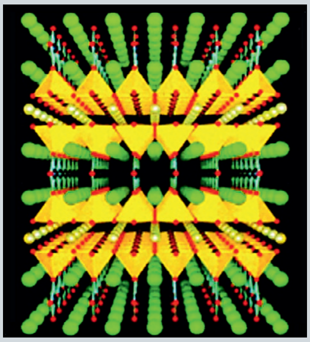
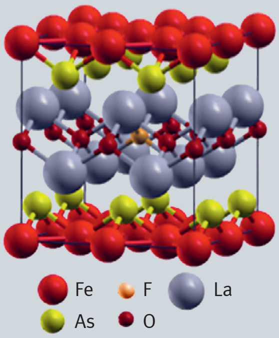
Present State, Potential and Perspectives of Superconductivity

Prof. Dr. Werner Hanke
Institute for Theoretical Physics
University of Würzburg



Cuprate SC



FE-based SC

Figure 1 (High-Temperature Superconductivity)

Present State, Potential and Perspectives of Superconductivity

Superconductivity (SC) is one of the most fascinating and at the same time most important topics of today's physics and technology research. At the physics level it is a “macroscopic quantum phenomenon“, where quantum effects on the scale of the distances between atoms conspire to dramatic effects. The most extraordinary one is a complete vanishing of the resistivity, i.e. a DC current flows without any loss in a “macroscopic“ material, for example a power cable. **This unique interplay of microscopic and macroscopic physics offers potential and perspectives for solving some of the most pressing “grand challenges“ of our times:** The German change in energy policy from nuclear power to natural (wind, etc.) resources obviously requires the transmission of the electrical current (superconductors have also ultralow AC losses) to cities far away from the production sites. Demonstrations of the corresponding enormous energy-saving possiblities have already been achieved in laboratories employing superconducting materials not only in power cables, but also motors/generators and magnetic energy-storage systems. These latter systems are directed towards another “application dream“, i.e. providing the electromagnetic power reserve which can, like the power reserve in e.g. a water reservoir (e.g. the US Hoover dam), quickly be released to stabilize the line voltage at peak consumptions in industry, households, etc. Another dramatic application perspective is magnetic levitation, where the SC floats without any friction on top of a normal magnetic material, as depicted in the above Fig. 1. In Japan, a magnetic levitation train based on this SC application reached the enormous speed of about 600 km/h, comparable also to that of the Chinese-German mag-lev train operating currently in Shanghai.

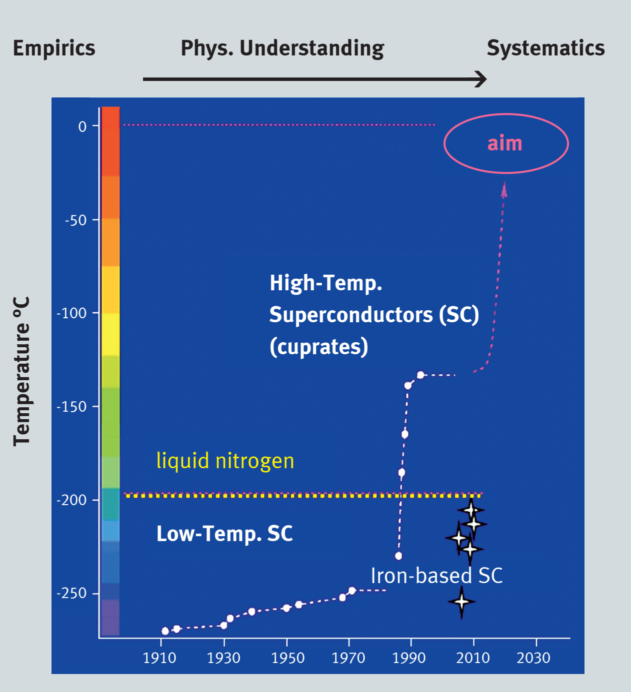


Figure 2 (Transition Temperature into SC State)

The picture in Fig. 1 was the official poster of the first International Conference, a huge event taking place in the Swiss Alps 1988, just after the detection of “High-Temperature Superconductivity“ (HTSC) in certain ceramic materials (cuprates, i.e. Copper-Oxide compounds (Ref. 3)). It very nicely summarizes our **quest for progress, the enormous potential, but also the ultimate challenge:** the SC looses its fascinating properties above a certain temperature called the transition temperature T_c and displays above this temperature (as in normal metals) resistivity. This is summarized in Fig. 2, which shows the SC materials development in the last 100 years since its first detection in mercury (Hg) in 1911. So, the optimistic conference poster in Fig. 1 conveyed the hope that „The limit is the Sky“ and that SC can be realized at least at the freezing temperatures of the Swiss mountains. However, despite an unprecedented world-wide search intensity after the HTSC detection, at this point, SC develops even in the “World-Record“ T_c-holder at lower temperatures: about minus 120 degrees Celsius is the highest value, where SC appears. Nevertheless, this is – in particular from the point of view of applications – a crucial progress: cooling down to the extremely low temperatures, required for the so-called Low-Temperature SCs (LTSC), needs very expensive liquid Helium, whereas the High-Temperature SC just require liquid nytrogen (which is essentially liquid air) – a comparably very cheap cooling substance.

The Global Market for SC, as summarized e.g. in the very informative Conectus brochure (Ref. 1) of the consortium of European companies determined to use superconductivity, predicts a total volume of about 4.5 Bill. € in 2013. Closer inspection reveals that it is still mainly (~90%) provided by LTSC, and also mainly (~70%) used in bio-medical (Magnetic-Resonance Imaging (MRI)) applications.

So, why is the great promise only realized to a limited extent exploiting the potential of SC? Clearly, the ultimate goal would be to find a material which displays the fascinating properties at elevated and possibly even up to the “dream of temperature“, i.e. room temperature. Even according to modest expectations, this would boost the Global Market by several orders of magnitude in a variety of crucial areas, ranging from large-scale (power cable, etc.) applications down to nano-scale products. An example in the latter area is the so-far semiconductor – dominated (computer-) chip industry, where the replacement by SC devices could potentially enhance the chip speed by factors up to 1.000 and more.

The central quest and challenge is also indicated in Fig. 2: **We have to replace the so-far mostly empirical search for improved SC properties by a systematic understanding, using the laws of physics combined with up-to-date material science.**

“Where are we at in understanding Superconductivity?“

In the last two decades since the amazing and unexpected detection of HTSC in ceramic materials (cuprates) leading research groups all over the world have concentrated on explaining the mechanism behind High-Temperature SC. **The enormous complexity of this task is obvious:** so-far the search for new SC materials, as displayed in Fig. 2, was more ore less entirely based on empirics and not on exact knowledge. However, to identify among the over 100 known chemical elements with their nearly infinite combination possibilities the most promising SC material, a definite guiding and construction principle is required. **Very recently, based on substantial progress on both fronts, i.e. physics and material-science research, such a principle becomes more and more evident.** This is discussed in what follows.

As summarized in Fig. 2, **two classes of SC exist.** Let us consider them in somewhat more detail:

The first class – the “Low-Temperature SC“ (LTSC) - known since about 100 years – conduct the current without any loss only close to the lowest temperature possible, i.e. the absolute zero-point of minus 273 degree Celsius. The about 20 year-old High-Temperature SC achieve this “supra-current“ already at values around minus 130 degree Celsius (Ref. 4). As already mentioned above, this difference is of crucial importance for the perspective of operating temperatures, which require much less expensive and less complex cooling.

However, despite this tremendous difference, both LTSC and HTSC share also one unifying aspect: **in the SC, the electrons form pairs, which enables them to travel without resistance through a wire.** This has a certain analogy to what all of us have experienced on a heavily-frequented freeway: to avoid a traffic congestion and eventually a traffic stop, the cars on the freeway have to be coupled very much like carriages in a train. Because all cars then move with the same velocity, no traffic stop can develop and the cars reach quickly their destination. However, to explain this “pairing of electrons“, we have to understand why the electrons, which normally

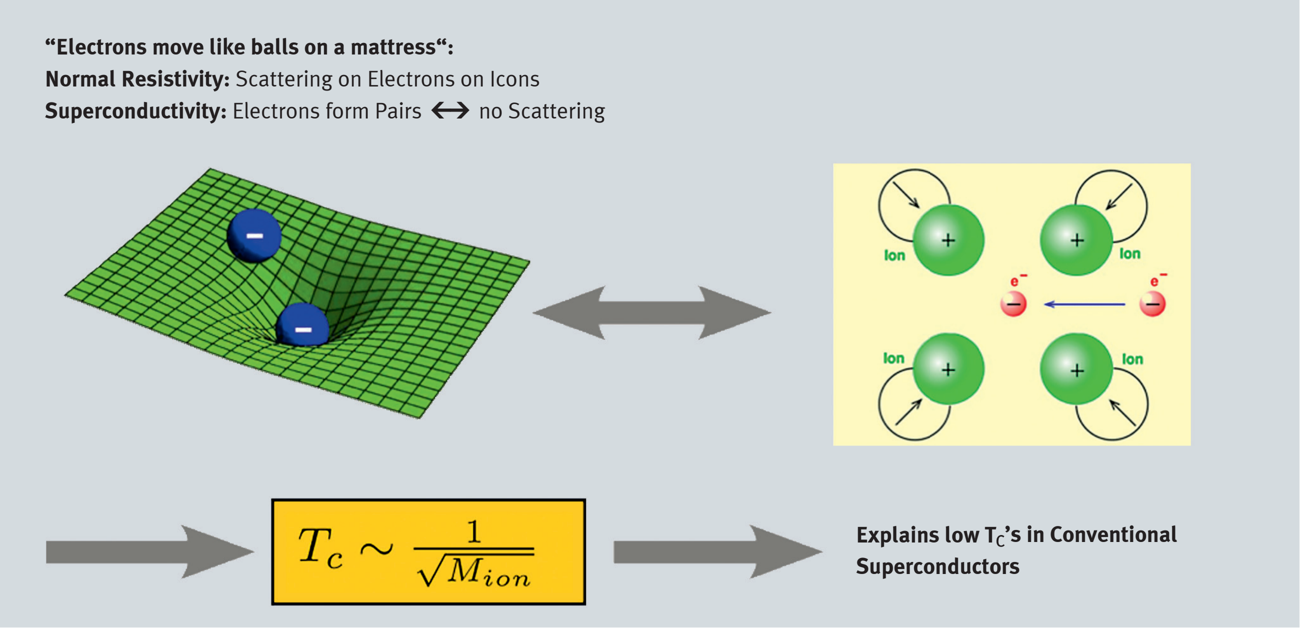


Figure 3

repel each other (because of their same charge), do attract each other in a SC. The fundamental secret behind this pairing is known since about 50 years for the LTSC (Ref. 2). In the HTSC, on the other hand, the “glue“ which binds the electrons to pairs was not exatly known. However, it is precisely at this point where substantial progress has recently been made.

In a normal conducting wire, when a voltage is applied, the electrons are accelerated through the crystal lattice and, thereby, create the current. In moving, they cannot avoid scatterings with the much larger ions and loose energy. This creates the well-known loss in current flow, i.e. the resistivity. In contrast, in a SC, the resistivity vanishes, because the electron pairs move with the “same velocity“. In a LTSC, we know that the crystal lattice, built up by the ions, is pivotal for this electron pairing – this is schematically depicted in Fig. 3: a first electron deforms – very much like a heavy ball on a mattress – the regular lattice, because the negative electron attracts the surrounding positive ions. Then, the second ball on the mattress, or in a SC material, a second electron feels this displacement (net positive charge) and is drawn into this deformation. Another well-known example from sports is the simultaneous trampoline jumping of two children, which are – enevitably – drawn into the same deformation.

However, as simple as this first building principle of SC may appear, we can already very roughly learn something from it concerning the SC transition temperatures: our intuition already tells us that the “easyness“ with which pairing appears and, thus, the temperature characteristic for **SC must then have something to do with the effectiveness with which the electrons can deform the heavy ions.** The lighter the ions, our intuition tells us, the less energy is required to achieve the deformation. **This intuition is indeed reflected in the microscopic quantum world of interacting electrons and ions,** as shown in the celebrated, seminal Nobel-prize decorated work for LTSC by Bardeen, Cooper and Schrieffer (Ref. 2): It relates the SC transition temperature to the ionic mass, i.e. $T_c \sim (M_{Ion})^{-1/2}$.

So what is then so different in the HTSC, with their so much elevated transition temperatures?

It is becoming more and more clear that in these materials completely different forces, namely **magnetic forces are responsible for the electronic pairing** and the loss of resistivity (Refs 5-7). These magnetic forces are due to the “spin“of the electron, i.e. the direction around which the electron processes.

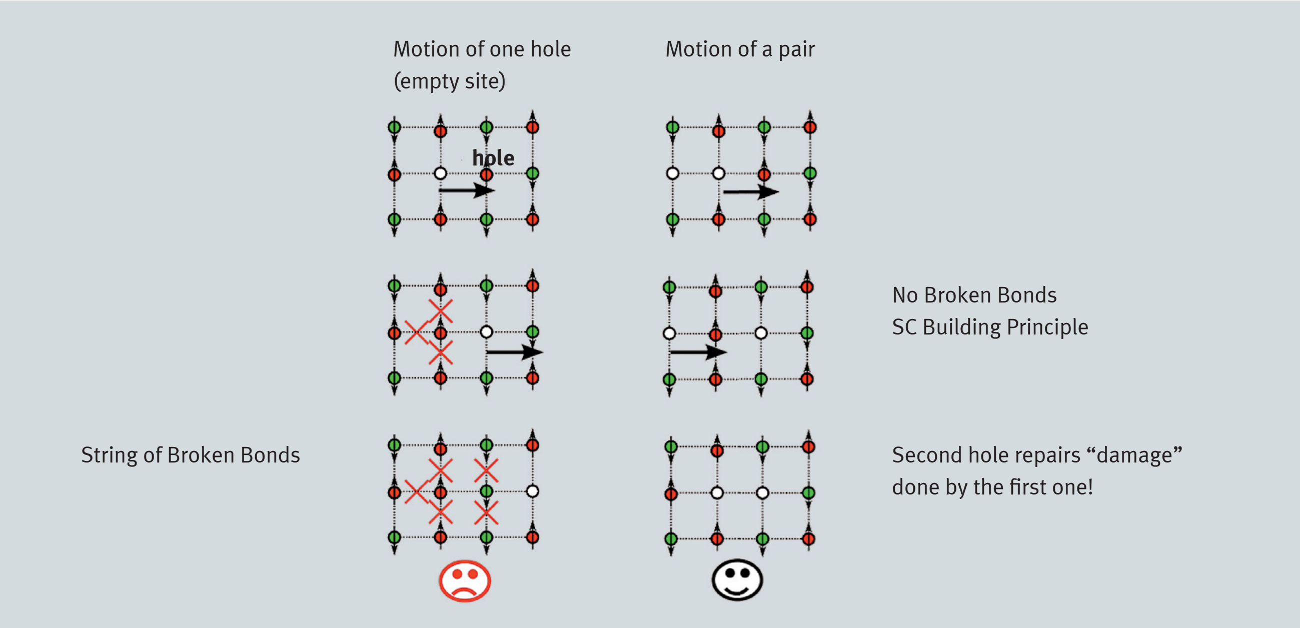


Figure 4 (Hole Doping and Pair Formation)

Such a spin can be considered as a minute little magnet with North- and South-pole, sitting like the ions in the crystal lattice of the SC at the regular crossing points (see Fig. 4 (a, b)). In case all the spins, i.e. all the minute magnets, point in one and the same direction, we have a ferromagnetic substance, like iron; if the spin alternates from one site to the neighboring site, we have an antiferromagnet – as in the case of the High-T_c cuprates. This is schematically displayed in Fig. 4.

Based on this picture an electronic pairing mechanism has been substantiated in recent research works (Refs 5-7 and other works cited in there). One may visualize the copper-oxide planes, which make up the HTSC cuprates, as a kind of checkerboard pattern built up by the (minuscule) magnets, which point alternatively “up“ (red) and “down“ (green). It is known that in the HTSC cuprates the SC properties are induced by doping with atoms of other elements (Ref. 3, 4), which disturbs the regular magnetic (spin) lattice: doping leaves empty (white) sites in our regular antiferromagnetic pattern (in Fig. 4 left-hand-side). Neighboring electrons can then hop with their spin orientation onto this empty site, somewhat like an empty site in a parking lot, which is filled by moving-in cars. This implies, for example, that the red (up) spin on the right-hand side of the empty side moves left. However, this rearrangement costs substantial energy (and, finally, is responsible for the resistance): the regular checkerboard order is broken in the new situation (indicated by red crosses), where now electrons with the same (parallel) magnetic orientation are nearest neighbors, which is energetically unfavorable.

However, this **unfavorable situation is completely removed if two empty sites (induced by the doping) are close to each other, i.e. perform the hopping as a “pair“:** then, as is easily realized in our magnetic pattern in Fig. 4 (right-hand-side), disturbances which are produced by the first “electron“ are repaired by the second electron. This can again nicely be visualized in Fig. 4: the two neighboring empty sites (and, therefore, also the two electrons hopping into these sites) which form the pair, can move in the magnetic checkerboard without leaving a disturbance. **Thereby, they transport charge i.e. current without „resistivity“. If, finally, an incredibly large number ~10^{23} of so-called Cooper Pairs conspire to a “coherent motion“, moving all with the same velocity, when we have SC, i.e. the “super current“ on the macroscopic scale of a wire or cable (Fig. 5).**

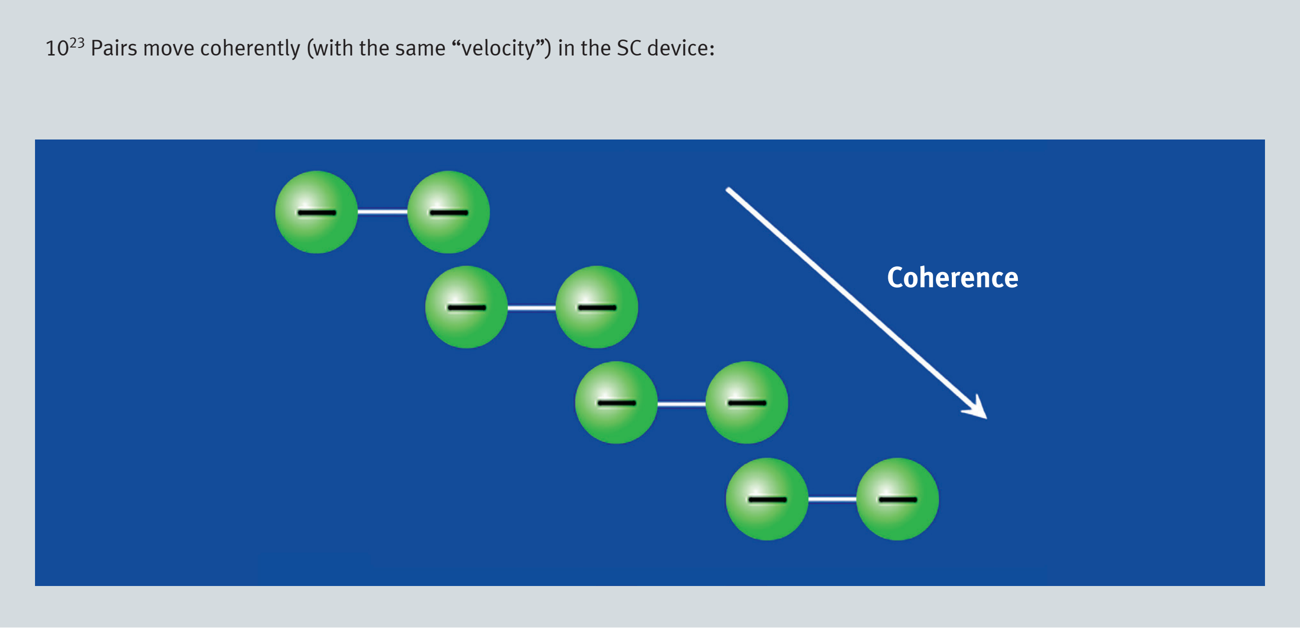


Figure 5 (Superconducting Current)

This explanation, which sounds relatively simple is anything but easy to proof in the quantum world of the 10^{23} interacting electrons. This can most effectively be done in state-of-the-art-simulations on the largest computers of the world. For example, a collaboration with physicists from the University of California, colleagues from Stuttgart, Dresden, Tübingen and our group has recently succeeded in showing that it is, indeed, the spin of the electrons, which provides the “glue“ for electronic pairing in the cuprate HTSC (Ref. 5). The great challenge needs world-wide collaboration: this is e.g. reflected in a rather similar (magnetically induced) electronic pairing mechanism found with colleagues from Princeton and Stanford (USA) to exist in the Fe-based HTSC (shown in Fig. 2) (Ref. 6). A substantial amount of other groups' theoretical work and decisive experiments have further corroborated this “common thread“ in SC pairing (for a summary and recent review see Ref. 7).

So, where are we at in superconductivity and what do we learn form such an electronic pairing mechanism?

There are two essential insights:

(i) at least there exists (e.g. Ref. 5) a formula, a first albeit approximative, guiding principle, which allows to estimate the temperature T_c, at which a normal metal converts to a SC. Ultimately, this **may also be used as a guiding principle** to find appropriate combinations of the chemical elements in compounds to reach higher SC transition temperatures. This latter step has inevitably to be done in collaboration with leading material-science groups: their expertise is crucial, since in technological applications the SC can loose its exciting properties and become a conductor with a normal resistivity. This happens if an applied magnetic field (Fig. 1) or the transport current exceed limiting values, which depend on the material and also its fabrication process.

(ii) In rough analogy to our **“intuition“** used for the low SC transition temperature in LTSC materials (the ~1.000 times heavier ions have to be displayed by the very light electrons), we would expect (this can indeed be made rather concrete in the above-mentioned computer simulations) that if the “glue“ for electron pairing is by itself of electronic (spin) nature, **pair formation is much “easier“ achieved, elevating the T_c-scale to significantly higher temperatures.**

Thus, in summary, **superconductivity and its potential and perspectives**, share a lot with an extremely fascinating and very demanding puzzle or also chess game: every little step, here first on the quantum level of the electrons, has to be understood **leading finally to one of the most promising solutions nature has to offer, i.e. a current which flows without any decay at an infinite time scale.**

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Prof. Dr. Werner Hanke

Institute for Theoretical Physics,
University of Würzburg, 97074 Würzburg, Germany

Festo AG & Co. KG

Ruiter Straße 82
73734 Esslingen
Deutschland
Telefon 0711 347-0
Telefax 0711 347-21 55
cc@de.festo.com
www.festo.com/gruppe