series (U-series) modeling is quantitatively compared with trace element modeling. Trace element fractionation depends on how much of the source is melted, whereas U-series disequilibria is dependent not only on how much of the source is melted but also on how rapidly it is melted. Both net elemental parent-daughter (e.g., U-Th) fractionation and the daughter (e.g., ^{230}Th) ingrowth contribute to the total U-series disequilibria. The relative contribution from net elemental fractionation and that from daughter ingrowth to total U-series disequilibria are further quantified. The daughter ingrowth is generally important in the generation of U-series disequilibria, particularly when the daughter has a short half-life (e.g., ^{226}Ra) and the melting rate is slow. Therefore, U-series disequilibria can not be attributed to net elemental fractionation alone. Some previous approaches to modeling U-series disequilibria using the equations for trace element fractionation are not sound in principle. Such approaches ignore the significant contribution from daughter ingrowth and would incorrectly require extremely small degrees of melting to explain the U-series disequilibria in young lavas.

SUPERCONDUCTIVITY – BASIC

"Magnetic" Ground State in Multiband Superconductors

Agterberg, D.F., NHMFL
Barzykin, V., NHMFL
Gor'kov, L.P., NHMFL

The pairing states due to the usual BCS mechanisms are considered[1,2] in substances of cubic and hexagonal symmetry where the Fermi surfaces form pockets around several points of high symmetry. It turns out that the symmetry imposed on the multiple pocket positions could give rise to a multidimensional nontrivial superconducting order parameter. If so, the time-reversal symmetry in the pairing state is broken. While all these non s-wave states are destroyed by non-magnetic impurities, the suppression is much weaker than would be expected for unconventional superconductors with isotropic non-magnetic impurity scattering. Several candidate substances where such ordering may appear. The list includes such materials as $CeCo_2$, $CeRu_2$, and LaB_6, all of which have the proper Fermi surface topology. In addition to the phase-sensitive experiments, nontrivial character of the order parameter may be observed by more traditional experiments provided that a Fermi surface pocket embraces the Zone center.

[1] Agterberg, D.F., *et al*., Europhys. Lett., **48**, 449 (1999).
[2] Agterberg, D.F., *et al.,* Phys. Rev. B, **60**, 14868 (1999).

Unconventional Cyclotron Resonance Observed in Sr_2RuO_4

Ardavan, A., Univ. of Oxford, Physics
Edwards, R., Univ. of Oxford, Physics
Rzepniewski, E., Univ. of Oxford, Physics
Schrama, J.M., Univ. of Oxford, Physics
Singleton, J., Univ. of Oxford, Physics
Maeno, Y., Kyoto Univ., Japan

The layered perovskite oxide superconductor Sr_2RuO_4 was discovered in 1994.[1] Since then it has generated much interest, both theoretical and experimental, including measurements of magnetic quantum oscillations, the effect of non-magnetic impurities, heat capacity, Knight shift, and muon spin rotation; evidence for a ferromagnetically-mediated spin-triplet p-wave groundstate seems strong.[2,3,4] Evidence for strong electron correlations has stimulated interest in measuring cyclotron resonance,[3] since it has been proposed that the contributions to the effective mass renormalization from electron-electron interactions and electron-phonon interactions can be separated by comparing the mass measured by cyclotron resonance with the effective mass found in thermodynamic measurements and the calculated band mass.[5] Recently, a measurement of cyclotron resonance in Sr_2RuO_4 has been reported.[3] In that study, however, there was no measurement of the dependence of the observed resonances on magnetic field orientation; measurement of the angle-dependence has been shown to be important in other low-dimensional systems.[6]

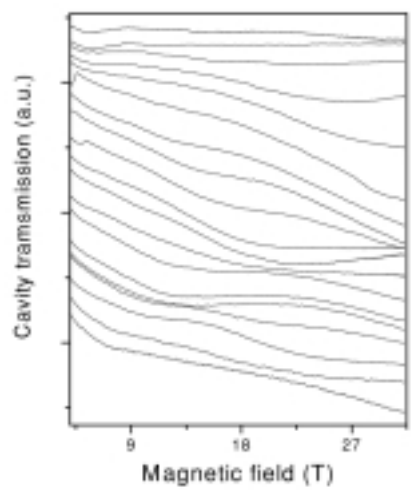

Figure 1. Millimeter-wave response of Sr_2RuO_4 at 70 GHz and 0.6 K; the amplitude transmission of a resonant cavity containing the sample is shown; a minimum corresponds to a resonance in the high-frequency conductivity of the sample. The angle range is 0 degrees (top trace) to 70 degrees (bottom trace). Several resonances are visible, exhibiting strongly angle-dependent behavior.

Using the 33 T steady fields at NHMFL, we measured the angle dependence of the millimeter-wave response of Sr_2RuO_4 at 70 GHz and 0.6 K. Figure 1 shows the raw data obtained (the amplitude transmission of a resonant cavity containing the sample is shown; a minimum corresponds to a resonance in the high-frequency conductivity of the sample). The angle range

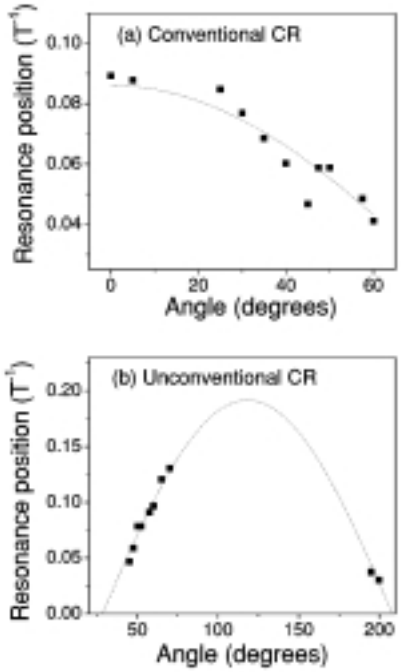

Figure 2. The positions of resonances (in inverse-field) are plotted as a function of polar angle, θ.

is 0 degrees (top trace) to 70 degrees (bottom trace). Several resonances are visible, exhibiting strongly angle-dependent behavior. The positions of resonances (in inverse-field) are plotted as a function of polar angle, θ, in Figure 2. One branch of resonances is found to follow the expected cos θ dependence for traditional two-dimensional cyclotron resonance (Figure 2(a)). Other resonances behave in quite different ways (Figure 2(b)), demonstrating that the interpretation as cyclotron resonance is over-simplified. The non-conventional behavior arises from a combination of factors: the measurement probes the interplane conductivity component[3,6] and the interplane warping in Sr_2RuO_4 is complicated.[4] We are developing a theoretical framework in which to explain our results; in the interim, we question the assignment of the resonances reported in reference,[3] and the "cyclotron masses" extracted from them.

1 Maeno, Y., *et al*., Nature 372, **532**, (1994).
2 For a review, see Maeno, Y., Physica C, **282-287**, 206 (1997).
3 Hill, S., *et al*., cond-mat/9905147.
4 Bergemann, C., *et al*., cond-mat/9909027.
5 See, for example, Singleton, J., *et al*., Phys. Rev. Lett., **68**, 2500 (1992).
6 Ardavan, A., *et al*., Phys. Rev. Lett., **81**, 713 (1998).

^{17}O NMR Evidence for Paramagnetic Vortex Pinning in $NdBa_2Cu_3O_7$ IHRP

Bachman, H., Northwestern Univ. and Science and Technology Center for Superconductivity
Mitrovic, V.F., NWU, STCS
Sigmund, E., NWU, STCS
Halperin, W.P., NWU, STCS
Kishio, K., Tokyo Univ., Physics
Kagayama, T., Tokyo Univ., Physics
Reyes, A., NHMFL
Kuhns, P., NHMFL
Moulton, W.G., NHMFL

We report ^{17}O NMR data on near-optimally doped $NdBa_2Cu_3O_7$ (NdBCO) aligned powder indicating that vortex pinning is influenced by the paramagnetism of the Nd ion. ^{17}O NMR spectra are broader than those of $YBa_2Cu_3O_7$ (YBCO). For $T << T_c$, the ^{17}O lineshapes at both 8.0 T and 23.2 T are near-gaussian showing that the vortex distribution is highly disordered, in contrast to the well-known asymmetric lineshape expected for a vortex lattice, as is seen in YBCO. The temperature dependence of the peak position of the spectra is shown in Figure 1.

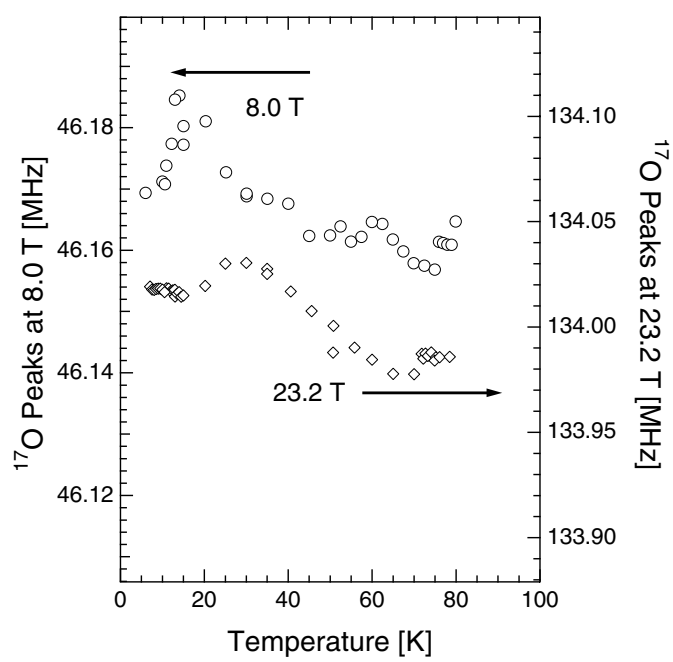

Figure 1. Peak positions of the NdBCO spectra at 8 T (circles) and 23.2 T (squares) as a function of temperature.

Above 40 K, the ratio of the temperature variation in shifts scales linearly with magnetic field confirming that Nd paramagnetism contributes significantly to the ^{17}O spectrum shifts. The interplay between the Nd ion and the vortices may cause a crossover in the arrangement of vortices inducing an intrinsic lineshape change as temperature is lowered below ~13 K for 8.0 T data and ~30 K for 23.2 T data. Spin-spin (T_2) relaxation exhibits exponential time decay from 6 K to room temperature

and is faster than that of YBCO. Vortex dynamics and Nd moment fluctuations likely cause the additional relaxation. As shown in Figure 2, T_2 data shows both magnetic field and site dependence. The convergence of the T_2 data for O(2,3) and O(4) sites at low temperatures is a strong indication that the relaxation is dominated by vortex dynamics, since no other physical process has a length scale sufficiently large to cause the two different oxygen sites to have such similar relaxation profiles.

Acknowledgements: This work is supported in part by the NSF (DMR 91-20000) through the STCS.

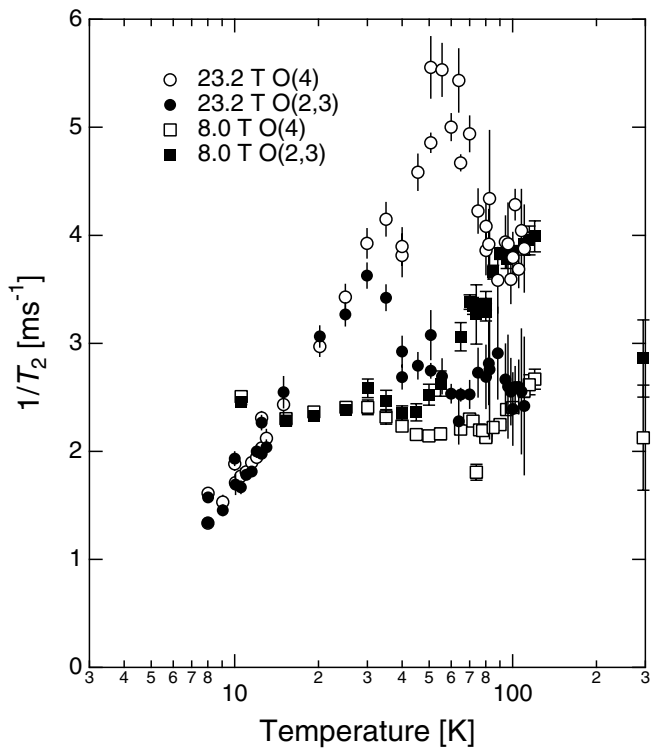

Figure 2. Spin-spin relaxation data at 8 T (squares) and 23.2 T (circles) for the O(4) (open symbols) and O(2,3) (filled symbols) sites.

Large, Linear c-Axis Magnetoresistance in $YBa_2Cu_3O_{7-\delta}$

Balakirev, F.F., NHMFL/LANL
Ando, Y., CRIEPI, Japan
Passner, A., Lucent Technologies-Bell Labs
Betts, J.B., NHMFL/LANL
Schneemeyer, L.F., Lucent Technologies-Bell Labs
Segawa, K., CRIEPI, Japan
Boebinger, G.S., NHMFL/LANL

We report a transport regime in underdoped high temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) with a large, positive c-axis magnetoresistance (MR) that is strikingly linear over a wide magnetic field range up to 60 T. This behavior is in stark contrast with negative c-axis MR that has been previously observed in many high-T_c compounds: YBCO[1,2]; $Bi_2Sr_2CuO_x$[3,4]; $Bi_2Sr_2CaCu_2O_x$[5,6]; and $(La,Sr)_2CuO_4$[7,8].

Figure 1 shows the MR in four samples of YBCO with different oxygen doping. The measurements are done in the longitudinal geometry, with current and magnetic field both along the c-axis ($I \parallel B \parallel c$). For each magnetic field pulse, the temperature is fixed. Data taken below T_c show a relatively sharp transition from the superconducting to a resistive state. The midpoint of this sharp transition approximately corresponds to the upper critical field H_{c2} determined from the reversible magnetization[6]. The subject of this study is the MR in the resistive state at magnetic fields well above the transition from the superconducting state (as highlighted in Figure 1 by the thicker line in the 60 K data from sample 2).

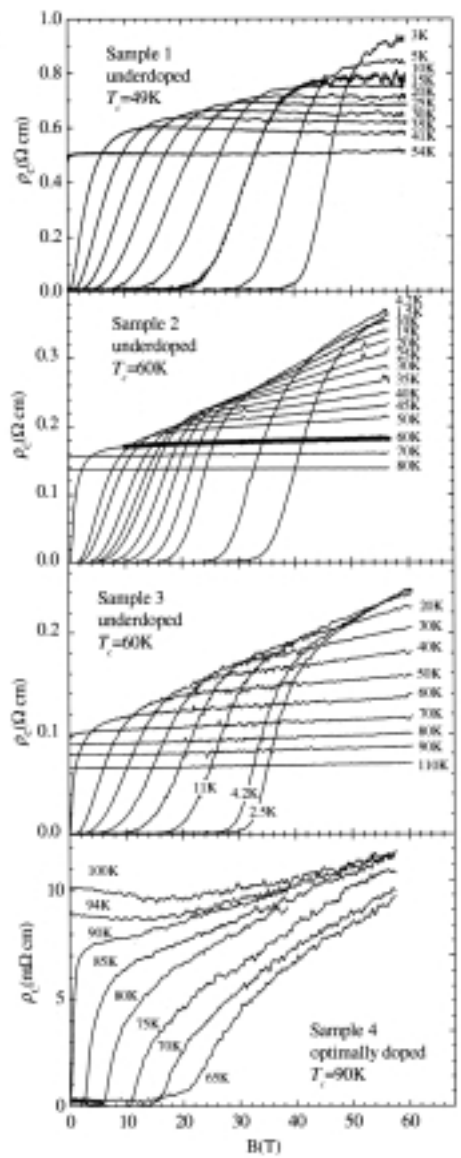

Figure 1. c-axis magnetoresistance in a series of four $YBa_2Cu_3O_{7-\delta}$ samples, with different oxygen doping ranging from strongly underdoped (sample 1) to near-optimal doping (sample 4).

The very underdoped sample (T_c ~49 K, top panel) shows a slight negative MR, consistent with that observed in other cuprates[1-8]. The large, positive, MR is observed once T_c becomes larger than ~55 K. In samples 2 and 3 the MR is clearly linear in magnetic field in the temperature range from ~10 K to ~80 K. The linear MR has a strong temperature dependence, being largest at the lowest temperatures, and extends to the highest available magnetic fields. The near-optimally-doped sample 4 shows some evidence of the linear MR region, although it is limited to temperatures near T_c. At the time, the mechanism for MR which is linear in field over a range of more than 50 T remains a mystery.

1 Yan, Y.F., *et al*., Phys. Rev. B, **52**, R751 (1995).
2 Axnäs, J., *et al*., Phys. Rev. Lett., **77**, 2280 (1996).
3 Ando, Y., *et al*., Phys. Rev. Lett., **77**, 2065 (1996).
4 Yoshizaki, R., *et al*., Physica C, **271**, 171 (1996).
5 Hashimoto, K., *et al*., Phys. Rev. B, **53**, 892 (1996).
6 Ando, Y., *et al*., Phys. Rev. B, **60**, 12475 (1999).
7 Kimura, T., *et al*., Phys. Rev. B, **53**, 8733 (1996).

Shared Transport Regimes in Two-Leg Spin-Ladders and High-T_c Superconductors

Balakirev, F.F., NHMFL/LANL
Betts, J.B., NHMFL/LANL
Boebinger, G.S., NHMFL/LANL
Motoyama, N., Univ. of Tokyo, Superconductivity
Eisaki, H., Univ. of Tokyo, Superconductivity
Uchida, S., Univ. of Tokyo, Superconductivity

Spin-ladder compounds make interesting analogs of the high-temperature superconductors,[1] because they contain layers of nearly one-dimensional "ladders" consisting of a square array of copper and oxygen atoms. Increasing the number of legs in the ladders provides a step-wise approach toward the two-dimensional copper-oxygen plane, that structure believed to be a key to high temperature superconductivity. Superconductivity has indeed been discovered in the two-leg ladder compound $Sr_{0.4}Ca_{13.6}Cu_{24}O_{41}$.[2]

There are numerous similarities in the properties of high-T_c and ladder cuprates, including an energy gap for spin excitations[3] and a crossover from insulator to metal upon hole doping. These suggest that the ladder compounds provide a valuable experimental laboratory for probing the unusual properties of the resistive normal state of the high-temperature superconductors.

We measured c-axis resistivity along the two-leg ladders in single-crystal samples of $Sr_2Ca_{12}Cu_{24}O_{41}$ that were grown by the traveling-solvent-floating-zone method.[4] We find that the two-leg spin-ladder shares three transport regimes in common with the high-T_c cuprates. In addition to the variable range hopping regime commonly observed at low temperatures in the presence of disorder, these two systems share two regimes for which the underlying physical mechanisms remain unknown. This is the regime with logarithmic insulating behavior[5], $\rho_c \sim log(1/T)$, observed between 2 K and 20 K (Figure 1), and the regime with nearly linear temperature dependence of resistivity, $\rho_c \sim T$, observed at higher temperatures (Figure 1, inset).

This data, together with the recent evidence of a one-dimensional charge transport regime associated with the stripe formation in high-T_c cuprates,[6,7] suggest that similar physical mechanisms can govern normal-state transport properties in the two-leg ladder compound and the high-T_c cuprates and that the log-T behavior in both the two-leg spin-ladder and high-T_c cuprates involves nearly one-dimensional charge transport in the presence of strong spin interactions.

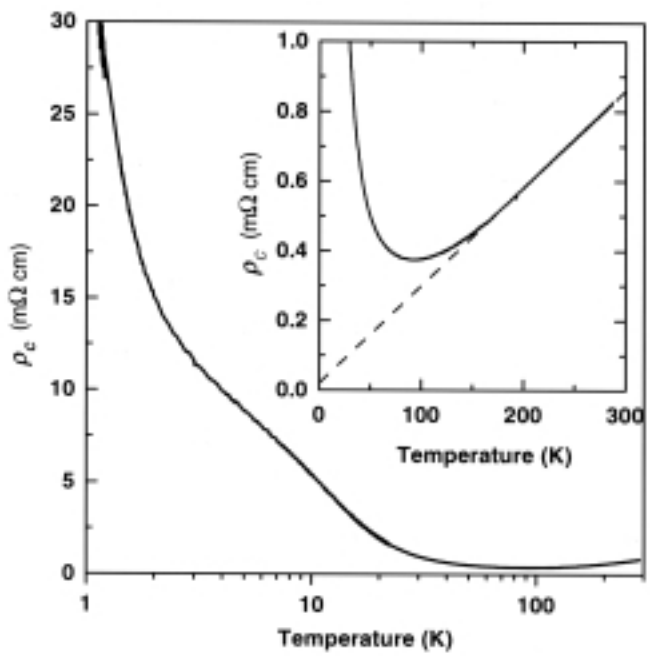

Figure 1. Transport regime in a $Sr_2Ca_{12}Cu_{24}O_{41}$ sample, which is best described by $\rho_c \sim log(1/T)$. The inset demonstrates the linear-T transport regime in the same sample. Dashed line is the best linear fit to $\rho_c \sim aT+b$.

1 Dagotto, E., *et al*. Science, **271**, 618 (1996).
2 Uehara, M., *et al*., J. Phys. Soc. Jpn., **65**, 2764 (1996).
3 Maguchi, K., *et al*., Phys. Rev. B, **57**, 11533 (1998).
4 Motoyama, N., *et al*., Phys. Rev. B, **55**, R3386 (1997).
5 Boebinger, G.S., *et al*., Phys. Rev. Lett., **77**, 5417 (1996).

Collective Mode of Complex Gap Superconductors

Balatsky, A.V., LANL
Kumar, P., NHMFL/UF, Physics
Schreiffer, J.R., NHMFL/FSU, Physics

We have determined the spectrum of collective modes of a $d_{x^2-y^2}$ superconductor in the presence of an external magnetic field. At a finite field, an order parameter of id_{xy} symmetry is introduced. The induced component is linearly proportional to the external field as well as the amplitude of the original order $d_{x^2-y^2}$ parameter. The resulting energy gap is nodeless over the entire Fermi surface, although the magnitude of the gap is anisotropic and its smallest value is proportional to the field. The presence of this additional OP component leads to an upward curvature in the temperature dependence of the upper critical field, a characteristic of nearly all-high T_c superconductors. There is an orbital magnetic moment arising from the supercurrents. We have also studied the collective modes of this 2-OP system. There are two collective modes: one, corresponding to the in phase motion of the 2 OP, is gapless. The other, where the 2-OP components oscillate out of phase, also corresponds to the longitudinal oscillations of the orbital magnetic moment. It has a field dependent gap (and a field dependent propagation velocity) proportional to the magnitude of the energy gap. This mode is an important fingerprint of the field broken time reversal symmetry of the d-wave superconductor.

Effect of Uniaxial Stress on the Field-Induced Spin-Density Waves Phase Diagram and Rapid Oscillations of $(TMTSF)_2ClO_4$

Balicas, L., NHMFL and Venezuelin Institute for Scientific Research
Choi, E.S., NHMFL and Seoul National Univ., Research Institute for Basic Sciences
Brooks, J.S., NHMFL/FSU, Physics
Qualls, J., NHMFL/FSU, Physics

We studied, by electrical transport techniques, the effect of stress (up to 8 kbar) along the **c*** axis, on the low temperature phase diagram of the organic superconductor $(TMTSF)_2ClO_4$. A priori stress along **c*** is expected to increase the inter-plane transfer integral t_c as well as t_c' (the unnested band integral along the c axis) and to decrease the amplitude of the inter-chain transfer integral t_b as well as t_b' due to Poisson effect. The unnested band integral along the b axis is considered to be the most relevant physical parameter in the so-called field-induced spin-density-wave phases (FISDW) standard model.[1] In this model, if t_b' decreases with stress then we should expect the magnetic threshold fields among FISDW transitions H_T^N also to decrease in value.

Figure 1 shows the magnetoresistance, as a function of field B, for several values of stress along **c*** and at a temperature $T = 2$ K.

Despite our initial expectations, and as seen in Figure 1, H_T^N (indicated by the change in slope) increases linearly with stress what is a clear indication that the coupling between the planes t_c, particularly t_c' instead of t_b' governs H_T^N.

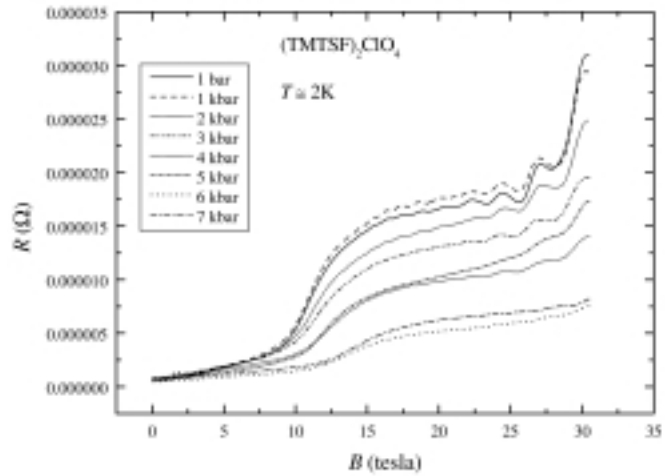

Figure 1. Magnetoresistance as a function of magnetic field B, for several values of stress applied along the c* axis at T = 2.0 K.

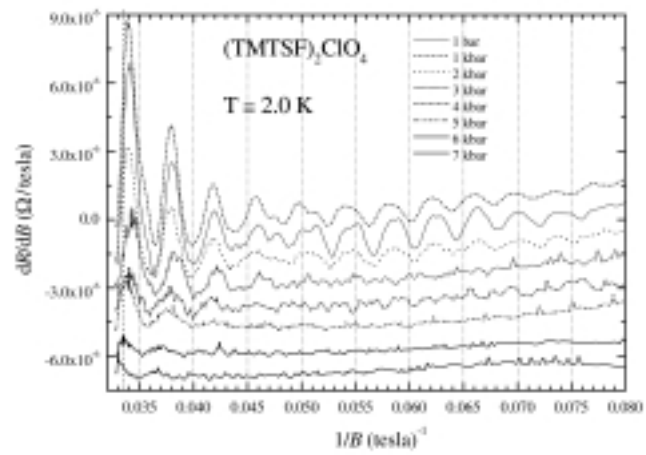

Figure 2. Derivative of the magnetoresistance (shown in Figure 1) respect to the magnetic field, dR/dB, as a function of inverse field 1/B.

In Figure 2, we show the derivative of the magnetoresistance respect to the magnetic field, *dR/dB*, as a function of inverse field *1/B* for several values of stress and at a temperature $T = 2$ K. As seen in this figure stress has little effect on the frequency F of the so-called magnetoresistance rapid oscillations (RO's): $F = 250$ T at 1 bar and increases up to ~ 280 T at 8 kbar.

On the other hand we did not notice any change on the unusual temperature dependence of the amplitude of the RO's. The major effect of stress is to decrease significantly the amplitude of the RO's, as well as the amplitude of the background magnetoresistance. In other words, as the system becomes progressively more metallic, due to the application of stress,

the RO's tend to disappear, which suggests that they are closely related to the density wave ground state.

[1] See for example: Gor'kov, L.P. and Lebed, A.G., J. Phys. (Paris) Lett., **45**, L433 (1984).
[2] Brooks, J.S. *et al*., Phys. Rev. B, **59**, 2604 (1999).

High Field Normal State of the Unconventional Superconductor Sr_2RuO_4

Bergemann, C., Cavendish Laboratory, Univ. of Cambridge, U.K.
Brooks, J.S., FSU, Physics/NHMFL
Mao, Z.Q., Kyoto Univ., Japan, Physics
Maeno, Y., Kyoto Univ., Japan, Physics

The layered perovskite oxide, Sr_2RuO_4, has recently attracted considerable scientific attention since it appears to be an ideal material to investigate unconventional superconductivity in real depth. While the superconducting state is believed to exhibit unusual spin-triplet p-wave pairing, there are good prospects of a complete understanding of the normal state properties within the standard Fermi liquid theory.

One major question has been how this normal state evolves in a magnetic field. This normal state is directly related to the proposed scenario of ferromagnetic spin fluctuation mediated superconductivity, and to the interpretation of recent high field cyclotron resonance studies.

We performed a high field study of the Haas-van Alphen (dHvA) effect in a high-purity sample of Sr_2RuO_4 (T_c = 1.44 K), using a capacitive torque sensor. A typical example of the torque signal vs. field and its dHvA frequency spectrum are shown in Figure 1. The temperature and field dependence of

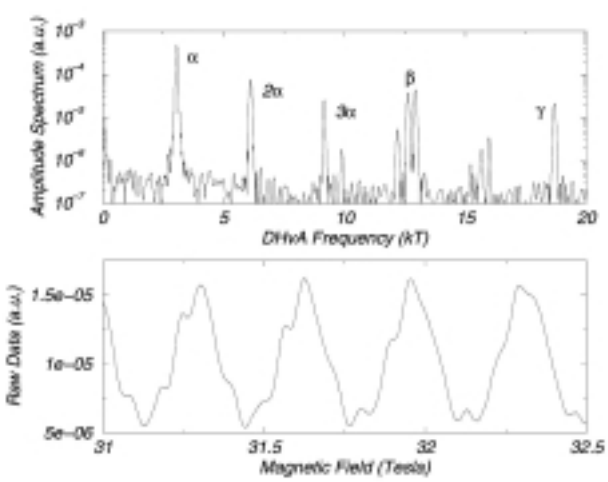

Figure 1. Example of the raw quantum-oscillatory magnetic torque (bottom panel) and the corresponding dHvA frequency spectrum (top panel).

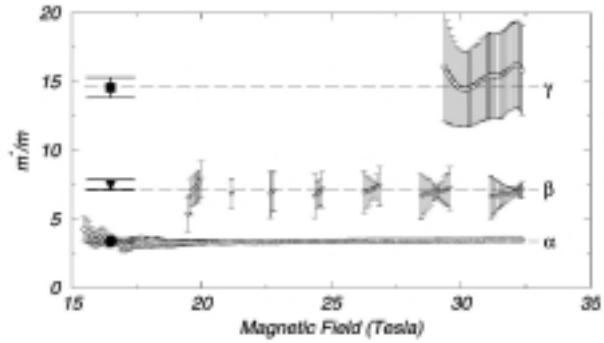

Figure 2. The extracted on-axis quasiparticle masses (small symbols) are field-independent to within the precision of our measurement and also agree with previously reported mass values at lower fields (large symbols). To reduce the error bars on the mass of the γ-sheet, additional very low temperature runs on a dilution refrigerator are necessary.

the oscillations corresponding to the three Fermi surface sheets was used to extract the field-dependent quasiparticle masses. The main results are

- Both the shape of the Fermi surface and the quasiparticle masses are field independent up to 33 T (see Figure 2), within our error limits
- No evidence has been found for magnetic breakdown effects
- The thermodynamically dominant γ- sheet is almost purely two-dimensional.

Acknowledgements: This work was supported in part through NSF grant DMR-NSF-9971474 and the U.K. EPSRC.

Study of Spin and Charge Fluctuations in the U-t-t' Model

Buhler, C., NHMFL/FSU, Physics
Moreo, A., NHMFL/FSU, Physics

Comparing experimental data for high T_c cuprate superconductors with numerical results for electronic models, it is becoming apparent that a hopping along the plaquette diagonals has to be included to obtain quantitative agreement. The values for t' discussed in the literature, however, were obtained comparing theoretical results in the weak coupling limit with photoemission data and band structure calculations. The goal of this paper[1] is to study how t' gets renormalized as the interaction between electrons, U, increases. For this purpose, the effect of adding a bare diagonal hopping t' to the two dimensional Hubbard model Hamiltonian is investigated using numerical techniques. Spin-spin correlations, n(k), <n> vs the chemical potential, and local magnetic moments are studied for several values of U/t and the electronic density. The spectral function A(k,w) is also discussed.

We introduce a new criterion to determine probable locations of Fermi surfaces at zero temperature. In general, we conclude that it is very dangerous to extract a bare parameter of the

Hamiltonian (t') from PES data where renormalized parameters play the important role.

[1] Buhler, C. and Moreo, A., Phys. Rev. B, **59**, 1 (1999).

Phase Fluctuations and the Pseudogap in the Cuprate Superconductors

Dorsey, A.T., UF, Physics
Kwon, H.-K., UF, Physics

One of the intriguing properties of the cuprate superconductors is the existence of a "pseudogap" regime in the normal phase, in which the materials exhibit a gap in the single particle spectrum (as measured by photoemission, for example) but are not superconducting. One explanation for this behavior, proposed by Emery and Kivelson, is that the pseudogap regime has local superconducting order, but large phase fluctuations destroy the long range phase coherence. Indeed, phase fluctuations are expected to be larger in the cuprates than in conventional superconductors, due to their low superfluid density (a property of doped Mott insulators).

We adopt this point of view in our work[1] and examine the effect of the phase fluctuations on the single particle properties that would be probed by photoemission or scanning tunneling spectroscopy. In our model the fluctuating phase induces a fluctuating Doppler shift in the spectrum of the quasiparticles. The properties of the transverse phase, or vortex, fluctuations change dramatically as one approaches the superconducting transition, which in our two dimensional model is a Kosterlitz-Thouless vortex-pair unbinding transition. In passing through this transition there is a significant broadening of the quasiparticle spectral function and a distinct pseudogap feature, similar to what is observed in the photoemission experiments. These results are currently being extended to the study of transport properties in the pseudogap regime.

[1] Kwon, H.-J. and Dorsey, A.T., Phys. Rev. B, **59**, 6438 (1999).

Indications of Spin-Charge Separation in the 2D Extended t-J Model IHRP

Eder, R., Univ. of Wuerzburg, Germany, Physics
Martins, G., NHMFL
Dagotto, E., NHMFL/FSU, Physics

The 2D extended t-J model is studied computationally in a broad region of parameter space, motivated by recent photoemission experiments for the undoped cuprate $Ca_2CuO_2Cl_2$ (Ronning, F., *et al*., Science 282, 2067 (1998)).[1] The one-hole ground state is shown to develop robust antiferromagnetic (AF) correlations between spins separated by the mobile hole (i.e. across the hole). This effect tends to decouple charge from spin, and the quasiparticle weight becomes negligible, particularly at momenta $(0, \pi)$-$(\pi, 0)$. Studies with more holes show precursors of metallic stripe formation, with holes sharing their individual spin arrangements, and AF-correlations generated across the stripe.

[1] Martins, G., *et al*., Phys. Rev. B, **60**, R3716 (1999).

Response to the Magnetic Field of Superconducting Materials from the Vicinity of the Superconductor-to-Insulator Transition

Gantmakher, V., Institute for Solid State Physics, Russian Academy of Sciences
Tsydynzhapov, G., Institute for Solid State Physics, Russian Academy of Sciences

The program of the experiments with NdCeCuO includes $B_{c2}(T)$ measurements on single crystals and detailed R(B,T) measurements on films with strong disorder, and both should be extended down to low temperatures. In November, 1999, the first part of this program was realized. Two NdCeCuO single crystals with superconductivity transition temperature T_c near 20 K were measured in the temperature range down to 25 mK and fields up to 18 T. The value of $B_{c2}(T)$ was defined as onset of the resistive transition on the isotherms R(B).

A sharp increase of B_{c2} in the low temperature range was registered on both samples: more than 25% when temperature decreased from 1.5 K to 25 mK with no tendency to saturation instead of approximately 1% expected in the frame of BCS theory where $B_{c2}(T)$ saturates when T approaches zero. This new result means that though NdCeCuO differs from other high-T_c superconductors in the sign of carriers, it behaves like other materials from the high-T_c families with low carrier density (like Tl- and Bi-based high-Tc superconductors, underdoped YBaCuO, etc.). Most likely, there should be a common explanation for such behavior of all these materials, and that based on boson-like nature of Cooper pairs is the most probable. The bipolaron theory predicts that function $B_{c2}(T)$ should diverge at low temperatures.

The theory predicts also for bosonic superconductor zero derivative dB_{c2}/dT at T_c and nonlinearity in its vicinity. We plan to extend the measurements on the same single crystals to higher temperatures up to T_c to confirm this prediction. The data will be presented at the international workshop on *Microscopic Structure and Dynamics of Vortices in Unconventional Superconductors and Superfluids* to be held in Dresden from February 28 to March 3, 2000. The article containing the combined data will be written immediately after that.

The data obtained for NdCeCuO, together with recently published similar data for YBaCuO, are strong evidence for boson model, but not the final evidence. We expect to get further arguments from comparison of high-field low-temperature behavior of NdCeCuO single crystals and disordered films (the

films are now under preparation). The absolute values of B_{c2} on two single crystals differed by 10% in spite of approximately the same values of T_c. This indicates that the high field phenomena are very sensitive to the disorder and reinforce expectations that NdCeCuO films will demonstrate different behavior in high magnetic fields.

The paper summarizing the above results is to be published.

Superconducting Properties Of $BaNbO_{3-X}$ Films

Gasparov, V.A., Institute of Solid State Physics, Moscow, Russia
Gasparov, L.V., UF, Physics
Wang, H.S., Penn State Univ., Physics
Li, Q., Penn State Univ., Physics
Brandt, B.L., NHMFL

Recently, we have discovered that $BaNbO_{3-x}$ ceramic compounds, with perovskite cubic structure and large oxygen nonstoichiometry, $0.6<x<1$, exhibit superconductivity with a T_c as high as 22 K, although stoichiometric $BaNbO_3$ is metallic but not superconducting.[1] While it is not completely clear whether the superconductivity is intrinsic property or is due to inter-crystalline phases, one of the interests currently is in superconducting properties of thin films of this new family of copper free, oxygen reduced niobates.

The films were grown on heated (100) $SrTiO_3$, Al_2O_3, YSZ, MgO and $NdGaO_3$ substrates by ablating a single target with a pulsed Nd-YAG laser, in a UHV chamber. Superconductivity was observed for films on Al_2O_3 only.[2] Assuming cubic perovskite structure, the lattice parameter of the films was determined in the range 0.412 to 0.414 nm, in comparison with 0.432 to 0.435 nm for ceramics.[1] No nitrogen and no other elements except for the original components were detected from the XPS spectra. The superconducting transition temperature, T_c = 14 K, of these films was determined from the temperature dependence of the fluctuation conductivity.

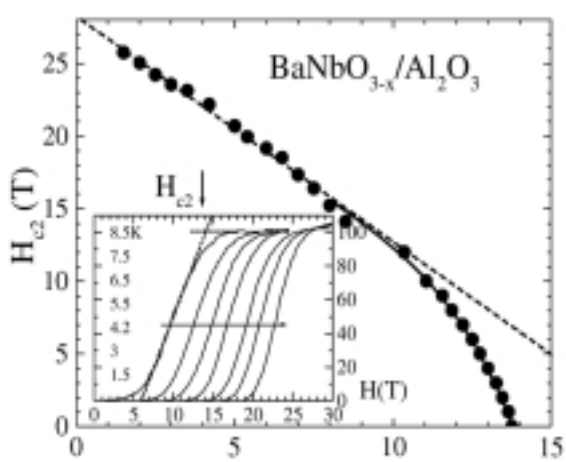

Figure 1. Temperature dependence of $H_{c2}(T)$ for films on Al_2O_3. Inset shows the perpendicular field resistive transition curves at different T.

As we can see from the Figure 1, the resistive upper critical magnetic field $H_{c2}(T)$ is found to be extremely high.[2] This field was derived from fluctuation para-conductivity ($T_c(H)$) at temperatures above and from linear extrapolation of the sheet resistance $R_s(H)$ curves below 10 K. Contrary to conventional Helfand-Werthamer theory,[3] we find that below 10K the $H_{c2}(T)$ dependence is linear with $H_{c2}(0)$ = 28 T ($\xi(0)$ = 34Å) and with no evidence of saturation down to 1.5K. This linear $H_{c2}(T)$ dependence is characteristic for 2D superconductors,[4] although the temperature dependence of fluctuation conductivity has a clear 3D form. Therefore, we have to point out that further work is necessary for higher T_c films preparation and further $H_{c2}(T)$ investigations for an unambiguous assignment.

Acknowledgements: We acknowledge support of U.S. Civilian Research and Development Foundation (Grant RE1-356), NSF Grant No.DMR-9876266, Russian Council on High-Temperature Superconductivity (Volna 4G), NSF Grant No. DMR-9527035, and the State of Florida.

1 Gasparov, V.A., *et al.*, JETP Lett., **60**, 440 (1994); Physica C, 291, 207 (1997).
2 Gasparov, V.A., *et al.*, Physica B, (2000), accepted for publication.
3 Helfand, E., and Werthamer, N.R., Phys. Rev. Lett., **13**, 686 (1964); Phys. Rev., 147, 288 (1966).
4 Prober, D.E., *et al.*, Phys. Rev. B, **21**, 2717 (1980).

Strongly Correlated Fermions

Henelius, P., NHMFL
Schrieffer, J.R., NHMFL/FSU, Physics

The spin orbit coupling of a magnetic impurity and the conduction electrons leads to an admixture of the superconductor $d_{x^2-y^2}$ order parameter with the component d_{xy}. We have calculated the interaction between two such patches of mixed order parameter to second order in the spin orbit coupling.

We find that the coupling falls off as the universe cube of the distance between impurities. These results are important as they relate to the experimentally observed low temperature phase transition which presumably arises when the impurity spins become aligned due to this coupling. The Josephson coupling between impurities adds to the coupling we have determined, however, it falls off exponentially and leads to a weaker coupling.

Cyclotron Resonance in the Layered Perovskite Superconductor Sr_2RuO_4

Hill, S., Montana State Univ., Physics
Brooks, J.S., NHMFL/FSU, Physics
Mao, Z.Q., Univ. of Kyoto, Physics, and CREST-JST, Japan
Maeno, Y., Univ. of Kyoto, Physics, and CREST-JST, Japan

The superconducting state in the layered Perovskite, Sr_2RuO_4, is a strong candidate for p-wave pairing.[1] In spite of the structural similarities between this compound and the high-T_c superconductors (HTS), striking differences set them apart, e.g. although strong electron-electron interactions (EEIs) feature in both, the normal state in Sr_2RuO_4 conforms to the behavior expected of a 2D Fermi-liquid (FL). Meanwhile, the itinerant ferromagnetism in related ruthenates contrasts with the antiferromagnetism found in close proximity to superconductivity in the HTS phase diagram.

The availability of high quality single crystals of Sr_2RuO_4 has enabled extremely precise experiments, including the observation of magnetic quantum oscillations.[2] These studies have, in turn, enabled rigorous comparisons with theory. We report the observation of cyclotron resonance (CR) in the normal state of Sr_2RuO_4.[3] By comparing CR masses with those deduced from de Haas-van Alphen (dHvA) measurements, we can gauge the strength of EEIs in the title compound, and further test the applicability of FL theory, which predicts that CR and dHvA measurements should differ in their sensitivity to EEIs.

Experiments were performed using a high sensitivity cavity perturbation technique over the frequency range from 40 to 80 GHz, and in fields up to 33 T. The single crystal was grown by a floating zone technique and has a T_c (mid point) of 1.44 K.

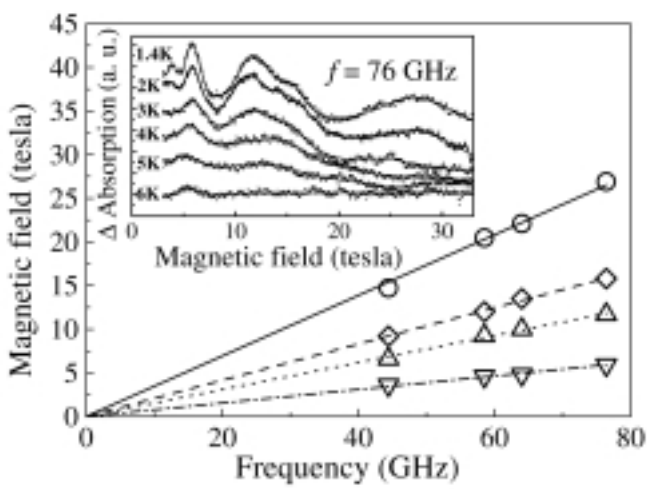

Figure 1. Inset: on cooling, CR are observed in the field dependent absorption within the cavity. The CR peak positions are plotted versus frequency in the main part of the figure. All of the data fall on straight lines passing through the origin, as expected for CR.

From fits to the CR peak positions vs. frequency (Figure 1), we are able to deduce CR masses for the three Fermi surfaces: $m_{c\gamma} = 9.7m_e$, $m_{c\beta} = 5.8\ m_e$ and $m_{c\alpha} = 4.3\ m_e$. For the most part, these values are lower than the dHvA masses ($m^*_\gamma = 14.6\ m_e$, $m^*_\beta = 7.5\ m_e$ and $m^*_\alpha = 3.4m_e$).[2] The ratio of the mass enhancements for the γ and β pockets, $[(m^*_\gamma/m_{c\gamma})-1]/[m^*_\beta/m_{c\gamma})-1] = 1.73$, is similar to the ratio of the thermodynamic masses, $m^*_\gamma/m^*_\beta = 1.95$, providing strong evidence that the mass enhancement scales with the density-of-states at the Fermi energy ($\propto m^*$), as expected for an interacting 2D FL.

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2 Mackenzie, A.P., *et al.*, J. Phys. Soc. Jpn., **67**, 385 (1998).
3 Hill, S., *et al.*, to be published in Phys. Rev. Lett. (2000).

d-Wave Superconductor in a Magnetic Field

Hirschfeld, P.J., UF, Physics

In the case of a weak field, the current response of the *d*-wave superconductor at low temperatures has long been treated in a local approximation. The nonlocal response of the condensate cannot be neglected at the lowest temperatures, however, despite the fact that the in-plane coherence length is nominally two orders of magnitude smaller than the penetration depth, since the effective coherence length for the quasiparticles is $v_F / {}_k$, which diverges along the nodal directions. The nonlocal energy competes with other energies, like the impurity bandwidth or the nonlinear field scale at easily accessible laboratory fields, leading to new physics. We have calculated the free energy of a d-wave superconductor in both the Meissner and vortex states, using an expansion in powers of the superfluid velocity and its gradients. The expansion is valid at all temperatures and fields up to several tens of teslas in the cuprates, allowing an extension of previous results in the Ginzburg-Landau regime. In the low field state, we discuss the effect of nonlocal physics on the breakdown of the nonlinear Meissner effect, which has not been observed.[1] In the vortex state, we investigate the role of induced subdominant pair components and search for low-temperature phase transitions that have been claimed to be responsible for "kinks" in the field dependence of the thermal conductivity of the cuprates.[2] No such transitions were found, casting doubt on these scenarios.

1 Li, M.R., *et al.*, Phys. Rev. B, **61**, 648 (2000).
2 Li, M.R., *et al.*, "Vortex State of a *d*-wave Superconductor at Low Temperatures," submitted to Phys. Rev. B.

Disorder and Order Parameter Suppression in *d*-Wave State

Hirschfeld, P.J., UF, Physics
Atkinson, W.A., UF, Physics

It is well known that impurities are strongly pair-breaking in d-wave superconductors, but the consequences of this fact for quasiparticle transport have never been explored. Because the superconducting order parameter is strongly suppressed

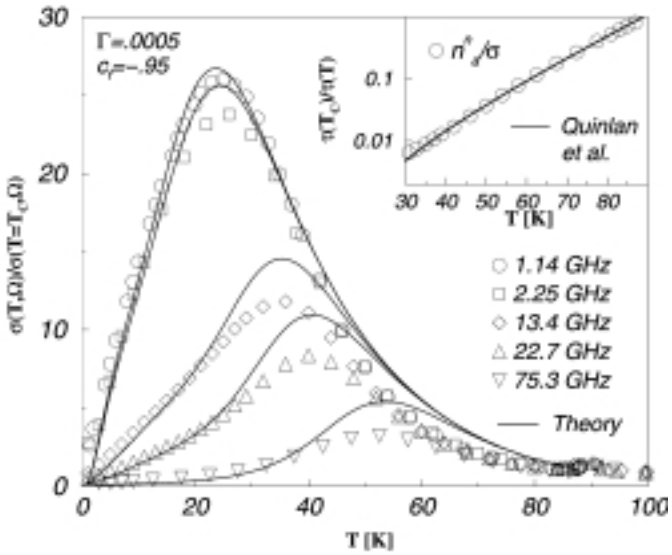

Figure 1. Microwave conductivity at various external frequencies for YBCO single crystal. The symbols are experimental data (Hosseini *et al*., cond-mat/9811041), theory (Hettler & Hirschfeld, 1999).

around each impurity site, quasiparticles are scattered by a self-consistently determined off-diagonal pair potential in addition to the bare impurity potential. With a local ansatz for the order parameter suppression consistent with the short coherence length in, e.g. the cuprate materials, we have constructed an impurity T-matrix including the off-diagonal scattering effects.[1,2] We found that there is a shift of spectral weight in the dissipative part of the electronic self-energy, leading to substantial changes in the low-temperature behavior of transport coefficients. In particular, the peculiar temperature and frequency dependence of the microwave conductivity in ultrapure crystals of YBCO measured by the British Columbia group was explained in some detail by accounting for these effects.

More recently, we performed large-scale numerical solutions of the Bogoliubov-de Gennes equations for a d-wave system including impurities.[3] We find the surprising result that the order parameter suppression leads to a dramatic ***suppression*** of the impurity-induced density of states near the Fermi energy. This is in dramatic contradiction to the usual "Swiss cheese" picture of small metallic regions around the impurity sites.

1 Hettler, M.H. and Hirschfeld, P.J., Phys. Rev. B, **59**, 9606 (1999).

2 Hettler, M.H. and Hirschfeld, P.J., "Order Parameter "Holes" and Theory of Microwave Conductivity in YBCO," submitted to P.R.L., cond-mat/9907150.

3 Atkinson, W.A., *et al*., "Effect of Order-Parameter Suppression on Scattering by Isolated Impurities in Asymmetric Bands," submitted to 6th Int'l Conference on Materials and Mechanisms of Superconductivity (Houston, Feb. 1999).

^{139}La High Field NMR in a $La_{1.90}Sr_{0.10}CuO_4$ Single Crystal

Julien, M.-H.,* Iowa State Univ./Ames Lab and Univ. of Pavia
Borsa, F., Iowa State Univ./Ames Lab and Univ. of Pavia
Kuhns, P., NHMFL

Although $La_{2-x}Sr_xCuO_4$ is probably the best studied high-T_c superconductor (HTSC) it still continues to reveal new phenomena that were not observed, or were overlooked, in the past. One of the most powerful techniques that was applied to this compound is the nuclear magnetic resonance (NMR). Although NMR has largely contributed to our understanding of magnetic properties of HTSCs,[1] it becomes now recognized that some important features were not detected. This is the case of the coexistence of superconductivity with a frozen magnetic state called a "cluster spin-glass," as revealed by recent studies.[2,3]

We initiated a re-investigation of the phase diagram with a ^{139}La NMR study of $La_{1.94}Sr_{0.06}CuO_4$ [4] at high field (23.2 T). The sample is a single crystal, which gives NMR spectra much more resolved than with a powder. Since the superconducting state expels any magnetic flux (and so expels the NMR excitation pulses) below T_c=26 K, we lower T_c down to a few K with the high field applied along the c-axis, and investigate the NMR properties of the normal state down to low temperatures. Interestingly, charge localization phenomena were recently evidenced at high magnetic field (H~60 T, ||c) [4] in these compounds. Since a relationship between charge localization and spin freezing is likely,[3] it is interesting to compare the results for spin fluctuations at high fields with those at low fields (obtained by NQR and/or by μSR).

As shown in Figure 1, the spin-lattice relaxation rate (1/T1) of ^{139}La nuclei is dramatically enhanced below ~40 K. This shows that the dynamics Cu^{2+} spins in CuO_2 planes continuously slows down on cooling, with fluctuations as low as the NMR frequency

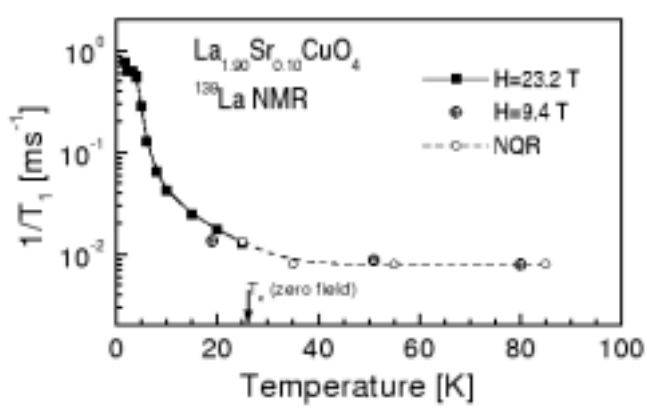

Figure 1. 1/T1 data of ^{139}La vs. temperature. The increase at low temperature is due to the slowing down of magnetic fluctuations.

(140 MHz) at low temperatures (the freezing temperature Tg is probably between 1 K and 2 K, although it could not be determined accurately). Within our experimental precision, the vast majority of Cu^{2+} spins are involved in the freezing process. This process does not depend on the magnetic field, since quantitatively similar results were independently found by μSR.[5] *So, we conclude that spin-freezing coexists with bulk superconductivity in* $La_{1.90}Sr_{0.10}CuO_4$ (the latter is confirmed by magnetization measurements in this sample[6]). Through high field ^{139}La NMR spectroscopy we could also detect a magnetic broadening of spectra below 40-50 K, i.e. a distribution of local magnetic fields, which we attribute to the growth of the mean value of paramagnetic Cu^{2+} moments, on approaching the ordered phase.

*Present Address: UJF, Grenoble, France

1 Berthier, C., *et al*., J. Phys. I, **12**, 2205 (1996); Rigamonti, A., *et al*., Rep. Prog. Phys., **61**, 1367 (1998).
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3 Julien, M.-H., *et al*., Phys. Rev. Lett., **83**, 604 (1999).
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6 Unpublished.

Enhancement of the Upper Critical Point in Heavy Ion Irradiated $YBa_2Cu_3O_{7-d}$

IHRP

Kwok, W.K., Argonne National Laboratory (ANL)
Olsson, R. J., ANL
Karapetrov, G., ANL
Paulius, L.M., Western Michigan Univ., Physics
Moulton, W.G., NHMFL/FSU, Physics
Hofman, D.J., ANL
Crabtree, G.W., ANL

The upper critical point was investigated in untwinned $YBa_2Cu_3O_{7-d}$ single crystals with dilute columnar defects. A series of crystals were irradiated at Argonne's Tandem Linear Accelerator System (ATLAS) with 1.4 GeV $^{208}Pb^{56+}$ to a dose matching field of B_Φ=50 G, 100 G, 500 G, and 1000 G. The vortex lattice melting transition was characterized with transport measurements up to H=17 T || c at the NHMFL in Tallahassee. Figure 1 shows the temperature dependence of the superconducting resistive transition for the B_Φ=1000 G crystal and compares it with an unirradiated reference crystal cleaved from the same sample. The sharp kink in the resistivity for the unirradiated crystal is associated with the first order vortex lattice melting transition and is observed from 0.5 T up to about 9 T where it disappears. For the irradiated crystal, we observe a similar kink in the resistivity starting near 4 T and extending to beyond 10 T, as shown by the arrows in Figure 1. First order melting is clearly demonstrated in the inset to Figure 1 where we show the temperature derivative of the resistivity for the irradiated crystal. The peaks in dρ/dT reflect the kink in the resistivity at the first order melting transition.

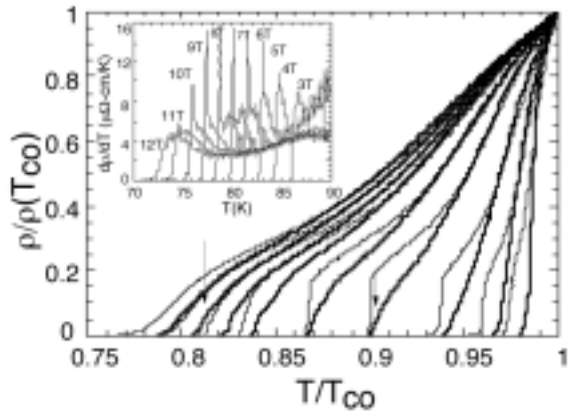

Figure 1. Temperature dependence of the resisitivity for the unirradiated (thin lines) and irradiated (thick lines) crystals for H=0.5, 1, 2, 4, 6, 8, 9, 10, and 11 T parallel to the c-axis. Inset: Temperature derivative of the resistivity for the irradiated crystal.

Figure 2 shows the phase diagram of the melting transition determined from the temperature derivative of the resistivity. First order vortex melting occurs in the region between the upper and lower critical points and is shown by triangles. Above the upper critical point, the squares represent the locations of the resistive zeros. For the first time, we report on a dramatic upward shift in the upper critical point from H_{ucp}=9 T to H_{ucp}=11 T after irradiation. We interpret this effect as due to the line-like longitudinal geometry of the columnar defect, which reduces the transverse wandering and entanglement of the vortices. This effect tends to increase the order of the lattice state, and stabilizes it against entanglement to higher fields. The increase in the upper critical point by columnar defects provides direct experimental evidence that entanglement is a key feature of the high field disordered state. Since point defects promote vortex line meandering, the addition of a few columnar defects suppresses the meandering, resulting in an enhancement of the upper critical point.

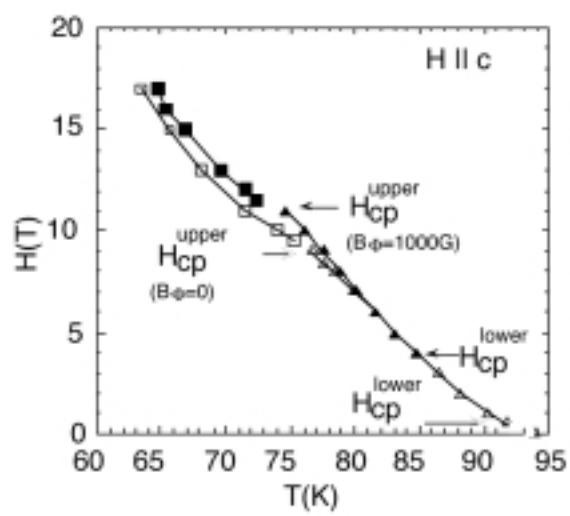

Figure 2. Superconducting phase diagram depicting the upper and lower critical points of the first order vortex melting transition in the unirradiated (open symbols) and irradiated (closed symbols) crystals.

Investigations of C-Axis Transport in Highly Anisotropic Layered Superconductors

Maley, M.P., LANL
Krusin-Elbaum, L., IBM
Morozov, N., LANL
Bulaevskii, L.N., LANL
Shibauchi, T., LANL/IBM

During this period we have carried out extensive measurements of c-axis transport properties of Bi-2212 single crystals in dc magnetic fields up to 33 T at NHMFL-Tallahassee and in pulsed magnetic fields up to 60 T in the long-pulse (LP) system at NHMFL-LANL. In the highly anisotropic high-temperature superconductors, HTS, current flows across layers by tunneling, both superconducting by Cooper pairs (Josephson tunneling) and normal by quasi-particles. We have previously discovered that quasi-particle tunneling in the superconducting state can be directly observed in single crystal "mesas" (micron-size stacks of copper-oxide planes) by exceeding the Josephson critical current and switching into the resistive state. The quasi-particle (QP) conductivity thus measured reflects the d-wave symmetry of the superconducting state and, in low magnetic fields, exhibits an enhancement produced by the effect of vortex currents on the quasi-particle spectrum (Volovik effect) followed at higher fields by a saturation caused by quasi-particle scattering from vortex disorder. Our experiments at NHMFL were intended to extend the investigation to measure the effects on QP conductivity of high magnetic fields and of the associated high concentration of vortices. For the pulsed field measurements we employed mm-size single crystals of Bi-2212, and used the high magnetic fields to suppress the Josephson tunneling currents. During the past 6 months we have made a number of interesting discoveries:

- The field dependence of the c-axis conductivity is consistently described by tunneling of Cooper pairs and quasi-particles across a d-wave superconductor. We have demonstrated that the maximum in $\rho_c(H)$, the c-axis magnetoresistance, (Figure 1) comes from the competition between these two conduction channels below H_{c2} and is not, as previously assumed, a signature of H_{c2}.
- At the highest magnetic fields (H>50 T) we observe a saturation of ρ_c (T) (Inset Figure 1) and show that it is a consequence of d-wave (gapless) superconductivity.
- We observe a remarkable linear-in-magnetic-field quasi-particle conductivity that extends to fields above any reasonable estimate for $H_{c2}(T)$, and which remains far below the normal state conductance. This may be reflecting the influence of the pseudo-gap.

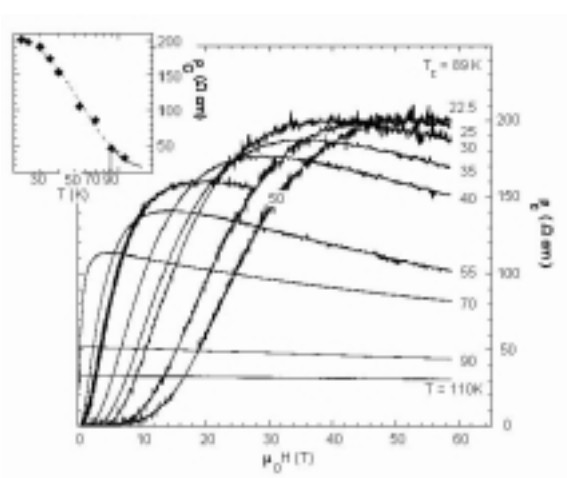

Figure 1. Out-of-plane resistivity ρ_c vs. H of Bi-2212 crystal in fields up to 60 T at different temperatures (j=0.05 A/cm^2). Inset: ρ_c vs. T at 55 T(♦) and at 0 T (line).

Hole Density Evolution of the One-Particle Spectral Function in Doped Ladders IHRP

Martins, G., NHMFL
Gazza, C., NHMFL
Dagotto, E., NHMFL/FSU, Physics

The spectral function A(q,w) of doped t-J ladders is presented on clusters with up to 2x20 sites at zero temperature applying a recently developed technique that uses up to 6 million rung-basis states.[1] Similarities with photoemission results for the 2D cuprates are observed, such as the existence of a gap at (π,0) near half-filling (caused by hole pair formation) and flat bands in its vicinity. These features should be observable in ARPES experiments on ladders. The main result of the paper is the nontrivial evolution of the spectral function from a narrow band at x=0, to a quasi-noninteracting band at x>0.5. It was also observed that the low-energy peaks of a cluster spectra acquire finite line-widths as their energies move away from the chemical potential.

[1] Martins, G., et al., Phys. Rev. B 59, 13596 (1999).

Magnetoresistance of Sr_2RuO_4 Under High Magnetic Fields Parallel to the Layer Plane

Ohmichi, E., Kyoto Univ., Physics
Maeno, Y., Kyoto Univ., Physics
Ishiguro, T., Kyoto Univ., Physics

The inter-plane resistivity, ρ_c, and the in-plane resistivity, ρ_{ab}, of the layered superconductor Sr_2RuO_4 were studied at 50 mK under magnetic fields, B, up to 33 T applied parallel to the conducting plane. The main motivation of the present work was to search for superconductivity recurrence under high magnetic fields applied precisely parallel to the superconducting plane in Sr_2RuO_4 after the prediction by Lebed and Yamaji.[1] The resistive decrease implying the emergence of the field-induced superconductivity, however, was not found up to 33 T for ρ_c and

ρ_{ab}.[2] This indicates that the threshold for the superconductivity recurrence, if it exists, is higher than 33 T, or the purity of the sample was not high enough, although it exhibited the residual resistance ratio reaching 10^3 and T_c of 1.41 K close to the intrinsic transition temperature.

In the normal state, it is expected that a parallel magnetic field induces confinement of the electrons within the conducting plane in Sr_2RuO_4 with two-dimensional electronic structure, when the inter-plane electron transfer is incoherent. The magnetoresistance showed a pronounced in-plane anisotropy. The temperature dependence of the magnetoresistance was negligibly small below 1.5 K, implying that the increase in ρ_c is not due to the induction of the nonmetallic state but due to the dynamics of electrons. ρ_c under a magnetic field parallel to the [100] direction, $\rho_c(B \parallel 100)$, was almost proportional to the field strength up to 33 T, while ρ_c $(B \parallel 110)$ showed superlinear dependence $\sim B^{1.6}$ in the broad field region. It is to be noted that $\rho_c(B \parallel 110)$ exhibited a sharp resistance peak centered at the parallel field direction, while $\rho_c(B \parallel 100)$ did not show such dependence. The results are attributable to the in-plane anisotropy of the inter-plane transfer energy giving a coherent electron transfer in the inter-layer direction.

On the other hand, $\rho_{ab}(B \parallel 110)$ (the current direction was along the [110] direction) depended weakly on the field below 10 T, but it grew notably above 15 T without exhibiting any decreasing behavior up to 33 T, with the resistance ratio of ρ_{ab} (33 T)/$\rho_0 \cong 70$. For ρ_{ab} $(B \parallel 100)$, however, we found an unusual decrease above 30 T, reaching ~10%, although it cannot be ascribed to the field-induced superconductivity, which should be very sensitive to the inclination angle.

We would like to express our sincere thanks to late Dr. Mark Whitton for his kind guidance and support during the experiment at NHMFL.

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2 Ohmichi, E., *et al*., Phys. Rev. B, **61**, 7101 (2000).

Low Temperature Normal State of the High T_c $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ Revealed by 60 T Magnetic Fields

Ono, S., CRIEPI, Japan
Ando, Y., CRIEPI, Japan
Murayama, T., CRIEPI, Japan
Balakirev, F.F., NHMFL/LANL
Betts, J.B., NHMFL/LANL
Boebinger, G.S., NHMFL/LANL

We investigated transport properties of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi-2201) high-T_c cuprate down to 0.5 K over a wide range of carrier concentrations by suppressing the superconductivity with 60-T pulsed magnetic fields. It was found previously that in the hole-doped $La_{2-x}Sr_xCuO_4$ (LSCO) system a metal-to-insulator (MI) crossover in the normal state takes place exactly at the optimum doping.[1,2] More recently, similar findings were reported for the electron-doped $Pr_{2-x}Ce_xCuO_{4+\delta}$ (PCCO) system.[3] Whether MI crossover is universally associated with the optimum doping in high-T_c cuprates is an important question, in particular for the so-called quantum critical point model of the high-T_c cuprates.

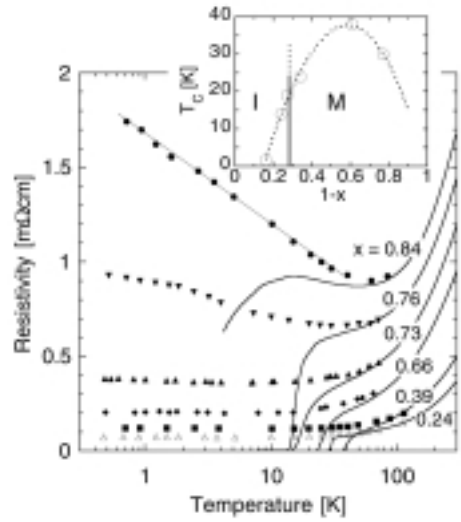

Figure 1. T dependence of ρ_{ab} of the $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ crystals in 0 T (solid lines) and 60 T (symbols). The straight line emphasizes the log (1/T) behavior. Inset: Phase diagram of T_c versus 1-x, in which the MI boundary is schematically shown.

Bi-2201 is a hole-doped high-T_c compound in which the carrier concentration can be varied in a wide range, from the overdoped to the underdoped region[4], which makes it an attractive system for the study of the low-temperature MI crossover. The single crystals of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ are grown for this experiment using a floating-zone technique for a wide range of La concentration x, from x=0.23 (overdoped) to 0.84 (heavily underdoped).[4] The resistivity is measured in the transverse geometry, with current along the Cu-O plane and magnetic field along the c-axis ($I \parallel ab$, $B \parallel c$). Figure 1 shows the T dependence of ρ_{ab} in 0 T and 60 T, for six x values (x=0.23, 0.39, 0.66, 0.73, 0.76 and 0.84). The x=0.39 sample is optimally doped with $T_c \sim 38$ K.

In zero field, all the samples are metallic ($d\rho_{ab}/dT > 0$) except for the x=0.84 sample. When we apply the 60 T field and completely suppress the superconductivity, the metallic behavior gradually changes to an insulating one ($d\rho_{ab}/dT < 0$) with decreasing carrier concentration (increasing x). Thus, the MI crossover in the BSLCO system is more gradual than that in the LSCO system.[1,2] A salient feature here is that a metallic behavior is found in an underdoped sample and therefore the MI crossover lies in the underdoped region, not at the optimum doping. This result is notably distinct from that reported for LSCO[1] or for PCCO[2], indicating that the metal-to-insulator crossover in cuprates is not universally associated with the optimum doping. We also note that $\rho_{ab}/(T)$ of the most underdoped sample (x=0.84) increases as log (1/T) with decreasing temperature for over almost two decades in temperature which bears essential similarity with the still

unexplained log (1/T) behavior reported for underdoped LSCO.[1]

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High Field Magnetic Resonance in $RuSr_2GdCu_2O_8$

Oseroff, S., San Diego State Univ., Physics
Fainstein, A., Centro Atomico Bariloche, Argentina
Talon, J., Industrial Research Ltd., New Zealand
Van Tol, J., NHMFL

The first example of microscopic coexistence of superconductivity and ferromagnetism has recently been reported in a high T_c superconductor, the hybrid ruthenate-cuprate compound $RuSr_2GdCu_2O_8$ (Ru_{1212}).[1] In this compound, structurally similar to the high-T_c superconductor $GdBa_2Cu_3O_7$ (Gd_{123}), ferromagnetism associated with the Ru^{5+} ions develops below T_{curie} ~ 133 K, while a superconducting onset is observed below T_c ~ 146 K without any apparent effect over the magnetic state. The interplay between superconductivity and magnetism has been an active subject of research for a long time. Cases have been reported where superconductivity coexists with antiferromagnetic long range order (e.g., in Gd_{123}, where Gd order antiferromagnetically below ~ 2.3 K[2]), or re-entrant systems, where the onset of ferromagnetism destroys the superconducting state (e.g., in $ErRh_4B_4$ [3]).

Marginal coexistence of ferromagnetic order and superconductivity, on the other hand, has been observed under some special conditions in the Chevrel phase compound $HoMo_6S_8$.[4] Shortly after its discovery, several publications have appeared addressing the structural, magnetic and transport properties of Ru_{1212}.[1,5-7] Concerning the magnetic properties, dc-magnetization and muon spin rotation experiments have been reported, providing evidence that the ferromagnetic phase is homogeneous on a microscopic scale, and that the magnetic order is not modified at the onset of superconductivity.[1,6] Numerous questions are still open, however, in particular concerning the specific magnetic structure of the Ru moments and the internal fields sensed by the superconducting planes. These points are essential to understand the coexistence of superconductivity and ferromagnetism in Ru_{1212}, and to devise further pertinent experiments.

To complement the 9 and 35 GHz magnetic resonance data, we have initiated a high field magnetic resonance study of Ru_{1212} polycrystalline samples in the temperature range of 5 to 300 K in order to address these questions. Magnetic resonance experiments have proved in the past to provide valuable data for understanding the complex magnetic properties of mixed paramagnetic-magnetically ordered systems similar in this sense to $RuSr_2GdCu_2O_8$. Figure 1 shows 110.33 GHz EPR spectra at 250, 120, and 30 K. The broad feature at 3.1 T is a background signal, not from the sample. Below the Curie temperature of 133 K, the Ru ferromagnetic resonance peak appears around 0.9 T. The Gd peak at 4 T shifts to lower fields and broadens when the temperature is lowered. Both transitions appear unaffected by the superconducting transition.

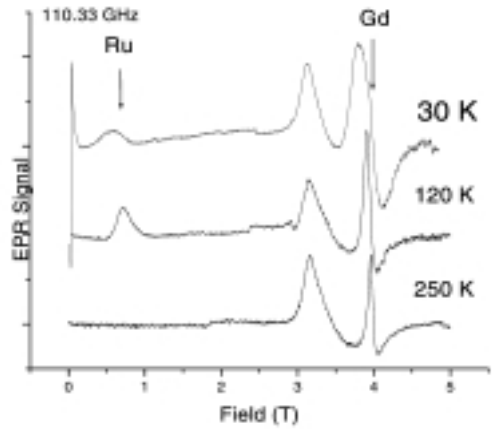

Figure 1. EPR spectra of $RuSr_2GdCu_2O_8$ at 110.33 GHz.

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Evidence for Ba-Site Occupation of Pr^{3+} in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ from Cu NQR

IHRP

Reyes, A., NHMFL
Abdelrazek, M., NHMFL/FSU, Physics
Kuhns, P., NHMFL
Moulton, W., NHMFL/FSU, Physics

Dow suggested recently that the depression of superconductivity in Pr-doped YBCO is due to pair breaking from Pr local moments on the Ba-O plane.[1] In this system, the atomic size matching allows for solubility of Pr into the Ba site, but its presence has not been proven directly, even though up to 15% occupation has been estimated. As a consequence of this site substitution, an otherwise empty site O(5) gets occupied by an oxygen ion. We have investigated its effects on the crystal electric field gradient (EFG) by $^{63,65}Cu$ nuclear quadrupole resonance (NQR) measurements on polycrystalline samples of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ (x=0.2, 0.5, 0.8, 1.0).

A typical NQR spectrum for x = 0.2 sample is shown in Figure 1. An anomalous peak was observed at 19 MHz on the Cu(1) line, which is non-existent in the x = 0 sample. We have interpreted this peak to be coming from the ^{65}Cu isotope with

a pair ^{63}Cu peak at around 20.6 MHz. No other extraneous peaks were observed for the Cu(2) site, indicating that only the Cu(1) site is sensitive to Pr substitution. We have performed a numerical Monte Carlo calculation of the lattice EFG taking into account the disorder brought about by oxygen deficiency on the chains and Pr concentrations as well as variations in the charge distribution within the crystal. We assumed that the on-site term does not change appreciably as a function of doping. These simulations show that (1) the effect of Pr/Ba substitution, combined with O(5) site occupation, is to introduce an extra line at almost half the EFG (~0.5 esu) of the main Cu(1) line, with the Cu(2) line mostly undisturbed; (2) without O(5) occupation and substituting Pr^{4+} on the Y^{3+} site, Cu(1) spreads into a wide peak at higher EFG and the Cu(2) spectrum broadens into multiple peaks; and (3) introducing oxygen disorder in the Cu-O chain wipes out the entire Cu(1) line as the spectrum distributes over a wide range of frequency. The simulations suggest that O(5) is indeed present in our samples and that the broadening that we see in the lines is not a result of disorder along the Cu-O chain or deficiency of the O(1) sites. The contribution of disorder on the Cu(2) lines puts a lower bound on the oxygen content of our sample to be better than $\delta = 0.09$. Additional broadening could come from some internal electronic structure.[2]

The presence of the anomalous peak at the Cu(1) site can be explained by numerical calculations and is consistent with the presence of oxygen on the anti-chain O(5) site. Although this result supports the picture of chain-superconductivity[1], it does not preclude the possibility that the suppression of superconductivity in this system is due to something other than the magnetic fluctuations in the Ba-O plane.

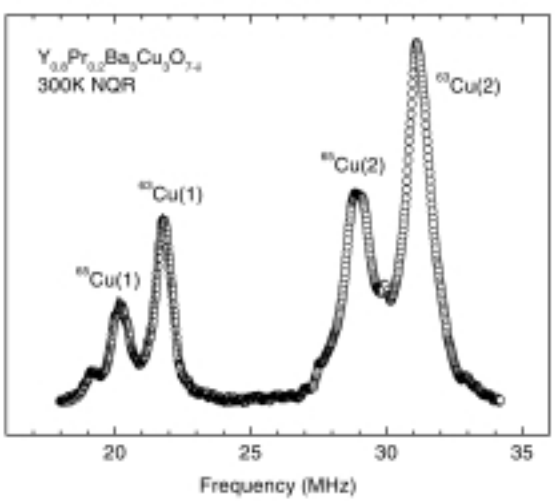

Figure 1. NQR spectrum for x = 0.2 sample. The solid line between 18 to 25 MHz is a fit to four Lorentzian peaks.

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Calorimetric Study of Flux-Lattice Melting in YBCO

Schilling, A., Lawrence Berkeley National Laboratory/ Univ. of Zurich, Physics
Fisher, R.A., LBNL
Phillips, N.E., LBNL
Welp, U., Argonne National Laboratory
Kwok, W.K., ANL
Crabtree, G.W., ANL
Hundley, M.F., LANL
Lacerda, A.H., NHMFL/LANL

The original discovery of thermodynamic first-order flux-lattice melting in YBCO[1] at LBNL utilized magnetic fields that extended only to 9 T. Those experiments indicated that the latent heat of the first-order melting transition was decreasing and would probably vanish at a critical point at some higher magnetic field. An apparatus, using the same Differential Thermal Analysis (DTA) technique used at LBNL, was designed for use in the 20 T magnetic facility at the NHMFL at LANL, and was constructed at the University of California at Berkeley. This apparatus was used to extend the investigation to above 9 T. In 1998, time constraints limited the amount of data that could be taken to H 14 T, and to constant magnetic field sweeps of temperature. This left unanswered some interesting questions about the nature of the melting at higher fields, and the region of the phase diagram in which irreversible effects are expected. In a final visit to NHMFL at LANL in January 1999 some low-field measurements were repeated, measurements during sweeps of temperature at constant field were extended to 18 T, and constant-temperature sweeps of magnetic field were made. The results give a complete picture of the flux-lattice melting to 18 T. The latent heat decreases with increasing field and goes to zero at ~10 T. At higher fields the melting is second order. The constant temperature sweeps of magnetic field have defined a region of irreversibility in both temperature and field. The results should be ready for publication in 2000.

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Thermal Expansion and Magnetostriction of $LuNi_2B_2C$

Schmiedeshoff, G.M., Occidental College, Physics
Beyermann, W.P., Univ. of California at Riverside, Physics
Lacerda, A.H., NHMFL/LANL
Smith, J.L., LANL

We have measured the volume thermal expansion and magnetostriction of a polycrystalline cube of the non-magnetic superconductor $LuNi_2B_2C$ from about 3K to 40 K and in magnetic fields to 18 T. The linear thermal expansion in zero field and in 18 T (with the dilation measured both parallel and perpendicular to the field) were identical within experimental uncertainty. (We find it somewhat surprising that the zero field data that includes a contribution from the superconducting state agrees so well with the high field data in which the

superconductivity is suppressed, however, the appearance of superconductivity can be subtle in thermal expansion measurements.[1])

The volume thermal expansion α_V below about 25 K was well fit by a function of the form

$$\alpha_V = aT+bT^3,$$

where a and b are constants characterizing the electronic and lattice contributions to the thermal expansion respectively.[2] Making use of values of the molar volume V_m, isothermal compressibility κ, and Sommerfeld coefficient γ from the literature we find an electronic Gruneisen parameter

$$\Gamma_{el} = V_m a/\kappa\gamma = 0.84,$$

consistent with $LuNi_2B_2C$ being a (relatively) simple metal.

The volume magnetostriction, is small and increases quadratically with field as expected for a slightly paramagnetic metal in the normal state. We did not observe any hysteresis in the superconducting state within experimental uncertainty.

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Competing Magnetic and Superconducting States in $RuSr_2GdCu_2O_8$

Sushko, Yu. V., NHMFL/Boston College, Physics
Wang, D.Z., Boston College, Physics
Yang, S.X., Boston College, Physics
Ren, Z.F., Boston College, Physics
Naughton, M.J., Boston College, Physics
Bianchi, A., NHMFL
Fisk, Z., NHMFL/FSU, Physics

The possibility of coexistence of ferromagnetism (FM) and superconductivity (SC) in a microscopic scale has been an intriguing subject for a long time. The two types of order are antagonistic and tend to suppress each other. Although there exist some exotic ways for coexistence (i.e., formation of a spiral magnetic structure where the magnetic moment cancels out on the scale of the superconducting penetrating depth), usually the occurrence of a spontaneous magnetic moment results in suppression of SC order in real systems. That is what the experiment revealed in reentrant systems, so-called ferromagnetic superconductors $ErRh_4B_4$[1] and $HoMo_6S_8$,[2] and the organic superconductor κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl.[3] Recently, however, a uniform coexistence between FM order and SC has been reported in the hybrid ruthenate-cuprate compound $RuSr_2GdCu_2O_8$ (Ru-1212).[4]

In view of such an unusual observation we have performed a detailed study of static magnetization of Ru-1212. Polycrystalline samples were prepared by a standard solid state reaction technique. DC magnetization measurements were carried out with the use of a commercial SQUID magnetometer. For both zero field cooling (ZFC) and field cooling (FC) processes, the data were collected on warming.

Our data allows us to distinguish two clear cases:

1. ZFC. M vs. T curves show a sharp cusp at ~130 K with M decreasing upon further cooling and leveling off on approaching ~50 K. A large SC diamagnetic shielding signal is detected below ~25 K, and another, much weaker one, below ~47 K. Increasing the strength of the applied field gradually resolves the upper SC transition, but simultaneously suppresses the more pronounced lower temperature one. Under 100 Oe applied field, the lower SC transition is completely suppressed.

2. FC. No cusp is observed in M(T) dependence. Instead, a steep increase of magnetization starts at ~130 K and continues all the way down to 5 K. The low temperature value of the magnetization M(50 K) is at least three times larger then in the ZFC case. No diamagnetic Meissner signal is detected, even in the limit of low applied field, ~1 Oe.

Such complex behavior with pronounced history effects does not allow us to corroborate the picture of a microscopic coexistence of long-range FM and SC order in $RuSr_2GdCu_2O_8$. Our results instead suggest that the magnetism associated with the transition at ~130 K is due to antiferromagnetic (AF) rather than FM ordering. And in the ZFC case, such a magnetic state indeed coexists with the superconductivity. A FC process, however, even in the presence of very low applied field, produces a net FM moment, presumably through canting of originally AF spins, and the thus established ferromagnetism kills the superconductivity, an effect evidenced by the complete absence of a Meissner effect.

Acknowledgements: The work of Z.F. Ren is supported by the Department of Energy. The work of M. Naughton is supported by the National Science Foundation.

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Stripe Stability in the Extended t-J Model on Planes and Four-Leg Ladders

Tohyama, T., Tohoku Univ., Japan, Physics
Gazza, C., NHMFL
Shi, C., National Center for High-Performance Computing, Japan
Chen, Y., Tunghai Univ., Taiwan, Physics
Lee, T., Institute of Physics, Academia Sinica, Taiwan
Maekawa, S., Tohoku Univ., Japan, Physics
Dagotto, E., NHMFL/FSU, Physics

The tendencies to phase-separation and stripe formation of the t-J model on planes and four-leg ladders have been here reexamined including hole hopping terms t', t'' beyond nearest-neighbor sites.[1] The motivation for this study is the growing evidence that such terms are needed for a quantitative description of the cuprates. Using a variety of computational techniques it is concluded that the stripe tendencies considerably weaken when

experimentally realistic t'<0, t''>0 for hole-doped cuprates are considered. However, a small t'>0 actually enhances the stripe formation.

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Indications of Unconventional Superconductivity in Doped Triangular Antiferromagnets

Vojta, M., Yale Univ., Physics
Dagotto, E., NHMFL/FSU, Physics

The possibility of superconductivity in a doped triangular antiferromagnet is discussed.[1] Using the Bethe-Salpeter (B-S) equation, it is shown that the exchange of RPA paramagnons on a triangular lattice Hubbard model leads to strong pairing correlations at and near half-filling. The dominant states for this system correspond to d-wave singlet (even-frequency) and odd-frequency s-wave triplet (odd-frequency). Analytical techniques applied to the hole-doped t-J model yield similar results. A t_1-t_2 Hubbard model interpolating between square (t_1=0) and triangular (t_1=t_2) lattices has a tendency only to d-wave singlet pairing for $t_1/t_2 < 0.8$. Experimental consequences for organic compounds κ-(BEDT-TTF)$_2$X are discussed.

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Theoretical Studies of Fulde-Ferrell-Larkin-Ovchinnikov Superconductors

Yang, K., NHMFL/FSU, Physics
Agterberg, D.F., NHMFL

It was suggested more than thirty years ago by Fulde and Ferrell,[1] and Larkin and Ovchinnikov,[2] that an inhomogeneous superconductor with an order parameter that oscillates spatially may be stabilized by a large external magnetic or internal exchange field. Such a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state has never been observed in conventional low-T_c superconductors. Recently the FFLO state has attracted renewed interest in the context of organic, heavy-fermion, and high-T_c cuprate superconductors. These new classes of superconductors are believed to provide conditions that are favorable to the formation of FFLO state, because many of them are (1) strongly type II superconductors so that the upper critical field H_{c2} can easily approach the Pauli paramagnetic limit; and (2) layered compounds so that when a magnetic field is applied parallel to the conducting plane, the orbital effect is minimal, and the Zeeman effect (which is the driving force for the formation of FFLO state) dominates the physics. Indeed, some experimental indications of the existence of the FFLO state have been reported recently.[3]

Motivated by these, we have been performing theoretical studies on the FFLO states. We have made progress in two different directions. Firstly, we have found a new way to detect the existence of the FFLO state, and to measure the momentum of its order parameter experimentally, using Josephson tunneling between an FFLO superconductor and a conventional BCS superconductor. We find, using both the phenomenological Ginsburg-Landau theory, as well as first-principle microscopic calculations, that the Josephson current between an FFLO superconductor and a conventional BCS superconductor is suppressed due to the difference in the momenta of their order parameters. The effect due to the difference in momenta, however, may be cancelled by applying a magnetic field parallel to such a Josephson junction, with a field that depends on the momentum of the order parameter of the FFLO state. Thus by looking for the magnetic field that recovers the Josephson current, one can actually measure the momentum of the order parameter directly. The method we propose here to study the FFLO state is the first that is sensitive to and directly measures the structure of the order parameter of the FFLO state.

Secondly, we have been studying the effects of non-magnetic impurities on the FFLO state that is formed in superconductors with unconventional pairing symmetry (non s-wave). We do so by calculating the Ginsburg-Landau free energy functional of the system, in the presence of both a large Zeeman splitting and impurity potential. We find the presence of impurities can lead to a phase diagram for the system that is qualitatively different from those previously derived for *s*-wave superconductors; in particular, the presence of impurities can *increase* the relative size of the temperature window for the existence of the FFLO state in non *s*-wave superconductors; this is in sharp contrast to what happens in *s*-wave superconductors, where the impurities suppresses the window of the FFLO state in the phase diagram.

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High Magnetic Field NMR Study of the d-Wave Vortex in the Overdoped High-T_c Superconductor

Zheng, G.-Q., Osaka Univ., Physical Science
Moulton, W.G., NHMFL
Kuhns, P., NHMFL
Reyes, A.P., NHMFL
Clark, W.G., Univ. of California at Los Angeles, Physics and Astronomy

The unconventional nature of the superconductivity in the high-T_c cuprates is of great interest. The most prominent difference between conventional superconductors and the high temperature superconductors is that in the latter the order parameter of the Cooper pairs is anisotropic, very likely of d-wave symmetry. This anisotropy leads to the unusual physical properties of the superconducting state. Most thermodynamic quantities exhibit power-law temperature dependence, instead of the exponential one that is seen in conventional superconductors. It also has great significance on the formation of structure of vortices, both topologically and electronically. In a conventional s-wave superconductor, the quasiparticle associated with a vortex is confined in the cylinder with diameter of ξ (ξ is the size of the Cooper pairs), and the energy spectrum is discrete, separated by $_0{}^2/E_F$ where $_0$ is the maximum of the order

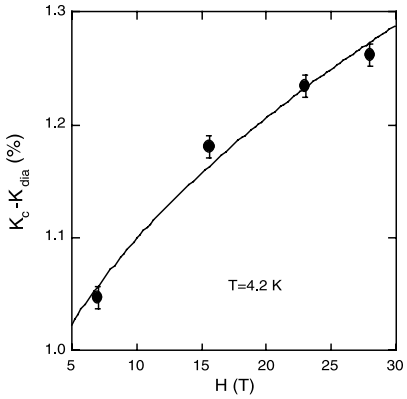

Figure 1. Magnetic field dependence of the Knight shift at T = 4.2 K.

parameter or energy gap and E_F is the Fermi energy. For high-T_c superconductors, this energy spacing would be of the order of 50 K if one applied this conventional theory. However, ξ in the high-T_c superconductors is anisotropic because the order parameter is. This may result in an extended quasiparticle state far outside the core center and moreover with the ungapped energy spectrum.

In the present study on an overdoped high-T_c cuprate $TlSr_2CaCu_2O_7$ (T_c = 60 K) under magnetic fields up to 28 T, we have investigated the electronic structure associated with a vortex by measuring the magnetic field dependence of the spin Knight shift, which is proportional to the density of states (DOS). Figure 1 shows the field-induced increase of the ^{63}Cu spin Knight shift at low temperatures as a function of H. The Knight shift is increased markedly by the field, which is not seen in an s-wave superconductor. This result is similar to what we have found previously in an underdoped high-T_c superconductor $YBa_2Cu_4O_8$,[1] but the field effect is much larger. The curve is a fit to K_c-K_{dia} = K_{orb}+K_s H. This result indicates that the field induces a finite DOS around a vortex, which is consistent with the theoretical prediction by Volovik for a d-wave superconductor.[2]

This work was done in collaboration with H. Ozaki, Y. Kitaoka, T. Kondo, Y. Shimakawa and Y. Kubo.

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SUPERCONDUCTIVITY – APPLIED

Sol-Gel Buffer Layers on Ni Tapes for YBCO

Celik, E., NHMFL and Sakarya Univ., Turkey, Metallurgy
Okuyucu, H., NHMFL and Gazi Univ., Turkey, Metallurgy
Mutlu, I.H., NHMFL and Harran Univ., Turkey, Physics
Hascicek, Y.S., NHMFL

$YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films on flexible metallic substrates, such as Ni, and Ni alloys have attracted much attention for long length superconducting tapes. Direct deposition of YBCO films on these substrate materials, however, causes numerous problems at their interface in addition to the degraded crystallinity due to lattice mismatch. Several buffer layers have been used to solve these problems.[1,2] The purpose of this study was to produce pinhole-free and crack-free thin films on Ni tapes using a reel-to-reel, sol-gel process for YBCO surface coated conductors.

Yttria stabilized zirconia (YSZ), perovskite ($SrTiO_3$, $LaAlO_3$, $PbTiO_3$, $BaZrO_3$, $BaTiO_3$, $NdAlO_3$, $BaSnO_3$, PLZT, $SrZrO_3$ and $CaZrO_3$), $MgAl_2O_4$, MgO, and $(RE)_2O_3$ (RE:La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu, Y, and In) buffer layers were prepared on Ni tapes using solutions of alkoxide and acetate organometallic compounds. They were dried at 300 °C for 1 min and the dried samples were then heat treated at 600 °C for 2 min in a vertical three zone furnace. These procedures were repeated to achieve the desired film thickness. Finally, the films were annealed to obtain texture at 1050-1150 °C for 10-30 min under 4%H_2-Ar flow in a horizontal furnace. Different architectures with YSZ/$(RE)_2O_3$ configurations was also applied on Ni tapes for YBCO. Surface morphologies of some buffer layers are given in Figure 1. The films were uniform, dense, and crack-free, and had good surface morphology. According to ESEM, XRD, DTA, and TGA studies, three main phenomena were determined from room temperature to oxide ceramic formation temperature; solvent removal, combustion of organic groups, and ceramic formation. As-deposited buffer layers are amorphous, and typically retain a significant organic fraction. Their nature at this stage is highly dependent on the characteristics of the solution, the precursor species, the solvent, and the chelating agent. The crystallization of buffer layers takes place at 450-600 °C. Intended phases were confirmed with XRD (Figure 2). Cracking in buffers depends on certain parameters, such as the pH value and the viscosity of the solution, thickness, film type, and annealing temperature and atmosphere. Moreover, buffer layers with texture are generally produced at 1150 °C for 20-60 min under 4%H_2-Ar flow. Some of these buffer layers were used for surface coated YBCO conductor development at the NHMFL.

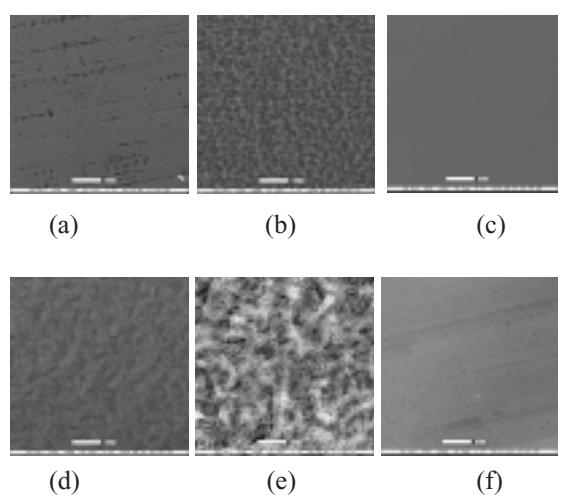

Figure 1. SEM micrographs of the surface of (a) YSZ, (b) $SrTiO_3$, (c) $LaAlO_3$, (d) $PbTiO_3$, (e) Er_2O_3 , and (f) Tb_2O_3 buffer layers on N tape.

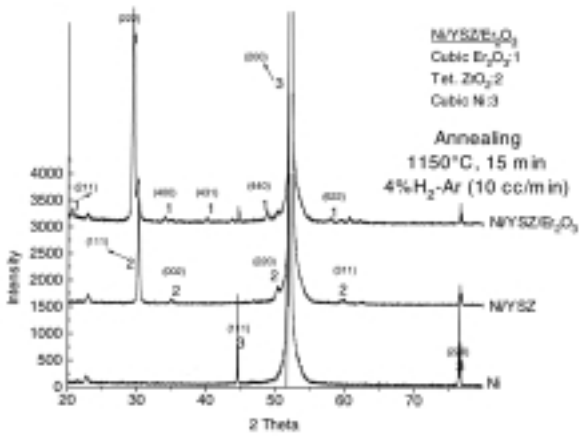

Figure 2. XRD patterns of Ni, Ni/YSZ and Ni/YSZ/Er_2O_3 films.

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Phase Formation and Superconducting Properties of Fluorine-Doped $(Hg,X)Ba_2Ca_2Cu_3O_y$ Superconductors

IHRP

Hamdan, N.M., King Fahd Univ. of Petroleum and Minerals, Physics
Sastry, P.V.P.S.S., NHMFL
Schwartz, J., NHMFL/FAMU-FSU College of Engineering

The average Cu-valence (the carrier concentration) is one of the crucial parameters that affect the superconducting properties of high-T_c materials. Due to its smaller ionic size and higher electronegativity than oxygen, fluorine (F), when substituted for oxygen, changes the structural and superconducting properties of high-T_c materials.[1,2] The effect of fluorine (F) addition on the phase formation and superconducting properties of $(Hg,X)Ba_2Ca_2Cu_3O_y$ (HgX1223) was investigated for X=Pb, Re, and Bi. Samples were prepared using $CaHgO_2$ as the external mercury source.[3,4] BaF_2 was used as the F source, which was inserted into a separate alumina sheath in the sealed quartz tubes used for reactions. Because the fluorine source is physically separated from the sample, it was possible to fix the cation composition of the samples while changing the fluorine content. Results of x-ray diffraction and microstructural investigations showed the formation of phase pure HgX1223 with large grains in F doped compositions. Magnetization measurements showed that the critical current density increased significantly by fluorination. Results of the studies on the effect of F content showed that there exists an optimum F content above which the properties started deteriorating. Figure 1 depicts the typical microstructure of fluorine-doped HgRe1223 samples. Figure 2 depicts the magnetization data of a series of HgRe1223 samples with varying flourine-content indicating an enhancement of magnetization hysteresis loop width in an optimally doped sample.

1 Hamdan, N.M., *et al*., Physica C, **314**, 125 (1999).
2 Peackock, G.B., *et al*., Physica C, **289**, 153 (1997).
3 Sastry, P.V.P.S.S., *et al*., Physica C, **297**, 223 (1998).
4 Sastry, P.V.P.S.S. and Schwartz, J., J. Supercond., **11**, 592 (1998).

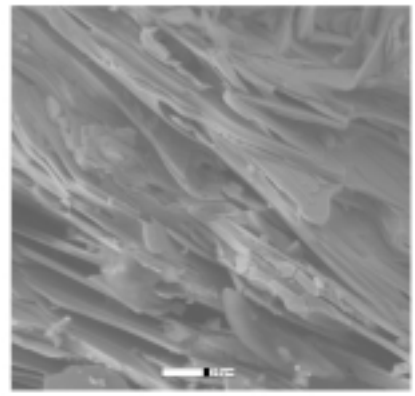


Figure 1. SEM micrograph of a typical fluorine-doped HgRe1223 sample.

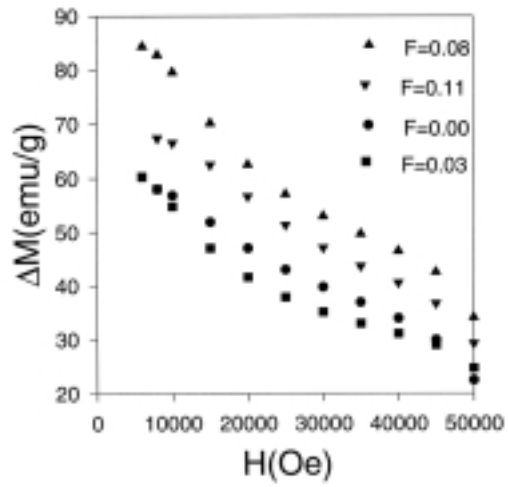


Figure 2. M versus magnetic field at 4.2 K for samples with different F contents (see legend).

Recent Developments of Nb_3Sn Superconducting Wire at Oxford Instruments, Inc., Superconducting Technology (OI-ST)

Hentges, R., OI-ST
Zhang, Y., OI-ST
Hong, S., OI-ST
Field, M., OI-ST

Development efforts at Oxford Superconducting Technology have been continuously improving the high field performance of Nb_3Sn wires for NMR use. The facilities at NHMFL have been used to test critical currents at high fields. Changes in wire construction and processing have been studied to maximize wire piece-lengths. Critical current measurements were taken at 4.2 K and 2.2 K at fields up to 25 T to measure the effect of these changes.

The Modified Jelly Roll (MJR) process was used to construct superconducting wires consisting of $(NbTi)_3Sn$ and $(NbTiTa)_3Sn$ filaments. Heat treatment studies were performed to find the optimum reaction for current density at a magnetic field of 21 T at 2.2 K. The wire was found to have engineering current density, J_e, (current normalized to overall wire cross section) greater than 150 A/mm^2 when tested on a TiAlV

mandrel. J_e exceeding 100 A/mm^2 was achieved when the samples were put under strain from the thermal contraction of a stainless steel mandrel. These results show that this wire has sufficient J_e for use as in the highest field regions of NMR spectroscopy magnets operating at 900 MHz.

Non-Vacuum YBCO Films on Buffer Layered Ni Tapes: Processing, Growth, and Properties

Mutlu, I.H., NHMFL and Harran Univ., Turkey, Physics
Celik, E., NHMFL and Sakarya Univ., Turkey, Metallurgy
Ramazanoglu, M.K., FSU, Physics
Akin, Y., UF, Material Science & Metallurgy
Crow, J.E., NHMFL/FSU, Physics
Hascicek, Y.S., NHMFL

In this study, YBCO films were prepared on $SrTiO_3$ buffer layered Ni tapes by a continuous, reel-to-reel sol-gel technique[1] using various precursors and solutions which were prepared from Y, Ba, and Cu based organometallic compounds.[2] Microstructure and T_c dependence on stochiometry in YBCO films and solutions were investigated. Thick, crack-free, pinhole-free sol-gel YBCO layers were grown on sol-gel $SrTiO_3$ buffer layered Ni substrate tapes, to characterize the stochiometry, structure, and phase as well as the resistance. Figure 1 shows X-ray diffraction patterns of the YBCO films with $SrTiO_3$ buffer layered Ni tape. As seen from the figure, the characteristic diffraction peaks of YBCO, Ni, NiO, and $SrTiO_3$ are present. Figure 2(a) shows an ESEM micrograph of polished cross-section of the film, and Figure 2(b) shows the $SrTiO_3$ buffer layer and YBCO in more detail together with part of the Ni tape. The thickness of YBCO is 7-10 µm. Figure 2(c) shows the YBCO surface which appears quite dense. Figure 3 shows the R-T curve of the sol-gel YBCO coated conductor as seen in Figure 2. This was a 4-wire transport measurement.

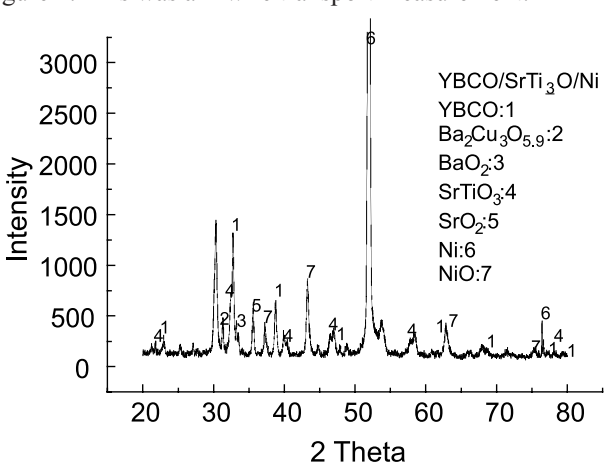
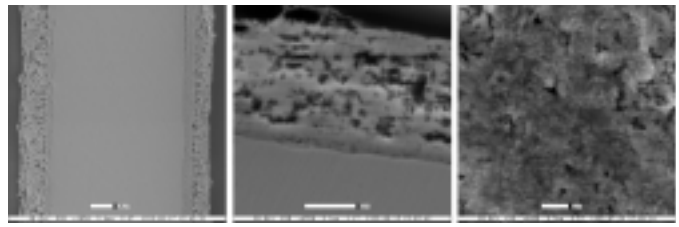


Figure 1. X-ray diffraction patterns of YBCO films with buffer layered Ni tape.

A sol-gel pinhole-free, crack-free YBCO surface coated conductor on $SrTiO_3$ buffer layered rolled Ni tape has been realized using a reel-to-reel, continuous set-up with an on-line furnace. SEM, XRD, and resistance measurements show that almost phase pure, thick (~10 µm), dense YBCO layers can be realized on sol-gel buffered rolled Ni tape. The next step is to introduce texture into the buffer layer and YBCO on textured Ni and Ni alloy tape substrates.



(a) (b) (c)

Figure 2. ESEM micrographs of polished cross-section and surface of sol-gel YBCO on $SrTiO_3$ buffered Ni tapes.

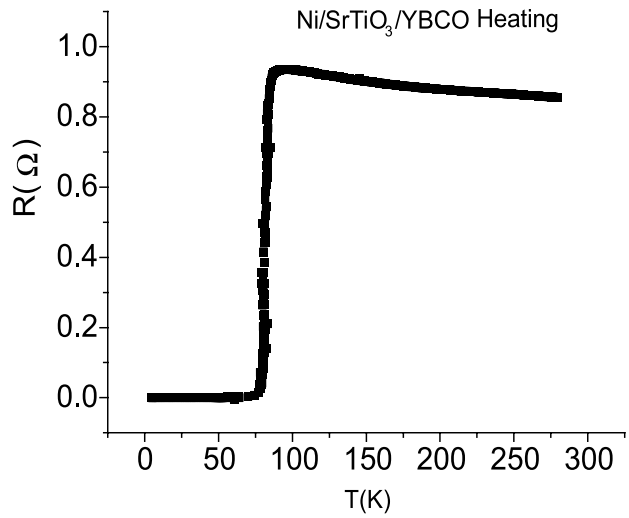


Figure 3. The R-T curve for a sol-gel YBCO coated conductor. The on set of critical temperature is 92 K.

[1] Celik, E., *et al.*, USA patent application pending, May, 1998.
[2] Mutlu, I.H., *et al.*, MT 16 Conference, 1999.

Nb_3Al Superconductors for Above 850 MHz NMR Magnets

Pourrahimi, S., Superconducting Systems Inc.

Production of high performance and cost effective Nb_3Al superconductors can play a key role in the fabrication of high field NMR magnets. In the first half of 1999, the National Institutes of Health funded a Phase I SBIR effort at Superconducting Systems Inc. (SSI) that aimed to establish a practical and economical method of fabricating high performance Nb_3Al wires. A powder metallurgy approach was used to fabricate several Nb_3Al precursor wires with Al concentration in the range of 6-9 wt%, and Al filament thickness in the range of 1-5 µm. The wire processing technique achieved a reliability level where a starting billet would yield a single piece-length wire. Typical precursor wires with lengths up to 80 m were reacted in a conventional tube-furnace using a reel-to-reel set-up at temperatures of 1200-1500 °C for 10-20 s.

After the reaction heat treatment, the wires were given a post-reaction heat treatment at 750 °C for 2-3 days. The critical current density and critical field of a series of samples were measured in the background magnetic fields of a 27 T resistive magnet at the NHMFL. The most significant finding of the work was that the critical field of the wires increased progressively with increased reaction temperature. Figure 1 shows the data for two of the Nb_3Al wires.

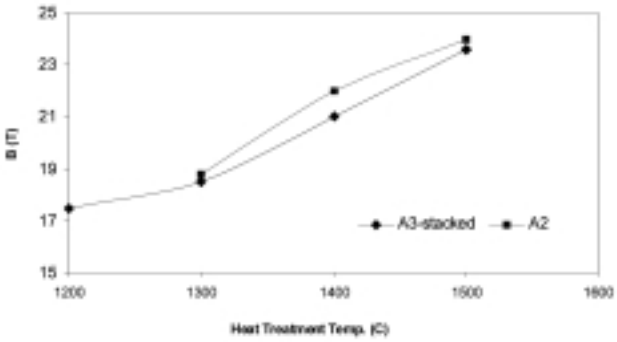


Figure 1. Effect of increasing the reaction temperature on the critical field of precursor wires that used Nb-9wt%. The average Al filament thickness in the A2 wire is 5 µm, and 1 µm for the A3-stacked.

Fabrication of C-Axis Textured $(HgRe)_1Ba_2Ca_1Cu_2O_y$ Thin Films on Single Crystal Substrates IHRP

Schwartz, J., NHMFL/FAMU-FSU College of Engineering
Sastry, P.V.P.S.S., NHMFL
Durbin, S.M., FAMU-FSU College of Engineering
Atwell, S.L., FAMU-FSU College of Engineering
Magaña, R. Jr., FAMU-FSU College of Engineering
Pelt, J.S., FAMU-FSU College of Engineering

The external mercury source reaction method developed at the NHMFL was used to form thin films of $(HgRe)_1Ba_2Ca_1Cu_2O_y$ (HgRe1212) superconductor on single crystal $LaAlO_3$ and other ceramic substrates. The precursor films were grown by Pulsed Laser Deposition using commercial BaCaCuO targets. The deposition conditions were optimized to produce uniform ReBaCaCuO films (1-2 µm). The precursor films were reacted with $CaHgO_2$ as the external mercury source.[1] The heat treatment conditions were optimized to achieve phase purity, grain growth and c-axis texture. Figure 1 depicts the XRD pattern of a typical film reacted using an optimized heat treatment. The presence of strong 00l lines indicates excellent c-axis texture. Figure 2 depicts the microstructure of a HgRe1212 film. Large regions (200-500 µm) of c-axis textured plate-like grains of HgRe1212 indicate grain growth. Magnetization measurements showed that the films are superconducting with T_c values in the range of 115-120 K.

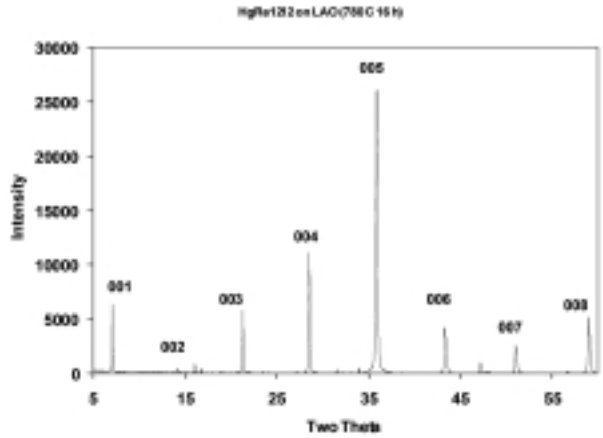


Figure 1. X-ray diffraction pattern of a HgRe1212 film on $LaAlO_3$.

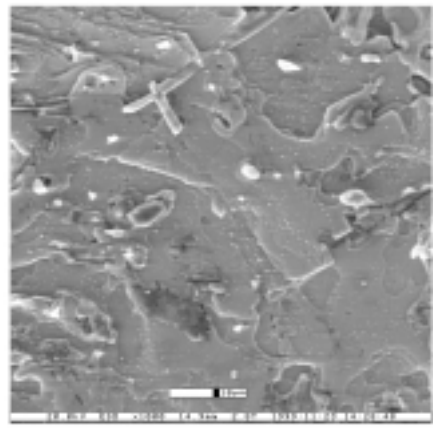


Figure 2. SEM image of a HgRe1212 film on $LaAlO_3$.

1 Sastry, P.V.P.S.S., *et al.*, Physica C, **300** 125-140 (1998).

High Field Critical Current Measurements in Nb_3Al Multifilamentary Superconductors

Sumption, M., Ohio State Univ., LASM, Materials Science
Tomsic, M., EURUS Technologies Inc.
Gregory, E., IGC Advanced Superconductors
Hascicek, Y.S., NHMFL

We measured the critical currents in high-temperature-quenched Nb_3Al multifilamentary superconductors. These conductors are presently being considered for applications in high field MRI and accelerator dipole magnets, and they may have applications in other high field research magnets. In the United States, these conductors are being made as part of a collaboration between EURUS, Ohio State University (OSU), and a number of U.S. superconducting wire manufacturers. The present precursors were supplied by IGC and were fabricated as a re-stack of monofilament "jelly-roll" type laminates of Nb and Al. Conductor designs with several different laminate sizes and Nb to Al ratios were measured. A conductor with an aluminum laminate size of 150 nm and a 3.75:1 Nb:Al ratio gave the best results, as shown in Figure 1. Critical current densities

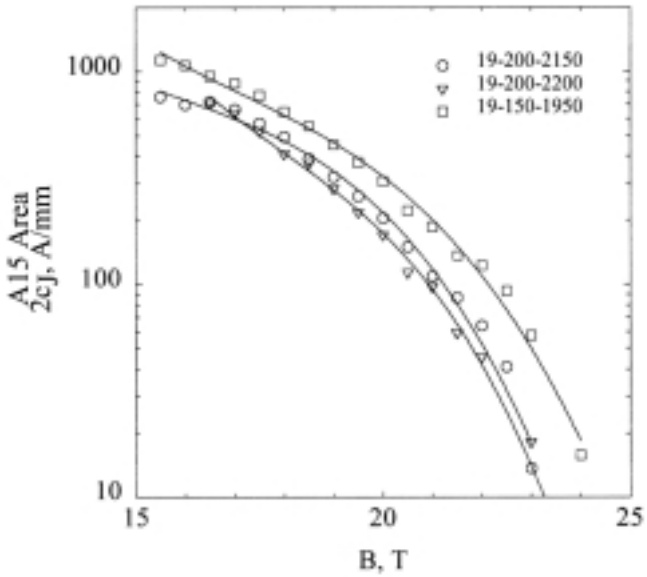


Figure 1. J_c vs. B for various Nb_3Al multifilamentary strand types measured at NHMFL. The first number in the strand code is the number of filaments, the second is Al laminate size in nanometers, and the third is the primary reaction temperature in centigrade.

of 300 A/mm^2 at 20 T have been obtained in this material, confirming that 100-200 nm laminate sizes are appropriate for the aluminum component of the laminates. Temperature optimization experiments at OSU in conjunction with these measurements have determined the temperature processing window in the primary (high temperature) heat treatment for optimal J_cs to be about 200 °C in height (with the optimum temperature near 2000 °C). These measurements have also determined a compositional band that is slightly Nb-rich but allows for optimal J_c values and small levels of porosity in the reacted conductor.

Further high field measurements of these materials will be essential in optimizing their performance in their expected operation range of fields 15 T and higher.

Enhanced Nb_3Sn Conductors for NMR Application Beyond 900 MHz

Thoener, M., VACUUMSCHMELZE GmbH, Germany

Bronze route Nb_3Sn conductors for high resolution NMR systems above 500 MHz were developed and produced at VAC since its first application. 800 MHz systems are commercialized already and 900 MHz NMR magnets are built up and tested presently. VAC has manufactured and delivered tons of Nb_3Sn material for such systems like the 900 MHz wide bore NMR magnet at NHMFL.

1000 MHz NMR systems need enhanced high J_c conductors to fulfill the economical requirements for the construction of such huge magnets.

The main parameters to improve the superconducting properties in high fields are the alloy composition, the conductor design and the reaction heat treatment parameters. The alloy composition was improved steadily in the last decade. Since 1997 the design parameters for such conductors were optimized and matched by modified heat treatment parameters culminating in an increase of Jc of more than 30% at 20 T and 4.2 K.

At the NHMFL such enhanced 1000 MHz conductors were measured—so far as we know—for the first time worldwide at the operating condition of 23.5 T and 1.8 K. In the 25 T Keck magnet, we have measured both rectangular and round wires, respectively with approx. 6.5 mm^2 total area including 20% Cu and 7% Ta outer stabilization. As a measuring technique, we have applied the well established method with helical sample on a G10 sample holder. With this method VAC has determined thousands of samples creating a database for research and development.

Results of the critical current exceed more than 300 A at 23.5 T and 1.8 K (0.1 μV/cm) corresponding to non(Cu+Ta) critical current density values of >80 A/mm^2.

One advantage of these types of high J_c Nb_3Sn conductors is the flexibility in easy variation of the total conductor cross-section within 2 to 9 mm^2 including of different Cu fractions and even increased Ta fraction for mechanical reinforcement. This is very important to fit the different design parameters of the various projects over the world.

Acknowledgement: We like to thank the colleagues of the NHMFL staff who have supported our measurements greatly, especially Iain Dixon and Hans Schneider-Muntau.

Microstructural Development and Superconducting Properties of Ba-Added $Bi_2Sr_2CaCu_2O_{8+\delta}$

Trociewitz, U.P., NHMFL/RWTH Aachen Univ. of Technology
Sahm, P.R., RWTH Aachen Univ. of Technology
Schwartz, J., NHMFL/FAMU-FSU College of Engineering

In the ongoing investigation on the effects of Ba additions on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) superconductors additional compositional, microstructural, and magnetization studies were carried out. In previous studies it had been shown that BaO_2 reacts with part of the Bi-2212 matrix to form second phases. Zero-field and in-field transport properties at 4.2 K had been improved.

Comparison between XRD-spectra of heat-treated Bi-2212 added with $BaCuO_2$, $BaBiO_3$, and BaO_2 revealed the nature of these second phases as a substitutional solid solution consisting of (Ba, Ca, Sr)BiO_3 , see Figure 1. Differential thermal analysis results showed that Bi-2212 starts reacting with BaO_2 at around 820 ^{o}C. In BaO_2 doped Bi-2212 pellets that were sintered at 820 ^{o}C, the average size of uniformly distributed Ba-containing areas

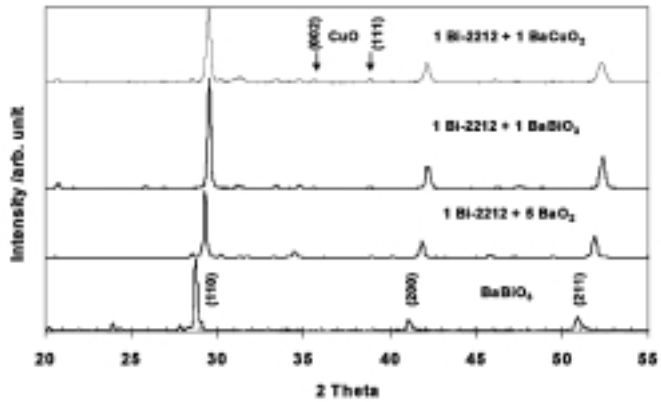


Figure 1. Comparison of x-ray spectra of reacted Bi-2212 bulk samples added with $BaCuO_2$, $BaBiO_3$, and BaO_2 with pure $BaBiO_3$. The shift in the characteristic lines in the upper three spectra indicates the formation of a substitutional solid solution consisting of $(Ba,Ca,Sr)BiO_3$. The arrows in the upper curve mark the CuO phase, which forms due to the decomposition of the $BaCuO_2$.

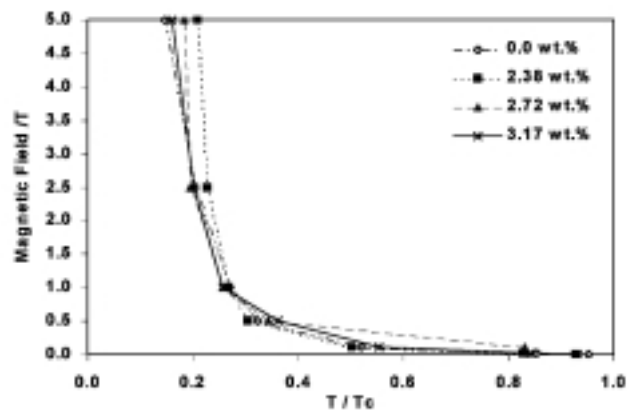


Figure 2. Irreversibility lines of BaO_2 doped and undoped tapes. Doped samples show slightly higher irreversibility fields at low temperatures.

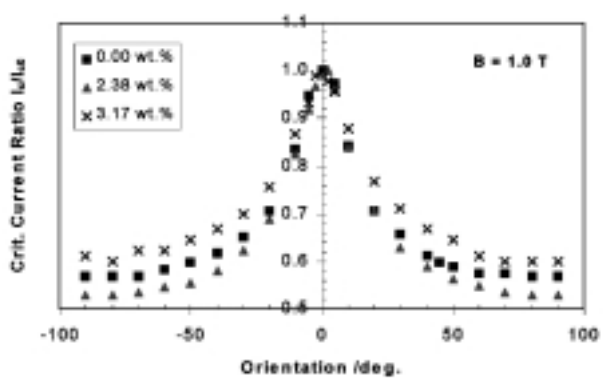


Figure 3. Transport critical currents of undoped, 2.38 wt.%, and 3.17 wt.% BaO_2 added tape samples versus orientation angle (c || B =: 90°). The 2.38 wt.% doped tape exhibits a higher degree of anisotropy than the undoped and higher doped tapes.

were found to be about 3 to 4 μm in diameter. Preliminary TEM studies on fully heat-treated samples also showed Ba-containing phases that were slightly smaller with sizes 0.5 to 1 μm.

Particle sizes of this order, however, are still too large to be directly effective as pinning sites. On the other hand, the comparison of the irreversibility lines measured on doped and undoped tapes revealed slightly higher irreversibility fields at low temperatures, see Figure 2. The cause for this behavior is believed to be induced by indirect pinning due to the formation of additional grain boundaries. In addition there is a distribution of particle sizes about the average, so a fraction of the Ba-containing phases are much smaller. This is supported by the measured size distribution of the BaO_2 particles in the BaO_2 powder and the tendency of the Ba containing phases to not agglomerate during partial-melt processing.

An influence on the texture development in the Bi-2212 by Ba additions was visible in SEM micrographs. Optimally doped tapes showed a higher degree of texture than undoped tapes. In-field transport measurements with variable orientation of the sample's crystallographic c-axis versus the applied magnetic field showed a higher anisotropic behavior for the transport critical current in optimally doped tapes compared with undoped tapes, see Figure 3.

Additional TEM and X-ray texture goniometric investigations are under way to gather more information about sizes and sites of possible pinning centers and the texture development in BaO_2 doped Bi-2212.

Trociewitz, U.P., *et al.*, "Effects of Ba additions on bulk Bi-2212 and Ag-clad tape," submitted to proceedings ICMC, Montreal 1999.

Influence of Thermal Cycling on Mechanical Properties $Bi_2Sr_2CaCu_2O_x$ Superconductors IHRP

Viouchkov, Y., NHMFL
Weijers, H.W., NHMFL
Schwartz J., NHMFL/FAMU-FSU College of Engineering

Significant differences in overall current density for the Ag and AgMg sheathed tapes were observed during development of the 3 T class high field insert HTS magnet.[1] Typically, Ag sheathed tape exhibits 20-30% higher J_c value than AgMg sheathed tapes. Significant differences in stress-strain curves due thermal cycling between room temperature and 77 K were observed for the Ag sheathed conductor (Figure 1). The effect was not observed for the AgMg sheathed conductor (Figure 2).

Significant differences in stress-strain curves for the Ag sheathed conductors indicate that the ceramic core is strengthening the Ag sheath through a process that resembles work hardening of the Ag sheath. The behavior is related to the differences in coefficients of thermal expansion between Ag and $Bi_2Sr_2CaCu_2O_x$.

The difference in thermal expansion was calculated using

$$\Delta\varepsilon = \int_{Ta}^{77K} \Delta\alpha \, dT = 0.18\ \%.$$

Where α is the difference in thermal expansion was calculated using thermal coefficients of Ag and $Bi_2Sr_2CaCu_2O_x$. Figure 3 presents a graphical analysis of the thermal-strain cycle of the Ag- sheathed conductor. The curve of non-thermal cycled tape has an unloading line at $\varepsilon = 0.18\%$. The unloading line indicates residual strain when the sample is unloaded ($\sigma = 0$). The residual strain at room temperature is calculated by

$$\varepsilon_{res} = \varepsilon\ \sigma_{0.18\%\ STRAIN} / E_{Ag} = 0.12\%.$$

Thus, the initial coordinate of the thermal cycled curve was then shifted by 0.12 % of strain to adjust stress lines. The expected junction point of the curves was set as the calculated difference in thermal expansion between $Bi_2Sr_2CaCu_2O_x$ and Ag at 77 K. The dashed line represents the calculated thermal strain.

The effect of thermal work hardening does not occur in AgMg-sheathed conductor (Figure 2). The AgMg sheath resists plastic deformation because of its higher yield point and strength.

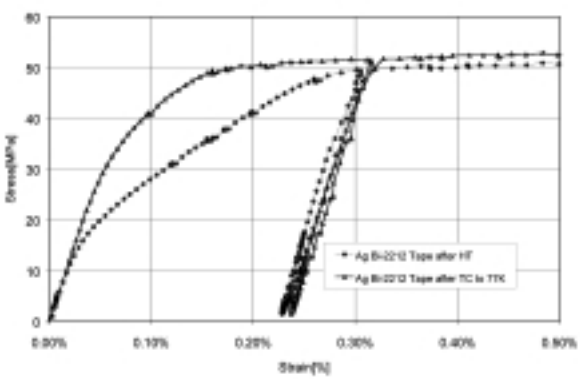


Figure 1. Ag - $Bi_2Sr_2CaCu_2O_x$ tapes before and after thermal cycling to 77 K (TC).

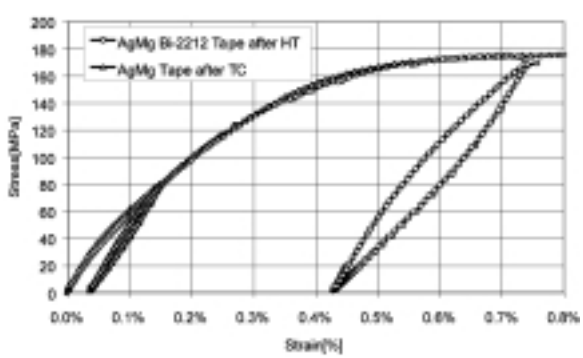


Figure 2. AgMg - $Bi_2Sr_2CaCu_2O_x$ tapes before and after thermal cycling to 77 K (TC).

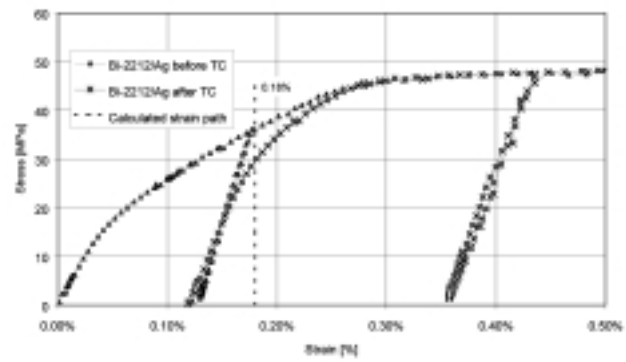


Figure 3. Modeling of strain effect due to thermal cycle of Ag - $Bi_2Sr_2CaCu_2O_x$ tape.

[1] Weijers, H.W., *et al.*, "Development and testing of a 3 T Bi-2212 insert magnet," Proceedings of CEC/ICMC 1999.

Mechanisms of Magnetic Field Induced Texture Development in High-T_c Materials IHRP

Yamada, Y., NHMFL/Tokai Univ., Metallurgical Engineering
Sastry, P.V.P.S.S., NHMFL
Viouchkov, Y., NHMFL
Schwartz, J., NHMFL/FAMU-FSU College of Engineering

Synthesis and processing of materials in magnetic fields to achieve improved texture is a new field of research. Several groups have attempted to improve texture of high-T_c superconductors by heat treating in magnetic fields. The magnetic field creates a torque on crystallites that have anisotropy in magnetic moment causing the grains to rotate with respect to the magnetic field. This principle has been successfully used in the room temperature magnetic alignment approaches for high T_c materials. There are a few reports on the application of magnetic field during high temperature partial-melt processing to enhance texture in YBaCuO and BiSrCaCuO superconductors. It is, however, not clear whether the magnetic field influences the nucleation process or the grain growth.

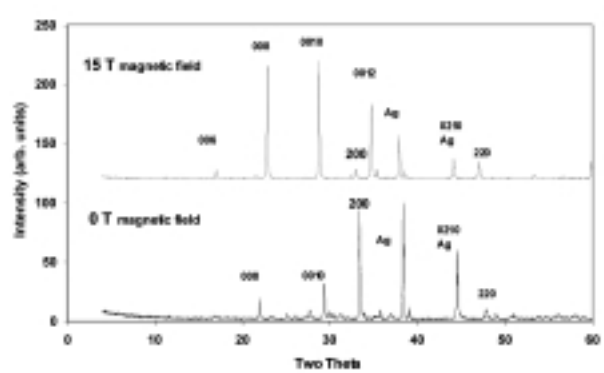
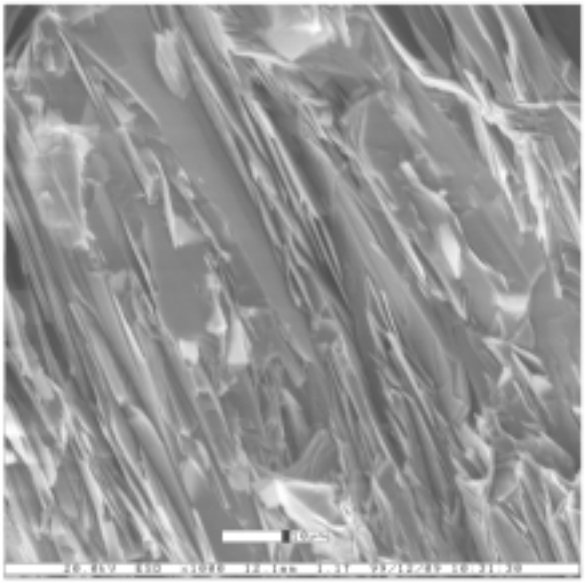


Figure 1. X-ray diffraction patterns of Bi2212 samples heat-treated in 0 T and 15 T magnetic field.



All the experiments were carried out using the 20 T, 195 mm bore resistive magnet at the NHMFL. The studies are aimed at understanding the systematics of magnetic field induced texture in several high-T_c superconductors. The principle objective is to understand and optimize the various reaction parameters to achieve maximum magnetic field induced texture.

Several samples of $Bi_2Sr_2Ca_1Cu_2O_8$ (Bi2212) superconductor with varying phase assemblages were heat treated in magnetic fields up to15 T. Figure 1 depicts XRD patterns of a bulk $Bi_2Sr_2Ca_1Cu_2O_8$ sample melt processed in a 15 T filed. The presence of strong 00l reflections indicates good c-axis texture in the sample. Figure 2 depicts the microstructure of a diffusion couple reacted in 15 T field.

Figure 2. SEM image of the diffusion couple region of the Bi2212 heat-treated in 15 T magnetic field.

Quantum Solids

Magnetism of ^{3}He Nano-Clusters in a ^{4}He Matrix

Adams, E.D., UF, Physics
Matsunaga, N., UF, Physics
Schuberth, E.A., Walther Meissner Institut
Shvarts, V.A., UF, Physics/NHMFL
Xia, J.S., UF, Physics/NHMFL

Simultaneous measurements of susceptibility and pressure have been made in ^{3}He nano-clusters, formed after phase separation of the initial ^{3}He-^{4}He mixture, at temperatures down to 0.5 mK. Pressures were in the range of 3.0 to 3.6 MPa, which produce three different, unique environments for the nano-clusters. At the highest pressure, which is above the melting pressure of pure bulk ^{3}He, the nano-clusters are completely solid, as observed from the pressure measurements. At pressures near 3.0 MPa, the ^{3}He forms as liquid droplets when the phase separation occurs, since the pressures is lower than of pure bulk ^{3}He. Upon cooling to lower temperatures, nano-clusters formed at intermediate pressures undergo partial melting, as observed by the pressure. Susceptibility measurements, using pulsed NMR, of the nano-clusters have been made in all three of these situations, with the temperature measured by pure ^{3}He melting pressure.

The sample studied most extensively was at a pressure of 3.36 MPa, which was observed to undergo partial melting at about 20 mK. From the change in pressure on partial melting, it was determined that a large fraction of the cluster did not melt. One possible explanation for this is that the van der Waals attraction by the more dense ^{4}He produces a dense layer of ^{3}He at the interface that remains solid, with only the center of the cluster undergoing melting. In contrast to pure bulk solid ^{3}He at this pressure, which orders antiferromagnetically at about 0.9 mK, this sample followed a Curie law, $\chi = C/T$, (with a negligible Weiss θ) to the lowest temperature of about 0.5 mK.

The sample at a pressure 3.5 MPa, which showed no melting since it was above the melting pressure of pure bulk ^{3}He, also deviated very little from the Curie law above 1 mK. At lower temperatures, however, there was a gradual increase of χ above the Curie behavior, indicating a tendency toward ferromagnetism. These preliminary results, which have been reported previously,[1-3] must be investigated further.

1 Adams, E.D., *et al.*, J. Low Temp. Phys., **113**, 375 (1998).
2 Matsunaga, N., *et al.*, Proc. LT-22, August 1999, Helsinki, Finland.
3 Adams, E.D., *et al.*, Invited oral presentation, QFS-99, August 1999, St. Petersburg, Russia.

Nonlinear Spin Dynamics of Dilute ^{3}He-^{4}He at Very High B/T IHRP

Akimoto, H., UF, Physics and Univ. of Massachusetts
Candela, D., Univ. of Massachusetts, Physics and Astronomy
Mullin, W.J., Univ. of Massachusetts, Physics and Astronomy
Adams, E.D., UF, Physics
Xia, J.S., UF, Physics/NHMFL
Sullivan, N.S., UF, Physics/NHMFL

Numerical simulations have been carried out to assess the feasibility of using spin-echo and spin-wave experiments to measure the polarization dependence of transverse and