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SUPERCONDUCTIVITY and CRYOELECTRONICS

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PREFACE

This volume contains results from the 22nd Symposium on Superconductivity and Cryoelectronics held in Georgenthal/Thüringen, Germany, on November 12–16, 1990.

The tradition of the symposium reaches back more than twenty years to the time when at the Friedrich Schiller University in Jena, a department of low temperature physics and cryoelectronics was established.

Fortunately, after the political changes in Europe, this meeting opened new opportunities of bringing together specialists from eastern and western countries. The symposium was an event of interest in topics of high temperature superconductivity, Josephson junctions and arrays, SQUIDs and applications and single-electron tunneling. More than fifty scientists from six countries participated in the symposium and about thirty talks were presented. Moreover, the friendly atmosphere stimulated fruitful discussions enhancing the productivity of future research.

Many thanks are due to the Deutsche Physikalische Gesellschaft, the Dr. Wilhelm Heinrich Heraeus and Else Heraeus Stiftung and the Bundesministerium für Forschung und Technologie for supporting the symposium.

W. Krech, P. Seidel and H.-G. Meyer

CONTENTS

Point-Contact and Tunneling Spectroscopy of High-T_C-Superconductors

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Abstract

We discuss literature data of tunneling and point-contact spectra of High-Temperature Superconductors (HTSC). They show several deviations from the well known I-V characteristics of traditional BCS-like superconductors. Four main deviations, namely the background in dI/dV vs. V characteristics, the broadening of gap features, structure in tunneling and point-contact spectra, and the energy gap will be examined. A quasiperiodic peak structure appearing frequently in the point-contact spectra of granular HTSCs will be discussed in the framework of three models.

1 Introduction

Tunneling and point-contact spectroscopy are important tools to obtain information about the energy gap and the pairing mechanism of superconductors. Unfortunately tunneling and point-contact data of the High-Temperature Superconductors (HTSC) show many more nonlinearities than the ones taken on the "conventional" superconductors. They are contact dependent and therefore much more difficult to interpret satisfactorily.

In section 2. we give an overview over literature data and try to formulate some important questions pertaining to point-contact and tunneling experiments with the HTSCs. In section 3. we present some of our own point-contact data taken on granular HTSC materials. We then discuss some special features seen in these data in the framework of three models.

2 Discussion of Literature Data

In Fig. 1. we recall for the readers convenience the well known I-V, dI/dV vs. V and dV/dI vs. V characteristics which are expected for BCS-like superconductors in the case of normal-conductor — insulator — superconductor tunneling (N-I-S) and normal-conductor — constriction — superconductor

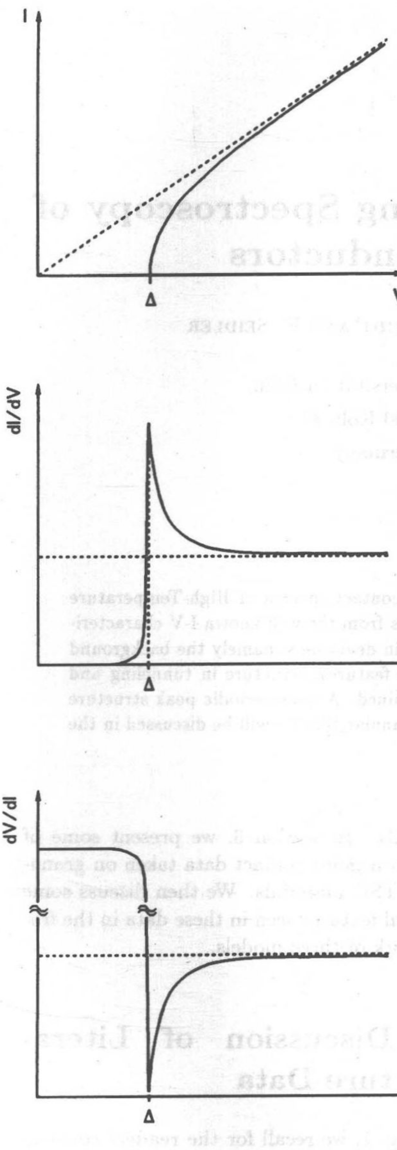

Fig. 1.a.: Tunneling characteristics for a N-I-S junction with a BCS-like superconductor.

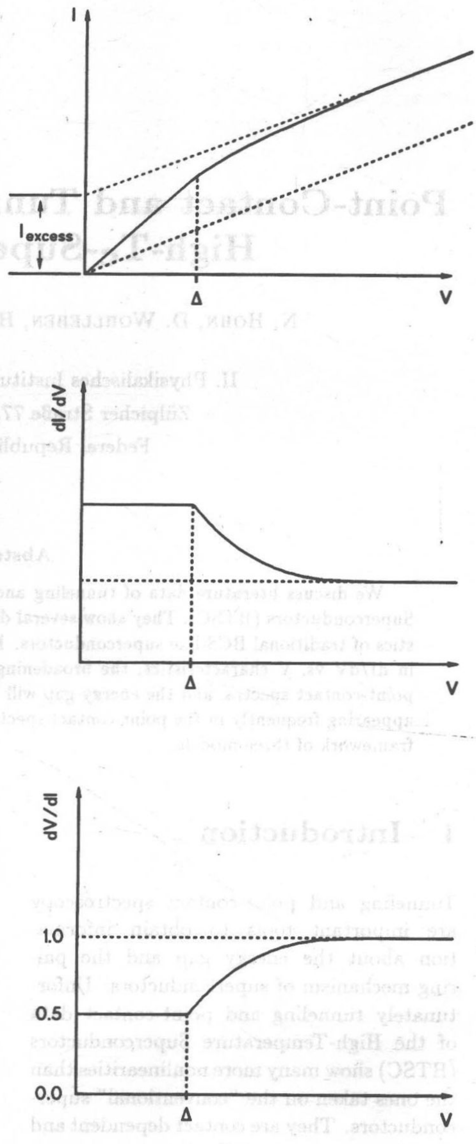

Fig. 1.b.: Point-contact characteristics for a N-c-S junction with a BCS-like superconductor.

metallic point-contact (N-c-S) junctions for a temperature far below the T_C of the superconductor. The main differences between tunneling and point-contact junctions are the size of the contact area and the barrier between the electrodes. The contact diameter is very small for point-contacts (usually some 100 to a few 1000 Å) and much larger for planar tunneling junctions. In the case of tunneling (N-I-S junctions) the barrier is quite high compared to the Fermi-energy of the involved electrodes, whereas the barrier can become very small compared to the Fermi energy in the metallic point-contact (N-c-S junctions).

In the I-V characteristic of N-I-S junctions one finds nearly zero current up to the gap-voltage, followed by a sharp increase of the current at $eV = \Delta$ (the gap voltage) and an approach to the normal state conductivity for high voltages (Ohm's law). This behavior can be seen more clearly in the first derivatives dI/dV vs. V, the differential conductivity, and dV/dI vs. V, the differential resistivity. There one finds a pronounced singularity at the gap-voltage. The differential conductivity is proportional to the density of states of the superconductor (for $T = 0$ and for very small transmission of the barrier). (Note the low differential conductivity in the tunneling case inside the gap and the constant conductivity at high bias in Fig. 1.a.)

Completly different are the characteristics found for the metallic point-contact case (N-c-S junctions). Here one finds an excess current in the superconducting state compared to the normal state, which is due to Andreev reflection. So one has an increased differential conductivity inside the gap, and a gradual approach to the normal state value for higher voltages ($eV > \Delta$).

A continous transition from a tunneling (high barrier, N-I-S junction) to a metallic (low barrier, N-c-S junction) behavior occurs in a technical point-contacts and can be observed in a measurement, when the contact pressure is increased continously. This transition can be described by the theory of G. E. Blonder, M. Tinkham, and T. M. Klapwijk [1]. The I-V characteristics of tunneling (N-I-S) and metallic (N-c-S) contacts can therefore be seen as two limiting cases of the BTK theory.

The literature data of HTSCs show several deviations from the above described standard behavior of BCS-like superconductors. In the following four deviations will be discussed:

- the background in dI/dV vs. V characteristics;
- the broadening of gap features;
- the structure found in tunneling and point-contact spectra and
- the energy gap itself.

2.1 The Background in dI/dV vs. V Characteristics

Instead of the constant conductivity at high bias in dI/dV vs. V characteristics for BCS-like superconductors, in the tunneling spectra of HTSCs a linear as well as a parabolic background is found frequently. An example for a linear background is shown in Fig. 2. for an $YBa_2Cu_3O_{7-x}$ – Au point-contact. A possible explanation of this behavior is given by the Zeller-Giaever model of tunneling across a planar insulating junction containing small isolated metallic particles (molecules or atoms) as "impurities" [3] (equivalent to Single-Electron-Tunneling, SET [4,5,6]).

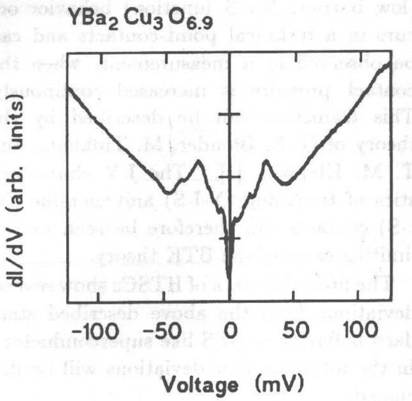

Fig. 2.: $YBa_2Cu_3O_{7-x}$ (polycrystalline) – Au point-contact. The linear background is clearly seen (from E. R. Moog et al. [2]).

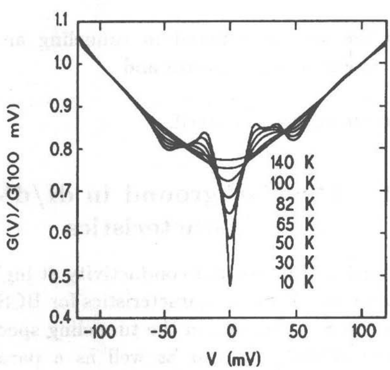

Fig. 3.: Planar tunneling contact of $YBa_3Cu_3O_{7-x}$ (single crystal) – Pb. The parabolic background is seen very clearly for the 140 K curve (from M. Gurvitch et al. [7]).

A parabolic background is for example seen in Fig. 3. for a planar tunneling contact of $YBa_3Cu_3O_{7-x}$ – Pb. This behavior can be explained by barrier effects according to standard tunneling theory. If the applied voltage is only slightly lower than the barrier height (which is the case for low barriers) a parabolic tunneling conductance results [8]. The shown contact in Fig. 3. is actually on the ab-plane of a single crystal, which contains etch pits. Therfore k_z is not a good quantum number here (the current tunnels parallel to the c-axis as well as parallel to the ab-plane in the etch pits) and the spectrum averages over the anisotropy of both tunneling processes.

2.2 Broadening of Gap Features

In the dI/dV vs. V tunneling characteristics of BCS-like superconductors a sharp singularity is found at the gap-voltage. For the HTSCs a broadening of the gap features is observed frequently. Inside of the assumed gap an increased conductivity is found and the ideally sharp structure around the gap-voltage (see Fig. 1.a.) is decreased in intensity and broadened. An example is shown in Fig 4. and 5. for a Ba-Pb-Bi-O single crystal – Al point-contact.

Therefore the question arises, whether this behavior is an intrinsic property of the HTSCs, i.e. whether the HTSCs have a well defined gap, or whether superconductivity causes merely a region of reduced density of states around the Fermi energy.

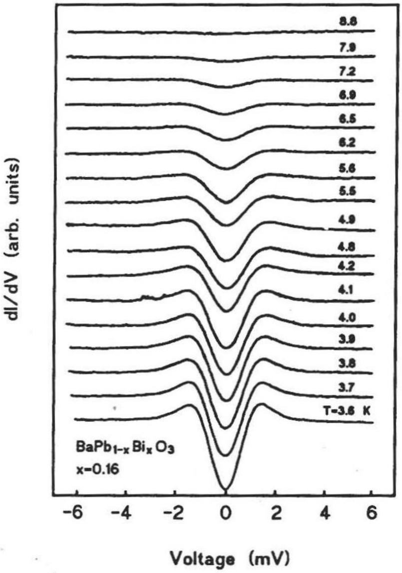

Fig. 4.: Ba-Pb-Bi-O (single crystal) – Al point-contact (from T. Ekino et al. [9]).

Several possible explanations for the broadening are discussed in literature:

- electronic states inside the gap (which would be an indication of gapless superconductivity);
- a short quasiparticle lifetime due to inelastic scattering processes (Dynes model) [10];
- effects according to strong coupling (smeared BCS [11], model by Zhao et al. [12]);
- broadening due to inhomogenities, i.e. more than one gap in the sample (Multigap model [11]). The inhomogenities may be caused by different phases with different T_C's in one sample;
- anisotropy of the gap of HTSCs, i.e. different gaps in different crystalline directions.

Due to the last two points an averaged gap value may be measured [8].

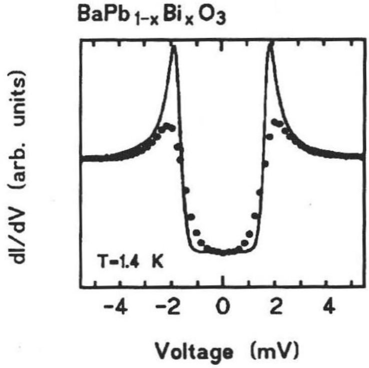

Fig. 5.: Ba-Pb-Bi-O (single crystal) – Al point-contact for 1.4 K. The solid dots are the measured data, the solid line indicates the calculated characteristic due to the BCS model (from T. Ekino et al. [9]).

Models which describe this broadening behavior of HTSCs are:

- the Dynes model [10] which accounts for the short quasiparticle lifetime due to inelastic scattering processes by introducing an effective density of states according to

$$\mathcal{D}(E) = \mathrm{Re}\left\{ \frac{|E - i\Gamma|}{\sqrt{(E - i\Gamma)^2 - \Delta^2}} \right\}$$

Fig. 6. shows a fit to the data of Fig. 4. within the Dynes model.

One should mention that the fit-parameters Γ are usually quite large compared to the gap value and to the temperature; Γ is sometimes even larger than the temperature (see Fig. 6 lowest curve), which seems unphysical.

- smeared BCS in the Multi-gap model [11] and the model of Zhao et al. [12]; here an imaginary part to the gap is introduced.
- gap distribution; Fig. 7. shows an example of a fit to measured data with a Gaussian gap distribution.

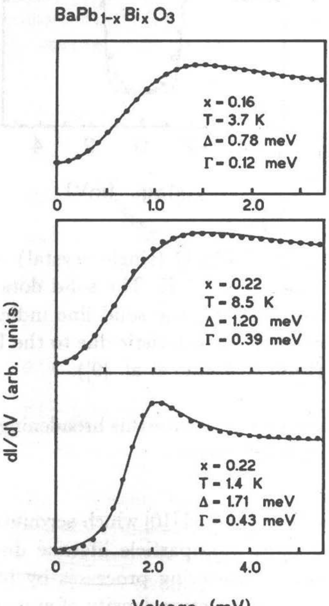

Fig. 6.: Comparison of the measured data (solid dots) from Fig. 4. with a fit due to the Dynes model (solid line); (from T. Ekino et al. [9]).

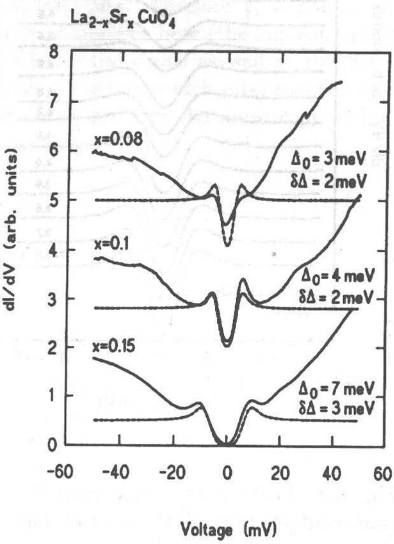

Fig. 7.: Gaussian distribution of the energy gaps for $La_{2-x}Sr_xCuO_4$ (polycrystalline); (from J. R. Kirtley [8]).

Fig. 8. gives an overview of the above mentioned models for the same measured data. The linear increase of dI/dV (background) is ***not*** included in these models.

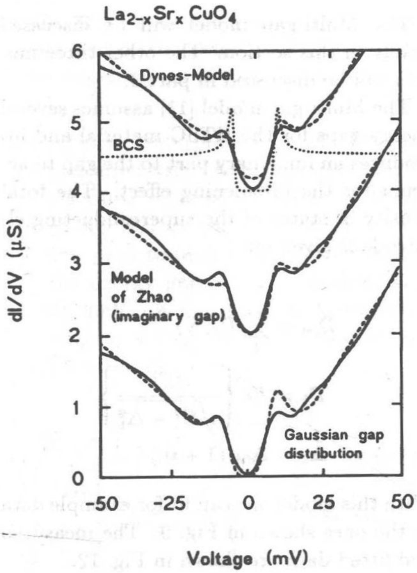

Fig. 8.: Different models describing the broadening of the gap.
Solid line: measured data for a $La_{2-x}Sr_xCuO_4$ – Pt point-contact.
Upper curves: BCS-characteristic (dotted line) and Dynes model (broken line);
middle curves: model due to Zhao et al. [12];
lower curves: Gaussian gap distribution;
(from J. R. Kirtley [8]).

2.3 Structure in Tunneling and Point-Contact Spectra

As another deviation from I-V characteristics of "conventional" superconductors one often finds pronounced structure in dI/dV or dV/dI characteristics of HTSCs, mainly above the energy gap and especially in point-contact spectra. Observed are:

- a few maxima and minima above the gap-voltage as in Fig. 9.;
- an oscillatory structure as in Fig. 10.;
- quite sharp structure above the gap-voltage as in Fig. 11.

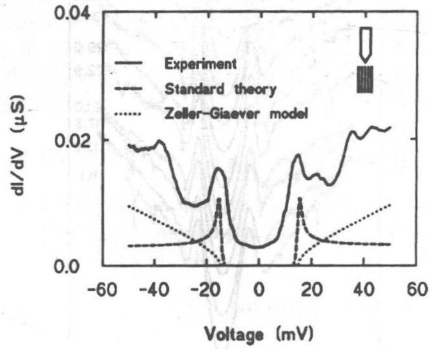

Fig. 9.: Tunneling contact of $YBa_2Cu_3O_{7-x}$ (polycrystalline) – PtIr (from J. R. Kirtley et al. [13]).

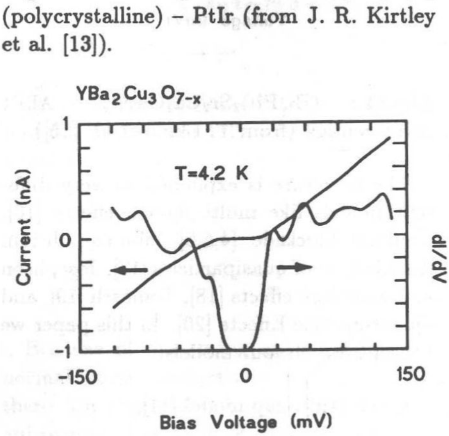

Fig. 10.: $YBa_2Cu_3O_{7-x}$ (single crystal) – W tunneling contact (from J. C. Wan et al. [14]).

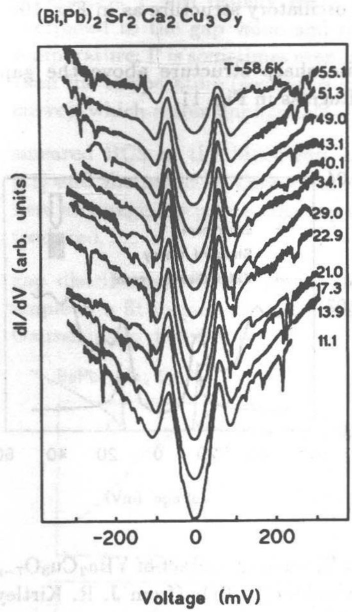

Fig.11.: $(Bi,Pb)_2Sr_2Ca_2Cu_3O_y$ – Al,Pt point-contact (from T. Ekino et al. [15]).

The structure is explained by very different models like multi-phonon effects [16], Coulomb-blockade [4,5,6], non-equilibrium distribution of quasiparticles [17], Josephson and weak link effects [18], Tomasch [19], and Quantum Size Effects [20]. In this paper we concentrate on four models:

- the Multi-gap model [11];
- the Coulomb Blockade (Coulomb staircase) [4,5,6];
- the S-c-N-model [17], and
- the Quantum Size Effect [20].

The Multi-gap model will be discussed briefly in this section. The other three models will be discussed in part 3.

The Multi-gap model [11] assumes several energy gaps for the HTSC material and introduces an imaginary part to the gap to account for the broadening effect. The total density of states of the superconducting electrode is given by

$$\mathcal{D}_{tot} = \sum_k \mathcal{D}_k(E)$$

$$\mathcal{D}_k = Re\left\{\frac{|E|}{\sqrt{E^2 - \tilde{\Delta}_k^2}}\right\}$$

$$\tilde{\Delta}_k = \Delta_{0k}\,(1 + iv)$$

With this model one can fit for example data as the ones shown in Fig. 9. The measured and fitted data are shown in Fig. 12.

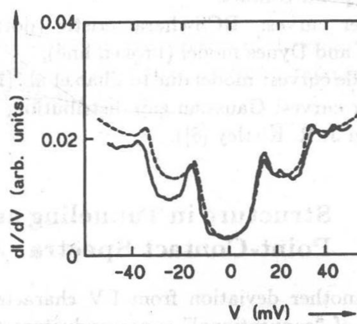

Fig. 12.: Measured data from fig. 9. (solid line) and fit due to the Multi-gap model (broken line) (from P. Seidel et al. [11]).

2.4 The Energy Gap

In the HTSCs a large scattering of the gap values and of the ratio $2\Delta/k_B T_C$ is found. Some explanations of this fact are:

- different interpretations of the same measured data. As an example a Bi-Sr-Ca-Cu-O – Mo point-contact of H. Tao et al. [21] is shown in Fig. 13. If the peak-to-peak distance is taken as the energy gap 2Δ one obtains $2\Delta = 68$ meV. If the data are fitted according to the Dynes model one obtains $2\Delta = 46$ meV;

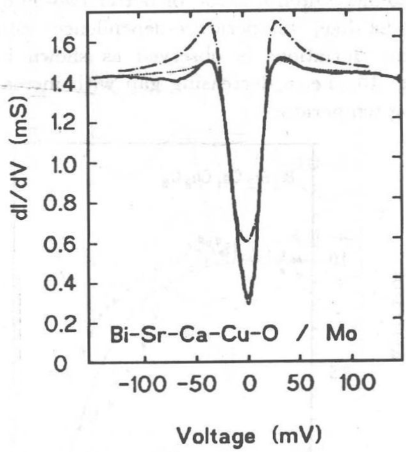

Fig. 13.: Bi-Sr-Ca-Cu-O – Mo point-contact; solid line: measured data; broken line: fit due to the Dynes model; dotted line: fit due to the model of Zhao et al. (from H. Tao et al. [21]).

- the large scattering in $2\Delta/k_B T_C$ may be due to the uncertainty of T_C; the surface T_C's do not have to be the same as the bulk T_C's;

- polycrystalline samples may contain different phases with different T_C's and different gap values.

However there are some common features which can be found especially in the more recent work of J. S. Tsai et al. [22,23], I. B. Al'tfeder et al. [24], and J. R. Kirtley [8]. These work give the following picture of HTSCs:

- the HTSCs have a gap;

- the energy gap of the HTSC scales with the T_C of the sample; this behavior is shown in Fig. 14.

- there exists a gap anisotropy with the values:

$$2\Delta_{ab}/k_B T_C \approx 5 - 8$$
$$2\Delta_c/k_B T_C \approx 3 - 4$$

(see also Fig. 14.).

In Table 1. we give the calculated gap values for the measured T_C's according to the relations

$$2\Delta_{ab}/k_B T_C = 6$$
$$2\Delta_c/k_B T_C = 3.5$$

Because of the strong anisotropy of the normal state conductivity ($\rho_c/\rho_{ab} \gg 1$), there are strong arguments against a gap anisotropy: The ratio of the band width in the ab-plane (w_{ab}) to that in the c-direction (w_c) should follow $w_{ab}/w_c \approx \rho_c/\rho_{ab}$. This suggests that $w_c < 100$ meV for Y-Ba-Cu-O and $w_c < 1$ meV for Bi– and Tl–HTSCs, i.e. w_c is of the order of or smaller than the "gap" in c-direction.

Table 1.: Calculated Energy Gaps 2Δ versus measured T_C of HTSCs

Substance	T_C [K]	$2\Delta_{ab}$ [meV]	$2\Delta_c$ [meV]
Ba-Pb-Bi-O	10	5.2	3.0
Nd-Ce-Cu-O	23	11.9	6.9
Ba-K-Bi-O	30	15.5	9.0
La-Sr-Cu-O	38	19.6	11.5
La-Ba-Cu-O	60	31.0	18.1
Y-Ba-Cu-O	92	47.6	27.7
Bi-Sr-Ca-Cu-O 2212	88	45.5	26.5
Bi-Sr-Ca-Cu-O 2223	110	56.9	33.2
Tl-Ca-Ba-Cu-O 2122	95	49.1	28.7
Tl-Ca-Ba-Cu-O 2223	120	62.0	36.2

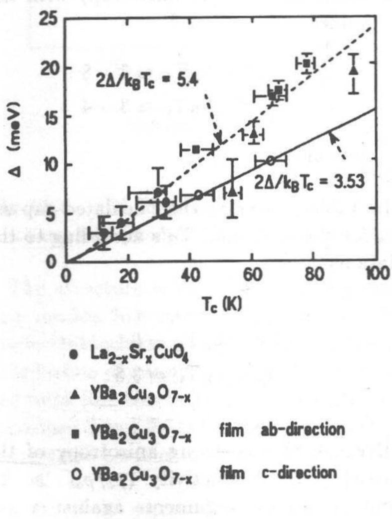

Fig. 14.: Energy gap Δ as function of T_C for the labeled samples (from J. R. Kirtley [8]).

For the temperature dependence of the energy gap of HTSCs contradictory behavior is found. Often a BCS-, or better two-fluid-model like, temperature-dependence with some deviations is observed as shown in Fig. 15., i.e. a decreasing gap with increasing temperature.

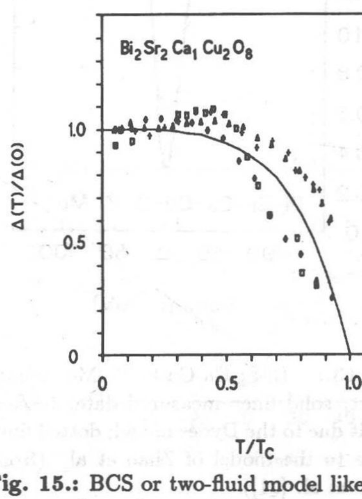

Fig. 15.: BCS or two-fluid model like temperature dependence of the energy gap (with some deviations; from B. A. Aminov et al. [25]).