High Temperature Superconductivity at Room Temperature?

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April 15, 2015 (STH31, HP95). Almost 30 years ago, high temperature superconductivity was discovered for the first time in cuprates by Bednorz und Müller [1]. Later Hosono and collaborators discovered in 2006 high temperature superconductivity also in the ferropnictides [2]. The highest superconducting transition temperature T_c =134 K was detected in the cuprate $HgBa_2Ca_2Cu_3O_8$ [3]. Under pressure the transition temperature in this compound could be raised to 160 K. Since the discovery of high T_c superconductivity it is a dream to increase T_c to room temperature. Moreover it is a dream to find a generally accepted theory for high T_c superconductivity.

Most of the high T_c superconductors evolve from an antiferromagnetic parent compound. Changing a control parameter such as doping, pressure, or chemical pressure it is possible to suppress the antiferromagnetic order. In a phase diagram temperature vs. control parameter, at the end of the antiferromagnetic range, a superconducting dome develops. In numerous attempts it was not possible to increase the superconducting transition temperature above 160 K.

A completely new control parameter is formed by optical pumping. Pumping by infrared or visible photons leads to electron-hole excitations which could induce a transient “optical doping”. By pumping with mid-infrared photons it is possible to excite particular lattice vibrations which could lead to completely new non-equilibrium phases. In this way it is possible to achieve a transient structure which cannot be reached by conventional changes of the control parameters.

The non-equilibrium state can be investigated by a second pulse by means of optical spectroscopy, angle-resolved photoemission spectroscopy, electron scattering, or x-ray scattering. Those experiments are generally called pump-probe experiments. In this way new vistas are opened up in solid state physics.

A collaboration of several international groups, conducted by Andrea Cavalleri from the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg, have tried to achieve in the cuprates for a short time interval a new non-equilibrium state with higher superconducting transition temperatures using excitations with mid-infrared photons. Evidence for superconductivity was provided by measurements of the optical reflectivity using photons polarized perpendicular to the CuO_2 layers: the data reveal Josephson plasmon resonances which are based on a collective vibration of Cooper pairs in between the CuO_2 layers, tunneling through the separating isolating layers. Moreover the existence of superconductivity is deduced from a strong enhancement of the optical conductivity at low energies.

In a first publication it was possible to transform the stripe order of spin and charge which causes insolating behavior in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$ by a 300 fsec mid-infrared pulse with a frequency of the in-plane Cu-O vibration into a superconducting state during a time interval of 100 ps [4]. The appearance of the superconducting phase was explained by the melting of the competing stripe phase.

In more recent publications the implication of non-linear optical lattice vibrations were studied in the superconductors $YBa_2Cu_3O_{6+\delta}$ ($0.45<\delta<0.6$) with superconducting transition temperatures between 35 und 62 K. In this case, vibrations of the apex O atoms perpendicular to the CuO_2 layers were excited [5,6]. Deviations from the equilibrium distance between the CuO_2 layers and the O apex atoms of the order of several percent could be achieved. Due to the complicated double layer CuO_2 structure (see Figure 1) of the compound two longitudinal and one transverse Josephson plasmon were detected. Based on the frequency and time dependent optical properties in the energy range 2 to 10 meV an increase of the superconducting density and a related enhancement of the superconducting transition temperature was derived. Surprisingly similar results were also observed for temperatures above the equilibrium superconducting transition temperatures. Temperature dependent experiments for δ=0.45 yielded evidence for superconducting properties up to a temperature of T= 370 K, well above room temperature.

In the latest work of this group [7] the transient lattice structure formed by the pulsed excitation was studied by femtosecond x-ray scattering experiments using the free electron laser in Stanford (LCLS). The results were compared with density functional theory (DFT) calculations. In the detected transient lattice structure the distance between apex O atoms and the layer is reduced, the Cu-O distance in the planes is increased, and the CuO_2 layers are more buckled (see Figure 1). In the DFT calculations this transient lattice structure leads to a transient increase of the Cu $3d_{x2-y2}$ character of the charge carriers at the Fermi surface and to an increase of the doping concentration of the layers. At a first glance these results are in contradiction to a compilation of T_c values [8], which predict an increase of the transition temperatures with *increasing* Cu-apex O distance. On the other hand, an increasing transition temperature at high pressures, related with a reduced Cu apex O atom distance was observed for $YBa_2Cu_3O_{6+\delta}$ (δ<0.6) [9].

The works indicate a new method how besides pressure or strain, the control parameter can be changed by non-linear photonics. This new method may lead to new lattice structures which may be related with new electronic structures. Although it is not absolutely sure that the employed optical probe definitely detects phase coherent superconductivity, the experiments signal the appearance of superconducting properties.

The application of the observed transient superconductivity at room temperature will be difficult since the new state exists only during some picoseconds and because a stabilization of the non-equilibrium state by optical excitations is probably not feasible. On the other hand, the results may help in search of chemically modified equilibrium structures which could reach higher superconducting transition temperatures.

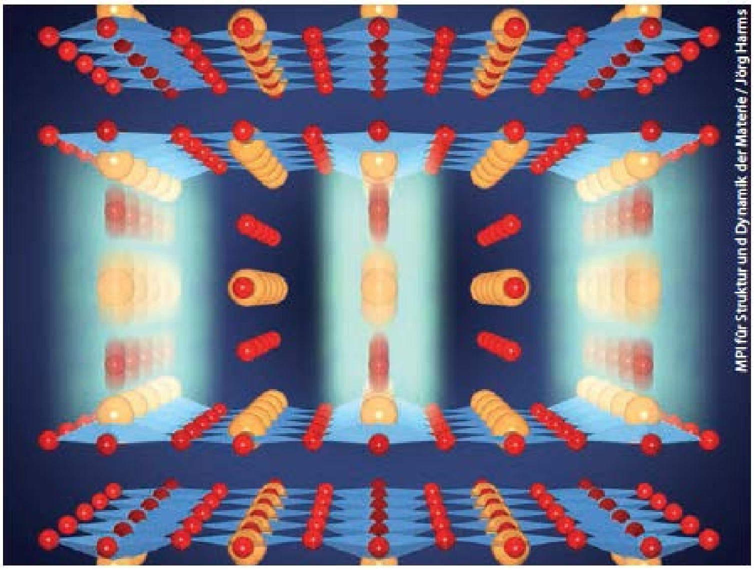

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Fig. 1. Structure of $YBa_2Cu_3O_{6+\delta}$: CuO_2 double layer (light blue), CuO_3 chains perpendicular to the projection plane, Cu atoms (orange), O atoms (red). Due to resonant excitation of apex O atoms (blurred), which are in between the double layer and the chains, the atoms are moved out of their equilibrium position.

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