Since the discovery of superconductivity by Kamerlingh Onnes in 1911 the phenomena has fascinated solid state physicists and material scientists. The disappearance of the resistivity below a critical temperature $T_c$ has been first detected for Hg below $T_c = 4.2$ K. A systematic search for further superconductors with higher critical temperatures lead to many new conventional superconducting compounds and alloys. The development of $T_c$ as a function of the year is shown in Fig. 1. Around 1980 the highest $T_c$ was observed for Nb3Ge with $T_c = 23$ K and there was almost no progress in $T_c$ over an entire decade. The discovery of high-$T_c$ superconductivity in cuprates by Bednorz and Müller in 1986 lead to an explosion of $T_c$ to a new superconducting ground state. At present we know from various experiments that also in the high-$T_c$ superconductors there is an interaction of the charge carriers with lattice vibrations (phonons) leads at low temperatures to a pairing of the electrons and thus to a new superconducting ground state. At present we know from various experiments that also in the high-$T_c$ superconductors there is a pairing of the charge carriers but there is no consensus on the origin of the pairing. It is even not clear if there are bosonic modes which couple the pairs. Among those bosonic modes phonons, spin fluctuations, or plasmons have been discussed. The present situation is best characterized in Fig. 1. Extrapolating the time scale of the conventional superconductors, a microscopic ‘XYZ’ theory for the high-$T_c$ superconductors is expected in the year 2022 and thus experimental input on the coupling of the charge carriers to other degrees of freedom is at present highly desirable.

Superconductivity in conventional superconductors such as Pb or Nb is explained by a formation of pairs of the charge carriers due to a coupling to lattice vibrations. In the cuprate high-$T_c$ superconductors the formation of singlet pairs of charge carriers has been demonstrated but the glue for the formation of pairs is not known. As a consequence, there is a consensus that there is at present no consensus on the microscopic theory for high-$T_c$ superconductivity. Using angle-resolved photoemission spectroscopy with unprecedented precision we have detected a very strong coupling of the charge carriers below $T_c$ to a bosonic mode with an energy of 40 meV. From the temperature and dopant dependence we conclude that this mode is related to spin fluctuations thus favoring an electronic mechanism for high-$T_c$ superconductivity.

Mass renormalization of the charge carriers in high-$T_c$ superconductors

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dispersion very close to the Fermi level can be determined. This dispersion is no more determined by the band structure alone. Rather, there is a renormalization of the dispersion due to a coupling of the charge carriers to other degrees of freedom of the solid. This coupling leads to a dressing of the particles or a mass enhancement, e.g., to a reduced dispersion which can be compared to that of the bare particles. The case of a coupling to a bosonic mode such as phonons, spin fluctuations, or plasmons has been treated by Engelsberg and Schrieffer [1]. Below the mode energy $E_m$ the mass is enhanced by $m^*/m = 1 + \lambda$ where $\lambda$ is the coupling constant. It is exactly this mass renormalization and the coupling constant which can be measured by high resolution ARPES. In addition high-intensity beam-lines at synchrotron radiation facilities are available which offer photons over a large energy range. In this way the energy dependence of the excitation probability of different bands can be used to separate overlapping bands.

The phase diagram of hole doped high-$T_c$ superconductors is shown in Fig. 2. The undoped cuprates are antiferromagnetic insulators. Upon hole doping, the long range antiferromagnetic order rapidly disappears but spin fluctuations remain at higher hole concentrations. The antiferromagnetic range is followed by the superconducting range, which is divided into the underdoped (UD), optimally doped (OP), and overdoped (OD) region. In the underdoped region, different from conventional superconductors, a (pseudo)gap is observed even above $T_c$ which disappears above $T^*$. Also for the optimally doped samples the normal state properties are very strange which is normally related to strong correlation effects in these cuprates where the CuO band is almost half filled. Only for overdoped samples a more Fermi-liquid-like behavior is observed.

One of the aims of the IFW’s Spectroscopy Group is to study the electronic structure of the high-$T_c$ superconductors in the normal and in the superconducting state. Most of the data have been taken on Pb doped Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Pb-Bi$_2$212) systems where well defined surfaces could be produced by cleaving single crystals. The Fermi surfaces of this system have been determined previously [2] and are schematically sketched in Fig. 3. This Fermi surface can be described by barrels around the points $(\pm \pi, \pm \pi)$ in the Brillouin zone. Due to the interaction between 2 adjacent CuO$_2$ planes which are only separated by a plane of Ca ions, there is a small bilayer splitting which is larger close to the points $(\pm \pi, 0)$ and $(0, \pm \pi)$ and smaller where the diagonals G-$(\pm \pi, \pm \pi)$ cut the Fermi surface at the nodal points, N. Assuming that at the Fermi level the dressing of the charge carriers is small it was possible to extract the dispersion of the bare particles [3]. In the following we compare the measured dispersions close to the Fermi level with the bare particle dispersions. In this way we obtain information on the dressing of the charge carriers as a function of the dopant concentration, the temperature, and the location on the Fermi surface. In this report we focus on ARPES measurements close to $(\pi, 0)$ [4]. Close to
At this point the superconducting gap is large and a large dressing of the charge carriers is expected. Contrary, at the nodal point, the gap is zero and smaller mass renormalizations are observed. In Fig. 4 we show a collection of ARPES intensity plots as a function of energy and wave vectors along the \((\pi,\pi)-(\pi,-\pi)\) direction of various Pb-Bi2212 superconductors. See text for details.

In Fig. 5 we show in more detail the measured dispersion of the bonding band of an optimally doped Pb-Bi2212 superconductor.

Fig. 5: ARPES intensity plot as a function of the energy and the wave vector along the \((\pi,\pi)-(\pi,-\pi)\) direction for the bonding band of an optimally doped Pb-Bi2212 superconductor.
below $T_c$ for UD samples there is really a huge coupling to a bosonic mode. Since the $\lambda$ values are about 8, the mass enhancement is about 9. It is interesting to note that in the conventional strong coupling superconductor Pb an electron-phonon coupling constant of $\lambda_{e-ph} = 1.5$ is reported. According to theoretical estimates [5] the energy of the mode is the difference between the kink energy ($\sim 70$ meV) and the gap energy ($\sim 30$ meV), i.e. $\sim 40$ meV. Fig. 4 shows that the renormalization decreases with increasing dopant concentration and disappears in the OD region.

It is remarkable that the coupling to this mode completely disappears above $T_c$ as shown in the fourth row of Fig. 4. No kink is observed at 70 meV. When compared to the bare particle dispersion, there is a mass enhancement of about 2 over a large energy range corresponding to a $\lambda$ value of about 1. This renormalization above $T_c$ is almost independent of the dopant concentration and is possibly caused by a coupling to a continuum of excitations. Interestingly, those coupling constants are also observed above and below $T_c$ at the nodal point.

It is difficult to interpret the huge coupling of the charge carriers at the $(\pi,0)$ point in terms of a conventional isotropic coupling to phonons. On the other hand inelastic neutron scattering experiments have revealed a spin fluctuations mode below $T_c$ at about 40 meV. Therefore it is tempting to assign the strong mass enhancement detected in the ARPES measurements to a coupling to this spin fluctuation mode.

This assignment is supported by the strong dopant dependence of the renormalization (it is difficult to explain why the electron-phonon coupling should show such a strong dopant dependence). The fact that the strong coupling to the mode appears at the $(\pi,0)$ points which are separated by a wave vector $(\pi,\pi)$ which corresponds to a wave vector of the antiferromagnetic lattice is also in favor of a spin fluctuation scenario. In summary the present measurements indicate above $T_c$ a more isotropic coupling to a continuum (probably of spin fluctuations) and below $T_c$ an additional strong highly anisotropic coupling to a spin fluctuation mode which is formed inside the superconducting gap. The transition between the two states is probably formed by a feedback process which starts at $T_c$. At present there is no microscopic theory for this transition. On the other hand, the present ARPES data are in favor of an electronic and not a phononic mechanism for high-$T_c$ superconductivity.

References

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