density waves. J. Phys.: Condens. Matter 9: 3901–3920.
[134] Gabovich AM, Voitenko AI (2012) dc Josephson current for d-wave superconductors with charge density waves. Fiz. Nizk. Temp. 38: 414–422.
[135] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y, Akimitsu J (2001) Superconductivity at 39 K in magnesium diboride. Nature 410: 63–64.
[136] Daghero D, Gonnelli RS (2010) Probing multiband superconductivity by point-contact spectroscopy. Supercond. Sci. Technol. 23: 043001.
[137] Putti M, Grasso G (2011) MgB_2, a two-gap superconductor for practical applications. Mater. Res. Soc. Bull. 36: 608–613.
[138] Tanaka Y (1994) Josephson effect between s wave and $d_{x^2-y^2}$ wave superconductors. Phys. Rev. Lett. 72: 3871–3874.

[139] Barash YuS, Galaktionov AV, Zaikin AD (1995) Comment on “Superconducting pairing symmetry and Josephson tunneling”. Phys. Rev. Lett. 75: 1676.
[140] Barash YuS, Galaktionov AV, Zaikin AD (1995) Charge transport in junctions between d-wave superconductors. Phys. Rev. B 52: 665–682.
[141] Xu JH, Shen JL, Miller JH Jr, Ting CS (1995) Xu et al. Reply. Phys. Rev. Lett. 75: 1677.
[142] Mineev VP, Samokhin KV (1999) Intoduction to Unconventional Superconductivity. Amsterdam: Gordon and Breach Science Publishers.
[143] Kashiwaya S, Tanaka Y (2000) Tunnelling effects on surface bound states in unconventional superconductors. Rep. Prog. Phys. 63: 1641–1724.
[144] Scalapino DJ (1995) The case for $d_{x^2-y^2}$ pairing in the cuprate superconductors. Phys. Rep. 250: 329–365.
[145] van Harlingen DJ (1995) Phase-sensitive tests of the symmetry of the pairing state in the high-temperature superconductors – evidence for $d_{x^2-y^2}$ symmetry. Rev. Mod. Phys. 67: 515–535.
[146] Leggett AJ (1996) Josephson experiments on the high-temperature superconductors. Phil. Mag. B 74: 509–522.
[147] Annett JF, Goldenfeld ND, Leggett AJ (1996) Experimental constraints on the pairing state of the cuprate superconductors: an emerging consensus. In: Ginsberg DM, editor. Physical Properties of High Temperature Superconductors V. River Ridge, NJ: World Scientific. pp. 375–461.
[148] Tsuei CC, Kirtley JR (2000) Pairing symmetry in cuprate superconductors. Rev. Mod. Phys. 72: 969–1016.
[149] Darminto AD, Smilde H-JH, Leca V, Blank DHA, Rogalla H, Hilgenkamp H (2005) Phase-sensitive order parameter symmetry test experiments utilizing $Nd_{2-x}Ce_xCuO_{4-y}$/Nb zigzag junctions. Phys. Rev. Lett. 94: 167001.
[150] Kirtley JR, Tafuri F (2007) Tunneling measurements of the cuprate superconductors. In: Schrieffer JR, Brooks JS, editors. Handbook of High-Temperature Superconductivity. Theory and Experiment. New York: Springer Verlag. pp. 19–86.
[151] Tsuei CC, Kirtley JR (2008) Phase-sensitive tests of pairing symmetry in cuprate superconductors. In: Bennemann KH, Ketterson JB, editors. Superconductivity. Vol. 2: Novel Superconductors. Berlin: Springer Verlag. pp. 869–921.
[152] Kirtley JR (2011) Probing the order parameter symmetry in the cuprate high temperature superconductors by SQUID microscopy. C. R. Physique 12: 436–445.
[153] Sun AG, Gajewski DA, Maple MB, Dynes RC (1994) Observation of Josephson pair tunneling between a high-T_c cuprate ($YBa_2Cu_3O_{7-\delta}$) and a conventional superconductor (Pb). Phys. Rev. Lett. 72: 2267–2270.
[154] Kouznetsov KA, Sun AG, Chen B, Katz AS, Bahcall SR, Clarke J, Dynes RC, Gajewski DA, Han SH, Maple MB, Giapintzakis J, Kim JT, Ginsberg DM (1997) c-axis Josephson tunneling between $YBa_2Cu_3O_{7-\delta}$ and Pb: Direct evidence for mixed order parameter symmetry in a high-T_c superconductor. Phys. Rev. Lett. 79: 3050–3053.
[155] Mößle M, Kleiner R (1999) c-axis Josephson tunneling between $Bi_2Sr_2CaCu_2O_{8+x}$ and Pb. Phys. Rev. B 59: 4486–4496.
[156] Ponomarev YaG, Khi CS, Uk KK, Sudakova MV, Tchesnokov SN, Lorenz MA, Hein MA, Müller G, Piel H, Aminov BA, Krapf A, Kraak W (1999) Quasiparticle tunneling in

the *c*-direction in stacks of $Bi_2Sr_2CaCu_2O_{8+\delta}$ S–I–S junctions and the symmetry of the superconducting order parameter. Physica C 315: 85–90.
[157] Li Q, Tsay YN, Suenaga M, Klemm RA, Gu GD, Koshizuka N (1999) $Bi_2Sr_2CaCu_2O_{8+\delta}$ bicrystal *c*-axis twist josephson junctions: a new phase-sensitive test of order parameter symmetry. Phys. Rev. Lett. 83: 4160–4163.
[158] Komissinski PV, Il'ichev E, Ovsyannikov GA, Kovtonyuk SA, Grajcar M, Hlubina R, Ivanov Z, Tanaka Y, Yoshida N, Kashiwaya S (2002) Observation of the second harmonic in superconducting current-phase relation of Nb/Au/(001)$YBa_2Cu_3O_x$ heterojunctions. Europhys. Lett. 57: 585–591.
[159] Ovsyannikov GA, Komissinski PV, Il'ichev E, Kislinski YV, Ivanov ZG (2003) Josephson effect in Nb/Au/YBCO heterojunctions. IEEE Trans. Appl. Supercond. 13: 881–884.
[160] Smilde HJH, Golubov AA, Ariando, Rijnders G, Dekkers JM, Harkema S, Blank DHA, Rogalla H, Hilgenkamp H (2005) Admixtures to *d*-wave gap symmetry in untwinned $YBa_2Cu_3O_7$ superconducting films measured by angle-resolved electron tunneling. Phys. Rev. Lett. 95: 257001.
[161] Bussmann-Holder A (2012) Evidence for s+d wave pairing in copper oxide superconductors from an analysis of NMR and NQR data. J. Supercond. 25: 155–157.
[162] Klemm RA, Rieck CT, Scharnberg K (2000) Order-parameter symmetries in high-temperature superconductors. Phys. Rev. B 61: 5913–5916.
[163] Zhao G-m (2001) Experimental constraints on the physics of cuprates. Phil. Mag. B 81: 1335–1388.
[164] Brandow BH (2002) Arguments and evidence for a node-containing anisotropic *s*-wave gap form in the cuprate superconductors. Phys. Rev. B 65: 054503.
[165] Arnold GB, Klemm RA, Körner W, Scharnberg K (2003) Comment on "*c*-axis Josephson tunneling in $d_{x^2--y^2}$-wave superconductors". Phys. Rev. B 68: 226501.
[166] Brandow BH (2003) Strongly anisotropic *s*-wave gaps in exotic superconductors. Phil. Mag. 83: 2487–2519.
[167] Harshman DR, Kossler WJ, Wan X, Fiory AT, Greer AJ, Noakes DR, Stronach CE, Koster E, Dow JD (2004) Nodeless pairing state in single-crystal $YBa_2Cu_3O_7$. Phys. Rev. B 69: 174505.
[168] Klemm RA (2005) Bi2212 *c*-axis twist bicrystal and artificial and natural cross-whisker Josephson junctions: strong evidence for s-wave superconductivity and incoherent *c*-axis tunneling. J. Supercond. 18: 697–700.
[169] Zhao G-m (2007) Precise determination of the superconducting gap along the diagonal direction of $Bi_2Sr_2CaCu_2O_{8+y}$: Evidence for an extended s-wave gap symmetry. Phys. Rev. B 75: 140510.
[170] Zhao G-m (2009) Fine structure in the tunneling spectra of electron-doped cuprates: No coupling to the magnetic resonance mode. Phys. Rev. Lett. 103: 236403.
[171] Zhao G-m (2010) Nearly isotropic *s*-wave gap in the bulk of the optimally electron-doped superconductor $Nd_{1.85}Ce_{0.15}CuO_{4-y}$. Phys. Rev. B 82: 012506.
[172] Zhao G-M, Wang J (2010) Specific heat evidence for bulk *s*-wave gap symmetry of optimally electron-doped $Pr_{1.85}Ce_{0.15}CuO_{4-y}$ superconductors. J. Phys.: Condens. Matter 22: 352202.
[173] Zhao G-m (2011) The pairing mechanism of high-temperature superconductivity: experimental constraints. Phys. Scripta 83: 038302.

[174] Zhao G-m (2011) Reply to Comment on "The pairing mechanism of high-temperature superconductivity: experimental constraints". Phys. Scripta 83: 038304.

[175] Harshman DR, Fiory AT, Dow JD (2011) Concerning the superconducting gap symmetry in $YBa_2Cu_3O_{7-\delta}$, $YBa_2Cu_4O_8$, and $La_{2-x}Sr_xCuO_4$ determined from muon spin rotation in mixed states of crystals and powders. J. Phys.: Condens. Matter 23: 315702.

[176] Sadovskii MV (2001) Pseudogap in high-temperature superconductors. Usp. Fiz. Nauk 171: 539–564.

[177] Klemm RA (2004) Origin of the pseudogap in high temperature superconductors. In: Morawetz K, editor. Nonequilibrium Physics at Short Time Scales. Formation of Correlations. Berlin: Springer Verlag. pp. 381–400.

[178] Norman M, Pines D, Kallin C (2005) The pseudogap: friend or foe of high T_c? Adv. Phys. 54: 715–733.

[179] Deutscher G (2006) Superconducting gap and pseudogap. Fiz. Nizk. Temp. 32: 740–745.

[180] Li Y, Balédent V, Yu G, Barišić N, Hradil K, Mole RA, Sidis Y, Steffens P, Zhao X, Bourges P, Greven M (2010) Hidden magnetic excitation in the pseudogap phase of a high-T_c superconductor. Nature 468: 283–285.

[181] Lee PA, Rice TM, Anderson PW (1973) Fluctuation effects at a Peierls transition. Phys. Rev. Lett. 31: 462–465.

[182] Lebed AG, editor (2008) The Physics of Organic Superconductors and Conductors. Berlin: Springer Verlag.

[183] Eremin MV, Larionov IA, Varlamov S (1999) CDW scenario for pseudogap in normal state of bilayer cuprates. Physica B 259-261: 456–457.

[184] Gupta AK, Ng K-W (2002) Non-conservation of density of states in $Bi_2Sr_2CaCu_2O_y$: Coexistence of pseudogap and superconducting gap. Europhys. Lett. 58: 878–884.

[185] Pereg-Barnea T, Franz M (2005) Quasiparticle interference patterns as a test for the nature of the pseudogap phase in the cuprate superconductors. Int. J. Mod. Phys. B 19: 731–761.

[186] Li J-X, Wu C-Q, Lee D-H (2006) Checkerboard charge density wave and pseudogap of high-T_c cuprate. Phys. Rev. B 74: 184515.

[187] Borisenko SV, Kordyuk AA, Yaresko A, Zabolotnyy VB, Inosov DS, Schuster R, Büchner B, Weber R, Follath R, Patthey L, Berger H (2008) Pseudogap and charge density waves in two dimensions. Phys. Rev. Lett. 100: 196402.

[188] Kordyuk AA, Borisenko SV, Zabolotnyy VB, Schuster R, Inosov DS, Evtushinsky DV, Plyushchay AI, Follath R, Varykhalov A, Patthey L, Berger H (2009) Nonmonotonic pseudogap in high-T_c cuprates. Phys. Rev. B 79: 020504.

[189] Kondo T, Khasanov R, Takeuchi T, Schmalian J, Kaminski A (2009) Competition between the pseudogap and superconductivity in the high-T_c copper oxides. Nature 457: 296–300.

[190] Yuli O, Asulin I, Kalcheim Y, Koren G, Millo O (2009) Proximity-induced pseudogap: Evidence for preformed pairs. Phys. Rev. Lett. 103: 197003.

[191] Norman MR (2010) Fermi-surface reconstruction and the origin of high-temperature superconductivity. Physics 3: ID 86.

[192] Alexandrov AS, Beanland J (2010) Superconducting gap, normal state pseudogap, and tunneling spectra of bosonic and cuprate superconductors. Phys. Rev. Lett. 104: 026401.

[193] Dubroka A, Yu L, Munzar D, Kim KW, Rössle M, Malik VK, Lin CT, Keimer B, Wolf Th, Bernhard C (2010) Pseudogap and precursor superconductivity in underdoped cuprate high temperature superconductors: A far-infrared ellipsometry study. Eur. Phys. J. Spec. Topics 188: 73–88.
[194] Okada Y, Kuzuya Y, Kawaguchi T, Ikuta H (2010) Enhancement of superconducting fluctuation under the coexistence of a competing pseudogap state in $Bi_2Sr_{2-x}R_xCuO_y$. Phys. Rev. B 81: 214520.
[195] Kristoffel N, Rubin P (2011) Interband nodal-region pairing and the antinodal pseudogap in hole doped cuprates. In: Bonča J, Kruchinin S, editors. Physical Properties of Nanosystems. Dordrecht: Springer Verlag. pp. 141–152.
[196] Okada Y, Kawaguchi T, Ohkawa M, Ishizaka K, Takeuchi T, Shin S, Ikuta H (2011) Three energy scales characterizing the competing pseudogap state, the incoherent, and the coherent superconducting state in high-T_c cuprates. Phys. Rev. B 83: 104502.
[197] Greco A, Bejas M (2011) Short-ranged and short-lived charge-density-wave order and pseudogap features in underdoped cuprate superconductors. Phys. Rev. B 83: 212503.
[198] Nistor RA, Martyna GJ, Newns DM, Tsuei CC, Müser MH (2011) *Ab initio* theory of the pseudogap in cuprate superconductors driven by $C4$ symmetry breaking. Phys. Rev. B 83: 144503.
[199] Rice TM, Yang K-Y, Zhang FC (2012) A phenomenological theory of the anomalous pseudogap phase in underdoped cuprates. Rep. Prog. Phys. 75: 016502.
[200] Yoshida T, Hashimoto M, Vishik IM, Shen Z-X, Fujimori A (2012) Pseudogap, superconducting gap, and Fermi arc in high-T_c cuprates revealed by angle-resolved photoemission spectroscopy. J. Phys. Soc. Jpn. 81: 011006.
[201] Fujita K, Schmidt AR, Kim E-A, Lawler MJ, Lee DH, Davis JC, Eisaki H, Uchida S-i (2012) Spectroscopic imaging scanning tunneling microscopy studies of electronic structure in the superconducting and pseudogap phases of cuprate high-T_c superconductors. J. Phys. Soc. Jpn. 81: 011005.
[202] Rourke PMC, Mouzopoulou I, Xu X, Panagopoulos C, Wang Y, Vignolle B, Proust C, Kurganova EV, Zeitler U, Tanabe Y, Adachi T, Koike Y, Hussey NE (2011) Phase-fluctuating superconductivity in overdoped $La_{2-x}Sr_xCuO_4$. Nature Phys. 7: 455–458.
[203] Nakayama K, Sato T, Xu Y-M, Pan Z-H, Richard P, Ding H, Wen H-H, Kudo K, Sasaki T, Kobayashi N, Takahashi T (2011) Two pseudogaps with different energy scales at the antinode of the high-temperature $Bi_2Sr_2CuO_6$ superconductor using angle-resolved photoemission spectroscopy. Phys. Rev. B 83: 224509.
[204] Schmidt AR, Fujita K, Kim E-A, Lawler MJ, Eisaki H, Uchida S, Lee D-H, Davis JC (2011) Electronic structure of the cuprate superconducting and pseudogap phases from spectroscopic imaging STM. New J. Phys. 13: 065014.
[205] Zabolotnyy VB, Kordyuk AA, Evtushinsky D, Strocov VN, Patthey L, Schmitt T, Haug D, Lin CT, Hinkov V, Keimer B, Büchner B, Borisenko SV (2012) Pseudogap in the chain states of $YBa_2Cu_3O_{6.6}$. Phys. Rev. B 85: 064507.
[206] Orenstein J, Millis AJ (2000) Advances in the physics of high-temperature superconductivity. Science 288: 468–474.
[207] Johnston DC (2010) The puzzle of high temperature superconductivity in layered iron pnictides and chalcogenides. Adv. Phys. 59: 803–1061.

[208] Bourges P, Sidis Y (2011) Novel magnetic order in the pseudogap state of high-T_c copper oxides superconductors. C. R. Physique 12: 461–479.

[209] Li Y, Balédent V, Barišić N, Cho YC, Sidis Y, Yu G, Zhao X, Bourges P, Greven M (2011) Magnetic order in the pseudogap phase of $HgBa_2CuO_{4+\delta}$ studied by spin-polarized neutron diffraction. Phys. Rev. B 84: 224508.

[210] Gabovich AM, Voitenko AI (2009) Model for the coexistence of d-wave superconducting and charge-density-wave order parameters in high-temperature cuprate superconductors. Phys. Rev. B 80: 224501.

[211] Voitenko AI, Gabovich AM (2010) Charge density waves in d-wave superconductors. Fiz. Nizk. Temp. 36: 1300–1311.

[212] Einzel D, Schürrer I (1999) Weak coupling theory of clean $(d+s)$-wave superconductors. J. Low Temp. Phys. 117: 15–52.

[213] Ghosh A, Adhikari SK (2001) Mixing of superconducting $d_{x^2-y^2}$ state with s-wave states for different filling and temperature. Physica C 355: 77–86.

[214] Yeh N-C, Chen C-T, Hammerl G, Mannhart J, Schmehl A, Schneider CW, Schulz RR, Tajima S, Yoshida K, Garrigus D, Strasik M (2001) Evidence of doping-dependent pairing symmetry in cuprate superconductors. Phys. Rev. Lett. 87: 087003.

[215] Gorbonosov AE, Kulik IO (1967) Temperature dependence of the Josephson current in anisotropic superconductors. Fiz. Met. Metalloved. 23: 803–812.

[216] Ledvij M, Klemm RA (1995) Dependence of the Josephson coupling of unconventional superconductors on the properties of the tunneling barrier. Phys. Rev. B 51: 3269–3272.

[217] Kouznetsov K, Coffey L (1996) Theory of tunneling and photoemission spectroscopy for high-temperature superconductors. Phys. Rev. B 54: 3617–3621.

[218] Nie Y-m, Coffey L (1998) Elastic and spin-fluctuation-mediated inelastic Josephson tunneling between anisotropic superconductors. Phys. Rev. B 57: 3116–3122.

[219] Nie Y-m, Coffey L (1999) Elastic and inelastic quasiparticle tunneling between anisotropic superconductors. Phys. Rev. B 59: 11982–11989.

[220] Shukrinov YuM, Namiranian A, Najafi A (2001) Modeling of tunneling spectroscopy in high-T_c superconductors. Fiz. Nizk. Temp. 27: 15–23.

[221] Hanaguri T, Lupien C, Kohsaka Y, Lee D-H, Azuma M, Takano M, Takagi H, Davis JC (2004) A "checkerboard" electronic crystal state in lightly hole-doped $Ca_{2-x}Na_xCuO_2Cl_2$. Nature 430: 1001–1005.

[222] McElroy K, Lee D-H, Hoffman JE, Lang KM, Lee J, Hudson EW, Eisaki H, Uchida S, Davis JC (2005) Coincidence of checkerboard charge order and antinodal state decoherence in strongly underdoped superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$. Phys. Rev. Lett. 94: 197005.

[223] Ma J-H, Pan Z-H, Niestemski FC, Neupane M, Xu Y-M, Richard P, Nakayama K, Sato T, Takahashi T, Luo H-Q, Fang L, Wen H-H, Wang Z, Ding H, Madhavan V (2008) Coexistence of competing orders with two energy gaps in real and momentum space in the high temperature superconductor $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$. Phys. Rev. Lett. 101: 207002.

[224] Shen KM, Ronning F, Lu DH, Baumberger F, Ingle NJC, Lee WS, Meevasana W, Kohsaka Y, Azuma M, Takano M, Takagi H, Shen Z-X (2005) Nodal quasiparticles and antinodal charge ordering in $Ca_{2-x}Na_xCuO_2Cl_2$. Science 307: 901–904.

[225] Bianconi A, Lusignoli M, Saini NL, Bordet P, Kvick A, Radaelli PG (1996) Stripe structure of the CuO_2 plane in $Bi_2Sr_2CaCu_2O_{8+y}$ by anomalous x-ray diffraction. Phys. Rev. B 54: 4310–4314.

[226] Fujita M, Goka H, Yamada K, Tranquada JM, Regnault LP (2004) Stripe order, depinning, and fluctuations in $La_{1.875}Ba_{0.125}CuO_4$ and $La_{1.875}Ba_{0.075}Sr_{0.050}CuO_4$. Phys. Rev. B 70: 104517.

[227] Kohsaka Y, Taylor C, Fujita K, Schmidt A, Lupien C, Hanaguri T, Azuma M, Takano M, Eisaki H, Takagi H, Uchida S, Davis JC (2007) An intrinsic bond-centered electronic glass with unidirectional domains in underdoped cuprates. Science 315: 1380–1385.

[228] Sharoni A, Leibovitch G, Kohen A, Beck R, Deutscher G, Koren G, Millo O (2003) Scanning tunneling spectroscopy of alpha-axis $YBa_2Cu_3O_{7-\delta}$ films: k-selectivity and the shape of the superconductor gap. Europhys. Lett. 62: 883–889.

[229] Bruder C, van Otterlo A, Zimanyi GT (1995) Tunnel junctions of unconventional superconductors. Phys. Rev. B 51: 12904–12907.

[230] Barash YuS, Burkhardt H, Rainer D (1996) Low-temperature anomaly in the Josephson critical current of junctions in d-wave superconductors. Phys. Rev. Lett. 77: 4070–4073.

[231] Bilbro G, McMillan WL (1976) Theoretical model of superconductivity and the martensitic transformation in A15 compounds. Phys. Rev. B 14: 1887–1892.

[232] Gabovich AM, Gerber AS, Shpigel AS (1987) Thermodynamics of superconductors with charge- and spin-density waves. Δ/T_c ratio and paramagnetic limit. Phys. Status Solidi B 141: 575–587.

[233] Gabovich AM, Li MS, Szymczak H, Voitenko AI (2003) Thermodynamics of superconductors with charge-density waves. J. Phys.: Condens. Matter 15: 2745–2753.

[234] Ekino T, Gabovich AM, Li MS, Pękała M, Szymczak H, Voitenko AI (2008) Temperature-dependent pseudogap-like features in tunnel spectra of high-T_c cuprates as a manifestation of charge-density waves. J. Phys.: Condens. Matter 20: 425218.

[235] Voitenko AI, Gabovich AM (2010) Charge-density waves in partially dielectrized superconductors with d-pairing. Fiz. Tverd. Tela 52: 20–27.

[236] Barash YuS, Svidzinskii AA (1997) Current–voltage characteristics of tunnel junctions between superconductors with anisotropic pairing. Zh. Éksp. Teor. Fiz. 111: 1120–1146.

[237] Mineev VP, Samokhin KV (1998) Intoduction into the Theory of Non-conventional Superconductors. Moscow: MFTI Publishing House. in Russian.

[238] Markiewicz RS (1997) A survey of the Van Hove scenario for high-T_c superconductivity with special emphasis on pseudogaps and striped phases. J. Phys. Chem. Sol. 58: 1179–1310.

[239] Khodel VA, Yakovenko VM, Zverev MV, Kang H (2004) Hot spots and transition from d-wave to another pairing symmetry in the electron-doped cuprate superconductors. Phys. Rev. B 69: 144501.

[240] Kordyuk AA, Zabolotnyy VB, Evtushinsky DV, Inosov DS, Kim TK, Büchner B, Borisenko SV (2010) An ARPES view on the high-T_c problem: Phonons vs. spin-fluctuations. Eur. Phys. J. Special Topics 188: 153–162.

[241] Annett JF (1995) Unconventional superconductivity. Contemp. Phys. 36: 423–437.

[242] Ambegaokar V, Baratoff A (1963) Tunneling between superconductors. Phys. Rev. Lett. 10: 486–489.

[243] Sommerfeld A, Bethe H (1933) Elektronentheorie der Metalle. Berlin: Springer Verlag.

[244] Harrison WA (1961) Tunneling from an independent particle point of view. Phys. Rev. 123: 85–89.

[245] Bardeen J (1961) Tunneling from a many-particle point of view. Phys. Rev. Lett. 6: 57–59.

[246] Xu JH, Shen JL, Miller JH Jr, Ting CS (1994) Superconducting pairing symmetry and Josephson tunneling. Phys. Rev. Lett. 73: 2492–2495.

[247] Kawayama I, Kanai M, Kawai T, Maruyama M, Fujimaki A, Hayakawa H (1999) Properties of c-axis Josephson tunneling between $Bi_2Sr_2CaCu_2O_8$ and Nb. Physica C 325: 49–55.

[248] Takeuchi I, Gim Y, Wellstood FC, Lobb CJ, Trajanovic Z, Venkatesan T (1999) Systematic study of anisotropic Josephson coupling between $YBa_2Cu_3O_{7-x}$ and PbIn using in-plane aligned a-axis films. Phys. Rev. B 59: 7205–7208.

[249] Anderson PW (1964) Special effects in superconductivity. In: Caianiello ER, editor. Lectures on the Many-Body Problem, Vol. 2. New York: Academic Press. pp. 113–135.

[250] Ekino T, Sezaki Y, Fujii H (1999) Features of the energy gap above T_c in $Bi_2Sr_2CaCu_2O_{8+\delta}$ as seen by break-junction tunneling. Phys. Rev. B 60: 6916–6922.

[251] Lee WS, Vishik IM, Tanaka K, Lu DH, Sasagawa T, Nagaosa N, Devereaux TP, Hussain Z, Shen Z-X (2007) Abrupt onset of a second energy gap at the superconducting transition of underdoped Bi2212. Nature 450: 81–84.

[252] Kurosawa T, Yoneyama T, Takano Y, Hagiwara M, Inoue R, Hagiwara N, Kurusu K, Takeyama K, Momono N, Oda M, Ido M (2010) Large pseudogap and nodal superconducting gap in $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$: Scanning tunneling microscopy and spectroscopy. Phys. Rev. B 81: 094519.

[253] Gürlich C, Goldobin E, Straub R, Doenitz D, Ariando, Smilde H-JH, Hilgenkamp H, Kleiner R, Koelle D (2009) Imaging of order parameter induced π phase shifts in cuprate superconductors by low-temperature scanning electron microscopy. Phys. Rev. Lett. 103: 067011.

[254] Yip S (1995) Josephson current-phase relationships with unconventional superconductors. Phys. Rev. B 52: 3087–3090.

[255] Gabovich AM, Moiseev DP (1986) Metalloxide superconductor $BaPb_{1-x}Bi_xO_3$: unusual properties and new applications. Usp. Fiz. Nauk 150: 599–623.

[256] Šmakov J, Martin I, Balatsky AV (2001) Josephson scanning tunneling microscopy. Phys. Rev. B 64: 212506.

[257] Löfwander T, Shumeiko VS, Wendin G (2001) Andreev bound states in high-T_c superconducting junctions. Supercond. Sci. Technol. 14: R53–R77.

[258] Kimura H, Barber RP Jr, Ono S, Ando Y, Dynes RC (2009) Josephson scanning tunneling microscopy: A local and direct probe of the superconducting order parameter. Phys. Rev. B 80: 144506.

[259] Gabovich AM (1993) Josephson and quasiparticle current in partially-dielectrized superconductors with spin density waves. Fiz. Nizk. Temp. 19: 641–654.

[260] Voitenko AI, Gabovich AM (1997) Josephson and one-particle currents between partially-dielectrized superconductors with charge-density waves. Fiz. Tverd. Tela 39: 991–999.

[261] Gabovich AM, Voitenko AI (1999) Nonstationary Josephson effect for superconductors with spin-density waves. Phys. Rev. B 60: 14897–14906.

[262] Gabovich AM, Voitenko AI (2000) Nonstationary Josephson tunneling involving superconductors with spin-density waves. Physica C 329: 198–230.

[263] Koren G, Levy N (2002) Experimental evidence for a small *s*-wave component in the order parameter of underdoped $YBa_2Cu_3O_{6+x}$. Europhys. Lett. 59: 121–127.

[264] Babcock SE, Vargas JL (1995) The nature of grain boundaries in the high-T_c superconductors. Annu. Rev. Mater. Sci. 25: 193–222.

[265] Hilgenkamp H, Mannhart J, Mayer B (1996) Implications of $d_{x^2-y^2}$ symmetry and faceting for the transport properties of grain boundaries in high-T_c superconductors. Phys. Rev. B 53: 14586–14593.

[266] Neils WK, Van Harlingen DJ, Oh S, Eckstein JN, Hammerl G, Mannhart J, Schmehl A, Schneider CW, Schulz RR (2002) Probing unconventional superconducting symmetries using Josephson interferometry. Physica C 368: 261–266.

[267] Aligia AA, Kampf AP, Mannhart J (2005) Quartet formation at (100)/(110) interfaces of *d*-wave superconductors. Phys. Rev. Lett. 94: 247004.

[268] Graser S, Hirschfeld PJ, Kopp T, Gutser R, Andersen BM, Mannhart J (2010) How grain boundaries limit supercurrents in high-temperature superconductors. Nature Phys. 6: 609–614.

[269] Aswathy PM, Anooja JB, Sarun PM, Syamaprasad U (2010) An overview on iron based superconductors. Supercond. Sci. Technol. 23: 073001.

[270] Seidel P (2011) Josephson effects in iron based superconductors. Supercond. Sci. Technol. 24: 043001.

[271] Johrendt D (2011) Structure-property relationships of iron arsenide superconductors. J. Mater. Chem. 21: 13726–13736.

[272] Wen J, Xu G, Gu G, Tranquada JM, Birgeneau RJ (2011) Interplay between magnetism and superconductivity in iron-chalcogenide superconductors: crystal growth and characterizations. Rep. Prog. Phys. 74: 124503.

[273] Hirschfeld PJ, Korshunov MM, Mazin II (2011) Gap symmetry and structure of Fe-based superconductors. Rep. Prog. Phys. 74: 124508.

[274] Richard P, Sato T, Nakayama K, Takahashi T, Ding H (2011) Fe-based superconductors: an angle-resolved photoemission spectroscopy perspective. Rep. Prog. Phys. 74: 124512.

[275] Hoffman JE (2011) Spectroscopic scanning tunneling microscopy insights into Fe-based superconductors. Rep. Prog. Phys. 74: 124513.