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A Road Towards High Temperature Superconductors

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14. ABSTRACT

The central issue in trying to make useful high temperature superconductors is obviously to discover superconductivity at higher temperatures. But there is also another issue, not less important: how to make such a superconductor a practical one. It should be recalled that the main problem with the currently available high Tc cuprates has only been partly their limited critical temperature: it has also been their insufficient performance under ac currents and in the presence of strong magnetic fields. The first part of this project deals with this question. It turns out that considerable progress in the behavior of the cuprates under applied fields can be made by using an unconventional pinning mechanism directly based on the Bond Contraction Pairing (BCP) mechanism proposed by Deutscher and de Gennes. In the second part a new mechanism for superconductivity that we may have uncovered in enhanced Tc granular Aluminum films. It turns out that free spins are present in these films, and that their local fluctuations may provide a retarded pairing mechanism. This mechanism may also be present in other not so well understood superconductors such as Kondo lattices.

During this research period a very successful effort to show what superconductivity can do to the public at large. Our videos on Quantum Levitation and Quantum locking have been seen by more than 9 million people the world over, possibly the largest number ever reached by any video on High Tc. Our post doc Dr. Boaz Almog was heavily involved in this effort.

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A ROAD TOWARDS HIGH TEMPERATURE SUPERCONDUCTORS

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Final report

Introduction

The central issue in trying to make useful high temperature superconductors is obviously to discover superconductivity at higher temperatures. But there is also another issue, not less important: how to make such a superconductor a practical one. It should be recalled that the main problem with the currently available high Tc cuprates has only been partly their limited critical temperature: it has also been their insufficient performance under ac currents and in the presence of strong magnetic fields. The first part of this report deals with this question. It turns out that considerable progress in the behavior of the cuprates under applied fields can be made by using an unconventional pinning mechanism directly based on the Bond Contraction Pairing (BCP) mechanism proposed by Deutscher and de Gennes (1).

In the second part we discuss a new mechanism for superconductivity that we may have uncovered in enhanced Tc granular Aluminum films. It turns out that free spins are present in these films, and that their local fluctuations may provide a retarded pairing mechanism. This mechanism may also be present in other not so well understood superconductors such as Kondo lattices.

I. **Inducing strong and isotropic vortex pinning**

In conventional low temperature superconductors strong vortex pinning can be achieved without a detailed understanding of the pairing mechanism. It is done mostly by introducing in the pristine material various defects, often called pinning centers, that locally reduce the superconducting order parameter on a length scale somewhat shorter than the coherence length. A vortex line has its energy reduced when it passes through such a center, because on that location no core condensation energy is lost. Thereby, the line is pinned. In the most widely used superconductor, NbTi, these defects are precipitates of a normal (non superconducting) phase, the alpha phase of Titanium. In NbTi the coherence length is on the order of 10 nanometers, and the precipitates should be a few nanometers in size. This is what has been realized.
In high temperature superconductors, the problem of engineering pinning centers cannot be separated from that of the high Tc mechanism itself. This is because all high Tc materials have a very short coherence length since according to BCS theory it is basically inversely proportional to Tc, all other parameters being the same. If

the coherence length is of the order of 1 nm, instead of ten nm, the size of an ideally engineering pinning center should be on the order of one lattice parameter, and therefore it cannot be a normal precipitate like in NbTi. What this really means is that in order to find out how to pin vortices in a high temperature superconductor, one should really understand the high Tc mechanism in the first place, while this is not necessary for a low Tc material.

We have shown that a solution to the vortex-pinning problem can be found based on the Bond Contraction Pairing (BCP) model (1). It consists in inducing strain in the High Tc matrix, which destroys local pairing by extending the Cu-O bond length (2) . As we have shown, a mirror but detrimental effect of Cu-O bond extension is the well known reduced critical current through grain boundaries (3).

A further problem in achieving good vortex pinning in high temperature superconductors is that they have a strongly anisotropic electronic structure, which translates into anisotropic critical current densities. This anisotropy is highly detrimental to the performance of devices such as coils in the presence of magnetic fields, because the field has different orientations with respect to the high Tc wire or tape. Then it is the orientation giving the lowest critical current that limits the overall coil performance. Reducing the critical current anisotropy is therefore a crucial issue. We believe that a solution to this problem has been found by the introduction of incoherent strain-inducing precipitates in the High Tc matrix (2).

Ia. Nature of the pseudo-gap and vortex pinning

There are clear experimental indications that in the cuprates strong Cu-O-Cu bond fluctuations precede the appearance of superconductivity (4). Such fluctuations are a distinct feature of high temperature superconductors. These findings are in agreement with the BCP model, since in that model bond fluctuations are a necessary prelude to the appearance of superconducting order: bond length fluctuations allow the dynamical local formation of Cooper pairs as the energy gained by contraction can be larger than the Coulomb repulsion when two holes are present at the extremities of the bond. Superconductivity occurs when fluctuating pairs eventually form a coherent superfluid.

It follows that the way to locally reduce the superconducting order parameter in order to induce vortex pinning on the *lattice length scale* is to locally quench bond *fluctuations*, which are in effect a measure of the pairing field. If bond length fluctuations are locally prevented, Cooper pairs cannot be formed on that location.

It has been known for some time that the critical current of high temperature superconductors can be enhanced by the introduction of insulating particles several nanometers in size. However the mechanism by which such particles enhance vortex pinning was unclear, because they are much bigger than the coherence length.

What we have shown in collaboration with the group of Obradors in Barcelona is that vortex pinning is actually achieved not by the particles themselves but rather by the lattice deformation of the matrix near the interface with the particles (2). This is borne out by a comparison of the pinning strength achieved by the inclusion of particles presenting different degrees of lattice mismatch with the matrix.

Particles having a small lattice mismatch are coherent with the matrix and induce only weak pinning, while vice-versa particles of the same size and concentration but with a stronger lattice mismatch are incoherent with the matrix and induce strong pinning.

So far our BCP model is the only one that has provided an explanation and theoretical guidance for these experiments. Local quenching of bond fluctuations is achieved by creating strained interfaces between the High Tc matrix and insulating randomly oriented incoherent precipitates, for instance Barium Zirconium Oxide (BZO), as we have shown in our work with the group of Obradors in Barcelona (2). One of the beauties of this method is that it also generates *isotropic* pinning, a necessary condition for the use of High Tc materials in rotating machines. In this way one of the main drawbacks of the layered structure of High Tc materials – a strong intrinsic anisotropy of the critical current – is overcome.

Ib. Practical high temperature superconductors

Some have argued that there is really no point in searching for superconductors having a higher critical temperature than have already been found, because such superconductors will necessarily have even shorter coherence lengths. Or in other terms, effective pinning centers cannot be engineered for such materials.
What we have shown is that such a pessimistic view is in fact wrong. Strong pinning can be achieved in short coherence length superconductors, but by using methods that are different from those used in low temperature – long coherence length superconductors.
The BCP model was developed originally for Cu-O-Cu based superconductors. We believe it also applies to the Fe-As-Fe based compounds, and more generally to all compounds where strong electron correlations are present: introducing local strain at interfaces with appropriate defects is the preferred solution to enhance vortex pinning, and make it at the same time isotropic.

II. Enhancing the critical temperature by generating a pseudo-gap through stronger electron correlation effects in the normal state – a counter intuitive approach to high Tc.

The existence of strong electron correlation effects in the cuprates and pnictides is well established, as they are not far from an anti-ferromagnetic state. They are marked inter-alia by the existence of a pseudo-gap above the critical temperature as seen for instance from NMR measurements, and a sub-linear temperature dependence of the normal state resistivity below the pseudo-gap temperature. The co-existence of strong electron correlation effects with a high Tc has represented from the start a major challenge for theorists, because in BCS theory stronger repulsive Coulomb interactions are detrimental to superconductivity. Hence the attempts by leading theorists to construct theories different from BCS, based entirely on electron-electron interactions, in which the attractive electron-phonon interaction plays no role at all. So far, they have remained controversial.

In order to shed some light on the possible favorable role of electron-electron interactions for the enhancement of the critical temperature of low Tc superconductors, we have gone back to the case of granular Al whose Tc can be several times higher than that of the bulk material. The conventional interpretation of this increase was that it is due to a stronger electron-phonon interaction resulting from soft phonon modes at the grains surfaces. But this interpretation was never substantiated. Could it be that it is in fact due to stronger electron-electron interactions?

Our recent measurements show in fact that an enhanced Tc and stronger electron-electron interactions go hand in hand with increased Coulomb interactions in granular Al (5).

IIa. <u>Evidence for a simultaneous increase of electron correlations and critical temperature in granular Al near the metal to insulator transition</u>

We have pointed out to the surprising and striking similarities between the transport properties of granular Aluminum films near the metal to insulator transition and those of Kondo systems, such as noble metals containing magnetic impurities and Kondo lattices (6). These similarities include a minimum of the normal state resistance at a temperature of several 10 K, a logarithmic increase of the resistance below that minimum, a negative second derivative of R(T) above it, and a negative magneto-resistance. We have shown that it scales at low fields as (H/T) with an exponent close to 2 (7).
In our most recent work we have studied in detail the behavior of the negative magneto-resistance in the very vicinity of the metal to insulator transition (8). We have found that its amplitude increases strongly. Eventually it fits a Kondo lattice regime where the number of free electrons per grain is of order unity, as is the number of free spins. These properties indicate strong electron-electron correlation effects. One might naively have expected that these should trigger a weakening of superconductivity, but just the opposite happens. Films near the metal to insulator transition have in fact critical temperatures 3 times higher than that of bulk Aluminum. This enhanced superconductivity in the presence of strong correlation effects poses difficulties similar to those posed by superconducting heavy fermions. It has been proposed that pairing in heavy fermions may be through *local* spin fluctuations (9). This proposition may apply to granular Aluminum as well, and explain the very high depairing field that we have observed in our Nernst effect studies (10).

Outreach activities

During this research period we have made a very successful effort to show what superconductivity can do to the public at large. Our videos on Quantum Levitation and Quantum locking have been seen by more than 9 million people the world over, possibly the largest number ever reached by any video on High Tc. Our post doc Dr. Boaz Almog was heavily involved in this effort.

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Submitted for publication

1. *Chemical solution growth of epitaxial $YBa_2Cu_3O_{7-x}$ fims on CeO_2/YSZ buffered sapphire substrates.*
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In preparation

1. *Transition to Kondo lattice superconductivity in granular Aluminum*
   N. Bachar, S. Lerer, B. Almog and G. Deutscher
2. *Nernst effect study of granular Aluminum: evidence for a very high depairing field.*
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