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HIGH TEMPERATURE SUPERCONDUCTIVITY

Guest Editors: Catherine Kallin and John Berlinsky

LA SUPRACONDUCTIVITÉ À HAUTE TEMPÉRATURE

Rédacteurs honoraires : Catherine Kallin et John Berlinsky

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PHYSICS IN CANADA
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Vol. 56 No. 5
September / October 2000
septembre / octobre 2000

TABLE OF CONTENTS / TABLE DES MATIÈRES

FEATURE ARTICLES / *ARTICLES DE FOND*

PHYSICS AND EDUCATION / LA PHYSIQUE ET L'ÉDUCATION:

OPINION : HIGH T_C - WHAT IS THE MECHANISM?

by/par

DEPARTMENTS / *RUBRIQUES*

FRONT COVER / *COUVERTURE*

"Concepts in High Temperature Superconductivity" by Canadian artist, Gerald Zeldin (2000).

«Notions de supraconductivité à haute température» de l'artiste canadien Gerald Zeldin (2000).

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– FOREWORD/PRÉFACE –

HIGH TEMPERATURE SUPERCONDUCTORS - A GRAND CHALLENGE FOR THE 21ST CENTURY

LES SUPRACONDUCTEURS À HAUTE TEMPÉRATURE - UN GRAND DÉFI POUR LE 21EME SIÈCLE

Since its discovery by Bednorz and Muller in 1986, high temperature superconductivity has remained arguably the most active and competitive research area in physics internationally. From the very beginning, when it precipitated the frenzied late-night session, dubbed the "Woodstock of Physics," at the 1987 March Meeting of the American Physical Society in New York City, it has been the source of an unprecedented and persistent torrent of meetings, talks and papers. It is also an area where Canadian physicists have managed to have a surprisingly large impact, in part as a result of networking supported by the Superconductivity Program of the Canadian Institute for Advanced Research.

This issue of Physics in Canada is devoted to high temperature superconductivity. It is intended to provide a useful introduction to the field, particularly for beginning graduate students, and it highlights many of the important Canadian contributions. We have also tried to incorporate some of the culture of the field, which has its own peculiar flavor mainly because of the intensity of the competition. The phrase "understanding the mechanism" of high Tc superconductivity is a kind of mantra for describing the ultimate goal of work in this field. Although a number of brave individuals have claimed, over the years, to have discovered or explained the mechanism, there is no broad consensus as there was when Bardeen, Cooper, and Schrieffer presented their BCS theory of the phonon mechanism of low temperature superconductivity. This will be evident from reading the short invited essays by leading theorists, entitled "High Tc: What is the mechanism?", interspersed throughout this issue.

Why is high Tc superconductivity so important, or, more precisely, why are so many condensed matter physicists, including many of the world's best researchers, driven to work on this subject? The answer is a combination of fundamental and practical considerations. On the fundamental side, one can say that the essence of the challenge is to solve the strong correlation problem - What happens when electrons in a metal can no longer be described by that paradigm of interacting electrons, Landau's Fermi liquid theory? How do electron-electron interactions change a half-filled band, which in the non-interacting case would make an excellent metal, into an insulating antiferromagnet? The search for answers to such questions is the subject of the pedagogical theory article by Tremblay, Bourbonnais, and Senechal, which is the first article in this issue.

However, the great theoretical challenges arising from the strong correlation problem would not in themselves be enough to sustain such a level of international activity. The fact that there is so much interest in high temperature superconductivity required an additional ingredient. That is the prospect that we might someday be able to make even higher temperature superconductors, i.e. superconductors that work at room temperature and above. The idea of practical, room temperature superconductors, with their distinctly quantum mechanical properties, such as the Meissner and Josephson effects, is both tantalizing and exciting. The possibility of making room temperature superconductors goes back to the mechanism, which, arising as it must from Coulomb interactions and quantum statistics, could, in principle, lead to Tc's of several hundred Kelvin. It is this combination of fundamental theoretical importance and exciting practical potential that drives the field.

What is a high temperature superconductor? At this point in time, there is only one class of materials that exhibit high temperature superconductivity. That is the class of rare earth copper oxides with various kinds of dopants. These are all layered materials consisting of CuO_2 planes, with the Cu atoms forming a square lattice and O atoms between each nearest-neighbor pair of Cu atoms. (See Fig. 1 of the article by Liang *et al.*) The rest of the atoms, rare earth atoms, dopants and excess copper and oxygen, lie in charge reservoir layers separating the square planar CuO_2 layers. These charge reservoir layers control the oxidation state of the planar coppers, which is either Cu2+ or Cu3+. The Cu2+ state has a single unpaired 3d electron while, in the Cu3+ state, all the 3d valence electrons are paired.

High temperature superconductivity occurs when the "undoped parent compound", which is an insulating antiferromagnetic material, is "doped with holes." In the undoped parent compound, all of the planar coppers are in the Cu2+ state, with one unpaired spin per site. These unpaired spins then order antiferromagnetically, so that neighboring spins are antiparallel. The insulating character of this state is thought to result, not from the antiferromagnetism directly, but from the strong on-site Coulomb repulsion, which is the energy cost of putting an extra electron on a Cu atom to make Cu1+. This Coulomb energy for double occupancy suppresses conduction, in systems with an average density of one electron per site, by creating a kind of collective Coulomb blockade. The result is called a "Mott insulator." Removing electrons or equivalently adding holes to these materials both destabilizes the antiferromagnetic spin order and relieves the electronic congestion, turning them from insulators to conductors.

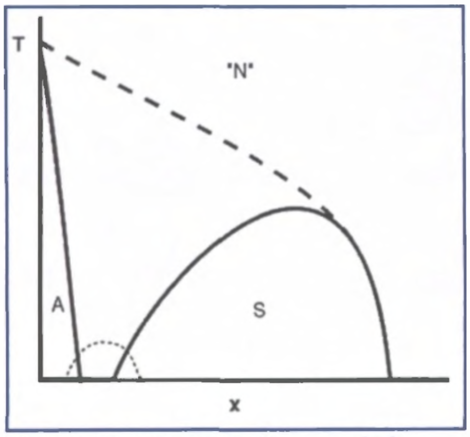

Fig. 1 Temperature, T, versus hole-doping, x, phase diagram for a typical high Tc superconductor, as described in the text.

In light of the above discussion, it is not surprising that high Tc materials are often described in terms of a phase diagram, where the axes are temperature, T, and doping, x. x=0 corresponds to the undoped, insulating state, and x itself is the number of excess holes per planar Cu site. Such a phase diagram is shown in Fig. 1. The solid lines in this figure are phase boundaries. There is an antiferromagnetic phase, labeled A, which has its maximum temperature for x=0. The transition temperature for this phase falls off rapidly with increasing x and appears to fall to zero for x of a few per cent. For larger values of x, there is another phase boundary, containing the superconducting phase, S. This phase has its maximum transition temperature at what is called "optimal doping". To the left of this point, materials are said to be "underdoped", and to the right they are "overdoped."

In addition to sharp phase boundaries there is also a well-defined crossover line to the so-called pseudogap phase. It is by now well established that, for underdoped materials, some kind of precursor to the superconducting energy gap occurs at temperatures much higher than the superconducting Tc. This is not a sharp transition, and so the bold dashed curve in Fig. 1 simply indicates the temperatures below which the existence of this pseudogap becomes evident. Finally there is a part of the phase diagram at low temperatures, indicated by the thin dashed line in Fig. 1, overlapping the region where antiferromagnetism disappears and superconductivity grows up, where the system may exhibit a variety of phases. In this region there is evidence for spin glass behavior and for charge-modulated mesophases called "stripes." It is even possible for the charge and doping to be modulated from layer to layer - a phenomenon familiar in intercalated graphite called "staging." For different high Tc compounds, different behaviors are observed in this region of the phase diagram. It appears that, in the vicinity of the crossover from antiferromagnet-ism to superconductivity, there are many competing phases that can be stabilized by small variations in the chemistry. As a result, this region is poorly understood.

Mention should also be made of the high temperature region, "N", above the superconducting phase. For a conventional superconductor, this would be the so-called "normal" state. However, for high temperature superconductors, this phase is by no means normal. The resistivity in the Cu-O planes for this phase varies linearly with T, which is not in itself so unusual for a metal. What is unusual is that it varies this way up to very high temperatures, where the resistivity of a normal metal would have saturated, and, for some high Tc compounds in which Tc is suppressed, it can remain linear down to rather low temperature with an intercept that, for clean materials, is close to zero. By comparison, the resistivity perpendicular to the planes varies roughly as 1/T, and its magnitude is very large, corresponding to a mean free path of less than the interlayer spacing. Thus these materials appear to be metals, albeit strange metals, in two directions and insulating in the third.

The low temperature thermodynamic and transport properties of a superconductor are largely determined by the size and wave-vector dependence of the superconducting energy gap $\Delta(k)$. Much of the early work in this field aimed at establishing whether the superconductivity in high Tc superconductors was conventional s-wave superconductivity, where $\Delta(k)$ is approximately independent of k on the Fermi surface, or unconventional superconductivity, such as d-wave, where the gap has nodes and changes sign at points on the Fermi surface. What is the significance of s- versus d-wave? Basically it is that d-wave is favored when electrons want to avoid each other at short distances. Thus one expects strong correlation mechanisms to give rise to d-wave superconductivity, while it is natural for the BCS phonon mechanism to induce s-wave superconductivity.

Early experimental studies usually assumed that the superconductivity was s-wave and interpreted all of the data in terms of that assumption. Of course much of the data hinted at nodes in the gap, but it was not until the measurements of Hardy, Bonn and co-workers (cf. the article by Bonn and Hardy in this issue), clearly demonstrating the linear temperature dependence of the low T penetration depth, that the broader community began to take seriously the possibility that the superconducting gap might have nodes and d-wave symmetry.

Since then there have been many experimental and theoretical studies of the d-wave properties of these materials. In particular, much has been learned about the properties of d-wave quasiparticles, which have Dirac-like spectra with the excitation energies proportional to the distance in wavevector from one of the nodes. Other phase-sensitive measurements have probed the sign changes of the gap around the Fermi surface. One surprising feature of these studies is how little they show about the strongly correlated state that underlies this d-wave superconductivity, which is, after all, occurring in a Mott insulator doped with holes. In order to probe those aspects, it is necessary to study the doping dependence of the superconducting state. Doping dependent studies require a high level of control of materials properties, as is evident from the article by Liang et al. Such control is essential before meaningful data can be taken.

What are the burning issues in high temperature superconductivity today? The most important issue is the mechanism: What drives superconductivity at 150K? Could it equally well work at 300K? How do strong correlations, i.e. electrons trying to stay out of each other's way, manage to stabilize d-wave superconductivity? What should be clear from this special issue is that there are many competing candidate mechanisms, and a broad range of experimental probes that can be brought to bear on this problem to distinguish them. The situation is in a state of flux, with highly developed and strongly held opinions crying out to be tested. The trick is to figure out what distinguishes these ideas and what are the key experimental tests for each of them. These are very difficult questions but the payoff is also very large for good answers and clever experiments. It is highly likely that these answers will be provided and the experiments will be done by graduate students who are just now beginning their studies. The results of such work are crucial for future progress in the development and applications of existing and new high temperature superconductors. At the same time, they will allow us to rewrite the textbooks on solid state physics, which were originally written in terms of one-electron physics in the 50's, to incorporate the physics of strongly correlated electronic systems for the 21st century.

John Berlinsky and Catherine Kallin, McMaster Univ.,
Honorary Editors

LES SUPRACONDUCTEURS À HAUTE TEMPERATURE - UN GRAND DÉFI POUR LE 21^{EME} SIÈCLE

Depuis sa découverte par Bednorz et Müller en 1986, on peut affirmer que la supraconductivité à haute température demeure le secteur le plus actif et concurrentiel de la recherche internationale en physique. Depuis le début, lorsqu'elle a provoqué la séance nocturne frénétique qu'on a qualifiée de « Woodstock de la physique » à la réunion de mars 1987 tenue à New York par l'American Physical Society, cette découverte a suscité une marée sans précédent de réunions, de discussions et de publications. C'est aussi un secteur où les physiciens canadiens ont eu un impact étonnement grand, entre autre grâce aux collaborations qu'a favorisées le Programme en Supraconductivité de l'Institut canadien de recherches avancées.

Le présent numéro de *La Physique au Canada* est consacré à la supraconductivité à haute température. Il vise à initier au domaine les nouveaux étudiants des 2^e et 3^e cycles surtout et à souligner nombre des importantes contributions de Canadiens. Ce numéro tente en outre de présenter certains éléments de la culture du domaine qui a sa saveur propre, notamment à cause de l'intensité de la concurrence. L'expression « comprendre le mécanisme » de la supraconductivité à haute Tc est une sorte de mantra décrivant l'objectif ultime des travaux dans ce domaine. Même si un certain nombre d'individus courageux ont prétendu au fil des ans avoir découvert ou expliqué ce mécanisme, il n'existe pas de consensus aussi vaste que lorsque Bardeen, Cooper et Schrieffer ont présenté leur théorie BCS du mécanisme à phonons pour la supraconductivité à basse température. Cela saute aux yeux à la lecture des brefs essais sur le thème « Les hautes températures critiques : quel en est le mécanisme? », qui ont été sollicités auprès de théoriciens de premier plan **qui sont répartis à travers le présent numéro.**

Pourquoi la supraconductivité à haute Tc est-elle si importante ou, plus précisément, pourquoi les physiciens de la matière condensée, dont plusieurs sont parmi les plus grands chercheurs au monde, sont-ils si nombreux à être attirés par ce sujet? La réponse est un ensemble de considérations fondamentales et pratiques. Sur le plan fondamental, on peut dire que le défi consiste essentiellement à résoudre le problème des electrons fortement corrélés : Qu'arrive-t-il quand les électrons d'un métal ne correspondent plus au paradigme d'électrons en interaction qu'est la théorie de Landau sur les liquides de Fermi? Comment l'interaction entre électrons peut-elle changer une bande semi-occupée, qui en cas de non-interaction ferait un excellent métal, en un isolant antiferromagnétique? La quête de réponses à ces questions est le sujet du premier article du présent numéro, un article pédagogique sur la théorie signé Tremblay, Bourbonnais et Sénéchal.

Les grands défis théoriques découlant du problème des fortes corrélations ne pourraient toutefois suffire à soutenir à eux seuls un tel niveau d'activité sur le plan international. Il faut un autre facteur pour expliquer l'intérêt si marqué que suscite la supraconductivité à haute température : la possibilité de fabriquer un jour des supraconducteurs à température critique encore plus élevée, c'est-à-dire fonctionnant à la température ambiante ou au delà. La perspective de supraconducteurs pratiques à température ambiante, avec leurs propriétés distinctement quantiques, tels les effets Meissner et Josephson, est à la fois alléchante et passionnante. Elle tient du mécanisme qui, découlant comme il se doit des interactions électrostatiques et de la statistique quantique, pourrait en principe mener à des Tc de plusieurs centaines de degrés Kelvin. C'est la combinaison des aspects théoriques d'importance fondamentale et des aspects pratiques au potentiel très excitant qui anime ce domaine de recherche.

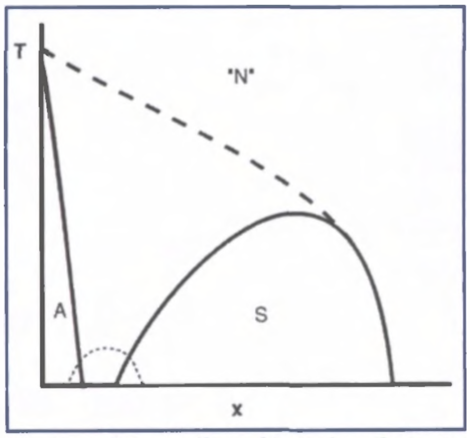

Fig. 1 Comme il est décrit dans le texte, la température T par rapport au dopage à l'aide de trous, x, diagramme de phases du supraconducteur à haute Tc typique.

Qu'est-ce qu'un supraconducteur à haute température? A l'heure actuelle, il n'y a qu'une seule catégorie de matériaux qui sont supraconducteurs à haute température, celle des oxydes de cuivre de terres rares avec divers types de dopants. Il s'agit de matériaux stratifiés consistant en un empilement de plans de CuO_2, les atomes de Cu formant un réseau carré et les atomes d'oxygène au centre de chaque paire d'atomes de cuivre les plus rapprochés (voir la figure 1 dans l'article de Liang et coll.). Le reste des atomes, des atomes de terres rares, des dopants ainsi que du cuivre et de l'oxygène excédentaire, forment des réservoirs de charge séparant les couches planaires carrées de CuO_2. Ces couches réservoirs contrôlent l'état d'oxydation des cuivres planaires : Cu2+ ou Cu3+. L'état Cu2+ comporte un seul électron 3d découplé tandis que, dans l'état Cu3+, tous les électrons de valence 3d sont appariés.

Il y a supraconductivité à haute température lorsqu'on « dope au moyen de trous » le « composé d'origine non dopé », qui est un matériau antiferromagnétique isolant. Dans ce composé non dopé, tous les cuivres planaires sont à l'état Cu2+, avec un spin découplé par site. Ces spins découplés s'orientent alors dans un ordre antiferromagnétique, de sorte que les spins voisins sont antiparallèles. La propriété isolante de cet état découlerait non pas de l'antiferromagnétisme directement, mais de la forte répulsion coulombienne du site, soit l'énergie nécessaire pour ajouter un électron à l'atome de Cu et le porter à Cu1+. Cette énergie coulombienne de double occupation supprime la conduction, dans les systèmes dont la densité moyenne est d'un électron par site, en créant une espèce de barrage collectif coulombien, ce qui donne l'« isolant de Mott ».Le fait d'enlever des électrons ou, ce qui revient au même, d'ajouter des trous dans ces matériaux a pour double résultat de déstabiliser l'ordre antiferromagnétique de spins et d'atténuer la congestion électronique, transformant les isolants en conducteurs.

À la lumière de ce qui précède, il n'est pas étonnant que les matériaux à haute Tc soient souvent décrits en terme d'un diagramme de phases, dont les axes sont la température T et le dopage x, où x est le nombre de trous excédentaires par site planaire de Cu et x=0 correspond à l'état isolant non dopé. C'est ce diagramme de phases qu'illustre la figure 1. Les lignes pleines de cette figure sont les limites des phases. Il y a une phase antiferromagnétique A dont la température maximale se situe à x=0. La température de transition pour cette phase baisse rapidement à mesure que x augmente et semble devenir nulle quand x atteint quelques points de pourcentage. Pour les valeurs supérieures de x, il y a une autre limite de phase qui contient la phase supraconductrice S. La température de transition maximale de cette phase se situe au point dit de « dopage optimal ». À la gauche de ce point, les matériaux sont « sousdopés » et à la droite, « surdopés ».

Outre les démarcations nettes de phase, il y a une ligne de crossover bien définie sous laquelle se trouve la phase du pseudogap Il est d'ores et déjà bien établi que, pour les matériaux sousdopés, un type de précurseur du gap d'énergie supraconducteur apparaît à des températures nettement supérieures à la Tc supraconductrice. Comme cette transition n'est pas abrupte, la courbe en pointillé gras de la figure 1 indique simplement les températures sous lesquelles l'existence de ce pseudogap devient évidente. Il y a une partie du diagramme de phases à basses températures, indiquée par le pointillé fin de la figure 1 et chevauchant la zone de disparition de l'antiferromagnétisme et de croissance de la supraconductivité, où le système peut afficher différentes phases. Dans cette zone apparaissent un verre de spin et des mésophases à modulation de charge appelées « bandes ». Il est même possible que la charge et le dopage soient modulés d'une couche à l'autre - phénomène courant dans le graphite intercalaire appelé « staging ». Pour différents composés à haute Tc, divers comportements sont observés dans cette zone du diagramme de phases. Il semble qu'au voisinage du passage de l'antiferromagnétisme et la supraconductivité, il y ait un certain nombre de phases concurrentes que de petites variantes chimiques peuvent stabiliser. Nous n'avons pour l'instant qu'une piètre compréhension de cette zone.

Il faut aussi mentionner la zone de température élevée « N » au-dessus de la phase supraconductrice. Pour un supraconducteur conventionnel, ce serait l'état dit « normal ». Pour les haut Tc, cependant, cette phase n'est pas du tout normale. La résistivité des plans de Cu-O pour cette phase varie linéairement en T, ce qui n'est pas si inhabituel en soi pour un métal. Ce qui est inhabituel, toutefois, c'est que cette dépendance en T se poursuive jusqu'à des températures très élevées, où la résistivité d'un métal normal serait saturée. De plus, pour certains composés à haute Tc où la Tc est supprimée, la dépendance en T linéaire jusqu'à une température assez basse avec une intersection qui, pour les matériaux propres, est presque nulle. Par comparaison, la résistivité perpendiculaire aux plans varie en gros en 1/T et a une valeur énorme qui correspond à un libre parcours moyen inférieur à la séparation entre les couches. Ces matériaux semblent donc être des métaux, quoique des métaux étranges, dans deux directions et des isolants dans la troisième direction.

A basses températures, les propriétés thermodynamique et de transport d'un supraconducteur dépendent en grande partie du gap supraconducteur $\Delta(k)$ et de sa variation en fonction du vecteur d'onde. Une grande partie des premiers travaux dans ce domaine visaient à établir si la supraconductivité des supraconducteurs à Tc était une supraconductivité conventionnelle d'onde-s , où $\Delta(k)$ est presque indépendant de k sur la surface de Fermi, ou plutôt une supraconductivité d'onde-d non conventionnelle, où le gap présente des zéros et change de signe en des points de la surface de Fermi. Quelle est la signification d'onde-s par rapport à onde-d? C'est essentiellement que l'onde-d est favorisée lorsque les électrons veulent s'éviter à faibles distances. On s'attend donc à ce que de puissants mécanismes de corrélation fassent naître la supraconductivité d'onde-d, tandis que le mécanisme des phonons BCS engendre naturellement la supraconductivité d'onde-s.

Selon les premières études expérimentales, on supposait généralement que la supraconductivité était d'onde-s et l'on interprétait toutes les données en conséquence. Bien sûr, une bonne partie des données suggéraient la présence de zéros dans le gap, mais il faudra attendre les mesures de Hardy, Bonn et de leurs collaborateurs (voir l'article de Bonn et Hardy dans ce numéro), montrant clairement la dépendance linéaire en température de la longueur de pénétration à basse température, pour que l'ensemble de la communauté scientifique commence à prendre au sérieux la possibilité que le gap supraconducteur ait des zéros et une symétrie d'onde-d.

Depuis, il y a eu de nombreuses études expérimentales et théoriques sur les propriétés d'onde-d de ces matériaux. En particulier, on a beaucoup appris sur les propriétés des quasi-particules d'onde-d, qui ont des spectres de type Dirac dont l'énergie d'excitation est proportionnelle à la distance en vecteur d'onde de l'un des zéros. D'autres mesures sensibles à la phase ont exploré les changements de signe du gap autour de la surface de Fermi. Un aspect étonnant de ces études est le peu d'information qu'elles nous apprennent sur l'état à forte corrélation qui sous-tend cette supraconductivité d'onde-d qui, après tout, se produit dans un isolant de Mott dopé de trous. Pour vérifier ces aspects, il faut étudier la dépendance en dopage de l'état supraconducteur. Les études sur cette dépendance exigent un degré élevé de maîtrise des propriétés des matériaux, comme il ressort de l'article de Liang et de ses coll. Pareille maîtrise est essentielle si l'on veut recueillir des données significatives.

Quelles sont actuellement les questions brûlantes en matière de supraconductivité à haute température? La plus importante est celle du mécanisme : Qu'est-ce qui cause la supraconductivité à 150 °K? Serait-elle également possible à 300 °K? Comment de fortes corrélations, soit des électrons qui tentent de rester hors de portée les uns des autres, peuvent-elles stabiliser la supraconductivité d'onde-d? Ce qui ressortira clairement de ce numéro spécial, c'est que de nombreux mécanismes concurrents sont possibles et qu'un vaste éventail d'études expérimentales peuvent servir à les distinguer les uns des autres. La situation évolue sans cesse et des modèles très avancés et défendus avec vigueur exigent d'être mis à l'essai. L'astuce est de trouver ce qui distingue ces différentes idées et quels sont les tests expérimentaux clés pour chacune d'elle. Voilà des questions très difficiles, mais les conséquences d'une bonne réponse ou d'une expérience ingénieuse sont aussi très importantes. Il est fort probable que les étudiants des 2^e et 3^e cycles qui viennent tout juste d'entreprendre leurs études seront ceux qui trouveront ces réponses et feront ces expériences. Les résultats de ces travaux sont essentiels pour le développement et les applications futures des supraconducteurs à haute température tant existants que nouveaux. Du même coup, ils nous permettront de récrire les manuels sur la physique des semi-conducteurs, qui ont été élaborés à l'origine d'après la physique à un électron dans les années 50, de manière à englober la physique des systèmes électroniques à forte corrélation du XXI^e siècle.

John Berlinsky et Catherine Kallin, Univ. McMaster,
Rédacteurs honoraires

LETTERS / COURRIER

SUSTAINABLE DEVELOPMENT ON A WARMING PLANET (July/August 2000 PiC)

A physicist friend passed me your editorial in the July/August 2000 CAP Journal. I enjoyed reading it - here are a few comments:

As an engineer (mechanical) I never thought of "civil engineer" as an oxymoron. Better be careful, or I'll spread the word that astrophysicists are still earning their keep telling fortunes!

Jesting aside, I maintain the web page (www.cns-snc.ca\branches\manitoba\manitoba.html) of the Manitoba Branch of the Canadian Nuclear Society (as well as being its chair). This provides me an outlet for various nuclear pieces, including my up-to-date graphs of reactor performance. On the performance page it's reported that, since 1962, Canadian reactors (i.e., those in Canada) have produced a net of 1,538,000,000 MWhe to May 31, 2000. Since the vast majority of Canadian reactors substituted for coal or oil-fired generation, one can assume that the above net generation replaced approximately 1.5 billion tonnes of CO_2 (~1 tonne CO_2 per 1 MWhe, for coal stations, depending upon the coal source and power plant). In addition, 9 CANDUs built in other countries have generated a net of approximately 235,000,000 MWhe, equivalent to a further ~0.2 billion tonnes of CO_2 avoidance.

Thus I believe that your number of "8 billion tonnes of CO_2 [avoided since 1958]" is a low estimate, even though some of the world's nuclear energy would have been generated by natural gas instead (~55% of the CO_2 emissions as coal, per unit electricity produced).

I liked the tone of your editorial - I got into the nuclear business because I saw it (and continue to do so) as a relatively low entropy and practical source of energy, without the heavy environmental burdens so many of our sources impose on our only planet. As for recycling, I have been involved in it for years, at one time president of Pinawa Recycling Inc. Although the methods and effectiveness of the system have improved considerably, it remains a labour-intensive effort.

I certainly hope you and your fellow physicists can play a major role in sustainable development. I hope we all can.

Morgan Brown
Atomic Energy of Canada Ltd.

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It is perhaps worth pointing out that nuclear power in Canada has contributed more than carbon dioxide avoidance. It was also the key requirement for Canada to meet its acid gas emission reduction quotas with the United States in the Acid Rain Treaty. During the 1980s, both countries agreed to reduce sulphur dioxide emissions, but methods varied in each country in executing these reductions. The United States introduced the Clean Air Act, which essentially created a cap and trade system for sulphur dioxide which rewarded clean burning fossil fuel operators at the expense of heavy emitters.

Canada achieved its quota by placing acid gas restrictions on two entities, Inco and Ontario Hydro. In the case of Inco, the company converted much of its nickel smelting operations to electrotechnology. In the case of Ontario Hydro, that utility was able to more than halve its coal burning through the completion of the 12 nuclear reactors at the Pickering B, Bruce B and Darlington nuclear stations. It is worth noting that acid gas emissions have again risen to levels very close to the permissible limits as a consequence of the 1997 shutdown of Pickering A and Bruce A stations. Exceeding Ontario Hydro's (now Ontario Power Generation's) limits has been avoided only through the large scale purchase of electricity from the United States, about 2.5 per cent of total electricity consumed in Ontario.

In retrospect, acid rain disappeared as an atmospheric emissions issue with the large scale reductions made possible by nuclear power. Emissions which had totalled about 400,000 tonnes annually from Ontario Hydro declined to less than 200,000 tonnes, thanks solely to nuclear power. Hence, any reduction of the amount of nuclear generation in Ontario is likely at least in the short term to raise concerns about sulphur dioxide again.

Colin Hunt
Policy Director
Canadian Nuclear Association

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RESPONSE TO R. BOLTON'S LETTER (July/August 2000 PiC)

I was saddened to read Richard Bolton's letter in the July/August issue of Physics in Canada, first because it reminded me once more of the tragic losses which our community suffered as a result of the 1996 federal budget, but also because of his apparent bitterness at the CAP.

If I were in Richard's position, I too would be angry and bitter at what happened to his Centre canadien de fusion magnetique (CCFM), but I do not believe that the facts support his criticisms of CAP. So, while Richard generously exempts me personally from his criticisms, I feel I must rise to the defense of all the other CAP volunteers who have spent untold hours in lobbying governments for all kinds of physics causes, including CCFM's.

The fact is that CAP, obviously with limited resources, mounted an extremely vigorous campaign in defense of all three physics laboratories whose closing was announced in the 1996 budget. An extensive letter-writing campaign, many direct contacts with key civil servants and politicians, and involvement of the press were just some of the efforts undertaken. I simply have no idea how we could have done more. With crucial help from others, one centre (the AECL neutron group) was saved. This was a very unusual success in the days of federal program review, when almost no cuts of any kind were reversed, for fear of 'opening the floodgates'. Moreover (unlike TASCC) CCFM received a several-year funding extension, which many of us hoped would give it a chance for a quiet reversal of the closure decision. As far as I know, CCFM never contacted CAP after 1996 to alert it that this was not happening and that further action might be helpful.

During my Presidency (which spanned most of the critical 1996 timeframe), it is not the case that I received "no support from the rest" in CAP regarding CCFM. I cannot recall a single time when I did not receive all possible support from those active in CAP's leadership. I also do not recall ever receiving a request from CCFM which was not acted on promptly and fully. Moreover, CAP was proactive in contacting Richard on several occasions to make sure that we were doing everything that we could. Specific requests from the other threatened centres were acted upon, but apart from this, as far as I recall, CAP spent equal time and effort on all three. In short, I believe, everything remotely possible was done to fight the CCFM closure: sometimes, however, one's best is just not enough.

Despite this, we know from people in government that our efforts in 1996 had a very substantial impact, even in the cases where the final decision went against us. Indeed, I believe they substantially contributed to the newfound awareness of science in government, which (after extensive and continuing lobbying in which CAP has played a leadership role) has led to so many extremely positive decisions for science in the intervening years. As just one example of the impact of our efforts during the CCFM campaign, one might cite the unprecedented exposure of the issue which occurred when the Bloc Quebecois initiated a major debate in Parliament on the matter, reading CAP's letter on the topic in its entirety into Hansard as one of its primary weapons.

Regarding CAP recognition of the excellent scientific work done at CCFM, the obvious mechanism would be via CAP's various Medals. It has always been open to any CAP member to propose such recognition, and the decision on such proposals is the function of independent committees, not of CAP itself. I am certainly not aware of any CAP bias against the work at CCFM or against plasma physics. However, I do agree with Richard that it would be appropriate to try to find other ways to celebrate the achievements of CCFM and of related efforts in Canada. I hope very much that Physics in Canada will be able to do this.

On a personal note, I was very sorry to hear that Richard has left physics. I wish him the best in his new efforts. No person should have to go through what Richard and his people did (nor what the TASSC people and others did), but in Richard's case at least physics' loss is urology's gain!

P.S. Vincett, FairCopy Services Inc.
(President of CAP, 1995-96)

SCIENCE POLICY / LA POLITIQUE SCIENTIFIQUE

CAP MEETS WITH PRIME-MINISTER'S OFFICE REGARDING THE CANADIAN NEUTRON FACILITY

by Paul Vincett, CAP Director, Communications

At the end of July, a CAP delegation met with a senior member of the Prime Minister's Office (PMO) to press the case for funding the proposed Canadian Neutron Facility (CNF). CAP was represented by Marie D'Iorio (Past-President), Bruce Gaulin, and Paul Vincett. As far as we know, this is the first time that any delegation has been able to get a meeting on the CNF at this level.

The PMO was represented by Marjory Loveys, who is Senior Advisor, Economic Development, on the Prime Minister's political staff. Ms. Loveys was clearly well aware of the CNF issue (presumably because of the many letters sent to the PMO recently by CAP members), and commented on the success of physicists in lobbying efforts generally.

The CAP delegation explained the world-leading excellence of neutron scattering research in Canada, and its significance to materials characterization and thus to research and the economy. We emphasized the enormous economic importance of materials in the 21st Century, and that Canada (unlike most countries) does not have a national multi-sectoral effort to support materials research. We pointed out that materials characterization, if Canada continues to support it adequately, is still a very important competitive advantage, and that it has nurtured academic excellence in materials research generally. All this could start to come unravelled if a key capability like the CNF ceased to exist. We argued that the CNF is an essential and synergistic complement to the Canadian Light Source and to the materials capabilities at TRIUMF, both of which facilities have received major funding recently.

We particularly emphasized the great urgency of a decision on the CNF, because of the looming 'neutron gap' and because of the danger of losing critical people soon. We argued that rather small seed funding now could get things going for a year, while the larger AECL questions are sorted out. We also pointed out the difficulties of having two government departments (NRCan and Industry) involved in the decision-making and asked that the PMO use its unique ability to facilitate a joint approach.

While it is always very difficult to gauge the success of a meeting like this, CAP was able to present the excellent case for the CNF at the PMO level, and to ensure that the PMO is aware of the very great urgency of the situation. There is little doubt that further letters from the community, particularly emphasizing the urgency, would help to drive home the message.

L'ACP RENCONTRE LE CABINET DU PREMIER MINISTRE POUR DISCUTER DU CENTRE CANADIEN DE NEUTRONS

par Paul Vincett, Directeur des communications

À la fin de juillet, une délégation de l'ACP a rencontré un cadre supérieur du Cabinet du premier ministre (CPM) afin de faire pression pour obtenir des fonds pour le Centre canadien de neutrons (CCN). Marie D'Iorio (l'ancienne présidente), Bruce Gaulin et Paul Vincett ont été mandatés pour représenter l'ACP. Pour autant que nous sachions, cette délégation est la première à obtenir une rencontre à cet échelon au sujet du CCN.

La représentante du CPM était Marjory Loveys, Conseillère principale au développement économique, membre du personnel politique du premier ministre. Manifestement, Mme Loveys était bien informée de la question du CCN (les nombreuses lettres expédiées par certains membres de l'ACP y ont sans doute contribué) et elle a fait des commentaires sur le succès des efforts des groupes de pression des physiciens (nes) en général.

La délégation de l'ACP a expliqué la supériorité, au niveau mondial, de la recherche canadienne en diffusion de neutrons et sa signification pour la caractérisation des matériaux et, donc, pour la recherche et l'économie. Nous avons insisté sur la très grande importance économique des matériaux au 21ème siècle, et sur le fait qu'au Canada (contrairement à la plupart des pays) il n'existe aucune concertation multisectorielle et nationale pour appuyer la recherche des matériaux. Nous avons souligné que la caractérisation des matériaux, si le Canada continue à l'appuyer de façon adéquate, constitue toujours un avantage compétitif de forte taille et, qu'en plus, celle-ci a développé l'excellence théorique au niveau de la recherche des matériaux en général. Tout ceci s'effritera peu à peu si un potentiel du genre du CCN disparaît. Nous avons argumenté que le CCN est un complément essentiel et synergique au Centre canadien de rayonnement synchroton et aux capacités des matériaux de TRIUMF, ces deux derniers étant des centres ayant récemment obtenu un important financement.

Nous avons particulièrement insisté sur l'urgence d'une décision relativement au CCN, en raison du "manque de neutrons" (neutron gap) qui semble imminent, ainsi que la menace de perdre des gens dont on ne peut se passer. Nous avons discuté qu'en ce moment, une modeste mise de fonds initiale permettrait de continuer le travail pour un an, en attendant que les questions un peu plus complexes reliées à l'EACL soient réglées. En outre, nous avons souligné les difficultés à avoir deux départements gouvernementaux (Ressources naturelles Canada et Industrie Canada) impliqués au niveau décisionnel et avons demandé au CPM d'employer leur habileté sans égale à simplifier une approche conjointe.

Bien qu'il soit toujours difficile de juger du succès de ce genre de rencontre, l'ACP a su présenter de bons arguments en faveur du CCN au CPM et s'est assuré que ceux-ci soient au courant de l'urgence de la situation. Il ne fait aucun doute que toute correspondance future, provenant de la collectivité et qui insiste particulièrement sur l'urgence, ne peut qu'aider à mieux faire comprendre le message.

CAP COUNCIL / CONSEIL DE L'ACP
CALL FOR NOMINATIONS - APPEL DE CANDIDATURES

Are you interested in having a voice in the management of the CAP? Do you want to help define the priorities of your association as we enter the new millenium? Volunteers for the 2001-2002 Council are now being sought for these important positions.

A brief call for nominations and a description of the roles and responsibilities of CAP Council members, can be found on the CAP's website at http://www.cap.ca or by contacting the CAP office at 613-562-5614 or by e-mail at CAP@physics.uottawa.ca.

Deadline for submission of expressions of interest is 2000 December 1.

Vous voulez avoir voix au chapitre dans la direction de l'ACP? Vous désirez définir les priorités de votre association à l'aube du nouveau millénaire? Nous sommes présentement à la recherche de personnes voulant se proposer comme candidate aux postes importants à combler au Conseil 2001-2002.

Si vous voulez voir un formulaire d'appel de candidatures et une description du rôle et des responsabilités des membres du Conseil de l'ACP, veuillez consulter les pages W3 de l'ACP à l'URL www.cap.ca ou contacter le bureau de l'ACP à 613-562-5614 ou par courriel à CAP@physics.uottawa.ca.

L'échéance pour la présentation des candidatures a été fixée au 1 décembre 2000.

CALENDAR / CALENDRIER

2000 OCTOBER / OCTOBRE

16-20 **IUPAP International Conference on the Fractal Aspects of Complex Systems (FACS 2000)**, Maceio. The Conference will be hosted by the Statistical Physics Group of the Departamento de Física (Universidade Federal de Alagoas). For more information please contact Dr. Marcelo Lyra, email: marcelo@ising.fis.ufal.br or website: http://facs2000.fis.ufal.br

23-27 **2000 International Congress on Plasma Physics/combined with 42nd Annual Meeting of the Division of Plasma Physics of the American Physical Society**, Quebec City, Canada. For more information, ICP-2000 website: http://www.inrs-ener.uquebec.ca/icpp/ or APS-DPP website: http://www.aps.org/meet/DPP00/

2000 NOVEMBER / NOVEMBRE

2-3 **Innovation 2000: The Grand Challenges in Managing and Sustaining Innovation, Toronto, Ontario.** *To full-time academics and to employees of small and medium enterprises (SMEs, enterprises with less than 500 employees worldwide) the Centres are providing for a special early bird registration rate of only $695. This is a saving of $700 off the full, advertised fee.* For more information: info@oce-ontario.org

18 **Canadian Light Source (CLS) 3rd Annual Users' Meeting**, University of Saskatchewan, Saskatoon, SK. Workshop on soft x-ray spectromicroscopy, infrared spectroscopy and microscopy and femtoerand x-ray diffraction on November 17 &19th. For more information please contact Sandra Ribeiro; email: clsuo@usask.ca or website: http://cls-ccrs.usask.ca

2000 DECEMBER / DÉCEMBRE

15-16 **Third World Congress of Physical Societies**, Berlin, Germany. For more information contact: Mireille Cubizolles, Main Secretariat, EPS, at e-mail: m.cubizolles@univ-mulhouse.fr.

2001 - **European Federation for Information Technology in Agriculture, Food and the Environment (EFITA) Congress**, Montpellier, South of France. For more information, contact Francis Sevilla at sevilla@ensam.inra.fr.

International Conference on The Radiological Protection of Patients in Diagnostic and Interventional Radiology, Nuclear Medicine and Radiotherapy, 25-30 March 2001, Malaga, Spain. For information: http://www.pruma.uma.es/ci2001.htmlx

XXVI International Symposium on Acoustical Imaging, Sept. 2001, University of Windsor. For mor information contact Dr. Roman Maev, maev@uwindsor.ca.

FUTURE CAP CONFERENCES / PROCHAINS CONGRÈS DE L'ACP

Congrès annuel 2001 Annual Congress, June 17-20 juin
University of Victoria / Université de Victoria, Victoria, BC.

Congrès annuel 2002 Annual Congress, June 9-12 juin
Université Laval University, Québec, QC

WWW.CAP.CA - Select 'Annual Congress' ; Option : Congrès annuel

CANADIAN NATIONAL IUPAP LIAISON COMMITTEE
CALL FOR NOMINATIONS / APPEL DE CANDIDATURES

Nominations are invited to fill one position (term ending Dec. 31, 2000) on the Canadian National IUPAP Liaison Committee (CNILC) for a term of three years commencing January 1, 2001. Although there are no restrictions on who is nominated, efforts will be made to ensure that there is a broad representation on the Committee covering the areas of geographic location, physics sub-discipline, and language requirements. The final decision remains with the CNILC Secretariat.

The current members of the Committee are:

H.M. van Driel (Chair) (Commission member 1999-2002) A.J. Alcock (Secretary)
H. Pépin (term ends Dec. 31/00) H.S. Freedhoff (term ends Dec. 31/01) B.W. Southern (term ends Dec. 31/01)
G. Ball (term ends Dec. 31/02) J. de Bruyn (term ends Dec. 31/02)

Ex-officio IUPAP Commission members (Sept. 1999 to Sept.2002) are:

R. Decoste	(Plasma Physics)	J.P. Harrison	(Low Temperature Physics)
A.B. McDonald	(Astrophysics)	E.L. McFarland	(Physics Education)
D.J. Rowe	(Mathematical Physics)	K.S.Sharma	(Symbols, Units, Nomenclature...)
R.M. Shoucri	(Computational Physics)	E.C. Svensson	(Struct. & Dynamics of Cond. Matt.)
H.M. van Driel	(Quantum Electronics)	W.T.H. van Oers	(Nuclear Physics)
W. van Wijngaarden	(Atomic. Mol. and Opt.Physics)	M. Wortis	(Biological Physics)
P.S. Vincett	(Physics for Development)	J.F. Young	(Semiconductor Physics)

Ex-Officio CNILC Members:

R.C. Barber (Vice-President of IUPAP)

It should be noted that the ex-officio commission members are eligible for nomination as CAP representatives on the CNILC.
Formal letters of nomination that include the nominee's curriculum vitae and a brief description of the nominee's involvement in international activities, must be sent to the Executive Director of the Canadian Association of Physicists, Suite 112, McDonald Building, 150 Louis Pasteur, Ottawa, Ontario K1N 6N5, by **2000 October 15**.

For further information, please contact Dr. D.J. Lockwood, CNILC Secretary, Institute for Microstructural Sciences, NRC (M-36), Ottawa. Tel. (613) 993-9614: FAX (613) 993-6486: E-MAIL - david.lockwood@ nrc.ca. Detailed reports on IUPAP matters can be found at http://www.iupap.org.

IUPAP SPONSORSHIP OF INTERNATIONAL CONFERENCES
PARRAINAGE DE CONFÉRENCES INTERNATIONALES PAR L'UIPPA

Each year IUPAP sponsors from 20 to 30 international conferences and awards grants to some of them. Conference organizers desiring IUPAP's sponsorship should communicate with the appropriate International Commission which will then make recommendations to the IUPAP Executive Council. ***April of the year preceding the proposed conference is the target date by which applications should be submitted to Commissions.*** Potential organizers of conferences to be held in Canada, during 2002 or early 2003, should obtain the support of the Canadian National IUPAP Liaison Committee (CNILC). In order for this to occur the relevant information must be sent to the address provided below by **February 28, 2001.**

It should be noted that conditions for IUPAP sponsorship are that the conference registration fee should not exceed the upper limit set by IUPAP each year (see IUPAP web site) and that circulars, other announcements, and the proceedings of the conference contain the following statement:

"To secure IUPAP sponsorship, the organizers have provided assurance that (Conference name) will be conducted in accordance with IUPAP principles as stated in the ICSU Document "Universality of Science" (sixth edition 1989) regarding the free circulation of scientists for international purposes. In particular, no bona fide scientist will be excluded from participation on the grounds of national origin, nationality, or political considerations unrelated to science."

Application forms and additional information can be obtained from the IUPAP web site: http://www.iupap.org or from the Secretary of the Canadian National IUPAP Liaison Committee:

D.J. Lockwood
Institute for Microstructural Sciences
National Research Council of Canada (M-36)
Ottawa, Ontario K1A 0R6
Tel.: (613) 993-9614 ; Fax: (613) 993-6486
E-mail: david.lockwood@nrc.ca

Chaque année, l'UIPPA parraine de vingt à trente conférences internationales et accorde des subventions à certaines d'entre elles. Les organisateurs de conférences souhaitant obtenir le parrainage de l'UIPPA doivent communiquer avec la Commission internationale appropriée, laquelle fera des recommmandations au Conseil exécutif de l'UIPPA. ***Les demandes de parrainage doivent être présentées aux commissions au plus tard le mois d'avril de l'année précédant la conférence proposée.*** Les éventuels organisateurs de conférences devant avoir lieu au Canada en 2002 ou au début de 2003 devraient obtenir l'appui du Comité national canadien de liaison avec l'UIPPA. Pour ce faire, ils doivent lui faire parvenir l'information nécessaire à l'adresse indiquée ci-dessous, d'ici le **28 février 2001.**

Il est important de noter que l'UIPPA ne parraine que les conférences respectant certaines conditions – les frais d'inscription à la conférence ne doivent pas excéder le montant maximal fixé par l'UIPPA (information sur le site internet d'UIPPA) et les circulaires, les autres annonces ainsi que les actes de la conférence doivent comporter l'énoncé suivant :

"To secure IUPAP sponsorship, the organizers have provided assurance that (Conference name) will be conducted in accordance with IUPAP principles as stated in the ICSU Document "Universality of Science" (sixth edition 1989) regarding the free circulation of scientists for international purposes. In particular, no bona fide scientist will be excluded from participation on the grounds of national origin, nationality, or political considerations unrelated to science."

Pour obtenir des formules de demande et toute autre information, il suffit de visiter le site suivant : http://www.iupap.org ou de s'addres-ser au secrétaire du Comité national canadien de liaison avec l'UIPPA :

D.J. Lockwood
Institut des sciences des microstructures
Conseil national de recherches Canada (M-36)
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Téléphone : (613) 993-9614 ; Télécopieur : (613) 993-4686
Courrier électronique : david.lockwood@nrc.ca

IN MEMORIAM

GEORGE MICHAEL VOLKOFF, 1914 - 2000

With the death of George Michael Volkoff in Vancouver, on April 24, 2000, Canada lost one of its eminent physicists and the Canadian Association of Physicists lost one of its early officers who was very active in the formative years of the Association. He died after being hospitalized for almost four years following a major stroke in the summer of 1996. George gained prominence as a theoretical physicist - especially for his pioneering work with Oppenheimer on neutron stars - and for his work on CANDU during the war, and then he played an important role at the University of British Columbia for many decades. In mid-century he was the blazing supernova illuminating the firmament of Canadian physics. During his active career as a Canadian physicist, from about 1940 to 1980, George was well known to most Canadian physicists and had a network of friends and admirers around the globe.

George Volkoff was born in Moscow on February 23, 1914. In 1924 his father, a Russian engineer, brought his family to Canada where he thought George might have a more promising future. However, the father could not find appropriate work in Vancouver and therefore moved the family to Harbin, Manchuria, in 1927, where he taught at a technical school in a large enclave of Russian emigres. George was a brilliant student in the secondary school in Harbin where he also made many life-long friends who prospered in global careers like his. This Harbin "mafia" was very important to George throughout his life.

Returning to Vancouver to enter UBC, George was persuaded by Gordon Shrum to study physics rather than engineering. Upon graduation in 1934 he had one of the best student records ever attained at UBC. In the meantime, rather poignantly, he lost the support of his family. His mother died in Harbin soon after the family moved there. In 1936 the father returned to Russia - having been assured by relatives that things were improving there - and was immediately caught up in the Stalinist purges. The father survived for only a few years in the arctic camps. Alone in North America, it did not help George emotionally that many of his associates continued to have rosy views of the Soviet Union. George was Russian culturally, proudly Canadian by choice and international in outlook.

He was fortunate, in 1936, to become a graduate student in Berkeley of J. Robert Oppenheimer. Although George published a number of important papers in his career his very first paper with Oppenheimer, on neutron stars, was also his most famous. Based on his thesis, this 1939 work calculated the collapse of a star, during a supernova explosion, into a neutron core. This work was ahead of its time. It came only a decade after the advent of quantum mechanics and only a few years after the discovery of the neutron. Until the discovery of pulsars, three decades later, neutron stars were an interesting scientific novelty, like the black holes pioneered simultaneously by Oppenheimer and Snyder. Unfortunately both Oppenheimer and Snyder died before their early work could be recognized, but Volkoff became an officer of the Order of Canada, in 1994, in significant measure for his early work on neutron stars. It pays to live long if you are ahead of your time!

After working briefly with Eugene Wigner at Princeton on tensor forces, George began his long career at UBC in 1940. In the same year he began a happy marriage of almost 60 years to Olga Okulitch who was also a Russian emigre and also an excellent scientist. She and three wonderful daughters (along with one spouse and three grandsons) survive George.

George had barely settled into UBC before he was summoned, in 1943, to work on the wartime Canadian heavy-water reactor program at the Montreal Laboratory. The atmosphere of that laboratory and Volkoff's involvement are vividly described in Phillip Wallace's recent article in PHYSICS IN CANADA (PIC 56, 123-134, 2000). For his atomic energy work Volkoff was awarded the M.B.E. in 1946 and also an honourary degree from UBC in 1945. At age 31, Volkoff was probably the youngest recipient of an honourary degree at any Canadian university.

In the years after WWII graduate education was initiated at many Canadian universities. One of Volkoff's students (Thomas L. Collins, who had a prominent career in accelerator physics at Fermilab) received the very first Ph. D. in any subject from the University of British Columbia. Another early Ph. D. student of Volkoff's was Howard Petch who had a distinguished career at McMaster and Waterloo universities before lengthy service as the President of the University of Victoria. Petch also served as CAP president (1967-68). Although he was a theorist, Volkoff initiated an NMR experimental research program at UBC which eventually was taken over with great distinction by Myer Bloom. Volkoff very generously nurtured many physicists. After Gordon Shrum's retirement Volkoff became head of the UBC physics department (1961-70) and then dean of science (1970-79) until his retirement.

Part of Volkoff's celebrity arose from his proficiency in his native language, Russian. In the early years of the cold war He was greatly sought after at international conferences to provide simultaneous translation of talks given by Russian scientists. Also, for many decades, he translated Russian articles in physics into English. He was an important bridge between the scientific communities of east and west.

Volkoff was involved in almost every area of national service. He served as editor of the Canadian Journal of Physics (1950-56) and as president of the CAP (1962-63) as well as on innumerable advisory boards and committees. In particular he chaired several CAP Committees concerned with the development of high energy physics in Canada. He was a very important early supporter of the TRIUMF project.

George emanated warm friendship and had a passion for music, mountains, literature and culture generally. He will be greatly missed by his host of friends across Canada and his many friends and associates around the globe.

E. Vogt, TRIUMF

SPIN-CHARGE SEPARATION IS THE KEY TO THE HIGH T_C CUPRATES

The most striking fact about the high-T_c cuprates is that in none of the relevant regions of the phase diagram is there evidence of the usual effects of phonon or impurity scattering. This is strong evidence that these states are in a "quantum protectorate", to borrow Laughlin's term. (Two striking experimental facts which demonstrate this are the absence of phonon self-energy in ARPES measurements, demonstrated recently by Johnson in BISCO[1], and the scattering-independent T_c in YBCO, even though the superconductivity is *d*-wave.) A quantum protectorate is a state in which the many-body correlations are so strong that the dynamics can no longer be described in terms of individual particles, and therefore perturbations which scatter individual particles are not effective.

The Mott-Hubbard antiferromagnetic phase is manifestly spin-charge separated (there is a charge gap, but no spin gap), and I propose this property extends throughout the phase diagram in different guises, and is the reason for the quantum protectorate. Quasiparticles are never the exact, long-lived elementary excitations ($Z = 0$ throughout) so that scattering of electrons does not necessarily disturb the excitations, especially the spinons, the Fermion-like elementary magnetic excitations with spin 1/2 and charge 0. This protectorate effect is incompatible with any perturbative theory starting from a Fermi liquid approach. The experimental situation presents us with a clean dichotomy, which cannot be repaired by "summing all the diagrams".

I propose that as we dope the antiferromagnetic state, two things happen. First, there is a first-order phase transition in the charge sector where the Mott-Hubbard gap closes, which sometimes leads to mesoscopic inhomogeneity (the stripe phenomenon). Second, and independently, we pass a critical point in the spin sector where antiferromagnetism vanishes and becomes a soft mode of the *d*-wave (or flux-phase-like) RVB.

T. Hsu, in his thesis[2], long ago showed that antiferromagnetism could be treated as an unstable mode of the "flux phase" i.e., the *d*-wave RVB. Hence when the latter becomes stable antiferromagnetism becomes a stable soft mode, which is seen as the notorious neutron resonance of Keimer. This RVB, which was postulated independently by Affleck-Marston-Kotliar and by Laughlin, is the spin gap phase, stable below a crossover T^* which is a rapidly decreasing function of doping. It is correct to think of this phase as analogous to the Mott insulator: where the Mott phase has a charge gap and no spin gap,this one has a spin gap -- for most momenta -- and no charge gap.

What is the phase *above* T^*? This is not a conventional Fermi-liquid, but the original "extended *s*-wave" RVB I proposed in 1987, equivalent to the "tomographic Luttinger liquid" I[3] derived for moderate densities in 1989. If there is an antiferromagnetic super exchange J this phase has a Cooper instability at T^* where the *d*-wave spin gap is favored.[4]

Why does T^* decrease so rapidly with doping? The Cooper instability occurs at $kT^* - p_F \upsilon_s \exp\left[- P_F \upsilon_s / Jeff\right]$ where v_s is the spinon velocity. When $x \to 1$, the spinon and holon velocities become equal, and equal to t/p_F, while as $x \to 0$, $\upsilon_s = J/p_F$; so we linearly interpolate $p_F v_s \approx J + x(t - J)$.

As for the interaction term, the antiferromagnetic interaction will tend to be compensated by a ferromagnetic double exchange term roughly proportional to x, which comes from loop (non-repeating) paths of the holes. For rough purposes, I estimate $J_{eff}(x) = J - tx$. This is adequate to account for the vanishing of T^* at around $x \sim 3$. This instability is not a true phase transition. Both the *s*-wave state and the $s + id$ retain the full symmetry of the Hamiltonian, $[SU(2)]_{spin}$ x $[U(1)]_{charge}$ x [Lattice Symmetry].

It is the conventional Fermi liquid which has an anomalous extra symmetry Z_2 mixing spin and charge: the Fermi liquid is itself a quantum critical point, as Haldane and I will discuss in a forthcoming preprint.

The RVB (spin gap) phase is not superconducting. The motivation which drives superconductivity and converts the spin gap into a superconducting gap is frustrated kinetic energy. The opening up of a gap in the spectrum at the Fermi level means that the distribution $n(k)$ cannot approach its optimal step-function form (or step-function-like, in the case of a Luttinger liquid). This effect may be quantified by using the Ferrell-Glover-Tinkham sum rule $\int_0^\infty \sigma(\omega)d\omega = e^2 < K.E.>$

It was observed by Orenstein *et al*, very early, that in the underdoped (spin-gapped) cuprates a gap in the optical conductivity opens up. The magnitude of $\int \sigma(\omega)\, d\omega$ is proportional to x (as noted by Sawatzky) so the relevant loss of kinetic energy is $\alpha\ x$. (P.A. Lee has estimated a similar effect quantitatively.) One may think of this effect as setting an upper limit to the transition temperature $T_c < T_{KE}\ \alpha\ x$. But if the spin gap T^* is smaller than this upper limit, essentially no spin gap can open without a charge gap as well, so T_c follows T^* down at high doping. The above is far from a quantitative theory of T_c. In particular, I believe there is still a role for the interlayer kinetic energy in the bilayer and multilayer cases. But contrary to my "Dogma V"[3] there is a one-layer mechanism for superconductivity which seems to be quite effective in some cases. But in all cases the relevant mechanism is the recovery of frustrated kinetic energy. Note that in the charge channel this is not a d-wave but an s-wave condensation, hence not strongly affected by ordinary scattering.

To summarize: The two-dimensional electron gas in the cuprates is dominated by the short-range repulsive interaction which remains relevant and causes spin-charge separation. A spin gap develops in the metallic phase below a crossover temperature T^*, at the Cooper instability caused by the antiferromagnetic super exchange. The extra kinetic energy required to open the spin gap is relaxed at a lower temperature Tc by making the charge fluctuations coherent.

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Due to space limitations, it was not possible to include many of the references which should have accompanied these short essays. -- Eds.

SUPERCONDUCTIVITY RESEARCH AND THE CIAR
LA SUPRACONDUCTIVITÉ ET L'ICRA

The Canadian Institute for Advanced Research (CIAR) is a unique institution, with no analog in other countries. With a budget coming equally from private and public funds, it supports a small number of programs in targeted areas of fundamental research for which a critical mass of Canadian expertise exists (for list of Programs, see back cover or go to www.ciar.ca.).

The Institute launched its Program on Superconductivity in 1988 to help coordinate Canadian research in the booming new field of high-temperature superconductivity. Ten researchers joined the Program, mostly based at either McMaster or UBC. Given the magnitude and competitiveness of the international effort, the importance of collaboration was recognized early on - between chemists who synthesize new materials and grow crystals, experimentalists who measure a range of complementary physical properties and theorists who explore the infinitely rich behaviour of interacting electrons. No single university department could hope to bring together all this expertise and the CIAR proved to be an ideal vehicle for fostering these fruitful interactions.

Fig. 1 Canadian institutions currently host to members of the CIAR Superconductivity Program.

Twelve years down the road, the Superconductivity Program has grown both in size and in scope: 25 members distributed in eight Canadian institutions work not only on high-temperature superconductivity per se but also on a broad range of related materials and phenomena. A highly collaborative mode of operation has evolved whereby, for example, the experimentalists in the Program plan their research in a concerted way, with each group producing a different set of materials and circulating samples for complementary measurements by other groups. Several of the main contributions of Program members are discussed in this issue.

The Program has also become more international, with several foreign scientists appointed in recent years and many invited as guest speakers at Program meetings. These meetings are vital: they are frequent and flexible in style, content and location. They have provided both the members and their students and postdocs with regular and priviledged contact with leading researchers in a way which is virtually impossible otherwise.

L'Institut canadien de recherches avancées (ICRA) est une institution unique au monde. Avec des revenus provenant à part égales de fonds publics et privés, l'Institut finance un petit nombre de programmes dans des domaines ciblés en recherche fondamentale pour lesquels il existe une masse critique d'experts canadiens. (Pour une liste de ces programmes, consultez la couverture arrière de ce magazine ou le site www.ciar.ca.)

L'Institut a lancé son Programme en Supraconductivité en 1988 pour aider à coordonner la recherche canadienne dans le tout nouveau domaine de la supraconductivité à haute température, en recrutant une dizaine de chercheurs, basés principalement à McMaster ou UBC.

L'importance de collaborer est vite devenue une évidence, étant donnés l'ampleur de l'effort international et le degré de compétition élevé. Ainsi se sont alliés chimistes qui synthétisent les nouveaux matériaux, expérimentateurs qui mesurent toute une batterie de propriétés physiques et théoriciens qui explorent le comportement infiniment riche des électrons en interaction. Aucune université aurait pu rassembler à elle seule toute cette expertise et l'ICRA s'est avéré être un véhicule idéal pour le développement de ces collaborations.

Douze ans plus tard, le Programme en Supraconductivité a bien grandi: il comprends maintenant 25 membres répartis dans huit institutions canadiennes qui étudient non seulement les supras haut-Tc mais tout un éventail de nouveaux matériaux et phénomènes associés. Un mode de fonctionnement très collaboratif s'est développé qui implique, par exemple, que les expérimentateurs planifient leur recherche en consultation; ainsi la synthèse des différents matériaux est partagée entre les différents laboratoires et les échantillons circulent d'un groupe à l'autre, rapidement soummis à de nombreuses mesures complémentaires. Quelques unes des principales contributions scientifiques des membres du Programme sont décrites dans ce numéro.

Le Programme est également devenu plus international: plusieurs scientifiques étrangers ont été fait membres, tandis que nombreux autres participent aux rencontres organisées par le Programme. Ces rencontres sont vitales

As Prof. Steve Kivelson of UCLA said at the close of a recent meeting: "I felt that the CIAR conference was unique among the conferences in high temperature superconductivity that I have attended in that strongly diverging views of the fundamental physics were frankly and honestly expressed, with no attempt to paper over essential disagreements between proponents of different approaches, and yet the tone of the conference was collegial and constructive - it was clear that the emphasis was on trying to identify that part of each work that was right and suggestive of a useful perspective, rather than on dismissing the various approaches on the basis of minor flaws."

One of the most significant and lasting benefits to Canada made possible by the CIAR is the appointment of outstanding researchers to Canadian university positions. As an example, in the past year alone the Superconductivity Program played a decisive role in the hiring of three highly promising young scientists from the US.

Fraser Mustard founded the CIAR twenty years ago with a bold vision for a new way of organizing and supporting research in Canada, centred on people and their interactions. The Superconductivity Program is but one successful realisation of his vision. I foresee a bright future for the Institute with its involvement in many of the most exciting areas of intellectual endeavour, ensured by the continued and generous support of private and public sectors alike.

Louis Taillefer
University of Toronto and CIAR

pour le maintien d'un mode collaboratif. Elles permettent aussi aux membres et à leurs étudiants et associés de recherche d'avoir un contact privilégié avec les meilleurs chercheurs dans le domaine.

A la clôture d'une récente rencontre, le professeur Steve Kivelson de UCLA déclarait: ``Parmi toutes les conférences sur les haut Tc auxquelles j'ai assisté, cette rencontre de l'ICRA est unique de par la franche expression d'opinions fortement divergentes sur le fonds, sans tentative d'occulter les désaccords essentiels entre défenseurs de différentes approches. Et malgré cela, le ton de la rencontre était amical et constructif : au lieu de tenter de discarter certaines approches, l'emphase était mise sur l'identification des aspects porteurs de chacune d'elles."

Un des bénéfices les plus durables que l'ICRA confère au Canada est l'embauche de chercheurs exceptionnels par les universités canadiennes. Par exemple, l'année dernière, le Programme en Supraconductivité a joué un rôle décisif dans le recrutement de trois jeunes chercheurs américains fort prometteurs.

Fraser Mustard a fondé l'ICRA il y a vingt ans sur sa courageuse vision d'une nouvelle façon d'organiser et de financer la recherche au Canada, centrée sur les gens et leurs interactions. Le Programme en Supraconductivité n'est qu'une des heureuses réalisations de cette vision. Je prédis un bel avenir à cet Institut, impliqué tel qu'il l'est dans plusieurs des domaines d'activité intellectuelle les plus excitants, et porté par l'investissement généreux des secteurs privés et publics.

Louis Taillefer
Université de Toronto et ICRA

NEWS / INFORMATIONS

QUANTUM PHYSICS SYMPOSIUM

A symposium celebrating the centennial of quantum physics, Planck's 1900 quantization of energy hypothesis, was held March 17--19, 2000 at the University of Saskatchewan. The symposium was organized by a University of Saskatchewan committee from the Departments of Physics & Engineering Physics, Mathematics & Statistics, and Chemistry. The symposium included speakers and participants from the disciplines of physics, chemistry and mathematics. The focus of the symposium was on our current understanding and frontiers of the foundations and applications of quantum physics. The invited speakers were A. Shimony (keynote speaker from Boston University), L. Ballentine (Simon Fraser University), P. Busch (University of Hull), R. Bader (McMaster University), and A. White (University of Queensland).

Symposium sponsors, images, presentation transparencies and other information related to the symposium is located on the symposium website http://physics.usask.ca/~steele/quantum/

STRONG CORRELATIONS IN LOW DIMENSIONAL CONDUCTORS:

WHAT ARE THEY AND WHERE ARE THE CHALLENGES?

by A.-M.S. Tremblay, C. Bourbonnais and D. Sénéchal

Quantum mechanics and statistical mechanics have provided us with the tools to understand the behavior of bulk matter. Nevertheless, except in the case where particles are independent, the problem of treating 10^{23} electrons is unmanageable by brute force application of the basic laws. A few concepts, and their mathematical implementation, were needed in order to develop both the qualitative and highly quantitative theories that nowadays explain the electronic and magnetic properties of solids. The computer revolution is in part the outcome of this understanding and of the massive experimental effort devoted to controlling semiconducting and magnetic materials, which are the basic elements of transistors, magnetic storage materials and other pieces of computer hardware.

Two points of view (localized *vs* delocalized electrons) sit at the extremes of a complex reality which is far from completely understood, despite the successes of "standard" Solid State theory.

In standard Solid State theory, semiconductors can be understood in the framework of *band theory*, in which electrons propagate in a periodic (effective) potential and occupy delocalized, plane-wave like states. In this scheme, electrons fill the Fermi sea according to the Pauli principle, but are otherwise independent: electron-electron interactions are treated in a "mean-field" manner, i.e., they produce some self-consistent periodic potential, like in the Hartree-Fock approximation. What remains of electron interactions, i.e., the part that cannot be incorporated into a self-consistent potential, can then be treated perturbatively. Phase-space considerations, at least in dimension two or more, indicate that such interactions, provided they are not too strong, simply turn electrons into quasiparticles with a finite lifetime and renormalized mass. Generalizations of these considerations are the object of Landau's Fermi liquid theory, which offers an adequate description of most metals and semiconductors. Residual interactions in delocalized electron systems are also ultimately responsible for phase transitions, the superconducting transition being one example.

At the other extreme, the magnetic behavior of localized electrons in standard Solid State Physics are treated with models such as the Heisenberg model, defined in terms of spin degrees of freedom. There, the residual interactions are strong and electrons are very strongly correlated, to the point of being completely localized.

These two points of view (localized *vs* delocalized electrons) sit at the extremes of a complex reality which is far from completely understood, despite the successes of "standard" Solid State theory. In fact, the latter fails in a large class of materials, of which high-temperature superconductors are one of the most famous examples. There the mysteries lay not only in the origins of the superconductivity itself, but also in normal state properties that one would have expected standard Solid State Physics to explain. Indeed, the failures of present day Solid State theory provide an intellectual challenge of the highest level. The Physics of strong electron-electron interactions and of systems in low-dimensional spaces (one or two dimensions) is what is at stake. This field of study is generally known as "Strongly correlated electrons" and refers to a rather broad class of problems originating basically from either strong interactions or singular scattering processes in low dimension.

EXPERIMENTAL EVIDENCE FOR FAILURES OF STANDARD SOLID STATE THEORY IN LOW-DIMENSIONAL CONDUCTORS

What do we mean by low dimensional conductors? In practice they can be formed, for example, by organic molecules stacked onto each other, or by copper oxygen planes separated by ions, as in the case of high-temperature superconductors. Despite the horrendous

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complexity of these structures, the Pauli principle tells us that for low-energy Physics we can concentrate only on the bands that are very close to the Fermi energy. It turns out that, in many realizable cases, there is only one such band. Furthermore, the eigenstates in that band may turn out to be very different depending on which axis one is looking from. In these very anisotropic cases, it is as if electrons moved preferentially in one or two dimensions, the latter being the case for the high-temperature superconductors. Let us see what non-Fermi liquid Physics can arise in the $d = 1$ and $d = 2$ cases.

ONE DIMENSION: SPIN-CHARGE SEPARATION IN THE ORGANICS

When electrons of opposite momentum are confined to move in one spatial direction, they cannot avoid each other and their interaction will be in some way enhanced in comparison with isotropic systems. As we will explain in the theory section, quasiparticles are absent in one dimension, and one has instead a "Luttinger liquid" where harmonic collective oscillations of both spin and charge are the true elementary excitations.

Here we present two clear experimental examples of the failure of the quasiparticle picture. Consider the normal phase of the $(TMTTF)_2X$ series of quasi-one-dimensional organic conductors (here, TMTTF stands for the tetramethylfulvalene molecule and X= PF_6, Br, ..., for an inorganic monovalent anion)[1] . As shown in Fig.1, there is a clear upturn in electrical resistivity at temperature T_ρ, which depicts a change from metallic to insulating behavior. Below T_ρ, charge carriers become thermally activated. In a band picture of insulators, the same thermally activated behavior should be present for spins since the only way to create spins in a band insulator is to excite quasiparticles across the gap between the filled and the empty bands. For the compounds shown in Fig.1, spin excitations instead are unaffected and remain gapless. This is shown by the regular temperature dependence of the spin susceptibility χ_s at T_ρ (inset of Fig. 1).

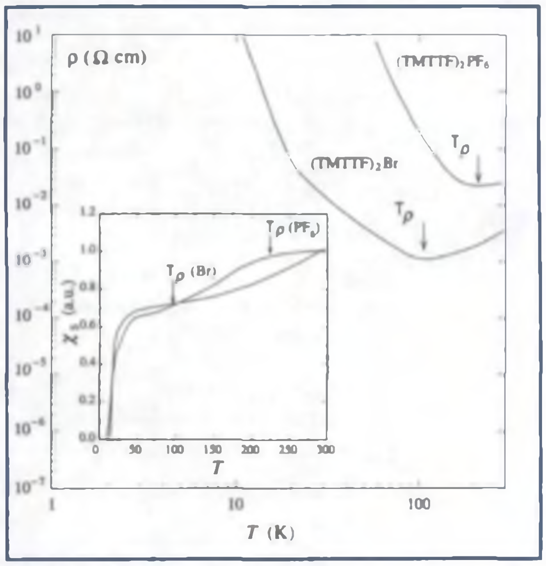

Fig. 1 **Electrical resistivity as function of temperature for two members of the $(TMTTF)_2X$ series. Inset: Temperature-dependent spin susceptibility, from Ref. [1].**

Among other experimental tools that are quite useful in probing signs of unusual behavior in low-dimensional organic conductors is Nuclear Magnetic Resonance, especially the temperature dependence of the nuclear spin-lattice relaxation rate, denoted as T_1^{-1} Nuclear and electronic spins being coupled through the hyperfine interaction, the measurement of T_1^{-1} can give valuable information about electronic spin excitations. While $(T_1T)^{-1}$ is temperature-independent in a Fermi liquid, the correct theory in one dimension for $(T_1T)^{-1}$ takes the form [3]:

$$(T_1T)^{-1} = C_1T^{K_\rho-1} + C_0\chi_s^2(T), \tag{1}$$

where the exponent $K_\rho \geq 0$ stands for the 'stiffness' constant of collective charge degrees of freedom. It gives rise to a power-law enhancement of $(T_1T)^{-1}$, which comes from antiferromagnetic spin correlations. For one-dimensional insulating compounds like $(TMTTF)_2X$, charge degrees of freedom are frozen so that $K_\rho = 0$. The resulting behavior $T_1^{-1} \sim C_1 + C_0\chi^2T$ turns out to be invariably found in all these insulating materials down to low temperature, where three-dimensional magnetic or lattice long-range order is stabilized [3]. Among the very few exceptions of quasi-one-dimensional organic materials that do not show long-range ordering, the case of $TTF[Ni(dmit)_2]_2$ is interesting [2]: This system remains metallic down to very low temperature and a power law enhancement ($K_\rho \approx 0.3$) of $(T_1T)^{-1}$ is maintained from $300K$ down to $1K$ or so (Figure 2).

TWO DIMENSIONS: THE PSEUDOGAP

Fig. 3 shows the band structure of La_2CuO_4. The last occupied band is essentially a linear combination of copper and oxygen orbitals corresponding to two-dimensional (planar) arrangements of CuO_2 atoms. One thus expects that electrons relevant for transport are essentially confined to two

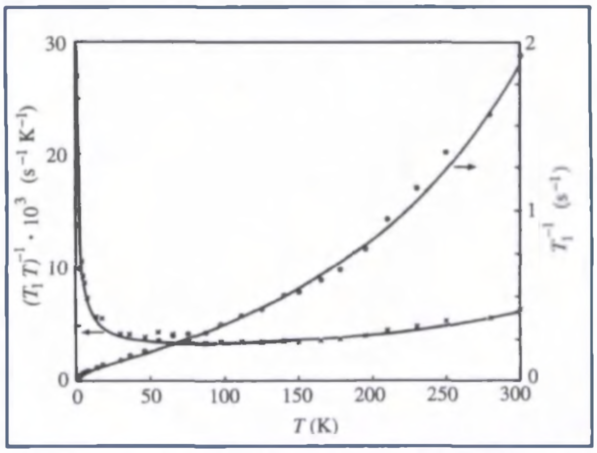

Fig. 2 **Temperature dependence of $(T_1T)^{-1}$ and T_1^{-1} (o)for $TTF[Ni\ (dmit)_2]_2$. The continuous line corresponds to the Luttinger liquid prediction, from Ref. [2].**

dimensions. This is confirmed by the highly anisotropic transport properties of these materials, as discussed by T. Timusk in this issue. The Fermi level crosses the last occupied band, so we expect a metal.

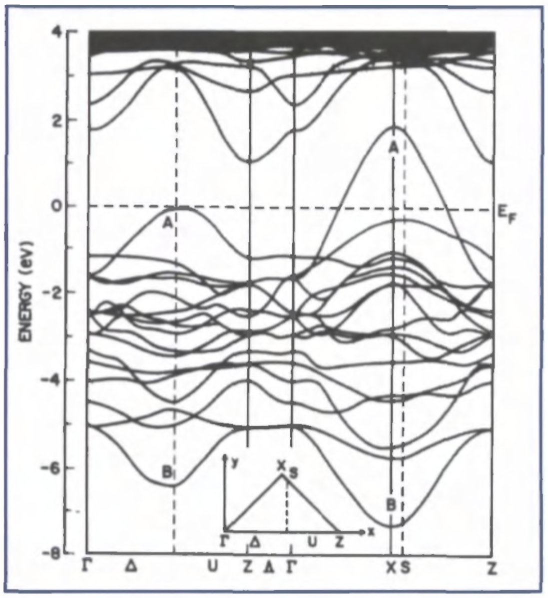

Fig. 3 Band structure of La_2CuO_4, taken from Ref. [2].

But in reality, La_2CuO_4 is an antiferromagnetic insulator! This is because of strong interactions. When La^{3+} cations located away for the conducting planes are replaced by Sr^{2+} cations, electrons are removed from the CuO_2 planes and $La_{2-x}Sr_xCuO_4$ becomes eventually a high-temperature superconductor. The generic phase diagram for high-temperature superconductors appears in the foreword. With hole doping, the superconducting T_c first increases. That is called the underdoped region. Then, a maximum T_c is reached at "optimal doping", decreasing thereafter in the "overdoped" region.

Let us look at the underdoped regime, above T_c. To see if the standard Fermi-liquid approach applies in this regime, we resort to Angle Resolved Photoemission Spectroscopy (ARPES). In these experiments, an X-ray is absorbed by an electron, which is ejected from the compound, a hole being created in the process. The energy and the momentum parallel to the surface are measured, and the corresponding quantities for the hole are extracted from conservation laws. Before we discuss the strange case of underdoped superconductors, let us look at Fig. 4, which presents the results for another compound ($TiTe_2$) that behaves as expected from the quasiparticle picture. The different curves correspond to different momenta. They give on the vertical axis a quantity proportional to the probability, times a Fermi function, that an electron of given momentum has the energy indicated on the horizontal axis. As one moves in the various directions of wavevector space, one reaches a point where the maximum intensity is very near zero energy (14.75^0 on the figure). The effect of the Fermi function is that for a probability that would be maximum *at* zero energy, the observed maximum is slightly *below* zero energy. At zero energy, the observed function is smaller than the value it would have had but it still has sizeable weight. In this way, one can thus map the wavevectors where there cease to be electrons to photoexcite. This is the Fermi surface (Fermi line in *d*=2).

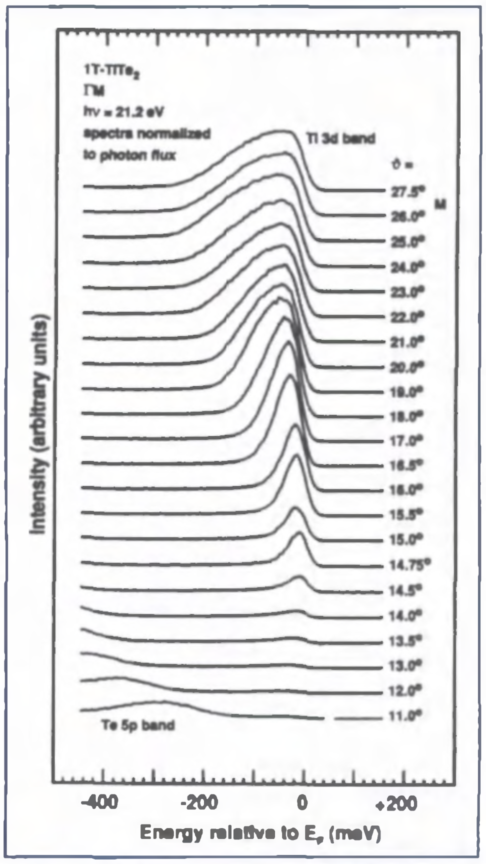

Fig. 4 ARPES spectra of 1-*T*-$TiTe_2$, taken from Fig. 1 of Ref. [5]

It is experimentally difficult to do ARPES in $La_{2-x}Sr_xCuO_4$, so we use results obtained from the CuO_2 planes of the so-called Bi2212 high-temperature superconductor. In Fig. 5(a), the solid line shows the location of the Fermi line expected from band structure calculations. Fig. 5(b), illustrates the ARPES spectrum obtained for various wavevectors along the (0,0) to (π, π) direction. At the wave-vector location expected from band structure, one finds the properties expected for a state at the Fermi surface, namely at zero energy the photoemission intensity is a sizeable portion of the value at the peak position. The surprise arises when one looks along the (π, 0) to (π , π) direction, Fig 5(c). None of the photoemission curves has the features expected from a state at the Fermi surface. It is as if the Fermi line had disappeared. This is the co-called pseudogap phenomenon. It is as if an energy gap had opened on part of what should have been the Fermi line (hence the "pseudo" prefix, since zero-energy excitations are left elsewhere in wave-vector space). If you think about it from a quasiparticle picture, this is completely crazy. Take an energy band in a two-dimensional system. The allowed wavevectors cover a finite region of the two-dimensional k_x,k_y plane. That is the Brillouin zone. Plot the energy corresponding to a given wavevector in the z direction. That gives a singly connected surface. Now, cut this surface by a plane parallel to the k_x,k_y plane. The intersection of that plane with the energy surface can only be of two types. Either it is a line that links one edge of the Brillouin zone to another (or the

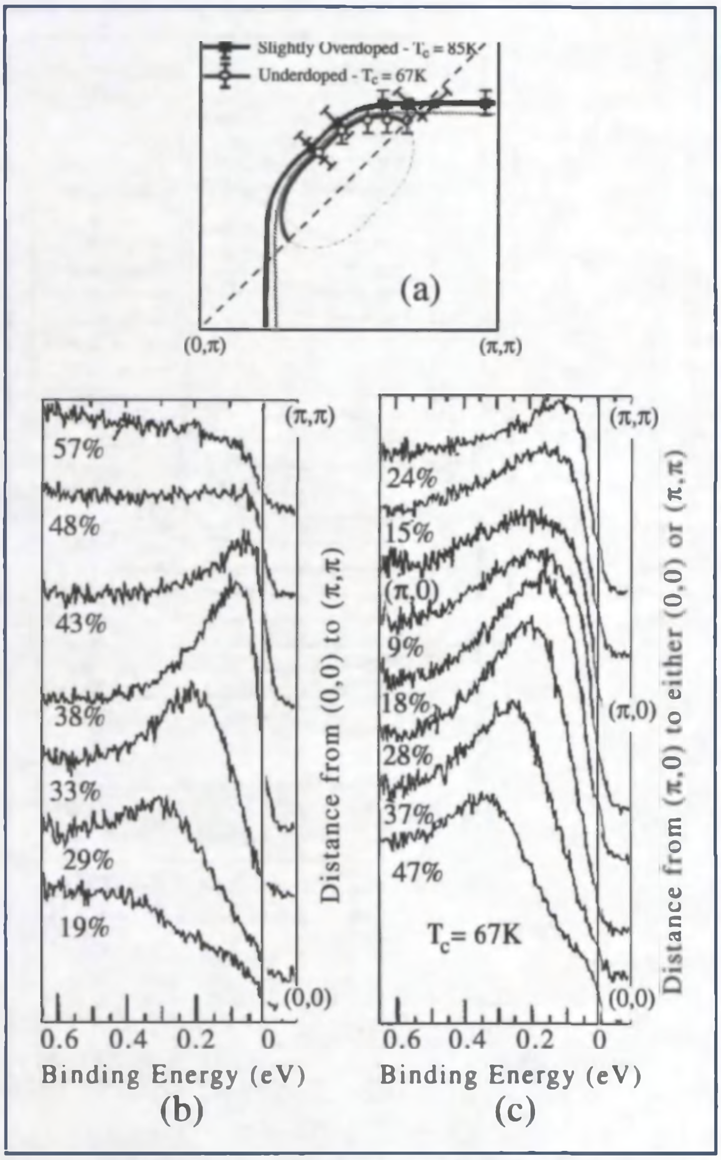

Fig. 5 ARPES spectra of O_2-reduced $Bi_2Sr_2CaCu_2O_{8+\delta}$ taken from Ref. [6].

same) edge, or it is a closed line inside the zone. The two possibilities can exist at the same time: In other words, there may be several Fermi lines in the Brillouin zone. But according to these simple geometrical considerations, there is no other possibility. If you cover the Brillouin zone with ARPES measurements, you find that in the underdoped high-temperature superconductors the Fermi line does something worse than disagreeing with band structure calculations. It disappears in thin air! That is a total no-no in the standard approaches. Remember that in these approaches, either you have quasiparticles and there is a Fermi line, or you have an insulator and there is no single-particle state at all at zero energy.

Other manifestations of the pseudogap, expecially in transport, are discussed elsewhere in this issue.

WHY DO THE STANDARD APPROACHES FAIL?

The failure of the standard approaches in low dimension is not a total surprise from a theoretical standpoint. On the contrary, for a long time there have been papers discussing the peculiarities of low-dimensional systems. For example, consider the Mermin-Wagner theorem, which states that a spontaneous breaking of a continuous symmetry (e.g. a rotation) cannot occur in low dimension.

To be more specific on what that means, let us give an example. In three dimensions, Heisenberg antiferromagnets exist at finite temperature. In two dimensions, thermal fluctuations forbid such order from occuring at finite temperature. A rough argument for that is as follows. At long wavelengths, the energy associated with a change in the relative angle between neighboring spins, θ, will be proportional to $(\nabla\theta)^2$, or $q^2\theta_q\theta_{-q}$ in Fourier space. The mean square of the local angle is given by the integral over all wavevectors of $\langle\theta_q\theta_{-q}\rangle$. Using the classical fluctuation-dissipation theorem, this means that $\langle\theta^2\rangle \propto \int d^dq\ (k_BT/q^2)$. That integral diverges logarithmically in two dimensions, which proves *ad absurdum* that long-range order cannot exist. At zero temperature, the above argument fails and antiferromagnetic long-range order may exist. In one-dimension, quantum fluctuations have a similar detrimental effect and, even at zero temperature, antiferromagnetic or superconducting long-range order does not exist.

All this classical and quantum fluctuation business is bad news for the quasiparticle approach. Indeed, even though long-range order does not set in, below a temperature of the order of what would have been the mean-field transition temperature, there are collective modes that spread over large distances, making the material appear ordered over large scales. This strongly scatters quasiparticles, and in some instances it may lead to short lifetimes, or even to pseudogap phenomena [7].

THE EFFECTS OF LOW DIMENSION IN WEAK TO INTERMEDIATE COUPLING

One Dimension

General considerations on phase space and the Pauli principle tell us that in high dimension, the scattering rate of quasiparticles at the Fermi surface is proportional to $(T/E_F)^2$ Since the relative width of the Fermi function is of order T/E_F it makes sense to expect that thermodynamic properties will not much be influenced by the $(T/E_F)^2 \ll T/E_F$ width of the quasiparticles. In one dimension, this argument fails. The width in perturbation theory is proportional to T, like the Fermi function. Right from the start, this invalidates the Fermi-liquid starting point. In addition, response functions diverge as $\ln T$ at low temperature. More specifically, what makes one dimension so special lies in the shape of the Fermi surface, which consists of two points ($\pm k_F$). Electron and hole states that are created by electron-electron scattering close to $\pm k_F$ lead to elementary superconducting (Cooper) and density-wave ($2k_F$ electron-hole) pairings; these are not only singularly enhanced at low temperature, but their confinement in k-space produces strong interferences between them that persist to all orders in perturbation theory. A striking outcome of this interference is an instability of the Fermi liquid towards the formation of a quite different quantum state called a Luttinger liquid.

The point of view has to change completely. The appropriate theoretical tools here bear the name of renormalization group [8] or bosonization [9]. They lead to the same final picture: It is best to consider spin and charge collective modes as the elementary excitations. In the resulting "Luttinger liquid" picture [10], which replaces the Fermi liquid as a general limiting case in one dimen-sion, the spin and charge of would-be quasiparticles separate, becoming the true elementary excitations that propagate at different velocities. We have illustrated experimental manifestations of this phenomenon in organic conductors in the previous section. The cases where the compounds were insulators displayed extreme examples of spin-charge separation. These compounds have a commensurate band filling and their insulating behavior is a manifestation of one-dimensional Mott localisation, a more general topic on which we return in the discussion on the effects of strong interactions.

Two Dimensions

Contrary to the one-dimensional case, the quasiparticle picture does not fail automatically in two dimensions. Theoretically, in two dimensions there are only weak logarithmic corrections to the standard phase space arguments of Fermi liquid theory. Stronger corrections occur when the Fermi surface has so-called nesting properties [11], or when one enters a fluctuation regime. Let us consider the latter case. The fluctuation regime may occur over a broad temperature range in two dimensions, basically from a temperature of the order of the mean-field transition temperature, all the way to zero temperature. Let ξ be the length over which the collective mode fluctuations are correlated. In the fluctuation regime, the scattering rate for quasiparticles at the Fermi surface is proportional to $\frac{T}{v_F} \int d^{d-1}q\,(q^2+\xi^{-2})^{-1} \propto T\xi^{3-d}/v_F$. In $d = 2$, the correlation length ξ diverges much faster than $1/T$ as $T - 0$, which implies a divergent scattering rate. It is difficult to have a stronger contradiction of the quasiparticle picture. When the correlation length ξ becomes much larger than the thermal de Broglie wavelength $\xi_{th} = (\hbar v_F/k_B T)$, the quasiparticles are moving in a locally ordered background. Then a pseudogap, precursor of the $T = 0$ ordered state, opens up at the Fermi surface [7]. As temperature decreases, it may open on certain segments of the Fermi surface before it opens on other segments. That is a consequence of the fact that the scattering rate, proportional to $T\xi/v_F$, may be very different on different parts of the Fermi surface. Close to half-filling in particular, the Fermi velocity nearly vanishes at certain points of the Fermi surface while it is large at other points.

THE EFFECTS OF VERY STRONG INTERACTIONS

When interactions are very strong, electrons avoid getting close to each other by localizing. When an odd number of electrons is localized on each atom, the charge does not move and the only degree of freedom left at low energy is essentially the spin. Note the contrast with the quasiparticle picture where a half-filled band is a metal. The low energy Physics in these systems, where electrons are localized by interactions, is then essentially governed by variations of the Heisenberg Hamiltonian described above. Many years ago, Mott imagined what would happen to a system as the strength of the interaction is increased. The transition from extended quasiparticle states to localized states produced by large interaction effects is refered to as the Mott transition. It is a first order transition whose Physics has become better understood in recent years [12], thanks to the development of calculational methods in the limit of infinite dimension [13]. In the Mott insulator, many properties are not strongly dependent on dimension, in particular when they concern high energy. That is why infinite-dimensional methods have been useful. Nevertheless, precursor effects caused by collective mode fluctuations have been seen in models of Mott insulators in low dimensions [14]. These effects do not occur in infinite dimension.

The Mott transition does not break any symmetry, and it may occur in any dimension. For example, V_2O_3 may exhibit such a transition, although questions regarding the effects of lattice symmetry change and of orbital degeneracies are still open [15]. A clearer example of a Mott transition has been discovered recently in two-dimensional organic conductors [16]. The phase diagram is illustrated on Fig. 6. The system is half-filled. The horizontal axis represents pressure. From a model point of view, increased pressure means larger overlap between atomic orbitals and hence increased kinetic energy. Indeed, at low pressure on this diagram, the system is either a paramagnetic insulator at high temperature, or an antiferromagnetic insulator at low temperature. At higher pressure, one crosses a first order transition that leads to a metallic state at high temperature and to a **d**-wave superconductor at low temperature.

HIGH-TEMPERATURE SUPERCONDUCTORS IN ALL THAT?

The high-temperature superconductors are Mott insulators at half-filling. Doping eventually leads to a *d*-wave superconducting state. Their electronic properties are also highly two-dimensional, in particular in the underdoped region. They thus manifest all the complexities described above. The high energy (100 meV) pseudogap described in our discussion of ARPES, is likely to be a strong-coupling pseudogap, in other words a pseudogap originating from the Physics of doped Mott insulators. However, closer to the superconducting phase transition, in the more metallic regime, one expects a fluctuation-induced pseudogap. Indeed, in photoemission, one can often identify a lower energy pseudogap that seems to occur in a fluctuation regime. A more detailed discussion appears in Ref. [17].

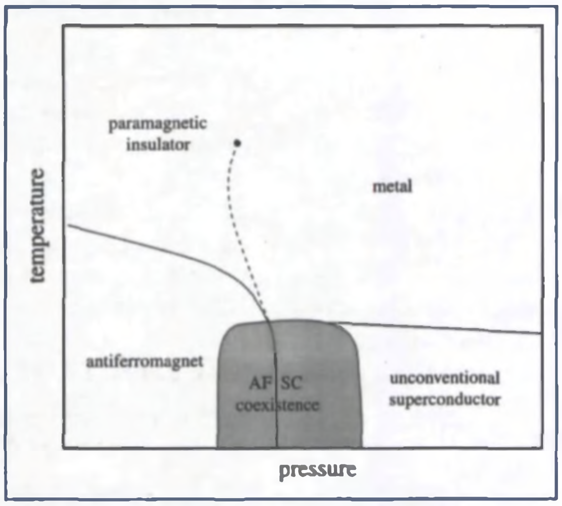

Fig. 6 Schematic phase diagram of the quasi 2D organic compound κ-(ET)$_2$Cu[N(CN)$_2$] C1, from Ref. [16].

THEORETICAL METHODS AND CHALLENGES

One of the most widely studied model Hamiltonians of correlated electrons is the so-called one-band Hubbard Hamiltonian:

$$H = -\sum_{\langle ij\rangle\sigma} t_{i,j}\left(c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma}\right) + U\sum_{i} n_{i\uparrow} n_{i\downarrow} . \qquad (2)$$

In this expression, the operator $c_{i\sigma}$ destroys an electron of spin σ at site *i*. Its adjoint $c_{i\sigma}^{\dagger}$ creates an electron and the number operator is defined by $n_{i\sigma} = c_{i\sigma}^{\dagger} c_{i\sigma}$. The symmetric hopping matrix $t_{i,j}$ determines the band structure, which here can be arbitrary. Occupation of a site by both a spin up and a spin down electron costs an energy U due to the screened Coulomb interaction. This Hamiltonian is clearly a caricature of reality, but what is important is that it has a minimal number of parameters and it allows one to describe the two limiting cases of delocalized and localized electrons, as well as the Mott transition between these two limits. Consider the case where the band is characterized by a single parameter t representing hopping between neighboring sites. At weak coupling, when $U/t \ll 1$, one can apply the standard quasiparticle approach. At strong coupling, when $U/t \gg 1$ one can show how this Hamiltonian becomes, at low energy and half-filling, the Heisenberg Hamiltonian for spins. Hence, it is a good starting point in both the strong and weak coupling limits, as well as in the intermediate coupling regime, characteristic of high-temperature superconductors, where neither of the two standard approaches work. At half-filling, the high-temperature superconductors become antiferromagnetic insulators that are well described by the Heisenberg model. At low energy and away from half-filling, the Hubbard model becomes, for $U/t \gg 1$, a variant of the so-called t - J model, widely studied also in the context of high-temperature superconductors.

It is hard to know from first principles if U/t will be large or small for a given system. But there are heuristic guides coming from Chemistry and from so-called "constrained LDA calculations". In general, the Hubbard Hamiltonian is an effective Hamiltonian. It is even useful in some cases to let $U < 0$ to study models of *s*-wave superconductivity. Despite the fact that the Hubbard model was proposed almost 40 years ago, it is only recently that it has become to be understood at intermediate coupling and in low dimension. Various methods have been developped to study this model. In one dimension, an exact solution was found by Bethe Ansatz [18], from which physical information is unfortunately quite difficult to extract. The linear dispersion of the one-dimensional electron gas in one dimension is at the root of an analogy with relativistic field theories which explains the success of field theoretic methods like the renormalization group [18], bosonization [19] and Conformal Field Theory [19]. In two and more dimensions, let us mention Slave-boson approaches [20], renormalized perturbation theory approaches [21], strong-coupling perturbation expansions [13] and the two-particle self-consistent approach [7]. Finally, infinite-dimensional methods have provided a dynamical mean-field theory methodology [12] that has been very useful in understanding the Mott transition. This approach can also be extended to lower dimensions. In $d = 2$ however, the effect of antiferromagnetic fluctuations are not included yet in this methodology, which limits somewhat the applicability of the method to high-temperature superconductors.

A major factor for progress is that it is now possible to do reliable numerical calculations that allow us to both develop physical intuition and check the validity of approximation methods. Exact diagonalizations are possible in any dimension but are restricted to a small number of electrons [22]. In one dimension, Density Matrix Renormalization Group [23] has provided a revolutionary method to obtain reliable results. In two dimensions, Quantum Monte Carlo simulations [24] remain a tool of choice. Such simulations have allowed us, for example, to choose between various analytical approaches that were giving different answers to the pseudogap question in weak to intermediate coupling [16].

How can we understand electronic systems that show both localized and propagating character? Why do both organic and high-temperature superconductors show broken-symmetry states where mean-field-like quasiparticles seem to reappear? Why is the condensate fraction in this case smaller than what would be expected from the shape of the would-be Fermi surface in the normal state? Are there new elementary excitations that could summarize and explain in a simple way the anomalous properties of these systems? Do quantum critical points play an important role in the Physics of these systems? Are there new types of broken symmetries? How do we build a theoretical approach that can include both strong-coupling and $d = 2$ fluctuation effects? What is the origin of d-wave superconductivity in the high-temperature superconductors? These are but a few of the basic open questions left to answer in this field.

ACKNOWLEDGEMENTS

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ANDERSON'S ELECTRONIC MECHANISM OF SUPERCONDUCTIVITY IN HIGH CUPRATES

In a recent Winter Conference, '50 Years of Condensed Matter Physics', at Aspen (January 2000) that honored P.W. Anderson, I presented a talk with a thesis that 'Anderson provided the "correct" solution for the mechanism of cuprate superconductity way back in 1987, in a fairly "sophisticated' fashion". In this essay I will summarize some of my arguments.

Condensed matter physics is a complex field and our degree of theoretical understanding is mainly measured by how well our theories and notions agree with "all" the experimental results both qualitatively and quantitatively. From this point of view RVB theory initiated by Anderson[1][2] has a lead compared to any other existing theory.

After Bednorz and Muller's discovery the major task of the theorists was to identify key ingredients and provide key concepts that were essential to develop a theoretical understanding the high Tc superconductivity. Anderson, in a pioneering pager[1], precisely undertook this task and provided an electronic mechanism of superconductivity after identifying key ingredients and concepts. He first provided what is now believed to be a correct model (one band t-J model in 2 dimensions) for describing the low energy physics of cuprates. Key ingredients that were identified were the two dimensionality of the the electron and spin dynamics, strong electron repulsion in a narrow band, the Mott insulating character of the parent insulator La_2CuO_4. The spin liquid or the Resonating Valence Bond character of the Mott insulator was an important concept that was borrowed from his own work in 1973. (Now it is recognized that the experimentally observed long range antiferromagnetic order is a spinon density wave of an underlying robust spin liquid state).

The next important step was to think of the Mott insulator with its enhanced singlet correlations (the spin liquid or RVB state) as the correct starting point to understand the doping induced superconductivity. The neutral singlets that get charged on doping and create a superconducting ground state was in marked contrast to the conventional BCS theory where superconductivity takes place in a fermi liquid state.

Anderson's mechanism brought out the possibility of superconductivity in a repulsive one band system in the most natural fashion without much sweat and labor. This should be contrasted with later attempts to show superconductivity in the Hubbard model starting from the metallic state - the main problem being the great difficulty in describing the anomalous normal state itself (and in numerical studies, the size limitations).

Having opened a new direction, Anderson along with his collaborators developed novel mean field methods (RVB mean field theory) [3] to understand the phases of the t-J model. In these theories extended s-wave superconductivity as well as d-wave superconductivity[4] appeared in a rather natural fashion. A novel gauge theory (RVB gauge theory) [5] was also developed to take care of the effect of fluctuations about the mean field solutions. This gauge theory paved the way for further developments such as the flux RVB state and the superconducting state with chiral symmetry breaking (these states have spontaneously generated RVB magnetic flux).

From 1988 onwards Anderson's attention was drawn into the study of the anomalous normal state - notions such as the spin charge decoupling in the normal state, tomographic Luttinger liquid state in 2 dimensions, c-axis confinement etc. were introduced. Interlayer pair tunnelling as a stabilizing mechanism of one layer superconductivity was also suggested (with hindsight, it was over emphasized, as experiments show one layer superconductivity in Tl-2201 without much help from interlayer pair tunnelling).

Looking back, every major step in RVB theory was motivated by experimental results. The ease with which Anderson did the model building depended on his deep insights on transition metal oxides through decades of early experience and familiarity with experimental results. Neutral fermions, later to be termed "spinons" were suggested based on results on Pauli like low temperature susceptibility of the Mott insulating state. The c-axis transport properties lead to the notion of "confinement". Certain interlayer regularities in Tc in the cuprate family lead to the interlayer pair tunnelling mechanism of superconductivity.

The electronic mechanism provided by RVB theory stands rather robust with good experimental support. Most of the experimental results, from transport to neutron scattering can be explained qualitatively within the RVB theory. Being a hard many body problem, quantitative calculations are rather hard at the moment and we should wait for further developments.

The situation is somewhat like in the Standard model for the unification of weak, electromagnetic and strong interactions: the right model with important notions such as colour confinement, chiral symmetry breaking, Higgs mechanism exists. However, non perturbative effects and low energy physics such as hadronization in high energy collisions and many questions in nuclear physics are hard to calculate from QCD.

While the RVB theory has made some mid course corrections, mainly inspired by experimental results, it has been moving in the right direction and has become the natural and correct starting point to understand the plethora of experimental results in the complex cuprate superconductors.

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Due to space limitations, it was not possible to include many of the references which should have accompanied these short essays. -- Eds.

HEAT TRANSPORT IN HIGH-TEMPERATURE SUPERCONDUCTORS

by L. Taillefer and R.W. Hill

Understanding the cuprates is one of the most challenging problems facing physicists today because the rich, complex and highly unusual behaviour of electrons in these materials is forcing us to re-examine the cornerstones of solid state theory. A remarkable property of the materials is the fact that a simple tuning of their chemistry can take any given compound all the way from insulator to superconductor, by doping electrons or holes into the CuO_2 planes which stack up to form the crystal structure. In attempting to unravel the mysterious ways of these doped carriers, scientists may be witnessing the breakdown of two hugely successful theories of 20th century physics: the Fermi-liquid theory of electrons in metals and the Bardeen-Cooper-Schrieffer (BCS) theory of electron pairing and condensation in superconductors. The concept of an electron as the basic particle carrying both spin and charge in the metallic state is being threatened. The notion of superconductivity as a phase transition at which both electron pairing and long-range phase coherence occur simultaneously is under siege. "Spin-charge separation" and "preformed pairs" are only two amongst several hotly debated issues. Others include the unification of magnetism and superconductivity and the microscopic nature of the vortex state produced in the presence of a magnetic field. Numerous experimental techniques have been brought to bear on this vast subject [1]. In this article, we outline what has been learnt from studies of heat transport. The most powerful applications of this technique - the thermal Hall effect and conduction at very low temperature - have only recently been developed to the point where they can lead to penetrating insights, and the first findings are the subject of this article. As we shall see, nothing in this will force us to go outside the framework of Fermi-liquid or BCS theory in their general form. However, note that much of the territory still lies ahead unexplored - for example, little has been done yet on the fascinating ("underdoped") regime between the superconducting state and the antiferromagnetic (insulating) state.

The concept of an electron as the basic particle carrying both spin and charge in the metallic state is being threatened.

HEAT TRANSPORT

Superconductors are perfect conductors of electric charge but very bad conductors of heat. This is because electric currents are carried by the Cooper pairs that form the superconducting condensate, which has zero entropy, while heat (or entropy) is only carried by the elementary excitations out of that ground state, or *quasiparticles*. A measurement of heat transport therefore probes the nature of the superconducting state via its quasiparticle energy spectrum, by giving access to the *gap function*, its defining characteristic.

The measurement involves passing a heat current through a sample and detecting the temperature gradient that develops along it. The ratio of power Q generated by a heater fixed at one end over the temperature difference ΔT between two points separated by a distance L is the thermal conductivity:

$$\kappa = \frac{Q}{\Delta T}\frac{L}{A} \qquad (1)$$

where A is the sample cross-section. The technique is straightforward as long as one has good control over the thermometry and ensures that no heat flows through secondary channels. Fig. 1 shows the thermal conductivity of $YBa_2Cu_3O_7$, for a carrier concentration slightly higher than "optimal" doping (*i.e.* maximal $T_c \approx 93$ K). The large peak below T_c, whose magnitude increases with increasing sample purity, is due to the tremendous growth of the electronic mean free path as the temperature is decreased below T_c, a result of the precipitous suppression of the strong electron-electron scattering present in the normal state as electrons condense into Cooper pairs. This understanding first

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came from electrodynamic studies at microwave frequencies (see article by Bonn and Hardy).

ELECTRONS AND PHONONS

The main difficulty with the interpretation of thermal conductivity data is that both electrons and phonons carry heat. For example in the data of Fig. 1, the conductivity above T_c is predominantly due to phonons. Two ways have been devised to accurately isolate the electronic contribution. The first is the thermal analog of the Hall effect, whereby a transverse magnetic field (normal to the CuO_2 planes) deflects the electrons but not the phonons. Measurements of the purely electronic thermal Hall conductivity $\kappa_{xy}(T)$ have been used to show that electrons are in large part responsible for the peak below T_c, while accounting for only 10% or so of the longitudinal κ_{xx} in the normal state[3]. As this novel technique further develops, a detailed comparison of κ_{xy} and σ_1 measured at microwave frequencies is expected to yield insight into the nature of electronic carriers and their mutual interaction. The second way of separating electron and phonon contributions is from their temperature dependences as $T \rightarrow 0$. Heat conduction is the product of specific heat, carrier velocity and mean free path:

$$\kappa = \frac{1}{3} cvl \tag{2}$$

At very low temperatures the mean free paths of electrons and phonons are independent of temperature; the electrons limited by impurity scattering and the phonons by the boundaries of the sample. In this case, temperature dependence is given entirely by the specific heat, which is linear in T for electrons and cubic in T for phonons.

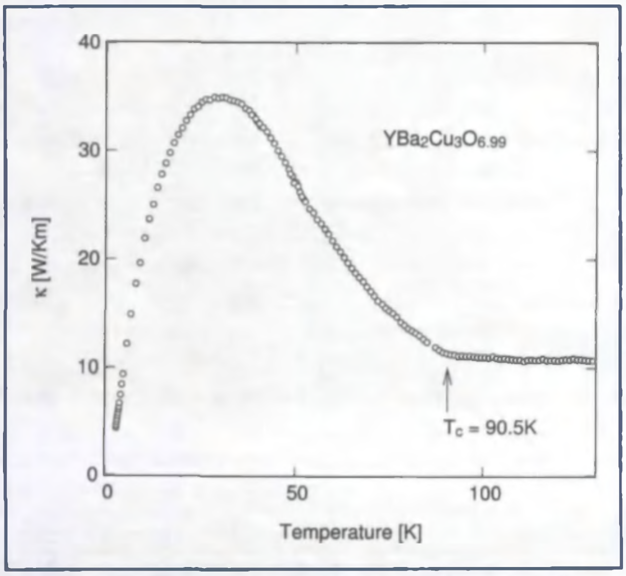

Fig. 1 Temperature dependence of the thermal conductivity of $YBa_2Cu_3O_{6.99}$, for a heat current along the a axis of the orthorhombic crystal. The arrow marks the transition temperature observed in resistivity. [2]

Therefore,

$$T \rightarrow 0: \quad \frac{\kappa}{T} = A + BT^2 \tag{3}$$

In the remainder of this article, we concentrate on the residual linear term A, the magnitude of which is directly related to the quasiparticle energy spectrum. The ability to probe the electron system at $T \rightarrow 0$ has two advantages: the strongly correlated electrons have settled into their simplest configuration, free from much of the complexity that develops at higher temperature, and theoretical results are more accurate and robust at $T = 0$.

LOW-ENERGY QUASIPARTICLES

The thermal conductivity of $YBa_2Cu_3O_x$ (YBCO) at temperatures below 200 mK is shown in Fig. 2, for the two extreme states of carrier concentration: 1) the insulating state ($x = 6.0$), with no mobile holes, and 2) the superconducting state near optimal doping ($x = 6.9$), with mobile holes in the CuO_2 planes. In the insulator, $A = 0$ in Eq. 3 and all conduction is due to phonons. Exactly the same result is found for a standard superconductor, characterised by a finite gap for all directions of electron motion (*s*-wave symmetry): the number of thermally excited quasiparticles below $T_c/10$ is exponentially small. When holes are added to the CuO_2 planes in YBCO ($x = 6.9$) via oxygenation, a sizable linear term is seen to develop, with a value $A = 0.14 \pm 0.03$ mW K^{-2} cm^{-1} [4]. A similar behaviour is found for the other two holed-doped cuprate superconductors $Bi_2Sr_2CaCu_2O_8$ (BSCCO)[5,6] and $La_{1.83}Sr_{0.17}CuO_4$ (LSCO)[6]. The observation of electronic conduction in a superconductor down to $T_c/1000$ is unprecedented, and it points unequivocally to the presence of itinerant fermionic excitations of zero energy.

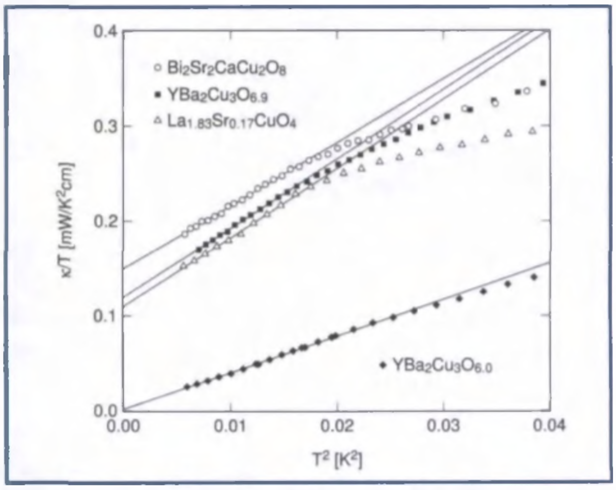

Fig. 2 Thermal conductivity of optimally-doped $Bi_2Sr_2CaCu_2O_8$, $YBa_2Cu_3O_{6.9}$ and $La_{1.83}Sr_{0.17}CuO_4$ at very low temperature. Insulating (deoxygenated) $YBa_2Cu_3O_{6.0}$ is also shown for comparison. The lines are linear fits to the data below 130 mK. [6]

We now show that this "residual normal fluid" is due to quasiparticles in a gapped spectrum with *d*-wave symmetry.

In BCS theory, the excitation spectrum in the superconducting state is given by

$$E(k)=\sqrt{\epsilon^2(k)+\Delta^2(k)} \qquad (4)$$

where k is the momentum vector, ϵk is the electronic energy in the metallic state (relative to the Fermi energy) and $\Delta(k)$ is the gap function. In a pairing state with $d_{x^2-y^2}$ symmetry, the quasiparticles are distinct from those in conventional superconductors in that they have a unique energy versus momentum relation as a result of their unconventional gap structure. This takes the approximate form $\Delta_d(k) = \Delta_0\cos(2\phi)$, where ϕ is the azimuthal angle in the (k_x,k_y) plane measured relative to the k_x axis. In comparison, a standard superconductor with isotropic gap has $\Delta_s(k) = \Delta_0$. Note that $\Delta_d(k)$ vanishes along the lines $\phi = \pm\frac{\pi}{4}$ and $\pm\frac{3\pi}{4}$ (or $k_x = \pm k_y$). As shown schematically in Fig. 3, this gives rise to four nodes on the Fermi surface of hole-doped cuprates, which in essence consists of a cylinder centered on each corner of the Brillouin zone at $\left(\pm\frac{\pi}{a}, \pm\frac{\pi}{a}\right)$, where a is the lattice constant. Near each node, the energy is given by

$$E(k)=\hbar\sqrt{v_F^2k_1^2+v_2^2k_2^2} \qquad (5)$$

where $v_2 = (d\Delta_d/d\phi)\,/\,(\hbar k_F)$ is the slope of the gap at the node, v_F and k_F are the Fermi velocity and momentum, and k_1 and k_2 are the components of $\mathbf{k}$ normal and parallel to the local Fermi surface. Eq. 5 describes a conelike spectrum (see Fig. 3), with a dispersion perpendicular and parallel to the Fermi surface given respectively by v_F and v_2. The density of states of "nodal" quasiparticles grows linearly with energy at low energy, a property which governs all low-temperature properties, for example the linear temperature dependence of the penetration depth (see article by Bonn and Hardy). In the next section, we will show how the heat conduction measured at $T\rightarrow 0$ is clear evidence for these *d*-wave nodal quasiparticles and how it provides a direct measure of their dispersion.

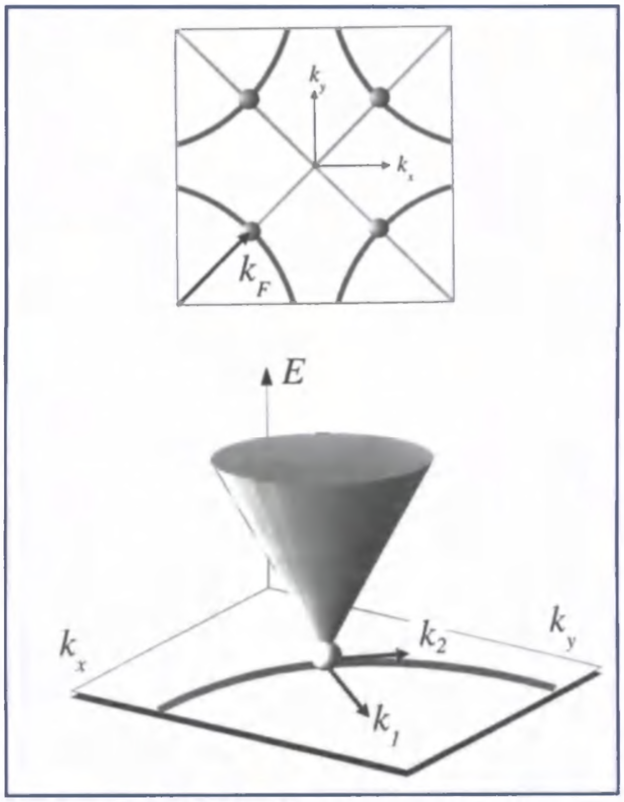

Fig. 3 **TOP PANEL: Planar section of the Fermi surface of a typical cuprate, made of cylinders centered on the corners of the Brillouin zone. The two diagonal lines correspond to directions along which Δ(k) vanishes for $d_{x^2-y^2}$ symmetry. Nodes in the energy spectrum are found where these lines cross the Fermi surface, shown as four dots. BOTTOM PANEL: Energy vs momentum relation for the nodal quasiparticles.**

UNIVERSAL CONDUCTION

In a crystal of $YBa_2Cu_3O_{6.9}$, the replacement by a Zn atom of 1 or 2 out of every 100 Cu atoms in the CuO_2 plane causes a major change in the transport properties. The electrical resistivity acquires a sizable constant term and the peak in the thermal and microwave conductivities below T_c disappears almost entirely, as the elastic scattering rate is increased by a factor of 10 to 100. Remarkably, such an increase in scattering rate was found to have no impact on the ability of the residual normal fluid to conduct heat[7]. This can arise in an unconventional superconductor because of the two-fold effect of impurity scattering: not only does it limit the mean-free path, it also generates a finite density of quasiparticles at zero energy, roughly speaking by broadening the apex of the cone in Fig. 3. In the case of a *d*-wave gap, those two effects compensate exactly at $T = 0$, resulting in a *universal* conductivity, independent of impurity concentration[8]:

$$T\rightarrow 0:\ \frac{\kappa}{T}=\frac{k_B^2}{3\hbar}n\left(\frac{v_F}{v_2}+\frac{v_2}{v_F}\right) \qquad (6)$$

where n is the number of CuO_2 planes per meter stacked along the *c*-axis. A measurement of the residual linear term in $\kappa(T)$ is thus seen to be a direct measure of the ratio of quasiparticle velocities, v_F and v_2. Using the data in Fig. 2 one gets $\frac{v_F}{v_2}$ = 14, 19 and 12 for YBCO [4], BSCCO [5] and LSCO, respectively. In the case of BSCCO, the dispersion at the node was measured spectroscopically by angle-resolved photoemission, giving $\frac{v_F}{v_2}$ = 20 for optimal doping [9]. This excellent agreement shows that the residual linear term in the heat transport is entirely due to *d*-wave quasiparticles, paving the way to a systematic study of the ground states of cuprates. Its observation in YBCO and LSCO, where the gap function has not been resolved via photoemission, confirms *d*-wave symmetry in these materials and gives us the dispersion. Once a value for v_F/v_2 is obtained, it can be used to compute various properties within the Fermi-liquid framework. For example, it is of fundamental interest to understand by what mechanism the superfluid density $n_s(T)$ is suppressed with increasing temperature (see Fig. 4 in article by Bonn and Hardy). Is the suppression due to fluctuations in the *amplitude* of the order parameter (*i.e.* thermally excited quasiparticles) or fluctuations in the *phase*? The quasiparticle contribution to $n_s(T)$ is proportional to v_F/v_2[8], and a comparison of heat transport and penetration depth data for YBCO and BSCCO reveals that there are enough quasiparticles at low temperatures to fully account for the drop in superfluid density, showing that phase fluctuations need not be invoked[5].

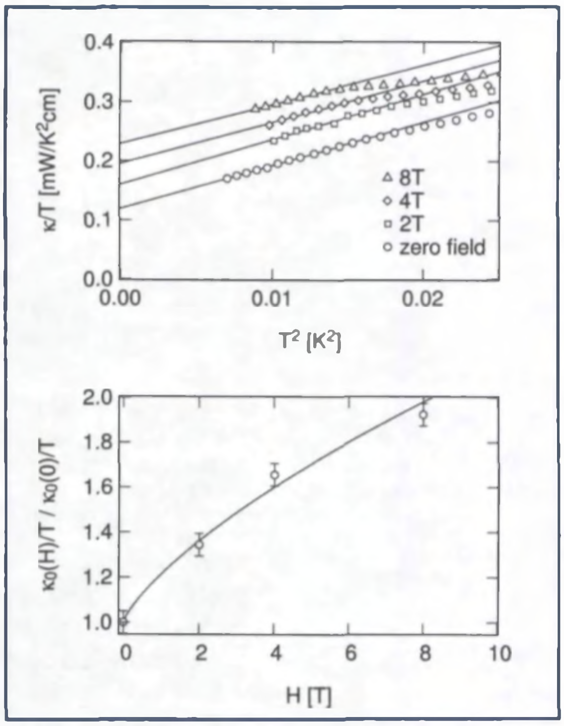

Fig. 4 TOP PANEL: Thermal conductivity of $YBa_2Cu_3O_{6.9}$ at very low temperature in a magnetic field along the *c*-axis, up to 8 Tesla. BOTTOM PANEL: Residual linear term as a function of field. The line is a semi-classical calculation[11]. From [4]

THE VORTEX STATE

An applied magnetic field *H* penetrates a superconductor in the form of vortices, *i.e.* lines at the centre of a rotating superfluid flow field. In the presence of this superfluid moving at velocity v_s, the quasiparticle energy is modified according to

$$E(k) \rightarrow E(k) + \hbar k \cdot v_s \qquad (7)$$

where $\mathbf{v_s} = \mathbf{v_s}(\mathbf{r})$ varies in magnitude and direction throughout the material, being largest close to the vortex centre. Therefore, depending on the local direction of v_s, the cone of excitation shown in Fig. 3 will either move up or down in energy. On average, this will induce a finite density of states at the Fermi energy proportional to $\sqrt{H}$, corresponding to those cones of excitation that have moved down in energy. The ideal way of probing these field-induced excitations is to look at the heat transport.

This is done in Fig.4 for YBCO. The application of a modest magnetic field (compared to the field needed to destroy superconductivity) clearly leads to an increase in the electronic conduction[4 10]. The field dependence of the residual linear term was reproduced qualitatively by semi-classical calculations based on the Doppler shift defined in Eq. 7 [11]. It is far from obvious why such calculations should work, as the usual basis for the description of electron states in a magnetic field may not hold for *d*-wave quasiparticles in the vortex state. Several issues need be explored, including field-induced phase transitions[12] and the absence of Landau quantization.

In conclusion, the picture that emerges from studies of heat transport in cuprates at *T* = *0* and optimal doping is completely in agreement with Fermi-liquid and BCS theory (generalized for *d*-wave symmetry). The question is: does this continue to hold true at high temperatures or in the underdoped regime, where other evidence of breakdown is rife and dramatic? The future will reveal whether we have a revolution on our hands or if the old guard of Landau and Fermi will hold their ground.

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HIDDEN ORDER PARAMETERS IN THE CUPRATES

Recent experiments on the cuprate superconductors have revealed a striking set of phenomena which have been collectively ascribed to a "pseudogap". A rough definition of it is that the system develops a gap -- similar to the superconducting gap -- but behaves, in some respects, more like an insulator than a superconductor. We propose [1] that these superconductors exhibit a new kind of order different from the charge, spin, and superconducting order already established in these materials, and we argue that the pseudogap phenomenon is due to the development of this order. There are a number of potential candidates for this, but we favor orbital antiferromagnetism, also known as "staggered flux" or "d-density wave" (DDW) order. Thus, we consider a broken-symmetry state with a density wave of $d_{x^2-y^2}$ symmetry.

The possible orderings [2] which we find most attractive phenomenologically are

$$\left\langle \psi^{\alpha\dagger}(k+Q,t)\,\psi_{\beta}(k,t)\right\rangle = i\Phi_{Q} f(k)\,\delta^{\alpha}_{\beta} \qquad (1)$$

and its triplet analog

$$\left\langle \psi^{\alpha\dagger}(k+Q,t)\,\psi_{\beta}(k,t)\right\rangle = i\Phi_{Q} f(k)\,\hat{n}\cdot\sigma^{\alpha}_{\beta} \qquad (2)$$

where $f(\mathbf{k}) = \cos k_x a - \cos k_y a$, $\mathbf{Q} = (\pi/a, \pi/a)$ ψ, $\psi^\dagger$, are electron annihilation/creation operators, and Φ_Q is the magnitude of the order parameter. The first type of order is characterized by local circulating charge currents arranged in a staggered manner; the second, by local circulating spin currents.

The specific *d*-wave variation of the order parameter implies that it does not couple to *s*-wave experimental probes, and thus it is quite effectively hidden. The DDW state is strongly affected by disorder. This explains why no transition has been seen, and also implies that the pseudogap "crossover" will sharpen into a transition as sample quality is improved.

The ideas discussed here are consistent with a large class of experiments, although the main experimental clues are (a) the angle resolved photoemission spectroscopy which shows a gap in the single particle excitation spectrum, whose anisotropy in the momentum space is similar to the anisotropy of the superconducting $d_{x^2-y^2}$ gap, (b) an analysis[3] of the magnetic resonance peak seen in neutron scattering experiments that is strongly suggestive of two order parameters with identical $d_{x^2-y^2}$ coherence factors, only one of which is superconducting, and, (c) the same resonance experiments in the lightly Zn-doped materials indicating that the new order parameter breaks the lattice translational symmetry.

A phase diagram incorporating such an order is depicted below. Note that the upper crossover scale, which is sometimes conflated with the pseudogap scale, is identified as the scale associated with the spin stiffness constant. At this magnetic crossover, the uniform susceptibility is expected to have a broad maximum. The lower scale, T^*, is the transition temperature for our new ordered state.

One of the most striking features of the phase diagram is the existence of a phase with both types of order. As a result, a phase transition is predicted within the superconductor!

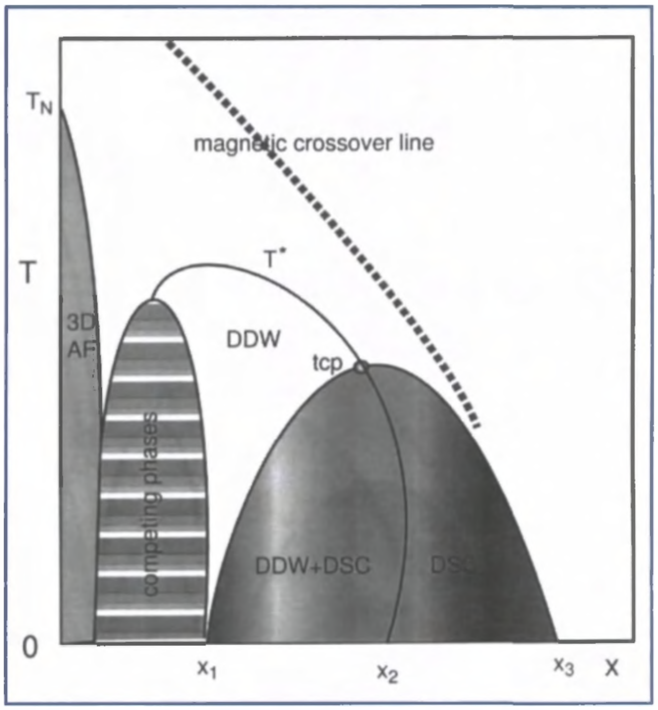

Fig. 1 The phase diagram in the temperature (T) - doping (x) plane. Here T_n is the antiferromagnetic transition temperature and *tcp* is a tetracritical point; x_1, x_2, and x_3 are quantum phase transitions at zero temperature.

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Due to space limitations, it was not possible to include many of the references which should have accompanied these short essays. -- Eds.

SPLINTERING THE ELECTRON: A ROUTE TO HIGH TEMPERATURE SUPERCONDUCTIVITY?

In addition to the striking high temperature superconducting state, the cuprate materials exhibit a rich variety of low temperature charge and spin ordered phases. Moreover, the "normal state" at higher temperatures is anything but normal, particularly in the underdoped regime where a strange "pseudo-gap" is observed. Distilling the underlying root cause of the high temperature superconductivity is greatly impeded by this complexity.

Perhaps the only small parameter available to the desperate theorist searching for the underlying mechanism is the temperature itself - the richness of behavior only sets in at temperatures well below electronic energy scales. Consequently, it seems likely that disentangling the secret behind the superconductivity will require an understanding of proximate zero temperature "quantum phases". History also serves as a useful quide here - the metallic phase above T_c in conventional superconductors is a quantum fluid with electron-like low energy quasiparticle excitations, characteristic of the $T = 0$ Fermi liquid phase. Within the much heralded BCS theory of conventional superconductivity, these quasiparticles pair together under the influence of a phonon mediated attraction. Condensation of the resulting charge $2e$ Cooper pairs causes superconductivity. Is the strange behavior of the cuprates outside the superconducting state similarly characteristic of a more exotic $T = 0$ phase, and if so does the high temperature superconductivity emerge naturally from it? A brash theoretical scenario, proposed originally by Phil Anderson[1] and fleshed out in recent years[2,3], identifies a culprit quantum phase within which the electron splinters into pieces. A number of recent experiments offer tantalizing supporting hints.

Many quantum phases can be characterized by an "order parameter", signifying the presence of charge or spin order in the ground state. For example, charge density wave order results when an electron pairs with a *hole*, and condenses into a finite momentum state. Such condensation invariably involves breaking a symmetry, oftentimes pushing the single electron excitations up above an energy gap, as in BCS theory. But sometimes quantum phases possess a much more subtle form of order. The fractional quantized Hall phases, which occur in semiconductor heterostructures in the presence of intense magnetic fields, are fluids with an energy gap but with no charge or spin order. Moreover, the elementary excitations above the energy gap carry fractional charge - of $e/3$ for the one-third filled Landau level. These phases do possess a hidden "topological" order[4], which can also be understood in terms of a "pairing and condensation" - each electron binds to three vortices, quantized swirls of electric current, and the electron-vortex composite condenses. The condensation of vortex triplets leads directly to electron "fractionalization" into thirds. The topological character of the resultant order is only directly manifest in a gedanken experiment - if the electrons are confined to move on a surface of non-zero genus the ground state is degenerate.

Soon after the discovery of high temperature superconductivity, Phil Anderson suggested that the electron was similarly being "fractionalized" in these materials [1], splintering into separate spin and charge carrying excitations. It is now apparent that such "spin-charge separation" implies a form of topological order quite analogous to the fractional quantized Hall effect [3,4]. When two vortices pair and condense, the electron is splintered into two pieces - the "chargon" which carries the charge of the electron, and the "spinon" which carries the electron's spin and Fermi statistics.

Do the undoped cuprate materials possess such a hidden topological order? Neutron scattering readily exposes the antiferromagnetic order, but is not an obvious probe of topological order. Very broad spectral features in angle resolved photoemmission experiments (ARPES) do suggest that the electron is decaying into constituent pieces. Further support is provided by mid-infrared optical absorption and Raman measurements which exhibit broad spectral features perhaps indicative of spinon excitations. Recently, a "smoking gun" experiment has been proposed on cylindrical cuprate samples which should enable a *direct* measurement of the topological order[3].

Why should one care if topological order is present in the "normal state"of the underdoped cuprates? Remarkably, its presence leads directly to a "non-pairing" mechanism of the high temperature superconductivity. How so? Superconductivity requires condensation of a charged boson, such as the Cooper pair of BCS theory. Since the electron has Fermi statistics a direct condensation is *not* possible. But with topological order the electron splinters, shedding its Fermi statistics to the spinon, leaving behind a charge e boson which *can* condense. Surprisingly, the flux quantization in the resulting superconductor is nevertheless $hc/2e$ - despite the absence of any pairing in the "normal state"

A virtue of spin-charge separation is that it offers the skeptic a sharp dichotomy - at $T = 0$ it is either present or not. The presence of such topological order in the undoped cuprates has profound implications, providing a natural "non-pairing"route to high temperature superconductivity upon doping. If absent one is forced to search for the cause of superconductivity via a more traditional route, looking for the glue which can somehow bind together two electrons into a Cooper pair.

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MICROWAVE PROPERTIES OF HIGH TEMPERATURE SUPERCONDUCTORS

by D.A. Bonn and W.N Hardy

Electrodynamic measurements at radio and microwave frequencies have played many roles in the long history of superconductivity[1]. They first helped elucidate a key feature of superconductors, their remarkable ability to expel magnetic fields. In the 1930's F. and H. London developed a model in which shielding of magnetic fields occurs by the flow of supercurrents in a surface layer now known as the London penetration depth λ, related to the superfluid density n_s via

$$\frac{1}{\mu_0 \lambda^2} = \frac{n_s e^2}{m^*} \qquad (1)$$

where m^* is the charge carriers' effective mass[2]. Typical values of λ are in the range of a few hundred to a few thousand Angstroms. At this early stage there was already a surprise: RF measurements found the λ to be larger than expected in superconducting elements such as tin[3], providing the first evidence of a second important length scale in superconductivity, the coherence length ξ.

The other major role played by microwave measurements involved the measurement of electromagnetic absorption. When a microscopic explanation for superconductivity was finally developed in 1957 by Bardeen, Cooper and Schrieffer, their theory indicated that a superconductor would have a small energy gap between its groundstate and lowest excited states[4]. In the same year, microwave and far infrared absorption measurements found a threshold for absorption very close to the expected gap energy in Pb, Al and Sn[5], providing evidence that was a key part of the acceptance of BCS theory.

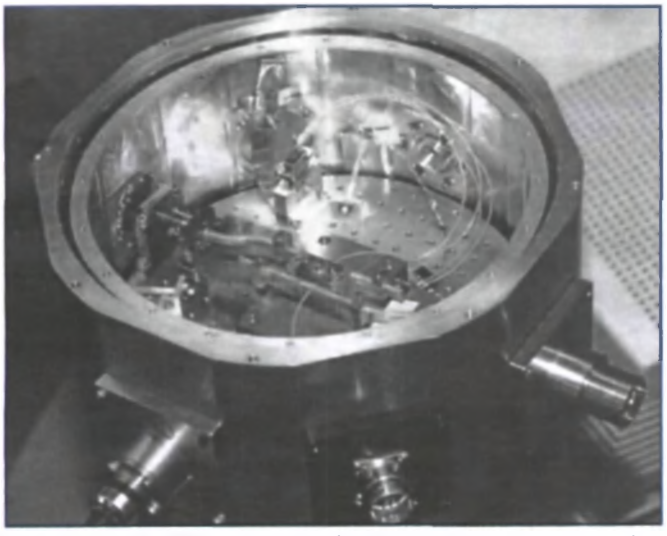

Fig. 1 A 75 GHz superconducting resonator system for cavity perturbation measurements.

The low microwave absorption for frequencies below the energy gap is the basis for many applications of superconductors.

The low microwave absorption for frequencies below the energy gap is the basis for many applications of superconductors. Microwave resonators, which are hollow cavities with metallic walls, have an infinite set of resonant modes. If the walls are made from a superconductor such as niobium or lead, the Q of the resonances, the ratio of the resonant frequency over the width of the resonance, can reach enormously high values, up to 10^{11}. When driven at high microwave power, such cavities produce intense electric fields that can be used in particle accelerators for research and for medical equipment.

The ability to make extremely high Q cavities from conventional superconductors is also the key to the techniques that we have used to study the penetration depth and microwave absorption in high temperature (HiTc) superconductors. This research has run in parallel with our development of highly perfect single crystals (see R. Liang's article in this issue). The development of novel superconducting resonators, tailored to the task of measuring small crystals, has led to a series of discoveries that continue to reveal how much the HiT_c superconductors differ from conventional superconductors. Below, we will give an overview of how these measurements are done and highlights of the surprising properties.

MICROWAVE MEASUREMENTS

For the electrodynamics of metals and superconductors[6] it is customary to express the material's properties in terms of a complex conductivity $\sigma = \sigma_1 - i\sigma_2$. However, in

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electrodynamic measurements, the measurable quantity generally involves a different, related pair of constants. In optics, this pair might be the magnitude of the reflectance and the phase shift of the waves upon reflection. In the case of microwave measurements it is the complex surface impedance, defined to be the ratio of the tangential electric and magnetic fields (e.g. E_x/H_y) and written as $Z_s = R_s + iX_s$, where R_s is the surface resistance in Ohms and X_s the surface reactance. In the limit of local electrodynamics, the conductivity is related to the surface impedance via

$$Z_s(w) = \left(\frac{i\mu_0\omega}{\sigma_1 - i\sigma_2}\right)^{1/2} . \tag{2}$$

The simplest possible expression for the low frequency conductivity of a metal is the Drude model

$$\sigma_{1N} - i\sigma_{2N} = \frac{n_n e^2}{m^*}\left[\frac{\tau}{1 + i\omega\tau}\right] \tag{3}$$

where ω is the frequency, τ is the scattering time of the normal fluid and n_n/m^* is the normal carrier density over the effective mass. At zero frequency, σ_{1N} reduces simply to the normal state DC conductivity $n_n e^2 \tau / m^*$. At low frequencies, where $\sigma_1 \gg \sigma_2$, inserting Eq. 3 into 2 yields

$$R_s = X_s = \left(\frac{\mu_0\omega}{2\sigma_1}\right)^{1/2} , \tag{4}$$

valid in the classical skin effect regime where the fields penetrate a distance $\delta = (2 / \mu_0 \sigma_1 \omega)^{1/2}$, which is typically microns at microwave frequencies.

In the superconducting state below T_c, the DC resistivity is zero and is represented in the conductivity spectrum by a delta function at $\omega = 0$ with an oscillator strength determined by the density of the superfluid or, equivalently, by the penetration depth. This term in the conductivity is $\sigma_1(\omega,T) = \pi\delta(\omega) / \mu_0 \lambda^2(T)$ and, through the Kramers-Kronig relation, gives rise to a dominant term in the imaginary part of the conductivity, $1 / \mu_0 \omega \lambda^2(T)$ [1]. Below T_c one can thus write a quite general expression for the conductivity away from $\omega = 0$

$$\sigma(\omega, T) = \sigma^*(\omega, T) - i\frac{1}{\mu_0 \omega \lambda^2(T)} . \tag{5}$$

The term σ^*, represents all contributions to the conductivity other than the superfluid contribution and is mainly real at low frequencies ($\omega\tau \ll 1$, where τ is the transport lifetime). So, at low frequency $\sigma^*(\omega,T)$ can be replaced by a purely real $\sigma_1(\omega,T)$, and the imaginary part of the conductivity is determined by the superfluid term in Eq. 5. Except near T_c, $\sigma_2 \gg \sigma_1$, and Eqs. 2 and 5 yield simple expressions for the surface impedance:

$$R_s = \frac{\mu_0^2}{2}\omega^2\lambda^3(T)\sigma_1(\omega, T) \tag{6}$$

$$X_s = \mu_0 \omega \lambda(T) \tag{7}$$

Thus, a measurement of $X_s(T)$ allows a very direct determination of $\lambda(T)$. On the other hand, $\sigma_1(T)$ can only be extracted from $R_s(T)$ if measurements of $\lambda(T)$ are also available.

In recent years an array of techniques has been developed to measure the penetration depth and surface resistance of superconductors. In order to study the physics of the high temperature superconductors, high quality single crystals are preferred and the microwave method of choice is cavity perturbation. This technique employs a microwave cavity made of either niobium or lead, cooled to about 1.2 K. One then measures the resonant frequency f and Q of a resonant mode in the cavity, with and without the sample inserted into the cavity. If the sample is thermally isolated from the resonator, this can be done as a function of sample temperature. When the sample is inserted into the resonator, the normal charge carriers and/or the superfluid screen the fields out of the bulk of the sample and cause a slight shift in the resonant frequency, mainly determined by the size and shape of the sample. However, the size of the frequency shift is slightly diminished by the fact that fields penetrate into the sample slightly. It is very difficult to measure the absolute magnitude of the penetration depth using this effect, but one can measure *changes* as one sweeps the temperature of the sample. In the superconducting state, the effect is strikingly direct: $\Delta f(T) = f(T) - f(T = 1.2\ \mathrm{K})$ is proportional to the change in penetration depth $\Delta\lambda(T) = \lambda(T) - \lambda(T = 1.2\mathrm{K})$. The change in cavity Q when the sample is inserted gives the surface resistance via $R_s(T) \propto (1/Q_s - 1/Q_0)$ where Q_0 and Q_s are the Q's with sample out and

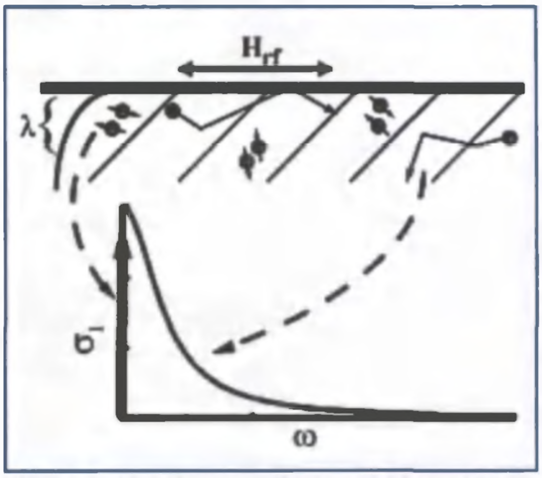

Fig. 2 The physics of the two-fluid model is illustrated above. A microwave field applied to the surface of a superconductor is screened out by the superfluid (represented here by pairs of electrons) and decays exponentially into the bulk. Within this depth λ, the remaining normal carriers give rise to microwave absorption. A simplified conductivity spectrum associated with this has a superfluid delta function plus a normal fluid component.

in, respectively. The challenge of the technique is that the effects are extremely small. The penetration depth must be resolved at the 1 Angstrom level or better, which might require measurement of the frequency of a 1 GHz resonator to 1 Hz, a resolution of 1 in 10^9. Similarly, the change in Q when the sample is inserted is miniscule.

PENETRATION DEPTH

A recounting of the various steps and mis-steps associated with the determination of the intrinsic temperature dependence of $\lambda(T)$ would be interesting, but lengthy. What is now known is that because of the *d*-wave character of the ground state, defects and impurities play an important role. In particular, the intrinsic behaviour is only seen in high quality single crystals and the very best thin films. The first clear evidence that $\Delta\lambda$ at low temperatures was linear in T, not quadratic or exponentially activated, came in 1993, more than 6 years after the discovery of the cuprate superconductors [7]. Fig. 3 shows $\Delta\lambda$ vs T in the range 1.2 to 30 K, from which one can see that $\Delta\lambda / \Delta T$ is about 4 Angstroms per degree, a clear linear power law caused by nodes in the gap in certain directions in *k*-space. This was one of the key results that led to the acceptance of the *d*-wave groundstate for the cuprates.

Using detwinned crystals and a cleaving technique to alter the aspect ratio of the samples, we are now able to measure $\Delta\lambda$ for all three crystallographic axes. Fig. 4 is a recent result for the a-axis penetration depth obtained on very high purity $YBa_2Cu_3O_{6.993}$ crystals [6] and plotted as $\lambda^2(0) / \lambda^2(T) \propto n_s$ (using a value $\lambda_a(0)$ = 1600 Angstroms obtained from Far-IR measurements [8]. This data, which was used to extract $\sigma_1(\omega, T)$ from $R_S(\omega, T)$ (discussed in the next section), displays the canonical features seen in high purity samples: a linear decrease in the superfluid density at low T, and evidence for critical fluctuations near T_c. In conventional superconductors the superfluid density approaches zero linearly as T approaches T_c. This so-called "mean field" behaviour is the result of the large number of Cooper pairs within a coherence volume. In the Hi T_c materials the coherence lengths are comparable to the lattice constants and fluctuations, never before seen in bulk superconductors, become important.

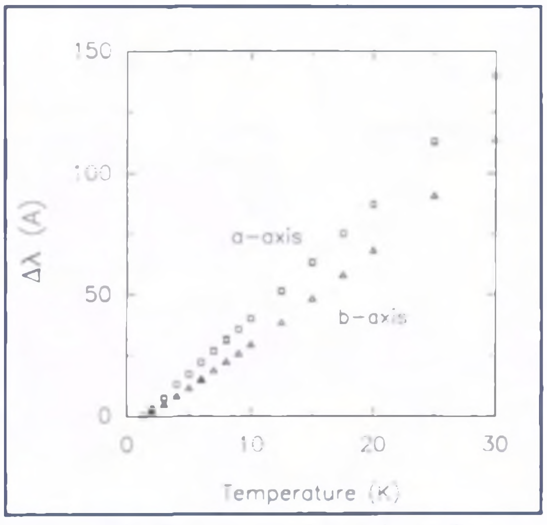

Fig. 3 The linear temperature dependence of the penetration depth for the in-plane directions in $YBa_2Cu_3O_{6.95}$ provided early evidence for a new superconducting state - $d_{x^2-y^2}$ pairing.

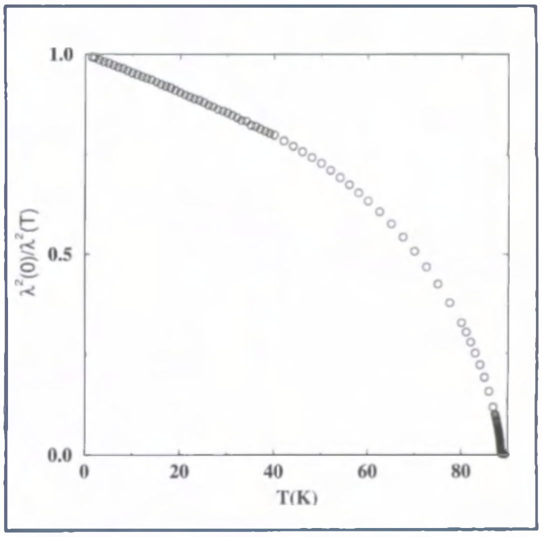

Fig. 4 The temperature dependence of the superfluid density in $YBa_2Cu_3O_{6.993}$.

SURFACE RESISTANCE

Fig. 5 shows the surface resistance of a high purity crystal of $YBa_2Cu_3O_{6.993}$, for currents running in the â direction parallel to the CuO_2 planes. The measurements are the culmination of a collaboration between 4 students using five different superconducting resonators, all studying the same crystal [6]. The rapid drop in $R_s(T)$ below T_c is due to the onset of screening by the superfluid, as seen in the $\lambda^3(T)$ term in the experession for the surface resistance. Below this initial drop, $R_s(T)$ varies as ω^2, also seen in Eq. 6. The surface resistance drops to a minimum at about 75 K and in the 1-10 GHz range the loss is extremely low. This has generated a great deal of activity aimed at producing high Q resonators that need only be cooled to liquid nitrogen temperatures.

The broad peak in $R_s(T)$ at lower temperatures is something not seen in conventional superconductors. The reason such a peak in $R_s(T)$ is so unexpected is that the source of the microwave absorption below T_c is the normal fluid, which is declining in density below T_c. Microscopically, in a *d*-wave superconductor, this normal fluid is composed of quasiparticles that are thermally excited out of the superconducting groundstate, mainly near the nodes of the superconducting gap. The peak in $R_s(T)$ is evidence that this small number of remnant quasiparticles have a very large conductivity. The reason for this is most evident if one uses the 5 frequencies to construct conductivity spectra $\sigma_1(\omega)$ at different temperatures, using Eq. 6. Fig. 6 shows this construction, along with fits to the data using a simple Drude model to describe the normal fluid conductivity. For temperatures below 20 K, the normal fluid has a large σ_1 with a very narrow width of about 9 GHz, indicating that the quasiparticles near the nodes have extremely long lifetimes and mean free paths of the order of several microns. These long lifetimes are only apparent in samples of very high quality with few defects.

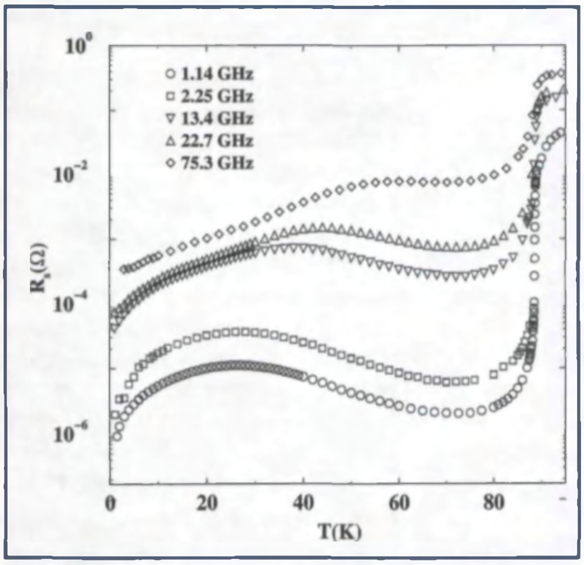

Fig. 5 Surface resistance of a $YBa_2Cu_3O_{6.993}$ crystal measured at five different frequencies.

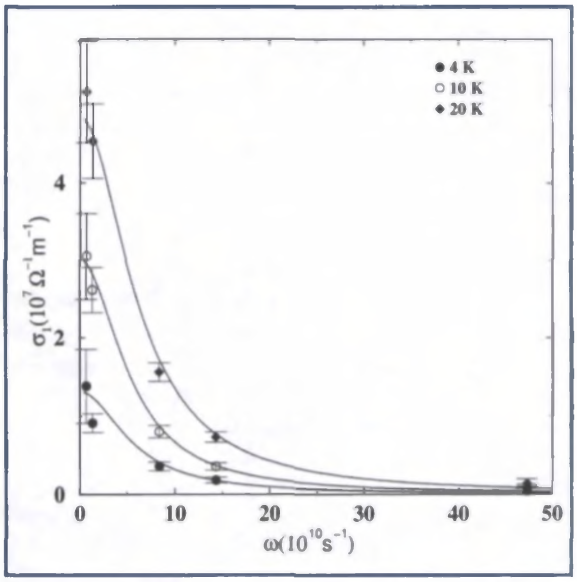

Fig. 6 The microwave conductivity $\sigma_1(\omega, T)$ of $YBa_2Cu_3O_{6.993}$. The narrow 9 GHz width of the peaks indicates quasiparticles with mean free paths of several microns in these high purity crystals.

CLOSING COMMENTS

In this article we have chosen to focus on a particular set of experiments, namely measurements of the microwave properties of the highest quality $YBa_2Cu_3O_7$ crystals available. A detailed review would have been out of the question due to space limitations, so we have attempted to give a feeling for the nature of the actual experimentation, and some idea of the type of information that can be learned. Lest the reader think that most of the important questions have already been answered, we point out that there is no consensus whatsoever on the mechanism of high temperature superconductivity, and the work of the last decade has just set the stage for the main challenges ahead. In addition to much progress in the theory, what *has* been achieved experimentally is an enormous improvement in the control of these difficult materials and, in parallel, impressive refinements in measurement techniques and development of new ones, again driven by the unusual character of the HiT_c materials. We now have a much better idea of what questions require precise answers - a good example concerns the nature of the pseudogapped state, a low entropy normal state universally observed in HiT_c materials with low hole concentrations. It is a state where strong correlations have been set up, but without the long-range coherence of superconductivity. It occurs in a region where electronic instabilities abound, so that sample inhomogeneities tend to obscure the fundamental properties. We believe that measurements of the microwave electrodynamics on carefully controlled materials will be a critical ingredient in sorting this out.

For 13 years Nature has confounded all attempts of the scientific community to unlock the deepest secrets of HiT_c superconductivity. The most exciting phase of the HiT_c story is yet to come!

ACKNOWLEDGEMENTS

The authors are indebted to countless people who have helped us in our understanding of high temperature superconductivity, an enormous list of collaborators too numerous to detail here. Above all, it has been a privilege for us to work with a talented group of students who have joined us in this journey of discovery; Chris Bidinosti, Pinder Dosanjh, Michael Gardner, Richard Harris, Ahmad Hosseini, Saeid Kamal, Rob Knobel, David Morgan, Paul Schleger, Patrick Turner, Andre Wong, and Kuan Zhang. Finally, the crucial role of the samples produced by our colleague Ruixing Liang cannot be overstated. This work was supported by the Natural Science and Engineering Research Council and the Canadian Institute for Advanced Research.

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PERFECTING THE GROWTH OF YBCO CRYSTALS

by Ruixing Liang, D.A. Bonn, and W.N. Hardy

The major obstacles for growing perfect YBCO single crystals include: the low chemical stability of YBCO, the low solubility of YBCO in BaO - CuO melts, the high corrosiveness of BaO - CuO melts, and the twinning problem. While optimization of the process conditions, development of $BaZrO_3$ ceramic crucibles, as well as development of detwinning techniques, have brought the perfection of small YBCO crystals to a very high level, challenges remain in scaling up the volume of the crystals to a few tenths of a cubic centimeter, while maintaining the high perfection.

The availability of high purity and nearly perfect single crystals has been, and will continue to be, one of the keys to the determination of the intrinsic properties of high T_c superconductors.

INTRODUCTION

All high T_c superconducting cuprates have a layered structure, which is a stacking of CuO_2 two- dimensional sheets and other oxide layers. The superconductivity occurs in the CuO_2 sheets and is very anisotropic: charge carriers are largely confined to the sheets, and along the perpendicular direction (usually *c*-direction) they move from one sheet to another by weak hopping. This anisotropy makes the use of single crystalline samples essential in most experiments.

It is also known that the superconducting energy gap in high T_c superconductors vanishes in certain directions, i.e. there are nodes in the gap. A consequence of these nodes is that the physical properties of high Tc superconductors are highly susceptible to impurities and crystalline defects [1]. Therefore, the availability of high purity and nearly perfect single crystals has been, and will continue to be, one of the keys to the determination of the intrinsic properties of high T_c superconductors.

CRYSTAL STRUCTURE OF YBCO

A large number of high T_c superconducting compounds have been found existing in many ternary and quaternary oxide systems containing copper. Among them, $YBa_2Cu_3O_{7-\delta}$ (YBCO) has received the most attention because it is relatively easy to prepare and, unlike most high T_c cuprates, it has a well-defined stoichiometric cation composition.

Figure 1 shows the crystal structure of $YBa_2Cu_3O_7$. There are two CuO_2 sheets per unit cell along the c-direction, separated by a layer of yttrium. Between the $Y(CuO_2)_2$ layers are barium ions and one-dimensional CuO_3 square planar chains running along the *b*-direction. The compound has a nonstoichiometric oxygen content 7-δ that varies from 6 to 7. When the oxygen content is reduced from 7, the chain oxygen O(1) site becomes deficient. At high temperatures or at oxygen content close to 6, the average occupancy for the O(1) site and the perpendicular site (between chain copper atoms) becomes equal and the structure becomes tetragonal. Since changing the oxygen content 7-δ changes the carrier doping level, YBCO is well suited for studying the fundamental properties at different doping levels.

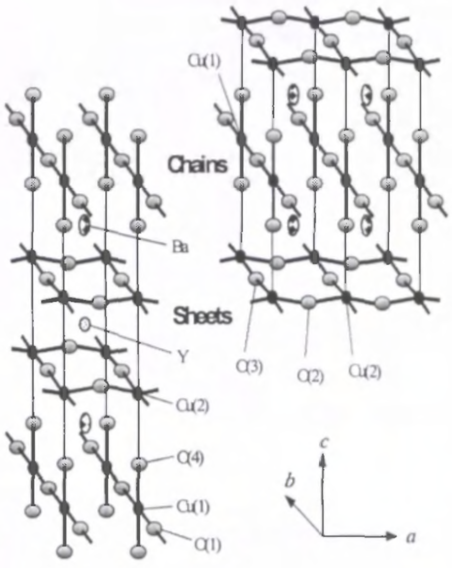

Fig. 1 Crystal structure of $YBa_2Cu_3O_7$

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GROWTH OF YBCO CRYSTALS

Single crystals of most substances are grown either from a stoichiometric melt or from a solution. Like all other high T_c cuprates, YBCO melts incongruently. This makes it impossible to grow YBCO crystals from its stoichiometric melt, and one has to find a suitable solvent (often called flux) to grow crystals from solution. It was found that YBCO decomposes in the usual kinds of flux used for growth of inorganic crystals, such as chlorides and low melting point oxides [2]. In fact, the only type of flux from which good YBCO single crystals can be grown is composed of BaO and CuO, components of YBCO itself.

Figure 2 shows the ternary phase diagram of the Y_2O_3 - BaO - CuO system [3,4]. The most important region for the crystal growth is the triangle connecting Y_2BaCuO_5 (called 211), $BaCuO_2$ and CuO. The incongruent melting point (called the peritectic temperature) of YBCO is 10^{10}± 5°C where it decomposes into the 211 phase (solid) and a melt:

$$YBa_2Cu_3O_{7-\delta} = Y_2BaCuO_5 + \text{melt}.$$

This reaction is called a peritectic reaction. The peritectic melt has a composition close to 3BaO·5CuO and contains only 0.6 at. % of yttrium [5], which is equivalent to 0.6 mol % YBCO. In the phase diagram, YBCO is the primary phase (the first crystalline phase to appear when a homogeneous melt is cooled) in the small dark region near the lower edge of the phase diagram. The wide grey area containing the $YBa_2Cu_3O_{7-\delta}$ composition is the peritectic region, where the 211 phase reacts with the co-existing melt to form YBCO when the system is cooled below the peritectic temperature.

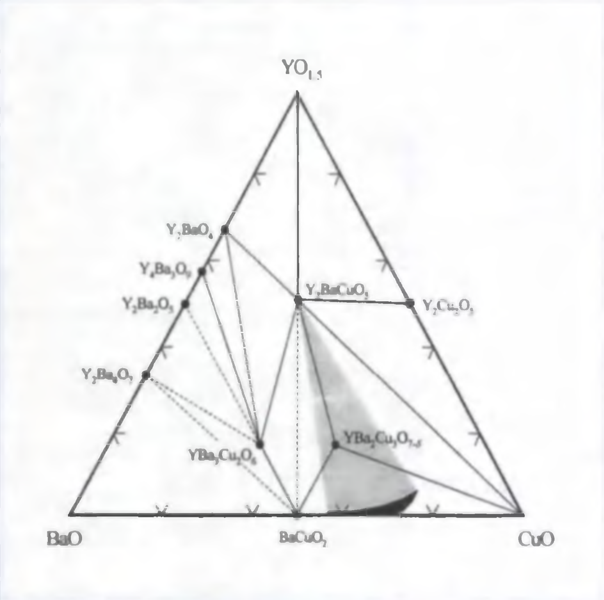

Fig. 2 Schematic diagram of $YO_{1.5}$ - BaO - CuO ternary system. The gray area indicates approximately the peritectic reaction region where Y_2BaCuO_5 (211 phase) reacts to the melt and forms YBCO when the system is cooled below the peritectic temperature. The small dark area near the lower edge of the diagram is the region where YBCO is the primary phase (only apprixmately known). The highest quality YBCO crystals are typically grown in this composition region, through theprecipitation of YBCO from the saturated melt.

The low solubility of YBCO in the BaO - CuO melts makes it difficult to maintain a steady supply of the solute (YBCO) at the growth front, making the growth of large size crystals difficult. To overcome this difficulty, crystal growth in the presence of the 211 phase has been widely investigated. The surface energy of the 211 phase leads to a large over-saturation of yttrium around the 211 particles, which provides a driving force for yttrium to diffuse to the growth front and form YBCO through the peritectic reaction [6-8]. While crystals grown by this mechanism can reach inch size, they typically contain large concentrations of defects. For example, crystals produced by solute- rich liquid-crystal pulling (SRL-CP) [9,10], a modified Czochralski technique, had a wide mosaic spread of 0.16° [10]. Although these crystals, may have potential for application, they are not good enough for much fundamental research.

The highest quality YBCO crystals are usually grown by slowly cooling the homogeneous melt having a composition somewhere in the dark region in Fig. 2, where YBCO is the primary phase. A widely adopted composition is 10 wt. % YBCO and 90 wt. % BaO - CuO eutectic (CuO:BaO = 72:28 in moles) flux, which corresponds to Y:Ba:Cu = 1:18:45 in moles and is located in the middle of the dark area. When the homogeneous melt is cooled below the liquidus temperature, YBCO starts to precipitate out. Further steady and slow cooling maintains the saturation and keeps the YBCO crystals growing.

The experimental setup of the crystal growth used by Liang *et al.* [11] is shown in Fig. 3. A ceramic crucible, fully filled with a powder mixture of Y_2O_3, CuO and $BaCO_3$, is placed near the end wall of a muffle furnace where there is a horizontal temperature gradient toward the center of the furnace. The quartz glass rod, which serves as an infrared light pipe, further increases the tempera-ture gradient and creates a cool spot at the furnace wall side of the crucible. The quartz glass rod may be replaced by an opening [12] on the furnace wall or by a gas cooled ceramic pipe [13]. The latter procedure allows even better control over the temperature of the cool spot.

It typically takes 12 to 24 hours at 1000°C to completely melt the powder mixture. Once a homogeneous melt is obtained, the temperature is lowered at a rate of 0.1 to 1.0 °C/h [11-13]. For the melt composition of Y:Ba:Cu = 1:18:45, YBCO crystals start to form around the cold spot at about 985°C. Typically the growth is terminated at 950°C by emptying the melt onto the porous ceramic (the crystals stay attached to the crucible wall). Continuation of crystal rowth to a lower temperature leads to worse crystal flux separation, due to a higher melt viscosity.

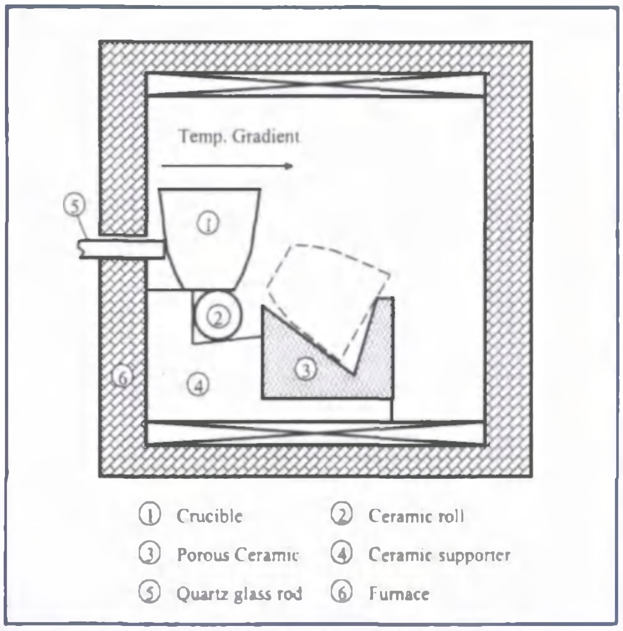

Fig. 3. **Experimental setup for YBCO crystal growth [11].**

Applying a horizontal temperature gradient of 2 to 5 °C/cm, measured between the cold spot and the opposite side of the crucible, improves the growth stability and enhances the growth rate. The existence of a cold spot prevents the occurrence of deep over-cooling, which may cause the sudden formation of a large number of small YBCO crystals. The temperature gradient also generates a steady convection of the melt, which reduces the thickness of the diffusion layer at the growth front and thus enhances transport of YBCO to the growth front. Without a temperature gradient, the growth rate along the c-direction is about 4 microns/hr, independent of melt composition and cooling rate [14]. Liang *et al.* [11] achieved a growth rate of >10 microns/hr under a temperature gradient of 2 to 5 °C/cm.

The YBCO crystals grown by this slow cooling technique are typically thin platelets up to a few millimeters wide, with {001}, {100} and {010} faces and the shortest dimension along the c- direction. The aspect ratio (width to thickness) decreases with slowing cooling rate and increasing temperature gradient. At a cooling rate of less than 0.3 °C/h, nearly isometric crystals can be grown and, in addition to the usual {001}, {100} and {010} faces, {011} faces often appear.

CRUCIBLE MATERIAL

Growth of high quality YBCO single crystals requires crucibles that will contain the corrosive BaO - CuO melt.

The BaO - CuO melt reacts with all of the inert metals used for crucibles. For example, it reacts with platinum to form $YBa_4Cu_2Pt_2O_Y$. Therefore, one had no choice but to use ceramic crucibles of high melting point oxides. However, oxide materials themselves are generally soluble in oxide melts, so that contamination from crucible materials was usually the major source of impurities in YBCO crystals. Finding a less contaminating crucible material was the key to achieving high purity.

In YBCO, Cu is nearly divalent at the crystal growth temperatures. Small divalent ions such as Zn^{2+}, Ni^{2+} and Mg^{2+} were found to substitute for Cu in the plane sites, and small trivalent ions such as Al^{3+}, Co^{3+}, Fe^{3+} and Ga^{3+} were found to substitute for Cu in the chain site. Therefore, oxides of these metals produce strong contamination. Early YBCO crystals grown using Al_2O_3 and MgO crucibles were found to contain large concentrations of Al or Mg.

Large trivalent ions such as most rare earth ions can substitute for Y in YBCO. Large rare earth ions like La^{3+} and Nd^{3+} can even substitute for Ba. Therefore, oxides of these metals are also contaminating materials. One exception is Y_2O_3, which is a component of YBCO. Y_2O_3 crucibles have been used in growth of YBCO crystals by the SRL-CP technique [9,10] and slow cooling method [12]. However, Y_2O_3 reacts with the BaO - CuO melts and forms the 211 phase, which leads to crystal growth via the peritectic reaction, regardless of starting composition. As mentioned in the last section, crystals grown in this mechanism tend to be defective. So far, crystals grown using Y_2O_3 crucibles, even though they are chemically pure, have not been reported to have a high degree of perfection.

Large tetravalent ions such as Th^{4+} substitute for Y in YBCO. The least contaminating crucible materials are oxides of small tetravalent ions such as Zr^{4+} and Sn^{4+}. The solubility of these ions in Cu sites is extremely small because of their much higher charge compared to Cu^{2+}. They also have no solubility in the Y site because their ionic size is much smaller than Y^{3+}. Therefore, YSZ (Y_2O_3 stabilized ZrO_2) crucibles have been widely used for growing YBCO crystals. These crystals contained less than 10 ppm of Zr [11], and had a mosaic spread of about 0.02°, as measured by the width of X-ray rocking curves [15]. Many remarkable results in high T_c physics between 1990 and 1997 were achieved on these crystals.

However, YSZ is not inert: it reacts with the melt and forms the perovskite compound $BaZrO_3$. This reaction changes the melt composition by consuming BaO and introducing additional Y_2O_3 into the melt. The reaction product, $BaZrO_3$ precipitate, disturbs the crystal growth and limits the crystal growth time by eventually turning the melt into a viscous slurry. Furthermore, because commercial ceramic crucibles are typically only 99% pure with impurities such as Al_2O_3, MgO, SiO_2, TiO_2 and Fe_2O_3, the corrosion brings impurities into the melt and limits the purity of YBCO crystals to around 99.9% despite the use of 99.995% pure starting materials for the melt [11].

The reaction product of the melt with ZrO_2, the compound $BaZrO_3$, then became the focus of attention. It ought to be inert in the melt because it is the reaction product and Zr^{4+} has little solubility in the melt. Considerable effort was devoted to fabricating dense $BaZrO_3$ ceramics for use in melt processing of YBCO. Despite the fact that there is no reaction between $BaZrO_3$ grains and BaO-CuO melt, grain boundaries of $BaZrO_3$ ceramics were found to be weak and easily percolated through by the melt. A remarkable breakthrough was made by Erb *et al.* [13,16], and followed by Liang *et al.* [15]. They successfully solved the grain boundary problem and fabricated $BaZrO_3$ ceramics that are impervious to percolation of the melt. This essentially solved the crucible material problem.

The use of inert $BaZrO_3$ crucibles has increased the purity of YBCO crystals to the level of starting chemicals, about 99.995 at. % (the purest commercially available). The inertness and long lifetime of the crucibles has also allowed more control and freedom over the flux composition and the growth process. For example, one can carry out very slow growth to improve the crystal perfection. This was impossible to do using other crucible materials due to the limited crucible lifetime. By carefully choosing the growth parameters, the YBCO crystals can have very low defect concentrations as indicated by very low magnetic vortex pinning in the mixed superconducting state [15]. They have mosaic spread of about 0.007°, as measured by the width of X-ray (006), (200) and (020) rocking curves. The (006) rocking curve is shown in Fig.4 [15]. Such a narrow mosaic spread is an excellent result, given the compositional and structural complexities of the compound. The high perfection has also made it possible to obtain highly ordered ortho-II phase crystals [17], which are important for the investigation of the superconductivity in the under-doped region.

POST ANNEALING

Generally, crystals grown from a melt have residual strain and a relatively high concentration of defects. Annealing at slightly below the growth temperature releases the strain and reduces the defect concentration. Accordingly, the YBCO crystals are post-annealed at 860 to 900°C in pure oxygen flow for 72 hours. We found that this process improves the maximum Tc of the crystals by about 0.5 K and reduces the magnetic vortex pinning in the mixed state.

Another aspect of the post-annealing is the setting of the oxygen content, 7-δ, in $YBa_2Cu_3O_{7-\delta}$. In equilibrium, the value of δ is a function of temperature and oxygen partial pressure [18,19]. For the whole volume of a crystal to reach the equilibrium oxygen content, oxygen has to diffuse over a distance of the size of the crystal. The diffusion constant is proportional to $e^{U/kT}$ (U is the activation energy), which increases rapidly with increasing temperature. Therefore, to reach equilibrium

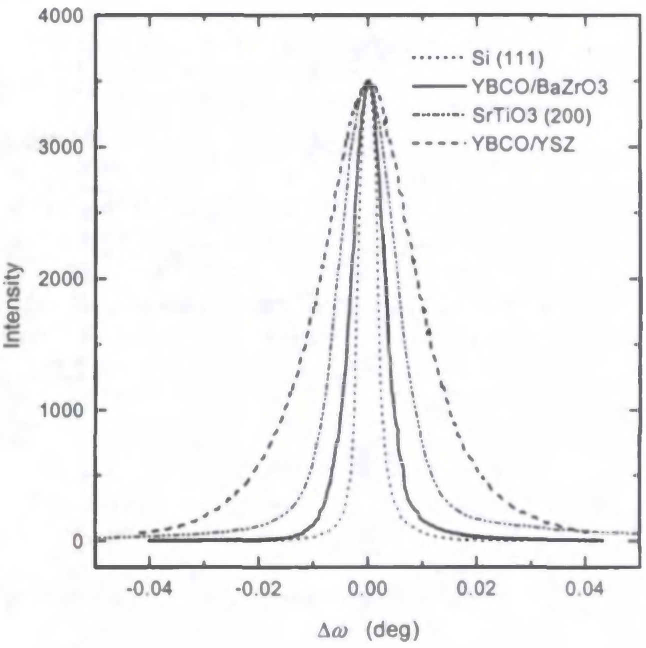

Fig. 4. The X-ray rocking curve (in order from inner to outer curves) of Si (111), $BaZrO_3$ crucible grown $YBa_2Cu_3O_{6.99}$ (006), $SrTiO_3$ (200) and YSZ crucible grown $YBa_2Cu_3O_{6.95}$ (006) reflections [15]. The FWHM is 0.004 , 0.007 , 0.013 and 0.021 , respectively for Si, YBCO/$BaZrO_3$, $SrTiO_3$, and YBCO/YSZ. The FWHM for Si (111) is believed to be the beam profile of the X-ray machine. The peaks are normalized to the same height for easy comparison of FWHM.

oxygen content at a low temperature (below 600°C), slow cooling of the crystals to the temperature from a higher temperature takes a far shorter time than simply annealing the crystals at the low temperature. Finally, the crystals are kept at the low temperature for sufficient time to ensure that equilibrium is reached.

The purity of oxygen gas used for annealing affects the quality, particularly surface quality, of the crystals. Water, organic vapors and carbon oxides in the oxygen gas are particularly harmful. A simple way to remove these impurities is to pass the oxygen gas through a furnace filled with platinum coated alumina balls at 550°C, where organic vapors are oxidized and carbon monoxide is converted to carbon dioxide. The water vapor and carbon dioxide are then removed using a liquid nitrogen trap.

REMOVAL OF TWIN BOUNDARIES

YBCO crystals with oxygen content $7-\delta > 6.3$ have the orthorhombic structure, and are typically twinned with (110) and (110) twin planes. The twins mix up *a*- and *b*-directions of the crystals. The twin planes also act as pinning and scattering centers, which are undesirable when one is trying to determine the intrinsic properties.

The twin planes are removed by carefully applying uni-axial pressure of 2 to 25 MPa along the *a(b)*-direction at 200 to 400°C [20]. For crystals thinner than 50 m, large twin free domains can also be generated by annealing at 400 to 600°C for a few weeks [21].

At the detwinning temperatures, YBCO reacts with moisture and CO_2 in the air. Therefore, the detwinning process is carried out under high purity oxygen gas flow.

SUMMARY

We have given a brief review of the process and the essential problems encountered in the growth of high quality YBCO single crystals. The melt composition, growth conditions and the conditions of the post-growth treatments are all important to the quality of YBCO crystals.

The successful development of inert $BaZrO_3$ crucibles by Erb *et al.* [13,16], followed by Liang *et al.* [15] essentially solved the crucible corrosion problem. The use of $BaZrO_3$ crucibles has increased the purity of YBCO crystals to the purity of starting chemicals and the perfection to a very high level [15].

One problem remaining to be solved is how to get around the low growth rate of YBCO, which is a result of the low solubility of YBCO in BaO - CuO melts and makes the growth of large size YBCO crystals difficult. The existence of 211 phase particles greatly increases the supply of YBCO, through the peritectic reaction, to the growth front and hence increases the growth rate. However, the crystals grown under these conditions tend to contain large concentrations of defects. Therefore, it remains a challenge to grow centimeter sized YBCO crystals, required for experiments such as neutron scattering, having the quality of currently available millimeter size crystals.

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STRIPES AND THE MECHANISM OF HIGH TEMPERATURE SUPERCONDUCTIVITY

Two distinct phenomena are associated with the onset of superconductivity - pairing and phase coherence. In conventional BCS superconductors, the phase rigidity (or superfluid density) is so large that phase coherence is automatic once pairing occurs - the superconducting T_c is entirely determined by the pairing (or gap) scale, Δ_0. This energy is, moreover, small compared to any bare electronic energy scale in the problem, making the problem too subtle for any brute-force numerical "ab intio"' approach to the problem; at the same time, the large correlation length, $\xi_0 = \hbar v_F/\Delta_0$, provides the small parameter, $a/\xi_0 \sim T_c a/\hbar v_F$, which makes BCS theory so singularly successful. (Here, a is a microscopic length, of order the lattice constant, and v_F is the Fermi velocity.)

In high temperature superconductors, because they are doped insulators, the superfluid density, and consequently the phase coherence scale is relatively small - when measured in units of temperature, the zero-temperature superfluid density is roughly equal to T_c. Conversely, the pairing scale is large - the spin-gap scale, $2\Delta_0$, as determined spectroscopically, is some 70meV, *i.e.* of order $J/2$ where J is the antiferromagnetic exchange energy. Thus, although the onset of long-range coherence still occurs at temperatures that are relatively small compared to J (typically, $T_c \sim$ 100K while J = 1500K), the pairing scale is not small. For this reason, *the correct theory of the mechanism of pairing should be able to make testable predictions for numerical experiments* on finite size systems, so long as the system size is large compared to ξ_0 which is only a couple of lattice constants.

There have been many numerical experiments carried out on models of strongly interacting electrons such as the t - J and Hubbard models. In no case has any such model in two dimensions shown strong evidence of a high pairing scale, *i.e.* a high energy scale for spin gap or spin pseudo-gap phenomena! By contrast, studies on t-J and Hubbard ladders, that is to say "fat" one dimensional systems, exhibit a large spin-gap scale, and strong evidence of a large superconducting susceptibility. The driving mechanism for spin-gap generation in ladder systems[1] is the "spin-gap proximity effect:" In a multi-band one-dimensional system, single particle tunnelling at low energy is forbidden by kinematics, but pair tunnelling between bands is allowed. Thus, under appropriate circumstances it is worth the energetic cost to pair electrons so that they can lower their zero-point kinetic energy transverse to the ladder direction. Indeed, on the basis of this reasoning, the phase diagram and energetics of the three-leg t-J ladder were correctly predicted.[1] As far as I know, no other proposed mechanism of pairing with repulsive interactions has made a similarly successful prediction for a numerical experiment.

How can ladder physics apply to the quasi-two dimensional world of high temperature superconductivity? The answer has been known[2] for some time - dilute doped holes in an antiferromagnet *always* form micro-phase separated structures, which under a wide variety of circumstances consist of self-organized quasi-one-dimensional rivers of charge, or stripes. We have proposed that the existence of stripes is an essential ingredient in the mechanism of pairing;[1] when the copper-oxide planes break locally into "ladders," the strong repulsive interactions lead to high temperature superconducting pairing.

On the other hand, phase ordering is strictly forbidden in one dimension, and so is clearly suppressed to relatively low temperatures in quasi-one-dimensional systems. Thus, an inescapable problem associated with a stripe mechanism of superconductivity is that stripe order tends to depress the phase ordering temperature, *i.e.* T_c. Moreover, competition between superconducting order and insulating charge density wave order has long been known to bedevil attempts to find quasi-one-dimensional superconductors. The more rigidly one-dimensional the physics, the more suppressed the phase stiffness transverse to the stripes, and the more likely the occurrence of an insulating state. Recently, we have shown[3] that transverse fluctuations of the stripes help to overcome both of these problems.

Thus, the physics of T_c involves[3] the competition between two effects of stripes; local stripe order is essential to pairing but phase coherence is enhanced the more violently the stripes fluctuate, *i.e.* the less rigidly they are defined. As the magnitude of the transverse stripe fluctuations increases, the phase ordering temperature rises. Optimal T_c ("optimal doping") is achieved when the characteristic stripe fluctuation frequencies are comparable to Δ_0. When the stripe fluctuations become more violent than this, the stripe induced pairing is lost, so T_c drops, again. Other important consequences of stripes include: 1) The existence of intermediate temperature and frequency ranges where one-dimensional physics, and the accompanying phenomenon of spin-charge separation and electron fractionalization are observable; 2) The existence[3] of a whole variety of new quantum phases of matter, "electronic liquid crystalline phases."

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Due to space limitations, it was not possible to include many of the references which should have accompanied these short essays. – Eds.

HIGH T_C SUPERCONDUCTORS IN THE INFRARED

by Tom Timusk

Spectroscopy is the art of mapping out properties of quantum mechanical systems as a function of energy. Infrared spectroscopy is a good tool to use on the new superconductors since it covers the range of energies that include both the superconducting gap and any low-lying excitations that might be involved with superconductivity. Using polarized light and oriented single crystals one can study separately properties in the different directions of these anisotropic materials.

It is useful to compare infrared with other complementary spectroscopic techniques such as angle resolved photoemission spectroscopy (ARPES) and neutron scattering. Whereas infrared response results from an average over all the states in the crystal, ARPES and neutrons are more discriminating and permit the exploration of individual momentum states. The cost of this additional power is a demand put on the growers of single crystals: neutrons need enormous thumb-size crystals and ARPES demands vacuum cleaved crystals perfect to the last atomic layer. The reality is that many new and interesting materials are often only available as millimeter size crystals with contaminated surface layers. These are sufficient for infrared studies. Finally, smaller crystals are often of higher quality and suffer less from flux inclusions, twin boundaries and secondary phases.

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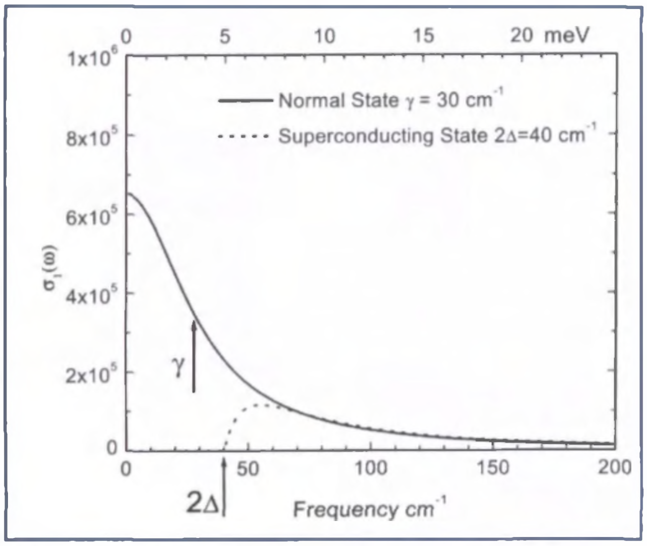

Fig. 1 The optical conductivity of a metal in the normal state (solid line) peaks at zero frequency and has a characteristic width γ. In the superconducting state, in an s-wave superconductor (dotted line), the conductivity develops a gap at 2Δ. If the width is much smaller than the gap (the clean limit), then the feature at 2Δ will be weak.

Optical spectroscopy measures the complex optical conductivity $\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$ as a function of frequency. Some techniques, such as ellipsometry or terahertz spectroscopy, yield these numbers more or less directly but require the use of custom built apparatus. Reflectance and transmission spectroscopy can make use of new generation commercial Fourier transform Michelson interferometers (FTIR) developed for analytical chemistry.

The two optical constants σ_1 and σ_2 can be found by Kramers-Kronig analysis of the power reflectance, measured over a very large range of frequencies, extending from the far infrared to the ultraviolet.

What do the optical constants tell us about superconductivity?

The energy gap Δ is the most important parameter of superconductivity. In classical BCS superconductors its value was first determined by infrared spectroscopy. Fig. 1 shows the real part of the calculated frequency dependent conductivity σ_1 for a BCS superconductor both in the normal state and in the superconducting state. In the normal state the conductivity has the Drude form which peaks at zero frequency and falls off towards higher frequencies, shown as the solid line in Fig1. For an s-wave superconductor, in the superconducting state, shown as the dashed line, the Drude conductivity is reduced to zero for all frequencies below the gap. The gap value, 2Δ, can be found easily as

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the onset of conductivity at a frequency $\hbar\omega = 2\Delta$. The conductivity obeys a sum rule that relates the area under the conductivity curve to the density of charge carriers n:

$$\int_0^\infty \sigma(\omega)\, d\omega = \omega_p^2/2, \quad \text{where } \omega_p = \sqrt{4\pi n e^2/m}$$

is called the plasma frequency. Here e and m are the charge and the mass of the charge carriers.

When the carriers become superconducting and a gap develops, to satisfy the sum rule, the spectral weight (the area under the conductivity curve) lost in the gap region has to end up in some other region of the spectrum. Where is the lost spectral weight? For a classical superconductor all of the lost spectral weight ends up in a sharp δ function peak at zero frequency. This delta function peak represents the lossless dc response of the superconductor. The area under the delta function can be measured through its contribution to the imaginary part of the conductivity of $4\pi\sigma_{2s} = \omega_{ps}^2/\omega$ where $\omega_{ps}^2 = 4\pi n_s e^2/m^*$. Here n_s is the condensate density and m^* the effective mass of the superconducting carriers. As a check one can use the conductivity sum rule to make sure that the area under the zero-frequency delta function equals the area lost at finite frequencies.

The condensate density n_s plays an important role in the electrodynamics of superconductors. It can be shown that the penetration depth λ of magnetic fields is given by $\lambda = c/\omega_{ps}$. This gives us another use of infrared spectroscopy in superconductivity. From the optical constant σ_2 one can find the condensate density and the absolute value of the penetration depth. In anisotropic superconductors such as the high T_c cuprates, the penetration depth is different for each of the three orthogonal directions. With the use of linearly polarized radiation, all three components of the penetration depth tensor can be determined. The article by W.N. Hardy in this issue shows that the temperature dependence of the penetration depth can be determined with great accuracy with microwave techniques, but for an accurate absolute value one has to turn either to infrared or to muon spin resonance.

The high temperature superconductors are not BCS s-wave systems, and it is important now to see how the real part of the conductivity σ_1 is modified for a d-wave superconductor. Figure 2 shows σ_1 for $YBa_2Cu_3O_{6.95}$, one of the most studied high temperature superconductors. In the normal state, for $T > T_c$, the conductivity has an approximate Drude form with the low frequency conductivity agreeing in magnitude with the dc conductivity and dropping off at high frequency with a characteristic width in frequency of $\gamma = 100\ \text{cm}^{-1}$ (12.4 meV or 3.00 THz).

The dotted line in Fig. 2 shows the conductivity in the superconducting state. There is a large loss of conductivity at low frequencies, and analysis of the imaginary part of the conductivity shows that the lost spectral weight has shifted to the zero frequency delta function of the condensate. However, there is no sign of a sudden onset of conductivity at the energy gap, $\hbar\omega = 2\Delta$, the characteristic signature of a superconducting gap in a conventional superconductor. When the high T_c superconductors were first discovered there was considerable controversy surrounding this issue of the absence of the expected sharp gap in the conductivity. After some ten years of intensive study by some dozen groups we are beginning to understand the broad features of Fig 2. but even this late in the history of the subject we do not have a full understanding of the conductivity in the superconducting state of the high temperature cuprates. Let us examine what we have learned about this issue.

It was recognized early that in spite of their complex chemical structure and rather messy crystal growth procedures, the high temperature superconductors are in the *clean limit*. This is the limit where the elastic scattering frequency from impurities $1/\tau_i$ is much smaller than the superconducting gap frequency: $1/\tau_i << 2\Delta$, a direct consequence of their large energy gap. In the clean limit the optical conductivity does not show a gap feature such as the step at a frequency 2Δ shown in Fig. 1. Calculations show that for an s wave

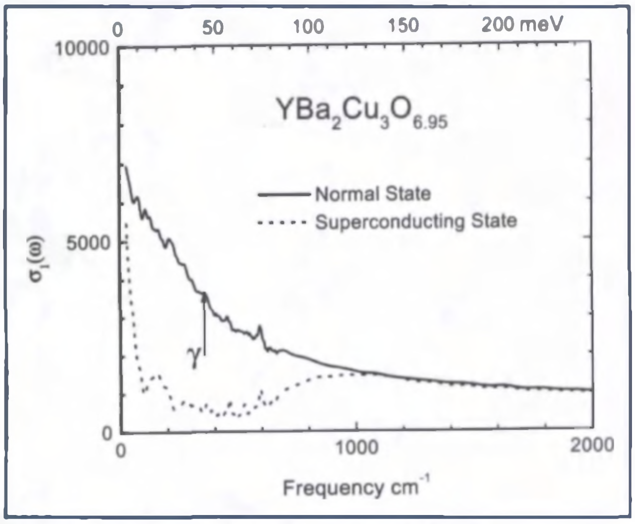

Fig. 2 The optical conductivity of a high temperature superconductor $YBa_2Cu_3O_{6.95}$ for light polarized along the copper oxygen plane. In the normal state (solid line) the conductivity is Drude like, peaking near zero frequency. In the superconducting state, dotted line, there is no clear gap like those seen in s-wave superconductor. There appears to be enhanced conductivity above 600 cm^{-1} region associated with inelastic processes.

superconductor the conductivity jumps at $\hbar\omega = 2\Delta$ from zero to approximately the value of the normal state conductivity at this frequency. In clean materials the Drude tail will not extend as far as 2Δ and the gap signature vanishes.

The loss of a gap signature at 2Δ in pure crystals follows from elementary physics. A photon carries energy $\hbar\omega$ but practically zero momentum. The lowest energy excitation that it can create in a conventional superconductor is a broken Cooper pair with the electron and hole having zero kinetic energy. For this threshold process $\hbar\omega = 2\Delta$. To conserve momentum, either the electron or the hole must collide with something: if it is an impurity, there will be an absorption threshold at the gap frequency, if it is some excitation in the system, such as a phonon in conventional superconductors, or some electronic excitation in the case of the high temperature superconductors, the onset frequency will be higher to allow for the energy of the excitation.

The obvious solution to the clean limit dilemma is to add impurities to the system to bring it closer to the dirty limit. In one such study Basov [1] used a small amount of zinc to introduce disorder into a very clean high temperature superconductor, $YBa_2Cu_4O_8$, the double chain version of YBCO. The outcome was totally unexpected. There was no sharp onset of absorption in the range of 400- 500 cm $^{-1}$, the expected gap frequency. Instead a new absorption peak appears at low frequency in the superconducting state. Its width is consistent with what one expects from the dc resistivity increase. The area under the new absorption peak reduces the area under the zero conductivity peak. Thus it appears that in a dirty d-wave superconductor there are two kinds of electrons, the superconducting ones that form a lossless condensate and a background of bound electrons that give rise to a low-lying absorption band.

Calculations of the conductivity of a dirty d-wave superconductor are in rough agreement with these results. No gap signature is expected at $\hbar\omega = 2\Delta$, and a low frequency peak is also predicted [2]. However, the magnitude and the shape are not in agreement with the observations. The role of impurities in d-wave superconductors is an area of active research.

So far, we have discussed the conductivity for currents parallel to the copper oxygen planes. The properties perpendicular to the planes, the c-axis direction, are dramatically different. Depending on the doping level and the material under study, the dc conductivity ranges from almost completely insulating to weakly metallic, suggestive of a doped semiconductor. However the frequency dependent conductivity is quite unlike that of any ordinary material and it has led to the suggestion that a clear understanding of c-axis charge transport will provide a clue to the nature of high temperature superconductivity. [3] From the beginning infrared spectroscopy has been used to investigate this difficult and interesting problem.

It was noticed early that in ceramic samples the optical reflectance showed a sharp drop from near-unit reflectance to a rather low value in the far infrared. Originally mistaken for a superconducting gap, this reflectance step was correctly identified as a plasma resonance, now called a Josephson plasma resonance, where the superconducting condensate electrons oscillate against the ions in the lattice. [4] In the normal state, the coupling between the copper oxygen planes is frustrated, probably as a result of spin disorder from plane to plane, but below T_c superconducting pairs can tunnel between the planes and form a three dimensional system. The phenomenon of c-axis transport is sometimes discussed in terms of the concept of spin-charge separation. [3] In this picture an insulating quantum fluid of paired spins forms within the copper oxygen planes, and when doped holes are added their spin and charge separate. To move from plane to plane, in the c-direction, spin and charge have to be brought together again to form an ordinary electron which can move outside this quantum fluid. Instead of the metallic conductivity with a sharp peak at low frequency, in the spin-charge separation scenario, the c-axis transport is nearly frequency independent. This is in clear contradiction with the physics of an ordinary metal where, at low temperature, one expects the electrons to travel as plane waves through the periodic lattice without scattering. The poor conductivity in the c-axis direction is a fundamental quantum effect, not well understood, and is another area of active research. Infrared spectroscopy has been an important tool in this work. [5,6]

Perhaps the strangest property of the new high temperature superconductors is the existence of a gap that resembles the superconducting gap but appears at high temperature where there is no superconductivity. [7] Many theorists believe that this *pseudogap* is associated with some kind of localized superconducting pairing. Infrared spectroscopy has been at the center of the pseudogap story. Figure 3 shows the c-axis optical conductivity from the work of C.C Homes in a crystal of YBCO. There is a clear gap-like depression of conductivity extending over a range of frequencies up to the gap energy and temperatures up to room temperature. When superconductivity sets in there is little change in the c-axis conductivity, suggesting that the pseudogap state is already a lot like the superconducting state.

A really useful way to display infrared data, particularly for the ab-plane properties, is in terms of the lifetime of the carriers which can be calculated from the optical conductivity. The reciprocal of the lifetime is shown in Fig 4 for an underdoped sample. Here the pseudogap manifests itself as a depression of scattering at low frequency and low temperature. The onset of scattering above 500 cm^{-1} is due to a combination of a gap and an excitation. The physics of this phenomenon is straightforward: If the incident photon energy is large enough to generate a final state consisting of a pair of carriers that are no longer bound to the condensate, which costs 2Δ of energy, plus a momentum conserving excitation of energy $\hbar\Omega$, the incident photon will be absorbed. The result of this process is an absorption threshold at $2\Delta + \hbar\Omega$. A recent suggestion that the 41 meV neutron resonance is the excitation responsible for this onset seems to give a consistent picture of the scattering in the superconducting state.[8]

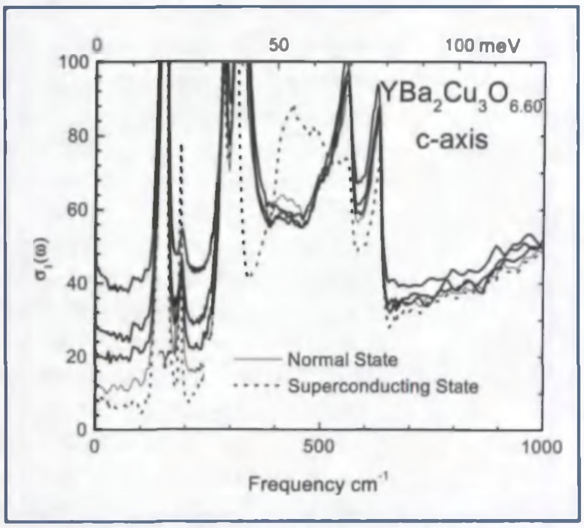

Fig. 3 The conductivity normal to the copper oxygen planes at different temperatures (from the top: 295, 150, 110, 70, and 10 K) is dominated by strong phonon peaks superimposed on a continuum. As the temperature is lowered a gap develops in the conductivity below 350 cm^{-1}. The superconducting transition temperature of this crystal is 58 K, and there is very little change in the spectrum as superconductivity sets in. This low frequency depression of conductivity was the first spectroscopic evidence for the existence of a normal state gap or a pseudogap.

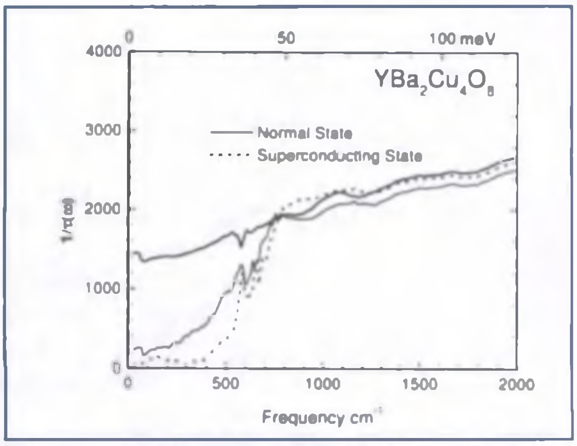

Fig. 4 The frequency dependent scattering rate of a high temperature superconductor. This quantity can be determined from the complex optical conductivity and is a measure of the processes that scatter the electrons. In the cuprate superconductors these scattering processes are very strong at room temperature, top curve. The middle curve is at a temperature just above the superconducting transition, and a pseudogap has formed in the scattering rate spectrum below 700 cm^{-1}. A further reduction in scattering occurs in the superconducting state (dashed curve). There appears to be little difference in the spectrum in the pseudogap state and the superconducting state leading to the suggestion that the pseudogap and the superconducting gap are closely related to one another.

It is clear that in both directions, parallel to the c-axis or along the ab-plane, the optical conductivity can be used to study the pseudogap. So far the pseudogap has been seen by infrared techniques in all high T_c cuprate systems studied.

The puzzle of high temperature superconductivity has not been solved. Infrared spectroscopy is a good tool to use on a large variety of systems, to look for a pseudogap, intrinsic anisotropy and a Drude response from impurities in the superconducting state, all signatures of cuprate high temperature superconductivity. In the future we need to find out to what extent these signatures are found in other superconducting systems or if they are confined to the copper oxygen systems.

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ORDER PARAMETER SYMMETRIES AND MECHANISMS OF SUPERCONDUCTIVITY

by Jules P. Carbotte

In Bardeen-Cooper-Schrieffer (BCS) theory the pairing potential is an effective residual attractive interaction between two electrons at the Fermi surface of a Fermi liquid. It is not specified explicitly but is rather modeled as a constant V within $\pm\omega_D$ (Debye energy) of the Fermi energy. This immediately gives a formula for the critical temperature of the form

$$T_c = 1.13\omega_D e^{-\frac{1}{N_0 V}} \qquad (1)$$

where N_0 is the electronic density of states at the Fermi surface. The potential V is an adjustable parameter fixed to get the measured value of T_c, once some choice for the cutoff ω_D is made. In view of the experimental evidence that T_c varies as the inverse square root of the isotopic mass, it is natural to take ω_D to be the Debye cutoff with $\omega_D \,\alpha\, 1/\sqrt{M}$ where M is the ion mass. The isotope effect supports the idea that it is the electron-phonon interaction (i.e. the dynamic lattice rather than the crystal potential) which is the mechanism of superconductivity in conventional materials but it certainly does not provide conclusive evidence. In fact, an isotope effect of - 1/2 is rarely observed.

To calculate the spectral density from first principles is complicated, of course, and requires knowledge of the electronic band structure, the phonon dynamics and the coupling between electrons and the displaced lattice.

A more general formulation of the theory is required to obtain quantitative information on mechanism [1]. Such a theory, based on the electron-phonon interaction, was provided by Eliashberg. The theory relies on Migdal's theorem which states that for a coupled system of electrons and phonons, vertex corrections are of the order of $\sqrt{m/M}$ where is m is the electron mass. If vertex corrections are left out, because they are negligible, the remaining diagrams in the perturbation expansion can be summed to infinite order. The result is a closed set of two nonlinear, coupled equations. These can be solved numerically for a general model of the electron-phonon interaction. An important point to realize is that the most general such interaction may be incorporated exactly in a single function $\alpha^2 F(\omega)$ which contains all the relevant details. It can be thought of as a phonon frequency distribution $F(\omega)$ weighted by the coupling to the electrons α^2 which in general will have some ω dependence suppressed in our notation. To calculate the spectral density from first principles is complicated, of course, and requires knowledge of the electronic band structure, the phonon dynamics and the coupling between electrons and the displaced lattice. Such calculations are possible in simple metals and have been successfully done in many cases. More important for us here, $\alpha^2 F(\omega)$ can also be measured in tunneling experiments on normal metal-insulator-superconductor junctions.

A tunneling junction (N-S) consists of a normal metal and a superconductor separated by an oxide layer. The oxide provides a potential barrier through which the electrons can tunnel quantum-mechanically. If a voltage is applied a current I will flow and its first derivative with voltage V is proportional to the superconducting density of states.

BCS theory is a one parameter theory which otherwise is universal, i.e. once the size of T_c is determined other properties take on universal values when properly normalized. As an example the gap to critical temperature ratio $\frac{2\Delta}{k_B T_c} = 3.54$, where k_B is the Boltzman constant. The energy gap Δ gives the binding energy of the electrons in the superconducting condensate which is made of spin-up, spin-down equal and opposite

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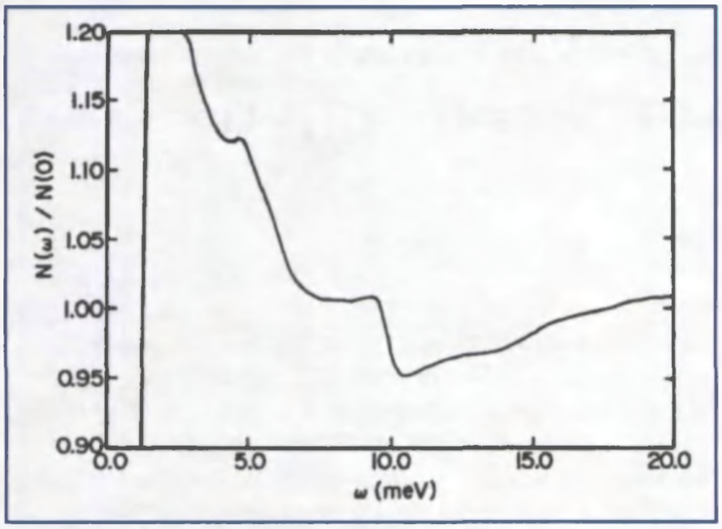

Fig. 1 Normalized quasiparticle density of states N(ω)/N(0) in superconducting Pb as a function of energy ω showing the gap around 1.5 meV and phonon structure around 6 and 10 meV.

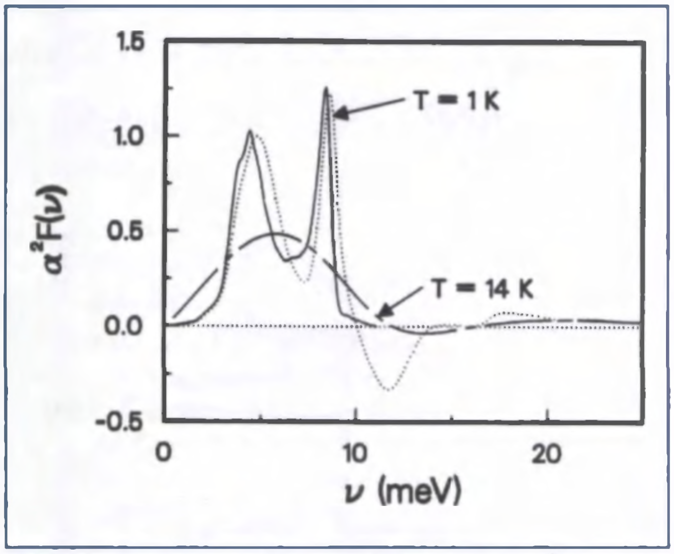

Fig. 2 The electron-phonon-spectral density $\alpha^2F(\omega)$ vs. ω for Pb (solid curve). The other curves are W(ω) vs. ω (Eq. 4) obtained from normal state conductivity calculations at different temperatures with the solid curve as input.

momentum Cooper pairs. If it is constant over the Fermi surface we say that it has *s*-wave symmetry. For *d*-wave symmetry there are zeros on the Fermi surface. Other famous ratios are the specific heat jump ΔC at T_c normalized to the normal state electronic specific heat γT_c, where γ is the Sommerfeld constant, $\Delta C/\gamma T_c = 1.43$. There are many others. In Eliashberg theory these ratios vary with material and capture some of the details of the microscopic mechanism responsible for superconductivity.

In BCS theory the excitations out of the superconducting condensate are stable quasiparticles with infinite lifetimes and have energy $E_k = \sqrt{\tilde{\varepsilon}_k + \Delta^2}$, where **k** is momentum and $\tilde{\varepsilon}_k$ is the normal state electronic dispersion relation measured with respect to the chemical potential μ. The quasiparticle density of states in energy *N(E)* in the superconducting state follows directly from the above dispersion relation and is

$$N(E) = N_0 \frac{E}{\sqrt{E^2 - \Delta^2}} \quad \text{for } E > \Delta \qquad (2)$$

and zero below the gap. As before, N_0 is the normal state electronic density of states associated with $\tilde{\varepsilon}_k$. In Fig. 1 we show a plot of the normalized density of states obtained in experiments on Pb junctions. There is no current below a finite gap value $\Delta \sim 1.5$ meV. This region gives evidence of the gap symmetry which in our case is *s*-wave. For a *d*-wave gap with zeros on the Fermi surface the region below the gap amplitude Δ would get filled in although it would remain depressed over its normal state value. At the gap there is a square root singularity in Fig.1 and above it the curve rapidly saturates to 1. For *d*-wave, the singularity is logarithmic instead. There are clear structures around 6 and 10 meV which are not part of BCS theory but which feature prominently in Eliashberg theory. These structures give a faithful image of the underlying electron-phonon spectral density $\alpha^2 F(\omega)$ which looks very much like the phonon frequency distribution *F(ω)*. For a delta function at $\omega = \omega_0$ in *F(ω)* a sharp drop is seen in $N(\omega)$ at $\Delta_0+\omega_0$. Results for the spectral density $\alpha^2 F(\omega)$ in Pb are shown in Fig. 2 as the solid curve. This curve was obtained directly from the wiggles seen in Fig. 1. The procedure used is called inversion of the Eliashberg equation and is due to McMillan and Rowell[2]. A guess is made for $\alpha^2 F(\omega)$ and the I-V characteristic computed from the nonlinear Eliashberg equations. A comparison is then made with dI/dV vs. V data and a correction generated to improve on the guess until convergence is reached for $\alpha^2 F(\omega)$ which can then be used to calculate other properties of the superconductor. These always deviate from BCS universal values. A first check on the measured $\alpha^2 F(\omega)$ is that it should give the right value of the critical temperature T_c. To within a few percent this is found to be the case. It should be mentioned that while $\alpha^2 F(\omega)$ plays the most prominent role in superconductivity of conventional superconductors a secondary, relatively more minor effect is due to Coulomb repulsion characterized by a single number μ^*. It too follows from the tunneling inversion so that there are no free parameters. Returning for a moment to the conductance shown in Fig. 1, and in summary a gap is clearly seen at low bias leaving no doubt that we have *s*-wave symmetry, i.e. a constant finite gap everywhere on the Fermi surface. At the higher bias the mechanism responsible for superconductivity shows up as phonon structure. It is fortunate that $F(\omega)$ has sharp peaks in energy within a few times the gap value Δ. If instead the weight in $\alpha^2 F(\omega)$ was distributed over a much larger energy interval and showed little structure it would be much more difficult to determine its shape from tunneling. The case for the electron-phonon interaction as the mechanism is very strong and in fact it has been possible to use superconductivity to measure details of the electron-phonon interaction in many conventional superconductors. It has also been possible to understand most observed deviations from BCS universal ratios. As an example we show in Fig. 3 the normalized specific heat jump $\Delta C(T_c)/\gamma T_c$ of superconductors as a function of T_c/ω_{in}. The solid dots come from numerical calculations of Eliashberg theory with tunneling derived spectral density. The solid curve is an approximate expression obtained analytically which provides an envelope for the variation of $\Delta C(T_c)/\gamma T_c$ as a function of coupling strength T_c/ω_{in}. Here, ω_{in} is an energy characteristic of $\alpha^2 F(\omega)$. Note that for some materials the normalized jump can be as large as 3. Many additional [1] results for other universal ratios can be obtained. In all cases the agreement with experiment is at the few percent level over a broad range of materials.

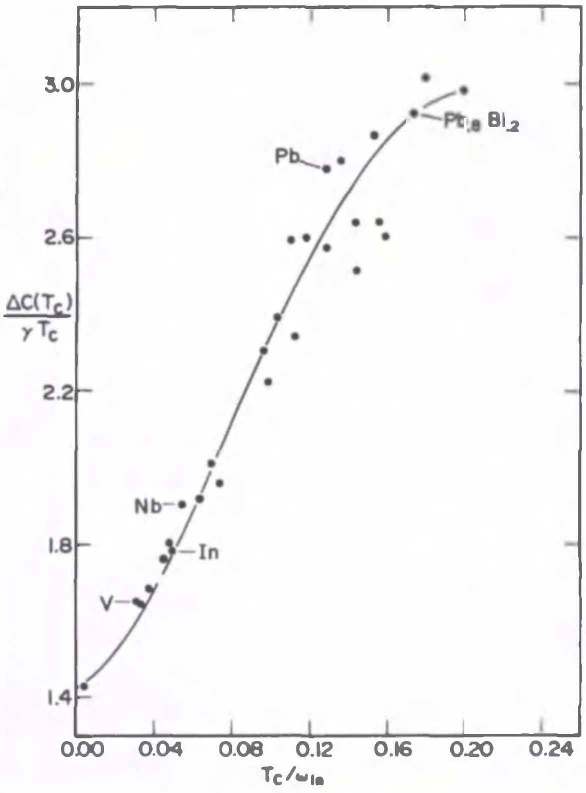

Fig. 3 **The normalized specific heat $\Delta C(T_c)/\gamma T_c$ for many different superconductors. The solid dots were all calculated from experimentally determined spectral densities only some explicitly identified.**

We next turn to optical conductivity. The simplest model goes back to Drude. The optical conductivity as a function of ω (frequency) is given by

$$\sigma(\omega) = \frac{ne^2}{m}\frac{\tau}{1 - i\omega\tau}, \qquad (3)$$

where τ is the mean free path. For inelastic scattering τ acquires a frequency dependence, i.e.: we need to change to τ(ω) in Eq. 3 and an effective optical electron mass $m^*(\omega)$, also frequency dependent, needs to be introduced. In Eq. 3, *n* is the free electron density, *e* the electron charge, and *m* its mass. There is a signature of $\alpha^2 F(\omega)$ in $\sigma(\omega)$. Marsiglio *et al.*[3] have introduced a function $W(\omega)$ defined as

$$W(\omega) = \frac{1}{2\pi}\frac{d^2}{d\omega^2}\left[\frac{\omega}{\tau(\omega)}\right] \qquad (4)$$

What they noticed was that in the phonon region $W(\omega) \approx \alpha^2 F(\omega)$ with some extra, sometimes negative wiggles beyond the phonon cutoff. This is shown in Fig. 2. Compare the solid line with the dotted curve. Note that the vertical scale is dimensionless and that in the phonon region the two curves are almost identical. The dotted curve gives results of theoretical calculations for $W(\omega)$ obtained from the input $\alpha^2 F(\omega)$ (solid curve) from which the conductivity is calculated using standard theory for the normal state conductivity of a normal metal due to the electron-phonon interaction. It is clear that $W(\omega)$ offers us a means of measuring $\alpha^2 F(\omega)$ provided only that the wiggles beyond the maximum phonon energy in $W(\omega)$ are ignored. The other curves in Fig. 2 are derived from conductivity calculations at different temperatures. It is clear that to get a reliable, detailed picture of $\alpha^2 F(\omega)$ from $W(\omega)$, low temperatures need to be used.

The technique just outlined has been employed with great success in K_3C_{60}. Inversion of normal state conductivity data give the results shown in Fig. 4 (solid curve). We stress that these results come directly from a numerical differentiation of experimental data. Negative tails in $W(\omega)$ have been left out in identifying $\alpha^2 F(\omega)$ (solid curve), but there has been no other manipulation of the data. It is remarkable that the spectral density obtained in this way gives the measured T_c for a value of μ^* star = 0.35-0.4 which is somewhat larger than in a conventional case because screening is reduced in K_3C_{60}. Also there is good agreement with incoherent, inelastic neutron scattering data on the phonon frequency distribution

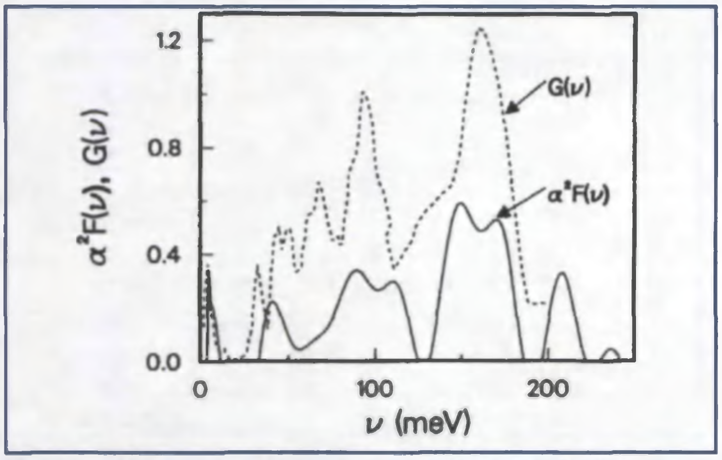

Fig. 4 The electron phonon spectral density $\alpha^2F(\omega)$ vs. ω obtained directly from the experimental conductivity in K_3C_{60} on application of Eq. 10 to obtain $W(\omega)$. The negative pieces are left out of $\alpha^2F(\omega)$. The dashed curve is for comparison and is the phonon frequency distribution $G(\omega)$ obtained from incoherent, inelastic neutrons scattering.

$G(\omega)$ (dashed curve)[4] . These data leave little doubt that even though K_3C_{60} shows narrow bands and other characteristics of a highly correlated system[4], it is nevertheless an electron-phonon superconductor. This is in sharp contrast to BaKBiO[5]. This material has a sharp *s*-wave gap that is clearly seen in tunneling, yet an analysis shows that the electron-phonon interaction in this system is much too weak to explain its superconductivity. Some new, yet unknown, mechanism must be operating in this case which remains to be identified.

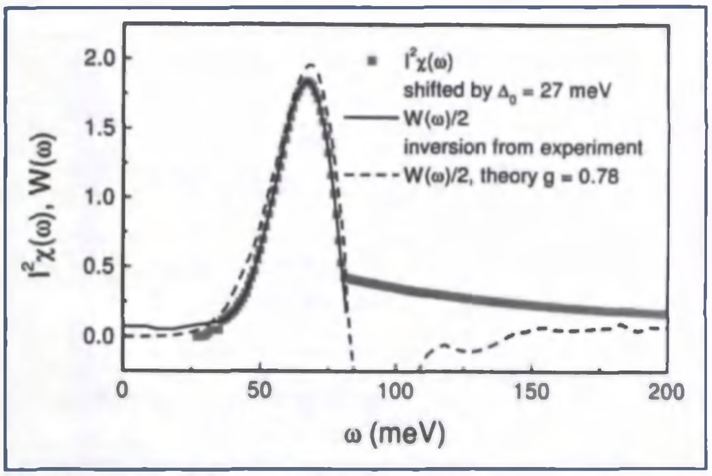

Fig. 5 The model charge carrier spin excitation spectral density $I^2\chi(\omega)$ (solid square) constructed from the conductivity date of Fig 6 for optimally doped YBCO. The dashed line which follows the grayed squares faithfully, except for negative oscillations just beyond the spin resonance around 68meV, is $W(\omega)/2$ obtained from our model $I^2\chi(\omega)$ (displaced by the gap energy Δ_0 in the figure). The solid line is the coupling to the resonance found directly from experimental.

An important, now well established feature of the high T_c oxides is that they are *d*-wave superconductors. As we have already mentioned, the quasiparticle density of states while depressed in the low ω region, nevertheless remains non zero. It is also well established that the electron-phonon interaction is not the operative interaction that leads to superconductivity. Recently, Carbotte *et al.*[6] have used optical data to provide strong evidence that instead it is the interaction between the charge carriers and the spin excitations of the system that are intimately involved. This situation is in strong contrast to ordinary superconductors and the mechanism is electronic in origin with attendant strong feedback effects. The onset of superconductivity coincides in some cases(optimal doping) with the observation of a new spin one resonance, not present in the normal state above T_c[7] . This famous 41 meV resonance seen in spin polarized, inelastic neutron scattering in YBCO is strongly coupled to the charge carriers. This can be demonstrated most directly through a generalization of the inversion technique we have described for the conductivity and which is embodied in Eq. 4. A generalization is needed for two reasons: a) the superconducting state conductivity $\sigma_s(\omega)$ is to be used instead of its normal state value because this is the only way to access low temperatures in the high T_c oxides; b) the resonance in optimally doped YBCO with a T_c = 93.5 K disappears at $T = T_c$. If the electrons are coupled to this spin resonance it should show up in $W(\omega)$. In fact $W(\omega)/2$ displaced by the gap on the ω-axis (corresponding to the logarithmic peak in the density of state of a d-wave superconductor) gives a reasonable first approximation for the coupling to the resonance. This rule of thumb was established through detailed calculations based on a variety of spin spectral densities. Moreover, since $W(\omega)$ is dimensionless it also gives us an absolute measurement of this coupling of the charge carriers to the spin resonance. This is seen in Fig. 5 where we show results for $W(\omega)/2$ (dashed curve) obtained from calculations of $\sigma_s(\omega)$ based on a charge carrier-spin spectral density $I^2\chi(\omega)$ shown as the grayed squares which have been displaced by the gap value Δ_0 = 27 meV along the ω-axis. For coupling to spins $I^2\chi(\omega)$ plays the role of α^2F and can be thought of as the coupling to the charge carriers $I^2\chi(\omega)$, which may depend on frequency, and $\chi(\omega)$ is the imaginary part of the spin susceptibility. The spin resonance is clearly seen around 68 meV. In the inverted curve for $W(\omega)/2$ (dashed) a strong negative oscillation occurs right above the main resonance peak. This feature is not in the input $I^2\chi(\omega)$. However, at higher energies the oscillations damps out and the dashed curve begins to agree again with the grayed squares representing the input spectral density used in the calculations of $\sigma_1(\omega)$. These calculations involve the solution of the Eliashberg equations generalized to account for the *d*-wave symmetry of the gap. The input spectral density (grayed squares) was constructed totally from consideration of conductivity data. We proceeded as follows. The data of Basov *et al.*[8] for the optical scattering rate $\tau^{-1}(\omega)$ vs. ω in optimally doped YBCO is reproduced in our Fig. 6. The solid line, quasilinear in ω, is at $T = T_c$ in the normal state.

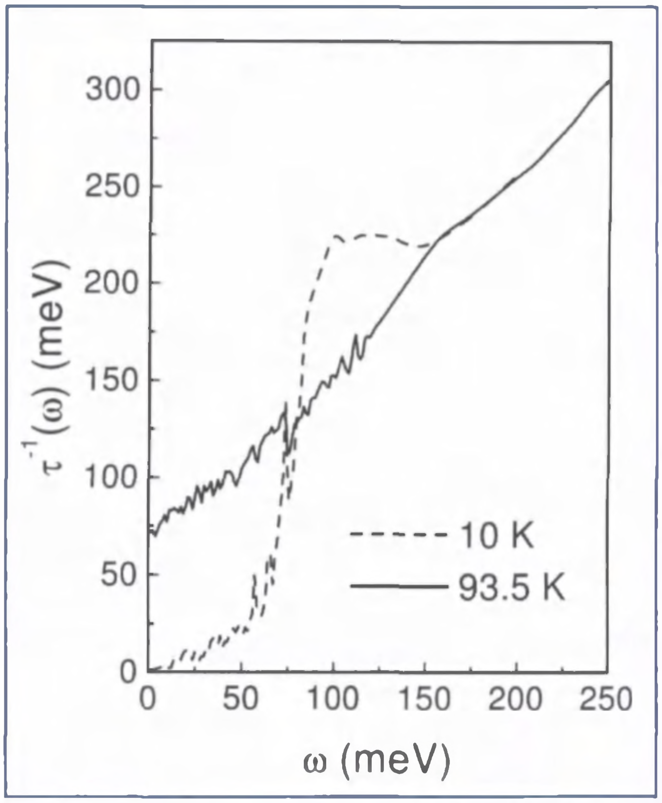

Fig. 6 The optical scattering rate $\tau^{-1}(\omega)$ obtained by Basov *et al.*[8] in optimally doped YBCO (T_c = 93.5K) vs. ω. The solid curve is for the normal state at $T = T_c$ and the dashed one for the superconducting state at T = 10K.

The dashed curve is at T = 10 K in the superconducting state. At high energies it matches with the normal state result but at low energies it shows very small intensity up to about 70 meV at which point it rises very rapidly over a relatively small range of ω and substantially overshoots the normal state result. The rise in the superconducting state is related to the spin resonance and direct differentiation of this raw data according to Eq. 4 gives the solid curve shown in Fig. 5, having left out the negative region above the resonance. This curve represents the contribution of the spin resonance at 41 meV to the coupling with the charge carriers and falls almost exactly at 68 meV which is equal to the spin resonance plus the gap (Δ_0 = 27 meV) value. From consideration of the normal state data (solid curve of Fig. 6 we also know that there is a spin fluctuation background which provides the scattering above $T = T_c$ where the spin resonance at 41 meV has disappeared. This background is simply added to the solid curve of Fig. 5 to get the model charge carrier-spin spectral density $I^2\chi(\omega)$ used in our work and shown as the grayed squares. There is no ambiguity in this interpretation of the conductivity data which gives us not only the position of the spin resonance in the superconducting state but also the strength of the charge coupling to it. There is an important feedback effect included in the work which has its origin in the fact that the pairing mechanism is electronic in origin. The highly correlated electrons pair themselves. As the superconductivity sets in, the spin resonance appears and coupling to this resonance further stabilizes superconductivity. A direct measure of this feedback is a gap to critical temperature ratio $2\Delta_0 / 2k_BT_c \approx 6$, much larger than the value of 4.3 which applies to a BCS *d*-wave superconductor. Such a BCS formulation of the theory is too simple and does not lend itself to a discussion of mechanism. The generalization of Eliashberg theory to the spin fluctuation case has proved to be quite powerful and has shown clearly that the charge carriers are strongly coupled to the 41 meV spin resonance observed in YBCO at optimal doping.

ACKNOWLEDGEMENTS

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WHAT IS THE MECHANISM ? THE CASE FOR SPIN FLUCTUATIONS

The case for the spin fluctuation mechanism in the cuprate superconductors consists of three parts: experimental evidence for a dynamical spin susceptibility arising from strong antiferromagnetic correlations between planar quasiparticles; theoretical predictions of the normal state properties, superconducting Tc, and pairing state for quasiparticles interacting via that susceptibility; and the experimental confirmation of these predicted properties. I take these up in order.

The first experimental evidence for strong antiferromagnetic correlations came from NMR experiments that showed a single spin component was responsible for the planar copper and oxygen Knight shifts and spin-lattice relaxation times, and that the strong commensurate antiferromagnetic spin fluctuations found in the insulating and lightly doped cuprates persisted, in the 123 material, up to optimal doping. Together with evidence from transport and ARPES experiments that planar quasiparticles were responsible for the anomalous normal state behavior, these raised the question of whether the normal state quantum protectorate -- a stable state of matter whose generic low energy properties, in this case near antiferromagnetism, are insensitive to microscopics and determined by a higher organizing principle and nothing else - might be a two-dimensional nearly antiferromagnetic Fermi liquid. A quantitative fit to the NMR experiments was obtained by Millis, Monien, and Pines using the generic low energy dynamic magnetic susceptibility appropriate for that protectorate,

$$\chi(q,\omega)=\frac{\chi_Q}{1+(Q-q)^2\xi^2-i\omega/\omega_{sf}} \qquad (1)$$

where **Q** is the commensurate wavevector, ξ is the antiferromagnetic correlation length, ω_{sf} is the frequency of the spin relaxational mode, and χ_Q is the static commensurate susceptibility. For optimally doped 123, one finds near T_c that ξ is of order twice the lattice spacing while χ_Q is of order 60 states/eV, large indeed compared to the anticipated Landau Fermi liquid value of 1 state/eV. Still stronger antiferromagnetic correlations are found in NMR and INS experiments on the underdoped 123 materials, 124, and 214 materials.

The near approach to antiferromagnetism of these materials requires that the dominant interaction between planar quasiparticles be spin-fluctuation exchange, proportional to the experimentally determined dynamic spin susceptibility. The consequences of this NAFL interaction were explored by Monthoux, Balatsky, and Pines in a weak coupling approximation and subsequently by Monthoux and Pines in a strong coupling Eliashberg calculation. Both groups found the pairing state to be $d_{x^2-y^2}$, a falsifiable prediction, that T_c would be large, and that the normal state resistivity should be linear in T over a broad range of temperatures. Monthoux and Pines found for optimally doped 123 that, with a coupling constant that yielded the correct magnitude and temperature dependence of the planar resistivity, the transition to a $d_{x^2-y^2}$ pairing state occurred at about 100K. Buoyed by this proof of concept of their NAFL approach, they challenged the experimental community to find their predicted pairing state, a challenge that was soon met. A second prediction of NAFL theory, subsequently confirmed by Raman and ARPES experiments, was strongly anisotropic quasiparticle behavior as one moved around the Fermi surface from the "hot" regions near $(\pi,0)$ that can be connected by Q, where quasiparticles feel the maximum consequences of the NAFL interaction, to the "cold" regions near the diagonals passing through (π,π) and $(0,0)$. Hot quasiparticles were found to have distinctly non-Landau Fermi liquid lifetimes, while the cold quasiparticles displayed Landau Fermi-liquid-like properties. This strong anisotropy was confirmed by Stojkovic, who carried out detailed calculations of the evolution of hot and cold quasiparticle behavior with doping and temperature that showed cold quasiparticles were responsible for the measured T^2 behavior of the cotangent of the Hall angle, while both hot and cold quasiparticles contribute to the linear in T resistivity at high temperatures. In subsequent work, Stojkovic obtained a quantitative fit to the experimental results on transport, magnetotransport, thermoelectric, and optical behavior in both overdoped and underdoped cuprates. Together with other experiments, his work established the inseparability of spin and charge behavior in the cuprates. Changes in spin dynamics are directly reflected in changes in quasiparticle behavior and vice versa.

The phase diagram obtained by combining the results of the specific heat and uniform magnetic susceptibility, χ_0, experiments of Loram and Tallon with the NMR experiments of the Slichter group and the INS experiments of the Aeppli group distinguishes between magnetically overdoped and magnetically underdoped materials. Let T_{cr} be the temperature at which χ_0 is maximum, and the AF correlation length in the normal state is ~2a, then magnetically overdoped materials lie to the right of the T_{cr} line. Extrapolated to temperatures below T_c, it intersects the origin at a doping level of 0.19, a candidate quantum critical point. For magnetically overdoped materials, then, one has a direct transition from the NAFL state to a strongly-coupled BCS- Eliashberg-like superconductor.

The nature of the novel state of matter found below T_{cr} in the underdoped materials remains to be determined, as does the physical origin of the hot quasiparticle energy gap that largely removes them from the normal and superconducting action as the temperature is lowered. Thus while the state of matter for dopings to the right of the quantum critical point has been identified as a highly anisotropic non-Landau Fermi liquid, the NAFL, the state of matter to the left has not yet been unambiguously identified. We know, however, that its physical origin is magnetic, since it is the strength of the AF correlations between the hot quasiparticles that distinguishes the magnetically underdoped from the overdoped materials, while it is plausible that a spin-fluctuation induced interaction between the cold (and ungapped in the normal state) quasiparticles is responsible for their weak superconductivity, with the low superfluid density and no specific heat jump identified by Loram and Tallon.

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Due to space limitations, it was not possible to include many of the references which should have accompanied these short essays. -- Eds.

POSITIVE MUON STUDIES OF HIGH TEMPERATURE SUPERCONDUCTORS

by G.M. Luke and J.E. Sonier

The positive muon μ^+ is a sub-atomic particle with a mass 200 times greater than an electron, a spin of ½ and a lifetime of about 2.2 μs. Implanted in matter, muons are very sensitive magnetic probes. At the TRIUMF laboratory in Vancouver, Canada, muons are produced from the decay ($\pi^+ \rightarrow \mu^+ + \nu_\mu$) of pions at rest in the surface layer of a graphite target, where the pions themselves are produced by collisions of high energy protons with the target nuclei. Owing to the parity-violating decay of the pion, muons are created essentially 100% spin-polarized; a beam of these low energy (4.1 MeV) muons can then be implanted (one muon at a time) into a sample, whereby they rapidly thermalize through interaction with the lattice.

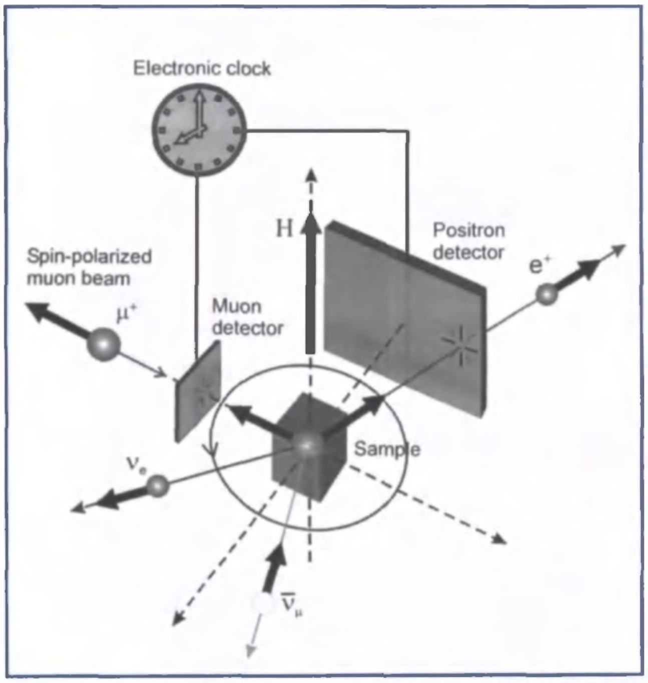

Fig. 1 Schematic view of the transverse-field (TF) μSR setup used for measurements in the vortex state.

Once implanted, each muon spin precesses about the instantaneous local magnetic field B at its site with a Larmor frequency

$$\omega_\mu = \gamma_\mu B, \tag{1}$$

where γ_μ is the muon gyromagnetic ratio. The collection of methods by which the muon's spin is used to probe the static or dynamic local electromagnetic environ-ment is known as muon spin rotation/relaxation/resonance (μSR) spectroscopy [1]. All of the information concerning the fields experienced by the muons is obtained by measuring the evolution of the muon spin polarization with time, a feat which is accomplished by detecting the fast positron which is emitted preferentially along the muon spin direction at the instant of its (also parity-violating) decay $(\mu^+ \rightarrow e^+ + \upsilon_e + \overline{\upsilon}_\mu)$. After forming a histogram of detected positrons as a function of time following implantation, the number of decay positrons recorded per time interval Δt in the i^{th} positron detector is given by

$$N_i(t) = N_i^\circ e^{-t/\tau_\mu}\left[1 + A_i^\circ P_i(t)\right] + B_i^\circ . \tag{2}$$

where N_i° is a normalization constant, A_i° depends on the experimental geometry and the properties of muon decay (and is typically 0.2 - 0.33), while B_i° is the time-independent random background. $P_i(t)$ is the time evolution of the muon spin polarization component in the i^{th} direction and is the signal of interest.

The collection of methods by which the muon's spin is used to probe the static or dynamic local electromagnetic environment is known as muon spin rotation/relaxation/resonance (μSR) spectroscopy.

A number of different experimental configurations are possible in μSR. Transverse field (TF-μSR) experiments involve the muon spin polarization precessing around

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an external field and are shown schematically in Fig. 1. In addition, measurements can be performed in zero magnetic field (ZF-μSR) and in a longitudinal magnetic field (LF-μSR). ZF-μSR measurements are typically used in the study of magnetic ordering; the presence of ferromagnetic or antiferromagnetic order results in muon spin precession in the absence of an external field. LF-μSR measurements are generally applied to study spin fluctuations (T_1-type processes).

The μSR technique has found wide application in the study of high temperature (HiTc) superconductivity. Experiments have been performed examining the magnetic behaviour (ordering, flucatuations etc.) of various superconducting and related compounds as well as studying the electrodynamic response of the superconductor to external fields (such as measurements of the magnetic field penetration depth).

ELECTRONIC PHASE DIAGRAMS

Shortly after the discovery of high temperature superconductivity in $La_{2-x}Ba_xCuO_4$ and $La_{2-x}Sr_xCuO_4$, ZF-μSR measurements exhibited muon precession in the absence of an applied magnetic field, indicating that the undoped insulating parent compound La_2CuO_4 underwent antiferromagnetic ordering[2]. Superconductivity is achieved in this series by the chemical substitution of Sr or Ba for La, which results in the doping of mobile holes to the CuO_2 planes. As holes are doped, μSR measurements demonstrated that the magnetic ordering temperature is quickly reduced, so that $T_N \approx 0$ K at around $x = 0.02$ doping. Above this doping level, spin glass magnetic order (where the muon spin polarization function *P(t)* has a characteristic time and field dependence) is seen up until roughly $x = 0.06$ where superconductivity appears, reaching a maximum $T_c \approx 40$ K for $x = 0.15$. Further doping causes a reduction of T_c, with superconductivity disappearing above about $x = 0.25$.

Similar electronic phase diagrams are seen in other cuprate superconductors in which the carrier concentation can be varied, including $YBa_2Cu_3O_x$ where the doping is controlled by the oxygen concentration. When $x = 6.0$, the system is an antiferromagnetic insulator, while with $x \to 7$, superconductivity with $T_c > 90$K is achieved. The details of this evolution have been extensively traced out with μSR[3].

In addition to doping with mobile holes, it is possible to dope electrons onto the CuO_2 planes[4], for example by the substitution of Ce for Nd in $Nd_{2-x}Ce_xCuO_4$. ZF-μSR measurements[5] demonstrated that these electron-doped cuprates have a qualitatively similar electronic phase diagram, although antiferromagnetism survives to somewhat higher doping levels. Figure 2 shows a composite phase diagram for both electron and hole doped cuprates. The materials shown, $Nd_{2-x}Ce_xCuO_4$ and $La_{2-x}Sr_xCuO_4$ are so-called single-layer materials as they contain single CuO_2 planes separated by charge reservoir layers, in contrast to materials such as $YBa_2Cu_3O_x$ which contain CuO_2 bilayers.

VORTEX STATE

The majority of superconductors (including all HiTc systems) are so-called type-II superconductors. In such systems, the application of a static magnetic field intermediate between critical fields H_{c1} and H_{c2} results in the penetration of magnetic field into the superconductor in the form of quantized flux lines, called "vortices". A number of fundamental issues can be explored through measurements of the spatially inhomogeneous magnetic field which exists in the vortex phase.

Under ideal conditions vortices arrange themselves to form a periodic array known as an Abrikosov lattice[6]. In general the magnetic field distribution of this lattice is a function of both space and time. Ideally, the time evolution of the i^{th} component of the total muon polarization is

$$P_i(t) = \int_0^\infty n(B)\cos\left(\gamma_\mu Bt + \Theta\right) dB, \qquad (3)$$

where *n(B)dB* is the probability that the muon experiences a local magnetic field between *B* and *B+dB*.

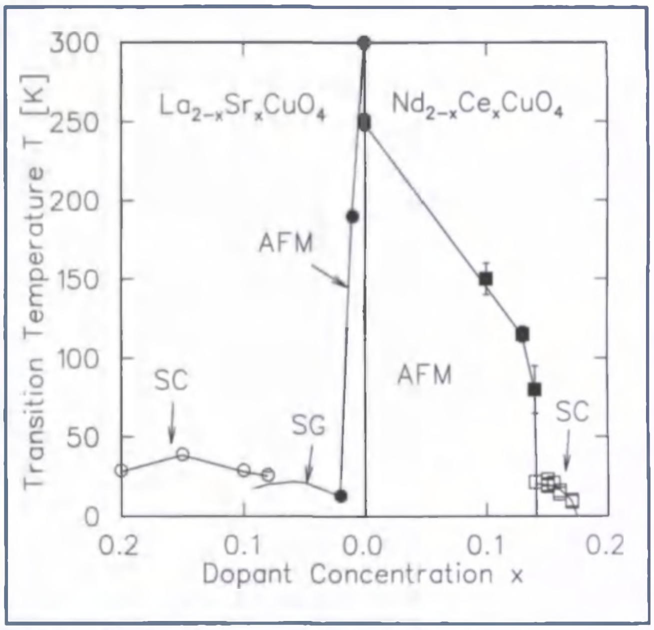

Fig. 2 Electronic phase diagram for single layer cuprates

The field inhomogeneity of the vortex state results in a dephasing of the muon spin precession signal (see, Fig.2). An approximate picture of the field distribution *n(B)* sampled by the muons is obtained by Fourier transforming the time signal. A detailed analysis of the time signal provides a determination of the magnetic penetration depth λ, the size of the vortex cores, and the formation of exotic vortex phases [7].

THE MAGNETIC PENETRATION DEPTH

The remarkable characteristics of a superconductor stem from theformation of pairs of electrons (or holes), called "Cooper pairs" which link together and carry charge through the sample with virtually no opposition. The penetration depth λ is directly related to the density of these pairs and is the length scale over which magnetic field decays from a vortex. μSR measurements of the absolute value of λ in the vortex state of HiTc superconductors complement microwave measurements of Δλ in the Meissner state (described elsewhere in this issue by Bonn and Hardy). However, in the vortex state λ can be measured over a wide range of magnetic field, providing an additional test of unconventional superconductivity.

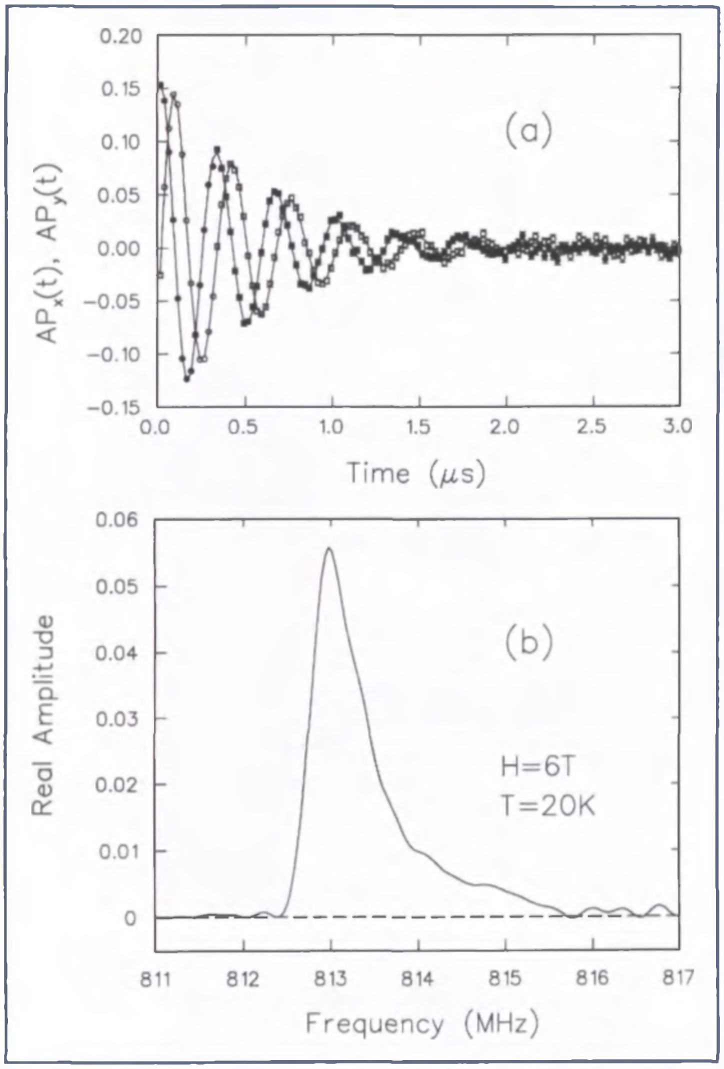

Fig. 3 (a) Muon spin precession signal at $T = 20$ K and $H = 60$ kOe displayed in a reference frame rotating at about 3 MHz below the Larmor precession frequency of a free muon in the external field[Note: A is the maximum precession amplitude]. (b) The FFT of (a) using a Gaussian apodization with a μs time constant.

Figure 4 shows the temperature dependence of λ_{ab}^{-2} recently measured in $YBa_2Cu_3O_{6.95}$ single crystals[8]. At low field and temperature, λ_{ab}^{-2} α T. This behaviour is characteristic of lines of zeros in the energy gap of the excitation spectrum. The existence of line nodes is in contrast to conventional *s*-wave superconductors, which possess a full isotropic energy gap at the Fermi surface. The first clear observation of the limiting *T* behaviour by μSR[9] contributed to the identification of $d_{x^2-y^2}$-wave pairing symmetry in the HiTc superconductors. The field dependence of λ_{ab} in Fig.4 is a further consequence of the $d_{x^2-y^2}$-wave character, reflecting the nature of the quasi particles near the gap nodes. These measurements have effectively ruled out predictions by several theorists that the field induces a transition to a mixed $d_{x^2-y^2} + id_{xy}$ or $d_{x^2-y^2} + is$ state.

THE VORTEX CORE SIZE

In recent years, μSR has been used to determine the size of the vortex cores in $YBa_2Cu_3O_x$ [11]. Currently, μSR is the only technique which can measure the behaviour of the core size deep in the superconducting state of a HiTc

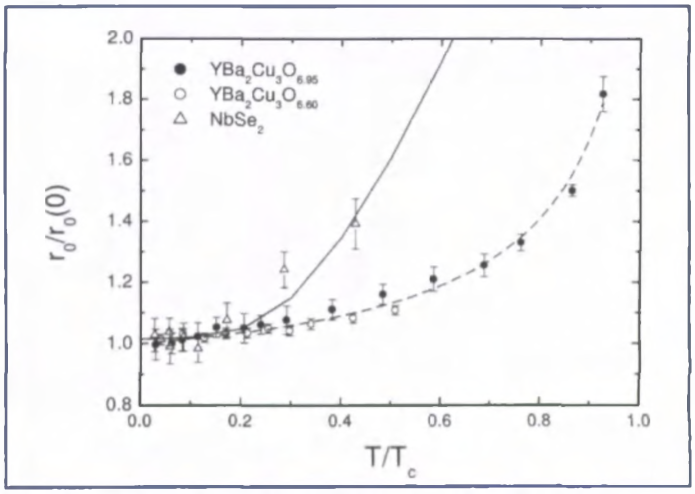

Fig. 4 Temperature dependence of λ_{ab}^{-2} at $H = 5$ kOe, 40 kOe and 60 kOe. The solid curve represents zero-field microwave measurements of $\Delta\lambda_{ab}(T)$ [10]

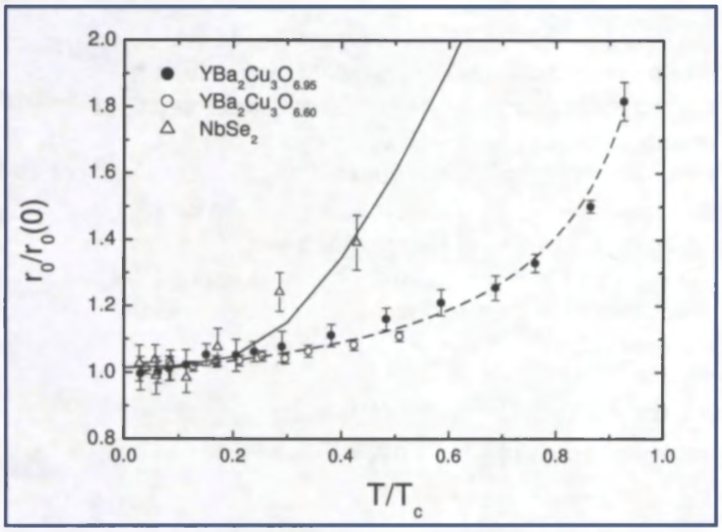

Fig. 5 Temperature dependence of the core size in $NbSe_2$, $T_c = 7$ K[12] $YBa_2Cu_3O_{6.95}$, $T_c = 93.2$ K and $YBa_2Cu_3O_{6.60}$, $T_c = 59$ K[11] at $H = 5$ kOe.

material. In a conventional superconductor like $NbSe_2$, the temperature dependence of the core size is substantial due to the thermal depopulation of bound quasiparticle core states. However, a comparatively weak temperature dependence is observed in $YBa_2Cu_3O_{7-\delta}$ (see, Fig.5) implying the absence of bound core states. Indeed theoretical calculations for a $d_{x^2-y^2}$-wave superconductor show that the quasiparticle states are not localized in the vortex core, but rather extend along the nodal directions of the order parameter with a continuous energy spectrum.

EXOTIC VORTEX PHASES

Vortices in the HiTc superconductors are highly two-dimensional due to the layered nature of the materials, and similar to atoms in a crystal are subject to thermal fluctuations and zero point motion. Consequently, deviations from the ideal Abrikosov vortex lattice are common. For example, the vortex lattice can undergo a transition to a liquid phase in which there is a loss of long-range spatial order of the vortices. The melting transition is recognizable from changes in the shape of the field distribution measured with μSR. In the HiTc materials the vortex lines are thought of as stacks of weakly coupled "pancakes" vortices which reside in the superconducting CuO_2 layers. The removal of oxygen from $YBa_2Cu_3O_{7-\delta}$ weakens the coupling between the CuO_2 layers. A recent μSR study[13] of oxygen deficient $YBa_2Cu_3O_{6.60}$ has revealed a thermally-induced breakup of the vortex lines well below the superconducting transition temperature T_c.

CLOSING COMMENTS

The above discussion has only scratched the surface of the ongoing application of μSR to studies of high temperature superconductivity. Extensive work has been done in studying the systematics of how the superconducting carrier density correlates with T_c, providing important constraints on possible theories[14]. Another area of current interest is the so-called stripe ordered phase, where charge and spin inhomogeneities phase-separate, a phenomena which may be central to understanding high temperature superconductivity.

To date, most studies have been performed on $YBa_2Cu_3O_x$, $La_{2-x}Sr_xCuO_4$ and $Bi_{2+x}Sr_{2-x}CaCu_2O_{8+y}$ due to the availability of high quality specimens. In the future, as specimens of similar quality become available for other cuprates, many additional exciting measurements will become possible.

ACKNOWLEDGEMENTS

This work was supported by the Natural Science and Engineering Research Council and the Canadian Institute for Advanced Research.

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PAIRING IN THE HIGH T_C CUPRATES: A DELICATE BALANCE

In the future, when we finally have a microscopic theory of the cuprates, it will be possible to write a short essay describing the pairing mechanism responsible for high T_c superconductivity. Now however, we are only part way towards constructing such a theory. That is, I believe that we have strong evidence that the Hubbard and *t-J* models contain much of the essential physics and, based upon these models, we have various pictures which provide insight into the mechanism. However, these are only pieces of the puzzle and the goal of creating a coherent theory of the high T_c cuprates remains. This is why this is an exciting area of condensed matter research. Here, following a brief description of the models, I'll discuss why I believe they contain the right physics and what they tell us about the pairing mechanism.

The 2D Hubbard model describes the CuO_2 plane of the cuprates in terms of a square lattice of sites with a one-electron hopping matrix element t connecting near-neighbor sites and an onsite Coulomb interaction U. The bandwidth $8t$ and U have energy scales of order eV's. At half-filling the Coulomb interaction favors having one electron per site. If near-neighbor sites have the same spin orientations, the Pauli principle prevents the electrons from hopping onto the same site. However, if the spins have opposite orientations, virtual intersite hopping processes lower the energy. This can be described in terms of an antiferromagnetic exchange interaction between near neighbor spins $J\vec{S}_i \cdot \vec{S}_j$ with $J = 4t^2/U$ when U is large compared with t. For the cuprates $J \approx 0.1eV$. In the *t-J* model, the kinetic and exchange energy terms are kept, but U is considered so large that doubly occupied sites are forbidden. In addition to the 2D lattices, $n \times L$ lattices with n = 2, 3, ... and L large have been studied and are believed to model the $Sr_{n-1}Cu_nO_{2n-1}$ cuprate ladder materials.

In retrospect, the antiferromagnetism, $d_{x^2-y^2}$ -wave pairing and striped domain wall formation found in early RPA, spin-fluctuation exchange[1] and Hartree calculations[2] for the 2D Hubbard and *t-J* models provided phenomenological evidence favoring these models. However, it is recent numerical calculations showing how delicately balanced these models are between various possible ground states that convinces me that they indeed contain the essential physics. For example, the ground state of a half-filled 2D lattice has long-range antiferromagnetic order while for a half-filled 2-leg ladder the ground state is a spin-gapped short-range resonant valence bond (RVB) state. When a 2-leg ladder is doped away from half-filling the added holes form $d_{x^2-y^2}$ like pairs and power law pair-field correlations appear[3]. On doped 8-leg *t-J* ladders, domain walls of holes separating π-phase shifted antiferromagnetic regions are found and when a small next-near-neighbor hopping t' is added, $d_{x^2-y^2}$ pairing correlations are favored over the striped domain wall configuration[4]. Thus, changes in the doping, the lattice, or the next-near-neighbor hopping terms easily alters the nature of the ground state. I believe that the remarkable similarity of this behavior to the range of phenomena observed in the cuprate materials provides strong evidence that the Hubbard and *t-J* models indeed contain the essential physics of the problem.

However, this same delicacy poses a problem for approximate calculations in which a particular type of mean-field order is posited and then self-consistently "found". The difficulty with strongly-interacting systems is that they can support self-fulfilling ansatzs, keeping the true nature of the ground state hidden. In addition, the description of "the mechanism" may depend upon one's starting ansatz. Thus, within the spin-fluctuation exchange approximation, one says that *$d_{x^2-y^2}$ pairing is mediated by the exchange of spin fluctuations in an early antiferromagnetic system*[1]. Indeed this view has some support from numerical Monte Carlo results which show that the effective pairing interaction $V(q,\omega)$ has a similar momentum, frequency, and temperature dependence to the magnetic spin susceptibility $\chi(q,\omega)$. However, the Monte Carlo calculations were carried out on small 8 x 8 lattices at relatively high temperatures $T \gtrsim J/3$. Alternatively, a short-range RVB variational approximation has been found to be in basic agreement with numerical density-matrix-renormalization-group (DMRG) calculations for a 2-leg ladder. In this case, the variational form of the ground state consists of a superposition of short range hole-pairs resonating with the singlet RVB background. Here the most natural description of the pairing mechanism is that *two holes arrange themselves so as to minimize the disturbance of the exchange energy background while at the same time resonately lowering their kinetic energy*[5]. Finally, DMRG calculations on an 8 x 24 *t-J* ladder show that the striped domain wall state is unstable when a small next-near-neighbor hopping t' is added. As t'/t increases, the stripes fade and $d_{x^2-y^2}$ pairing correlations appear. One interpretation is that stripes and pairing compete [4], and this is certainly true for static stripes, but another is that *fluctuatingstripes provide a medium which leads to enhanced pairing*[5].

ACKNOWLEDGMENTS

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ANTIFERROMAGNETISM AND SUPERCONDUCTIVITY ARE TWO SIDES OF THE SAME COIN

One of the most remarkable properties of the high T_c superconductor is its close proximity to an insulator. When Bednorz and Mueller first looked for a new class of superconductors, they started from the most implausible place, namely a class of ceramic insulators called perovskites. Somehow, the world's worst conductor turns into the world's best conductor when only a small percent of dopents are introduced into the system.

A theory has been recently proposed to explain this deep mystery[1]. This theory argues that an insulator and a superconductor are actually two different sides of the same coin. They are related to each other by a symmetry principle based on the SO(5) group. The insulating phase of the high T_c superconductors is a antiferromagentic insulator. Without artificially introduced dopents, there is one valence electron per copper atom, and the spins of these electrons form an antiferromagnetic pattern. This state of matter can be described by a three component order parameter pointing in the direction of the electron spins. On the other hand, the superconducting state is described by a complex order parameter, which has two real components. The SO(5) theory unifies the three components of the antiferromagnet and the two components of the superconductor into a five dimensional object called superspin. The rotation in this five dimensional space is described by a mathematical group called the SO(5) group.

The SO(5) symmetry principle can teach us a number of important things about the nature of high T_c superconduc-tors. First of all, it explains the phase diagram of these materials and predicts that the antiferromagnetic transition temperature T_N should intersect the superconducting transition temperature T_c at one point. This prediction can help us in finding new superconductors with even higher T_c. The general strategy is to try to find antiferromagnetic insulators with high T_N, which can also be doped easily.

The SO(5) theory also predicts a new collective mode in the high T_c superconductors, which is the symmetry partner of the usual phase mode which is present in all superconductors. According to the SO(5) theory, this new collective mode is a spin triplet and occurs near momentum (π,π), but most remarkably, it appears only below T_c. Such a collective mode has indeed been discovered in a certain class of high T_c superconductors. Since this mode appears only below the superconducting state, one might expect that it could be intimately linked to the microscopic mechanism of superconductivity. Indeed, Demler and Zhang [2] argued that the occurrence of this mode in the superconducting state lowers the antiferromagnetic exchange energy and, therefore, this mode could be directly responsible for the condensation energy. Since both the intensity of this mode and the condensation energy could be measured independently, this prediction could be checked directly in experiments. Recent experiments have indeed verified this relationship quantitatively in YBCO superconductors, both as a function of temperature and of applied magnetic field.

The *SO(5)* theory also predicts that the core of a superconducting vortex is an antiferromagnetic insulator [3], rather than a normal metal, as conventional BCS theory would predict. This theory could explain a puzzling experiment where the system was found to be insulating above H_{c2}, the critical magnetic field above which superconducitivity is destroyed. However, this remarkable prediction remains to be tested directly in experiments.

Over the course of the past 13 years, many theories of high temperature superconductivity have been proposed. However, the SO(5) theory bears a unique distinction in that it has a number in the title. Remarkably, the number 5 of the SO(5) theory turns out to be experimentally measurable! The theory of critical phenomenon states that the critical exponents depend only on the dimension of space d and the number of symmetry components n. Therefore, by experimentally measuring the critical exponents, and taking $d = 3$, one can in principle measure the number n and test the SO(5) theory in the most direct way. A class of organic superconductors have phase diagrams similar to that of high T_c superconductors. Recently, critical exponents have been measured and analyzed in these systems[4]. From these experiments, the number of symmetry components has been determined and it is indeed very close to 5, giving the most direct experimental evidence of the enhanced SO(5) symmetry at the bicritical point.

Symmetry concepts play a central role in physics. For example, before the 19th century, electricity and magnetism were viewed as rather different phenomena, but they can actually be unified by Einstein's theory of relativity, and its associated space-time symmetry. The *SO(5)* symmetry principle unifies the antiferromagnetic and the superconducting phases and can explain many puzzling phenomena in the transition region between these two states. If the unification of antiferromagnetism and superconductivity turns out to be successful in high T_c superconductors, it can also serve as a general organizational principle for other condensed matter systems as well.

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NUCLEAR MAGNETIC RESONANCE APPLIED TO THE CUPRATES

by W.A. MacFarlane and B.W. Statt

Nuclear Magnetic Resonance [1] (NMR) has played a vital role in our understanding of conventional superconductors and continues to make important contributions to our study of the new high T_c superconductors and other strongly correlated electronic materials. NMR employs the small magnetic moments possessed by many nuclei to detect magnetic fields locally. The magnetic field at a given nucleus in a solid is determined by the applied external field and the internal field due to the magnetization of the sample. The magnetization is primarily that of the electrons and is simply related to the magnetic susceptibility, which for a pure system can be expressed as a function of wave-vector, frequency and temperature $\chi(\vec{q},\omega,T) = \chi' + i\chi''$[2]. Like the specific heat or resistivity, χ is an important quantity determined by the electronic state of the solid, and the dramatic changes occurring at a superconducting transition are reflected in $\chi(T)$.

> The multi-element cuprates are much more complex than most conventional superconductors and exhibit many novel phenomena that add interest to (as well as complicating the interpretation of) the results of NMR experiments.

NMR measurements of the characteristic changes in χ below T_c in conventional low temperature superconductors were instrumental in establishing the nature of the superconducting groundstate and verifying the Bardeen-Cooper-Schrieffer (BCS) theory. Superconductivity follows the formation of Cooper pairs in which electrons are paired to form composite bosons which condense into a phase coherent ground state. In conventional Cooper pairs electrons of opposite spin and momentum are bound in a spin-singlet state with total spin $S = 0$, thus they do not contribute to χ. In contrast, in the normal state, the T independent conduction electron spin (Pauli) susceptibility shifts the NMR frequency from the free Larmor frequency. This shift, known as the Knight shift K, falls sharply below T_c approaching zero as $T \to 0$, verifying the singlet nature of the pairing in conventional superconductors.

While the NMR shift reflects the nature of the ground state, the low energy electronic excitations determine the rate at which the nuclear magnetization recovers its thermal equilibrium value after a disturbance. In homogeneous systems, this 'spin-lattice' relaxation rate (SLR) is often characterized by a single exponential time constant T_1. In metals T_1 is usually dominated by the contribution of the conduction electrons, yielding a linear T dependence of the rate $1/T_1$, known as the Korringa Law. Cooper pair condensation at the superconducting transition causes strong deviation from the Korringa law. Naively one would expect $1/T_1$ to decrease below T_c as Cooper pairs cannot cause spin relaxation. At low temperatures this is necessarily the case. However, Hebel and Slichter observed that the SLR rate actually *increases* just below T_c, as expected within BCS theory due to the nature of the BCS wave function and in contrast to the phenomenological two fluid model that preceded BCS. This result was extremely important in establishing the correctness of the BCS concept of the superconducting state.

The superconducting state is characterized by an order parameter, or gap, $\Delta(T)$. At the onset of superconductivity the order parameter increases from zero and reaches its full value $\Delta(0)$ at zero temperature. Conventional superconductors have an *s*-wave gap which is nearly isotropic around the Fermi surface. Thus at low temperatures the quasiparticle excitation spectrum is fully gapped, leading to exponentially activated observables such as the specific heat, Knight shift and SLR rate. Measurement of the T dependence at low temperature of these quantities thus yields the important parameter $\Delta(0)$. For a review of NMR in conventional superconductors see Ref. [3].

With NMR established as a powerful tool in the study of conventional superconductivity, it was natural to apply it

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to the high-T_c cuprate superconductors. This was aided by the relatively modest sample requirements of NMR. However, the multi-element cuprates are much more complex than most conventional superconductors and exhibit many novel phenomena that add interest to (as well as complicating the interpretation of) the results of NMR experiments. For example, they are obtained by doping antiferromagnetic insulating parent compounds[1] which retain some of this antiferromagnetic character in the metallic state. We present below a brief summary of the progress of NMR in the cuprates. For a more complete discussion consult the reviews of Ref. [5].

PROPERTIES OF THE SUPERCONDUCTING STATE

Like conventional superconductors, and in contrast to superconductors thought to possess spin *triplet* Cooper pairs (e.g. Sr_2RuO_4 [6]), the NMR shift in high-T_c superconductors falls sharply at T_c (Fig. 1). However, the expected Hebel-Slichter peak in the relaxation rate below T_c is never observed. Instead the rate falls quite sharply below T_c (Fig. 2). Furthermore, neither the shift nor the relaxation rate exhibit the exponential T dependence of an s-wave superconductor at low temperature.

The unconventional low T behaviour of K and $1/T_1$ indicates that the excitations of the superconducting state are not fully gapped. Unconventional superconductors [7] can have a non s-wave symmetry. The symmetry of the gap is a fundamental property determined by the pairing interaction and is thus of much interest. In some unconventional superconductors the gap $\Delta(\vec{k})$ changes sign around the Fermi surface causing nodes in the gap, i.e. specific directions where $\Delta(\vec{k})$ is zero. Little energy is required to excite quasiparticles near the nodes, resulting in power law T dependences in thermodynamically averaged quantities. In principle, power laws deduced for quantities such as $1/T_1$ may be enough to determine, or at least severely restrict, the gap symmetry. Before the symmetry was convincingly determined by phase sensitive means (using tunnel junctions), NMR measurements of the Knight shift and SLR which are sensitive to the shape of the magnitude of the gap were found to be consistent with a d-wave gap, where $\Delta(\vec{k}) = \Delta_0(\cos(k_x) - \cos(k_y))$. The low temperature power laws are $K_s(T) \alpha T$ (Fig. 1) and $T_1^{-1}(T) \alpha T^3$ (Fig. 2).

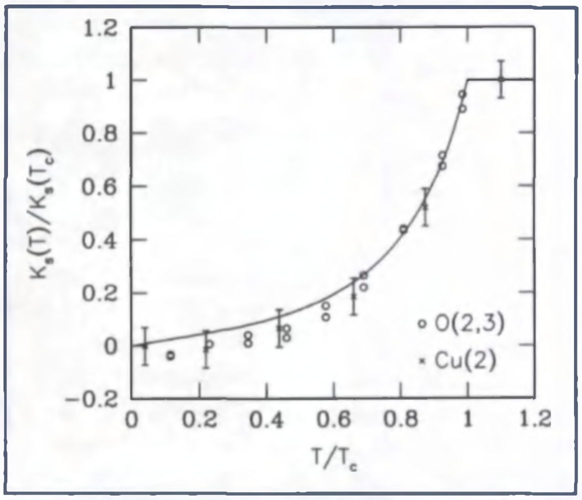

Fig. 1 **The loss of spin susceptibility in the supercon-ducting state of optimally doped YBCO as mea-sured by the Cu and O Knight shifts, with a fit to a d gap form (N. Bulut and D.J. Scalapino, PRL 68 706 (92) and PRB 45, 2371 (92)).**

The absence of the Hebel-Slichter peak is generally believed to be a consequence of unconventional superconductivity. The peak is usually not observed in other unconventional systems such as organic and heavy fermion superconductors. Anisotropy of the gap, even small, can suppress the peak significantly, so the strong anisotropy of the d-wave order parameter is at least in part responsible for the absence of the peak. However, a different mechanism may be even more important in the case of the cuprates. From the fluctuation-dissipation theorem, the SLR is related to χ by the Moriya expression:

$$1/T_1 \, \alpha \sum_{\vec{q}} \left|A(\vec{q})\right|^2 \chi''(\vec{q},\omega_L)/\omega_L \, ,$$

where A is the hyperfine coupling form factor and ω_L is the nuclear resonance frequency. Unlike conventional metals, where the only important contributions to the SLR come from near the Fermi surface ($\vec{q} \to \vec{k}_F$), the remnant (dynamic) antiferromagnetism of the CuO_2 planes away from the Fermi surface (at $\vec{q} = \vec{Q}_{AF}$) yields important terms in the Moriya sum, particularly for the plane Cu, where $|A(Q_{AF})|$ is large. These antiferromagnetic spin fluctuations are coupled to the itinerant holes, which are dramatically modified below T_c. The consequent drop of T_1^{-1} may simply overwhelm the coherence effects which normally give rise to the Hebel-Slichter peak.

As all the cuprates are type-II, NMR measurements usually are done in the vortex state. Here flux penetrates the sample in quantized bundles with the field decreasing away from the vortex core on a length scale λ_L, the London penetration depth. Usually the field is large enough that the intervortex spacing d is much less than λ_L, yielding only small inhomogeneities in the internal field $\Delta B \, \alpha \, (d/\lambda_L)^2$. The resulting field distribution is

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[1] NMR has also been extensively applied to the study of ordered magnetic systems [4].

sampled by the nuclear spins, spaced at atomic distances $a \ll d$. Vortices typically arrange themselves into a lattice resulting in a specific NMR lineshape. In principle one can model the lineshape and determine which type of vortex lattice could give rise to it. However the vortex lineshape is generally convoluted with other sources of broadening, but some information on the vortices can still be extracted from the NMR linewidth. At sufficiently low temperatures the vortex lattice pins to disorder in the atomic lattice. This is of great technological importance as the motion of vortices in a field leads to dissipation. To be of any use in most applications the vortex lattice must be stationary. At higher *T* the vortex lattice will depin or even melt and become a vortex liquid. In the case of a pinned lattice each nucleus sees a particular static field whereas if the vortices are in motion each nucleus will sample all values of the field leading to motional narrowing of the lineshape. Thus the temperature dependence of the NMR linewidth can be used to determine such a melting transition, e.g. near 40K in BSCCO at typical NMR fields.

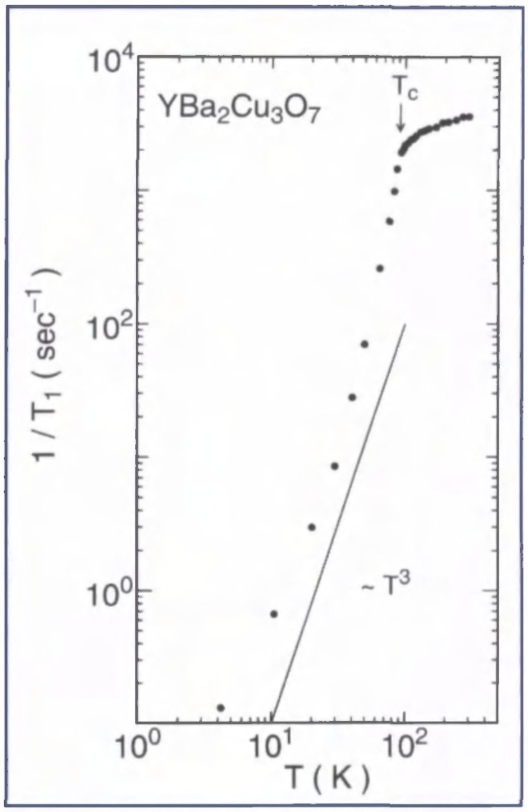

Fig. 2 **The low temperature variation of the SLR rate measured by Cu NQR in zero applied field from K. Ishida *et al., J. Phys. Soc. Jpn.* 62, 2803 (93), together with the T^3 behaviour expected for a purely d-wave superconductor.**

The complications of the vortex lattice may be avoided using nuclear quadrupole resonance (NQR). These measurements are conducted in zero applied magnetic field and use the splitting of the magnetic levels by interaction of the electric field gradient with the electric quadrupole moment of nuclei with spin greater than 1/2. Of course one cannot measure the Knight shift by this method but the SLR rate can be measured. The best low temperature measurements of the T^3 behaviour are made this way (Fig. 2).

PROPERTIES OF THE NORMAL STATE

Probably the most important open question in solid state physics is the pairing mechanism in high-T_c superconductors. While studying the rich behaviour of the superconducting state itself has provided important clues, in order to understand what drives the transition, we must understand the "normal" state. Again NMR has made important contributions in this regard.

Faced with the complexity of these compounds, if theorists are to have any chance of constructing a simple fundamental theory, experiments must be used first to identify the relevant properties. The first is that the key structural unit in cuprate superconductors is the CuO_2 plane. The other layers contribute to the structural stability and act as charge reservoirs for the planes. Strong electronic correlations make an understanding of even these simpler units a challenge, as is attested by the spectacular failure of local density approximation band structure theory to correctly predict that the undoped planes, e.g. in La_2CuO_4, are insulating. Minimal *ab initio* models of the electronic structure of the planes involve the local moment bearing Cu 3*d* orbital of $x^2 - y^2$ symmetry and two oxygen $2p\sigma$ orbitals (overlapping the Cu $3d_{x^2-y^2}$ lobes). These two kinds of electrons can in principle form two distinct energy bands. The important simplification that there is effectively only one band determining the properties of the doped planes is suggested by the fact that the NMR shifts of all nuclei coupled to the CuO_2 planes have the same *T* dependence. Furthermore, in compounds without other magnetically active sublattices, these shifts are proportional to the macroscopic susceptibility. From analysis of the hyperfine couplings, the electrons yielding χ reside primarily (but not entirely) on the plane Cu orbitals. In contrast, if multiple bands were important, one would expect distinct temperature dependences for the various nuclei, with the macroscopic χ proportional to the sum. The 'single spin-fluid' suggested by these measurements lends strong support to single band effective theories such as that of the Zhang-Rice singlet[8].

Empirically, the magnitude of the susceptibility of cuprates, both metallic and insulating is in the range of Pauli susceptibilities[9]. At optimal doping the *T* dependence of the $\chi(0,0)$ as clearly measured by NMR is also very weak, as in a normal metal. The apparently conventional behaviour is quickly lost when we move to the underdoped state. $\chi(0,0)$ acquires a significant *T* dependence far above T_c. Moreover, at all doping levels, the behaviour of the *T* dependent SLR rates do not follow the Korringa law (Fig. 3) Some nuclei exhibit constant $1/T_1TK$, while the planar Cu $1/T_1$ peaks at some T above T_c. Thus the normal state of the cuprates does not behave as a conventional metal, and we must question all the attendant concepts from the conventional theory of metals, including the existence of well defined quasiparticle excitations.

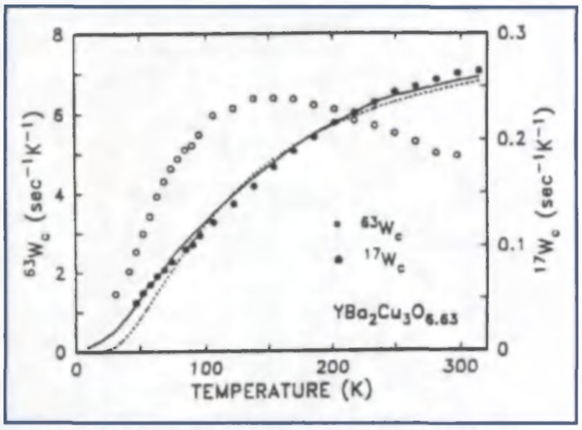

Fig. 3 The T dependence of the $W=1/T_1T$ of planar Cu and O in the normal state of underdoped YBCO, from C.P. Slichter (Ref. [5]).

Difficulties arise even with the single spin-fluid model when one tries to *quantitatively* understand the SLR rates. Unlike the shift, the nuclei coupled to the CuO_2 planes have quite different T_1^{-1} (T) (Fig.3). It is generally accepted that this is a consequence of antiferromagnetic spin fluctuations. The plane oxygen (and interplane Y) reside in sites of high symmetry in the static AF structure, so they are not as sensitive as the Cu nuclei to fluctuations at the AF wavevector $\vec{Q}_{AF}$. This statement is reflected in $A(\vec{q})$ which is zero at $\vec{Q}_{AF}$ for these sites. The relaxation rate of the plane Cu nuclei and the neutron scattering can be simultaneously described by a single phenomenological χ''[10]. The contribution of AF fluctuations to the oxygen T_1 using this χ'', though, is too large compared to the observed rate. The origin of this and similar discrepancies is a topic of current controversy.

An aspect of the normal state of the underdoped cuprates which has received much attention is the presence of the pseudogap[11]. The pseudogap is an apparent loss of magnetic and charge response below some characteristic temperature greater than T_c. In a normal metal, this could be a manifestation of a loss of density of states at the Fermi surface due to the partial opening of a gap. The pseudogap was originally discovered by NMR[12] where it appears as a loss of the shifts ($\chi'(0,0)$) with decreasing T as well as of the Cu SLR rate ($\chi''(\vec{Q}_{AF}, \omega_L)$). Subsequently the pseudogap has been observed with many other techniques. The presence of the pseudogap is found to be independent of disorder in the CuO_2 planes while T_c is highly sensitive. The effects of disorder in the normal state have been investigated extensively with NMR, cf. the review[13]. The origin and relation to the superconducting transition remains controversial. Is it the result of stronger antiferromagnetism in the approach to the metal insulator transition, or a sign of incomplete superconducting pairing of the mobile charges (can these even be separated?). Or perhaps it is the consequence of an incipient density wave instability. Contributions of NMR to this debate have been and will continue to be crucial.

PROSPECTS

After more than a decade we have few answers but a much clearer set of questions regarding the cuprates. Are they Fermi-liquid like or does spin and charge separate? What is the mechanism that leads to *d*-wave pairing? What role does the microstructure (stripes) play? Important to practical applications is the incredibly rich behaviour of vortices in the cuprates. All of these questions, each involving spin dynamics, are currently being tackled with NMR.

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HIGH SCHOOL TEACHERS CONFERENCE ON HIGH TEMPERATURE SUPERCONDUCTIVITY

by Catherine Kallin and John Berlinsky

The Institute for Theoretical Physics (ITP) at the University of California, Santa Barbara, is an NSF-funded institute which, each year, runs a number of workshops, each lasting several months, on subjects at the forefront of theoretical physics. One of the two workshops this semester, organized by Catherine Kallin (McMaster), Robert Laughlin (Stanford), Patrick Lee (MIT) and Doug Scalapino (UCSB), was on High Temperature Superconductivity. The workshop began in August, with a conference from August 14-18. On August 19, the ITP, led by Doug Scalapino and Matthew Fisher (ITP), organized an additional one-day conference for high school physics teachers, entitled "High Temperature Superconductivity: What is it?" About 50 high school teachers from all over the United States attended the conference. In addition, the conference was broadcast in real time over the Web, using the Apple QuickTime format. The talks from this conference, along with all of the talks from the weeklong conference that preceded it, may be viewed on the Web at http://online.itp.ucsb.edu/online/.

Superconductivity is not a highly popularized subject, like black holes or string theory. The teachers came in to the conference knowing very little. Nevertheless, by the end of the day, it was clear that their interest and enthusiasm had been aroused.

Superconductivity is not a highly popularized subject, like black holes or string theory. The teachers came in to the conference knowing very little. Nevertheless, by the end of the day, it was clear that their interest and enthusiasm had been aroused. This was accomplished by a combination of clear explanations, demonstrations, and anecdotes, ranging from fundamental physics to applications, and one-on-one discussions between high school teachers and physicists.

The speakers were a mixture of theorists and experimentalists. Laura Greene, from the University of Illinois at Urbana-Champaign, gave an "Introduction to Superconductivity: Exploring Forbidden Pathways" which first described how superconductivity comes about and then emphasized the effects of macroscopic phase coherence. This was an excellent lead-in to a talk by Doug Scalapino on "Superconducting Quantum Interference Devices (SQUIDS)", which included a cameo appearance by Robin Cantor of Star Cryotronics of Los Alamos, who demonstrated how Mr. SQUID, a high T_c SQUID cooled by liquid nitrogen, is a sensitive and accurate sensor of magnetic fields. The teachers were fascinated by this device, and one of their first questions was about the cost (US$2,500) and how such an instrument might be acquired for classroom laboratories.

John Kirtley, of IBM's T.J. Watson Research Center in Yorktown Heights, gave a talk entitled "Surfing the d-wave" which emphasized the symmetry of the order parameter in high T_c superconductors and how it can be determined by measurements on tri-crystal films. This talk attempted to explain the meaning of the internal symmetry of the order parameter, building on earlier discussions of phase coherence.

After a lunch outside the ITP, near cliffs overlooking the Pacific (fig. 1), the first talk was by Paul Grant, formerly of IBM and now Science Fellow for the Electric Power Research Institute (EPRI). Grant described a number of promising applications of high T_c materials in communications and in the distribution of electric power. He was particularly optimistic about the use of high T_c materials in cellular telephone

Fig. 1 *Lunch with high school teachers, outside the ITP. In the centre, with suspenders, is Nobel Laureate, Robert Laughlin.*

C. Kalllin (kallin@mcmail.cis.McMaster.ca), and J. Berlinsky (berlinsk@mcmail.cis.McMaster.ca), McMaster University, Hamilton ON L8S 4M1

systems, where he said that it is just a matter of time before they will gain widespread acceptance. His observation was that, "When interference and coverage issues converge with greater user density, then high T_c materials will be the *only* solution."

With regard to electric power transmission, Grant described the situation in Detroit. For several years, he said, Canada has allowed casinos to operate in Windsor, attracting U.S. gambling dollars from Detroit. Now Detroit is building its own casinos, along with a new football stadium and baseball park. The net effect is like building Detroit on top of Detroit, creating a huge demand for more electrical power with virtually nowhere to put the transmission lines, except in the underground space occupied by old ones. This year, with the help of funding from EPRI and the Department of Energy, Detroit Edison will install three liquid-nitrogen-cooled high T_c cables, each carrying 2400 A at 24KV, three times the current carrying capacity of conventional cables in the Detroit Frisbie substation.

Theory of Everything

$$\mathcal{H} = -\sum_j \frac{\hbar^2}{2m}\nabla_j^2 - \sum_\alpha \frac{\hbar^2}{2M_\alpha}\nabla_\alpha^2 - \sum_{j,\alpha}\frac{Z_\alpha e^2}{|\mathbf{r}_j-\mathbf{R}_\alpha|} + \sum_{j<k}\frac{e^2}{|\mathbf{r}_j-\mathbf{r}_k|} + \sum_{\alpha<\beta}\frac{Z_\alpha Z_\beta e^2}{|\mathbf{R}_\alpha-\mathbf{R}_\beta|}$$

- Hydrogen atom
- Methane molecule
- Water
- Air
- Rocks
- Concrete
- Steel
- Glass
- Plastic
- Buildings
- Cities
- Continents

- Proteins
- DNA
- Viruses
- Bacteria
- Yeast
- Slime mold
- Butterflies
- Sharks
- Rats
- Lawyers
- [illegible]
- Legislatures
- Civilizations

- Flowers
- Trees
- Cows
- Cheese
- Sauce Bernaise
- Computers
- Television
- Cars
- Jets
- Lawnmowers
- Sewage
- Spotted Owls

...

Fig. 2 The fundamental Hamiltonian, $\mathcal{H}$ of condensed matter physics and the phenomena that emerge from this Hamiltonian. A knowledge of $\mathcal{H}$ is not, in itself, sufficient to predict the phenomena that emerge.

Grant's talk was followed by a Town Hall discussion, chaired by the Director of the ITP, David Gross, in which the teachers were asked to comment on the content and format of the conference. Of particular interest to the ITP was the low attendance at the meeting. ITP had sent out letters, including the suggestion that financial support might be available, to 7000 teachers. The response, in terms of actual attendance, was less than 1%, about 1/3 of what could have been accommodated. An earlier teacher's conference on Black Holes did attract 150 teachers, but most of these applied at the last minute after it was known that Stephen Hawking would be a speaker. The problem of reaching teachers and attracting them to such an event is a difficult and perplexing one. While the numbers were disappointing, the level of teacher enthusiasm was not. Several teachers stated emphatically that they would attend any future such conferences. "We would kill to come back here..." one teacher said.

What teachers get out of such a meeting is a certain degree of stimulation and encouragement that physics can indeed be exciting. They learn something about what physicists actually do now, and they learn where to find educational material to pass on to their students. One teacher said, "When I came here I knew beans about superconductivity. Now I know squash, but at least I know enough to tell my students where to go to look for information about superconductors." Another commented, "[In our courses,] we talk about stuff that nobody does any more, and then we spend two days talking about what physicists actually do."

The grand finale of the day was the talk by Nobel Laureate, Robert Laughlin on "Mesoscopic Protection". The talk was a stimulating mixture of science, philosophy, and humor. Laughlin addressed the question of why the problem of high temperature superconductivity is so difficult and what kind of solution one might expect. Along the way, he attacked the reductionist concept of a "theory of everything," (fig.2) and emphasized the fact that, when dealing with systems with macroscopic numbers of particles, entirely new kinds of phenomena can emerge.

Laughlin defined mesoscopic protection as a phenomenon described by a stable renormalization group fixed point. Of course few if any of the teachers knew what this meant, but he then went on to illustrate the idea with some examples, such as hydrodynamic modes, where the long wavelength behavior is "protected" or universal, independent of the details of the microscopic structure. Laughlin implied that he expected the explanation of high temperature superconductivity to be similarly independent of the microscopic details, but to involve new physical ideas. He calls such ideas "higher organizing principles." Of course the other possibility also exists, that high T_c superconductivity results from some peculiarity of CuO_2 planes which is highly specific and finely tuned, or that it arises from a multiplicity of conventional phases.

One point to Laughlin's talk was that phenomena emerge, in the behavior of large collections of particles, which exhibit behavior that can hardly be predicted from studying the underlying interactions and equations of motion. This is why physics is an experimental science and why just knowing the fundamental forces between elementary particles is only one step toward understanding the richness of phenomena in the universe.

BOOKS RECEIVED / *LIVRES REÇUS*

The following books have been received for review. Readers are invited to write reviews, in English or French, of books of interest to them. Books may be requested from the book review editor Erin Hails by email at ehails@physics.uottawa.ca or c/o CAP Office, Suite 112, McDonald Building, 150 Louis Pasteur Avenue, Ottawa, Ontario K1N 6N5. Tel: (613) 562-5614; Fax: (613) 562-5615.

Les livres suivants nous sont parvenus aux fins de critique. Celle-ci peut être faite en anglais ou en français. Si vous êtes intéressé(e)s à nous communiquer une revue critique sur un ouvrage en particulier, veuillez vous mettre en rapport avec le responsable de la critique des livres, Erin Hails par courrier électronique via ehails@physics.uottawa.ca ou a/s de l'ACP, bureau 112, Immeuble McDonald, 150, rue Louis Pasteur, Ottawa (Ontario), K1N 6N5. Tél. : (613) 562-5614. Télécopieur : (613) 562-5615.

GENERAL INTEREST

Biography of a Germ, A. Karlen, Ramdom House of Canada, 2000, pp: 178, ISBN 0-375-40199-7 (hc); Price: $32.95.

The Force of Character And the Lasting Life, J. Hillman, Ramdom House of Canada, 2000, pp: 221; ISBN 0-345-42405-0 (pbk); Price: $21.95.

Cosmic Catastrophes: Supernovae, Gamma-Ray Bursts, and Adventures in Hyperspace, J.C. Wheeler, Cambridge University Press, 2000, pp: 280, ISBN 0-521-69195-6 (hc); Price: $24.95.

GRADUATE TEXTS AND PROCEEDINGS

Glasses For Photonics, M. Yamane and Y. Asahara, Cambridge University Press, 2000, pp: 263, ISBN 0-521-58053-6 (hc); Price: $90.00

The Galaxies of the Local Group, S. van den Bergh, Cambridge University Press, 2000, pp: 294, ISBN 0-521-65181-6 (hc); Price: $69.95

The Origin and Evolution of Planetary Nebulae, S. Kwok, Cambridge University Press, 2000 pp: 222, ISBN 0-521-62313-8 (hc), Price: $69.95.

Dynamics of Galaxies, G. Bertin, Cambridge University Press, 2000, pp: 402, ISBN 0-521-47262-8 (hc), 0-521-47855-3 (pbk); Price: $95.00/$34.95.

Magnetic Reconnection: MHD Theory and Applications, E. Priest and T. Forbes, Cambridge University Press, 2000, pp: 583, ISBN 0-521-48179-1 (hc); Price: $85.00.

BOOK REVIEWS / *CRITIQUES DE LIVRES*

A DIFFERENT APPROACH TO COSMOLOGY - FROM A STATIC UNIVERSE THROUGH THE BIG BANG TOWARDS REALITY,, F. Hoyle, J.V. Narlikar and G. Burbidge, Cambridge University Press, 2000, pp: 357, ISBN 0-521-6623-0 (hc); Price $59.95.

It would almost be true to say that once I had started this book I could hardly put it down until I had read it through. In fact it took three long sessions. Much of this I suspect is due to Sir Fred Hoyle who, as well as being a first rate theoretical physicist, has written a number of exceptional 'hard' science fiction books.

The book does three distinct things. First, it provides an excellent survey of the development of modern cosmology, of observational, continuous creation and of the Big Bang. Second, it debates the validity of the two main theories. Third, it advances a new theory which may be described as 'multiple bangs'.

The critique is accompanied by an enormous number of literature references for each chapter as well as a voluminous terminal bibliography.

Along the way are attacks on authority, some undoubtedly merited, and it is certainly true that very original, off-main-stream proposals have a hard time with most granting committees. One illustration in the book shows a flock of geese following a leader!

The authors develop a number of interesting theories in detail as well as providing numerical criticism of existing work, a very large quantity of actual data are reproduced so that interested readers may verify or extend the presented theory. For the physicist or graduate student, many research problems are suggested and these too will be invaluable.

I would suggest that, before starting the book, the reader peruse Pages 311 to 320 which provide an overview of the text. Otherwise the book is a 'must' for anyone interested in modern cosmology.

A.D. Booth,
Sooke, B.C.

METHODS OF MATHEMATICAL PHYSICS - THIRD EDITION, Jeffreys & Jeffreys, Cambridge University Press, 2000, pp: 709, ISBN 0-521-66402-0 (pbk); Price: $39.95.

That this book was first published in 1946 and has since seen 3 editions and been reprinted eight times are a sufficient indication of its merit.

Both authors were distinguished applied mathematicians and constructed a text which contains the best features of British Applied Mathematics; subsuming features from Hilbert, Heaviside, G.H. Hardy and Whittaker and Watson. In effect the reader will learn the most useful features from all of these Classical writers.

Rigorous treatments of Real and Complex variable theory, Matrix and Tensor analysis, Ordinary and Partial Differential equations and the special functions of mathematical physics are well covered. An important feature is the wealth of examples from the real world. There are also problems for the student at the end of each chapter.

The only negative comment might be that the treatment of numerical analysis, and particularly of linear systems, while accurate, does not do justice to the advances made possible by modern computers.

I have used earlier editions in my 4th year courses for a number of years and would certainly do it again. At this price, it is a real bargain.

A.D. Booth,
Sooke, BC

McMaster University

MEDICAL PHYSICS - TENURE-TRACK APPOINTMENT

McMaster University invites applications for a tenure-track appointment in the Medical Physics and Applied Radiation Sciences Unit of the Department of Physics & Astronomy. The position is targeted to begin on 1st July, 2001, although some flexibility either way can be accommodated. Candidates should possess a PhD and have demonstrated both an excellent research record and an aptitude to teach. The ideal candidate will possess core strengths in the fundamentals of medical imaging. She/he would be expected to contribute particularly to the graduate programmes in Health & Radiation Physics and Medical Physics through mounting one or more courses, attracting research funding and mentoring graduate students. There would also be some expectation that the person appointed would contribute to undergraduate education through, for example, the Honours Medical and Health Physics or other Physics programmes.

McMaster has been successful in winning investment from the Canadian Foundation for Innovation and the Ontario Innovation Trust to the Medical Physics and Applied Radiation Sciences area. The University itself has supported these initiatives through the creation of this Unit and the creation of the McMaster Institute of Applied Radiation Sciences, as well as through financial investment. This has built on strong, long standing partnerships with Hamilton Health Sciences Corporation and Cancer Care Ontario in bringing together research and education in Medical Physics. The successful candidate for this position will join an enthusiastic, multidisciplinary, multi-institutional team that is looking forward to capitalizing on its recent success to build further opportunities in the future.

Existing research fields within the Medical Physics and Applied Radiation Sciences Unit include laser and light propagation in tissue for photodynamic therapy and tissue characterization; the cellular and molecular basis of photodynamic therapy; the role of DNA damage and DNA repair processes in carcinogenesis and in the response of tumour cells to radiotherapy and chemotherapy; novel methods of imaging bone architecture and joint structure non-invasively; dosimetry of diagnostic and brachytherapy radioisotopes; imaging in PET and MRI, particularly for neurological and cardiac studies; and nuclear and atomic techniques used for body composition studies. McMaster has major facilities for Radiation Science research, including a nuclear reactor, an accelerator laboratory and a cyclotron used for production of PET isotopes. Candidates should consider how they would interact with and extend existing research and be able to exploit facilities.

In accordance with Canadian immigration requirements, priority will be given to Canadian citizens and permanent residents. McMaster University is committed to employment equity and encourages applications from all qualified candidates including aboriginal peoples, persons with disabilities, members of visible minorities, and women.

Applications, including a statement of research interests and letters from three referees should be sent by **November 30th, 2000** to :
Dr. D.R. Chettle, Medical Physics and Applied Radiation Sciences Unit, Department of Physics & Astronomy, McMaster University, Hamilton, Ontario, L8S 4K1, Canada. Telephone (1) 905 525 9140 ext 27340, FAX (1) 905 528 4339, e-mail: chettle@mcmaster.ca.

THE UNIVERSITY OF BRITISH COLUMBIA
DEPARTMENT OF CHEMISTRY

The Department of Chemistry of the University of British Columbia is seeking to fill tenure-track openings at the assistant professor level starting July 1, 2001.

Nuclear–Physical Chemistry

Applicants are expected to develop a research program at the TRIUMF cyclotron and/or its new Isotope Separator and Accelerator (ISAC). TRIUMF is a 500 MeV cyclotron with proton beam intensities up to 150 μA, with a strong program in μSR. ISAC is a new radioactive ion beam facility with developing programs in Nuclear ChemistryPhysics and Materials Science, the latter utilizing polarized ion beams and a β-NMR spectrometer. TRIUMF/ISAC is a highly interdisciplinary research environment and the successful applicant is expected to take full advantage of this environment.

Theoretical/Computational Chemistry

These positions require a Ph.D. degree, postdoctoral experience preferably, and a proven research track record. The successful candidates will be expected to teach Chemistry courses at the undergraduate and graduate level, and to develop vigorous and creative research programs. Salaries will be commensurate with experience.

In order to address under-representation of members of designated equity groups among senior faculty, we may consider making an appointment at a higher rank for a woman, visible minority, disabled, or aboriginal applicant with exceptional qualifications, subject to the availability of funds.

UBC hires on the basis of merit and is committed to employment equity. We encourage all qualified persons to apply. In accordance with Canadian Immigration requirements, priority will be given to Canadian citizens and permanent residents.

Applications should consist of a curriculum vitae, list of publications, summary of research interests, a detailed research proposal, and the names and addresses of at least three references. The applicants should arrange for the complete application to be sent by **November 15, 2000**, to:

UBC

Head, Department of Chemistry
University of British Columbia
2036 Main Mall
Vancouver, BC Canada V6T 1Z1
Email: head@chem.ubc.ca

FACULTY POSITION

Department of Physics, Simon Fraser University

The Physics Department at Simon Fraser University invites applications for a tenure track Assistant Professorship, to take effect in September 2001, subject to final budgetary approval. We are searching for an individual of outstanding background and exceptional promise who will establish a vigorous independent research program and who will have a commitment to undergraduate and graduate teaching. The Physics Department has a very broad research program in condensed matter physics as well as research programs in archaeometry, dynamical systems, high energy theory and experiment, and classical and quantum gravity. Our first priority in the current search is an experimentalist with expertise in magnetic nanostructures but excellent candidates in any area that complements the aforementioned research programs will be given serious consideration. The Physics Department's home page can be accessed via http://www.sfu.ca/physics.

In accordance with Canadian Immigration Requirements, this advertisement is directed to Canadian citizens and permanent residents. Simon Fraser University is committed to the principle of equity in employment and offers equal employment opportunities to qualified applicants.

Applications should include a curriculum vitae, publication list and a short statement of research and teaching interests. Candidates should arrange for three letters of recommendation to be supplied in confidence. All correspondence should be directed to :

Professor Michael Plischke,
Chair, Department of Physics,
Simon Fraser University,
8888 University Drive, Burnaby BC, Canada V5A 1S6

by December 1, 2000.

FACULTY POSITION IN EXPERIMENTAL CONDENSED MATTER PHYSICS

Department of Physics & Astronomy, McMaster University

The Department of Physics & Astronomy at McMaster University invites applications for a tenure-track appointment at the Assistant Professor level or higher in experimental condensed matter physics.

The successful candidate will have a PhD in experimental condensed matter physics or a related discipline. We are looking for individuals of exceptional promise who will lead vigorous independent research programs that complement and enhance existing research strengths in the department. Candidates who would be potential members of programs within the Canadian Institute for Advanced Research on Nanoelectronics or Superconductivity are of particular interest (see http://www.ciar.ca, under "The Institute and Its Programs"). The successful candidate will also have interests in innovative approaches to undergraduate and graduate education in physics. Our condensed matter group has an interdisciplinary outlook and benefits greatly from the extensive facilities and expertise provided by the Brockhouse Institute for Materials Research at McMaster (http://www.science.mcmaster.ca/bimr).

The position is available as of July 1, 2001. Salary will depend on qualifications and experience. More information about the department can be found on our Web page: http://www.physics.mcmaster.ca/

Applications, including curriculum vitae, a research plan, and letters from three referees should be submitted by **Dec. 1, 2000** to:

Dr. A.J. Berlinsky,
Chair, Department of Physics & Astronomy, ABB-241,
McMaster University, 1280 Main Street West
Hamilton, Ontario L8S 4M1

E-mail and FAX applications will NOT be accepted.

In accordance with Canadian immigration requirements, this advertisement is directed to Canadian citizens and permanent residents. McMaster University is committed to employment equity and encourages applications from all qualified candidates, including women, aboriginal peoples, persons with disabilities, and members of visible minorities.

POSTDOCTORAL RESEARCH POSITION

Experimental High Energy Physics
University of Victoria

The High Energy Physics Group at the University of Victoria has an opening for a Postdoctoral Fellow to work on the BaBar experiment at the SLAC B Factory. The position will be based at SLAC and is available immediately. The successful applicant will contribute to the University of Victoria group's institutional responsibilities for the ongoing operations of the drift chamber and associated software; participate in data taking and play an active role in physics analysis. A recent Ph.D. in experimental particle physics is required with demonstrated software and data analysis experience.

This position is a two-year appointment, with the possibility of renewal. Candidates should send a CV, with list of publications, description of research interests and three letters of reference to:

Professor Michael Roney (email: mroney@uvic.ca)
Department of Physics and Astronomy
University of Victoria,
P.O. Box 3055 Stn CSC
Victoria, B.C.
CANADA, V8W 3P6

This position will be filled as soon as a suitable candidate is identified. For full consideration, candidates should be able to join the group by January 2001.

In accordance with Canadian immigration regulations, priority will be given to Canadian citizens and permanent residents, but all qualified individuals are encouraged to apply.

CANADA RESEARCH CHAIRS:
FACULTY POSITIONS IN MOLECULAR BIOPHYSICS AT MCMASTER UNIVERSITY

The Department of Physics and Astronomy and the Department of Biochemistry at McMaster University invite applications from outstanding scientists for two Canada Research Chairs, one senior and one junior, which will be appointed jointly in the two departments. The senior chair will be appointed as a tenured professor and the junior chair will be appointed as a tenure-track assistant or associate professor. The purpose of these positions is to initiate an area of research, Molecular Biophysics, which is new to McMaster, and to create strong research and educational links between the Departments of Physics and Astronomy and Biochemistry. Information about the two departments can be viewed at http://www.physics.mcmaster.ca/ and http://www.science.mcmaster.ca/biochem/. Complete information about the Canada Research Chair Program may be found on the site http://www.sshrc.ca.

We encourage applications from individuals with a strong interdisciplinary background in physics and in the biological sciences and whose research complements the current strengths and interests at McMaster, which include structural biology, biomolecular interactions, molecular imaging, drug discovery, chemical biology, bioinformatics, and theoretical biophysics. We are particularly interested in individuals who have or intend to establish independent research programs in supramolecular assemblies and molecular machines, molecular motors, laser tweezers, biophotonics, nanotechnology, and/or computational biophysics.

Applicants must have a PhD in physics, biophysics, or a closely related field, and have a proven record of research excellence in their area of expertise. Successful applicants are expected to establish a vigorous, externally funded research program, and to participate in undergraduate and graduate education.

Applicants should submit a curriculum vitae, a statement of research interests and future plans, and arrange for three letters of recommendation to be sent to:

Molecular Biophysics Search Committee
Department of Physics and Astronomy
McMaster University, 1280 Main Street West
Hamilton, Ontario, Canada L8S 4M1

Applications will be considered after December 1, 2000. There is no restriction with regard to nationality or residence. Offers will be made in keeping with immigration requirements associated with the CRC program. *McMaster University is committed to employment equity and encourages applications from all qualified candidates, including women, aboriginal peoples, persons with disabilities, and members of visible minorities.*

CANADIAN INSTITUTE FOR THEORETICAL ASTROPHYSICS
INSTITUT CANADIEN D'ASTROPHYSIQUE THÉORIQUE

POSTDOCTORAL FELLOWSHIPS

CITA is a national centre for theoretical astrophysics located at the University of Toronto. The Institute expects to offer several postdoctoral fellowships of two to three years duration this year. The starting date will be 1 September, 2001. Funds will be available for travel and other research expenses. Fellows are expected to carry out original research in theoretical astrophysics under the general supervision of the faculty at CITA whose interests include: cosmology, interstellar matter, nuclear and relativistic astrophysics, gamma ray bursts, solar physics, star and planet formation.

HOW TO APPLY:

> We would prefer electronic submissions. See the CITA web page at: http://www.cita.utoronto.ca for instructions.

Applicants unable to access the web should mail: a curriculum vitae; statement of research interests; and arrange for three letters of recommendation to be sent to:

Professor J. Richard Bond, Director
Canadian Institute for Theoretical Astrophysics
University of Toronto
60 St. George Street
Toronto, Ontario
CANADA M5S 3H8

DEADLINE FOR APPLICATIONS AND ALL LETTERS OF RECOMMENDATION IS 1 DECEMBER, 2000.

CANADIAN INSTITUTE FOR THEORETICAL ASTROPHYSICS
INSTITUT CANADIEN D'ASTROPHYSIQUE THÉORIQUE

SENIOR RESEARCH ASSOCIATE POSITIONS

CITA is a national centre for theoretical astrophysics located at the University of Toronto. The Institute expects to offer one or more senior research associate positions of three to five years duration this year. The starting date will be 1 September, 2001. Applicants should have an excellent research record in astrophysics and postdoctoral experience. Funds will be available for travel and other research expenses. The primary duty is to carry out original research in theoretical astro-physics, but senior research associates are also expected to work with postdoctoral fellows and to assist with administration of the Institute.

All applications for senior research associate positions will also be considered automatically for postdoctoral fellowships.

HOW TO APPLY:

> We would prefer electronic submissions. See the CITA web page at: http://www.cita.utoronto.ca for instructions.

Applicants unable to access the web should mail: a curriculum vitae; statement of research interests; and arrange for three letters of recommendation to be sent to:

Professor J. Richard Bond, Director
Canadian Institute for Theoretical Astrophysics
University of Toronto, 60 St. George Street
Toronto, Ontario CANADA M5S 3H8

DEADLINE FOR APPLICATIONS AND ALL LETTERS OF RECOMMENDATION IS 1 DECEMBER, 2000.

Although first consideration will be given to Canadian citizens and permanent residents, we strongly encourage all qualified candidates to apply. The University of Toronto is committed to employment equity and encourages applications from qualified women and men, members of visible minorities, aboriginal peoples and persons with disabilities.

EXPERIMENTAL RESEARCH SCIENTIST

TRIUMF, Canada's national research facility for particle and nuclear physics, is currently accepting applications for a Research Scientist who will support the experimental scientific program at ISAC, TRIUMF's Isotope Separator Accelerator. By the end of the year 2000, ISAC phase-1 will provide intense radioactive beams of light elements (A 30) with energies up to 1.5 MeV/u, and ISAC phase-II will extend the mass reach to A 150 and the energy reach to 6.5 MeV/u.

The successful candidate will have recent postdoctoral experience in nuclear physics or nuclear chemistry, and be capable of providing creativity and leadership in one or more of ISAC's experimental scientific programs, primarily in nuclear astrophysics and nuclear structure with radioactive ion beams. This is a full time research position leading to a continuing Board Appointment within five years, with possibilities existing in the future to direct graduate student theses and to teach at local universities.

TRIUMF is an equal opportunity employer offering an attractive benefits package and a salary commensurate with relevant experience. While preference will be given to Canadian citizens or permanent residents, all qualified applicants are invited to submit their resumes, along with a brief summary of scientific interests, the names of 4 references and quoting **competition No. 793-0816, by October 31st, 2000** to:

TRIUMF

**TRIUMF, Attention:
Human Resources,
4004 Wesbrook Mall,
Vancouver, BC V6T 2A3
Fax: (604) 222-1074**

TENURE TRACK POSITION IN THEORETICAL PHYSICS

Department of Physics and Astronomy, University of Victoria

The Department of Physics and Astronomy at the University of Victoria invites applications for a tenure-track position at the rank of Assistant Professor in the area of theoretical particle physics or theoretical particle astrophysics. Applicants are expected to possess an exceptionally strong and internationally recognized research record and outstanding promise for future research accomplishments. The successful candidate will have a commitment to graduate and undergraduate education.

The Department of Physics and Astronomy consists of approximately 17 faculty members working primarily in the research areas of particle physics, astronomy/astrophysics and ocean physics. The department has a successful and productive association with the near-by TRIUMF laboratory. The particle physics group has an ongoing participation in the OPAL and ATLAS experiments at CERN and the BaBar experiment at SLAC. The astronomy group benefits from close relations with the nearby Herzberg Institute of Astrophysics and its staff, telescopes and instrumentation, and also has access to facilities such as the Canada-France-Hawaii and the James Clerk Maxwell telescopes and the Gemini telescopes. See http://www.phys.uvic.ca for further information.

The University of Victoria is an equity employer and encourages applications from women, persons with disabilities, visible minorities, and aboriginal persons. In accordance with Canadian immigration requirements, this advertisement is directed to Canadian Citizens and permanent residents. Others are encouraged to apply, but are not eligible for appointment unless a search among qualified Canadian applicants proves unsuccessful.

Applications, including a curriculum vitae, publication list, statement of present and future research interests, and the names and addresses of at least three referees, should be sent to:

Charles Picciotto, Chair
Department of Physics and Astronomy, University of Victoria
P.O. Box 3055 Stn Csc, Victoria, BC V8W 3P6 Canada

Applications will be accepted until 31 December 2000, with an intended starting date of 1 July 2001.

INSTITUTIONAL MEMBERS / *MEMBRES INSTITUTIONELS*

– Physics Departments / *Départements de physique* --

(as at 2000 August 28 / *au 28 août 2000*)

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Collège Montmorency
Concordia University
Dalhousie University
École Polytechnique
Laurentian University
McGill University
McMaster University
Memorial University of Newfoundland
Mount Allison University
Okanagan University College
Queen's University
Royal Military College
Saint Mary's University
Simon Fraser University
St. Francis Xavier University
Trent University
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Université de Moncton
Université de Montréal
Université du Québec à Montréal
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University of Alberta
University of British Columbia
University of Calgary
University of Guelph
University of Lethbridge
University of Manitoba
University of New Brunswick
University of Northern B.C.
University of Ottawa
University of Prince Edward Island
University of Regina
University of Saskatchewan (and Eng. Phys.)
University of Toronto
University of Victoria
University of Waterloo
University of Western Ontario
University of Windsor
Wilfrid Laurier University
York University

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(as at 2000 August 28 / *au 28 août 2000*)

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Robert L. Clarke
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Elmer H. Hara
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CORPORATE MEMBERS / *MEMBRES CORPORATIFS*

(as at 2000 August 28 / *au 28 août 2000*)

The Corporate Members of the Canadian Association of Physicists are a group of corporations, laboratories, and institutions who, through their membership, support the educational activities of the Association. The entire proceeds of corporate membership contributions are paid into the CAP Educational Trust Fund and are tax deductible.

Les membres corporatifs de l'Association canadienne des physiciens et physiciennes sont un groupe de corporations, de laboratoires ou d'institutions qui supportent financièrement les activités éducatives de l'Association. Les revenus de leurs contributions déductibles aux fins d'impôt sont entièrement versés au Fonds Educatif de l'ACP.

Atlantic Nuclear Services Ltd.
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Elcan Optical Technologies
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Gennum Corporation
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GSI/Lumonics
Institut national d'optique
JDS Uniphase Inc.
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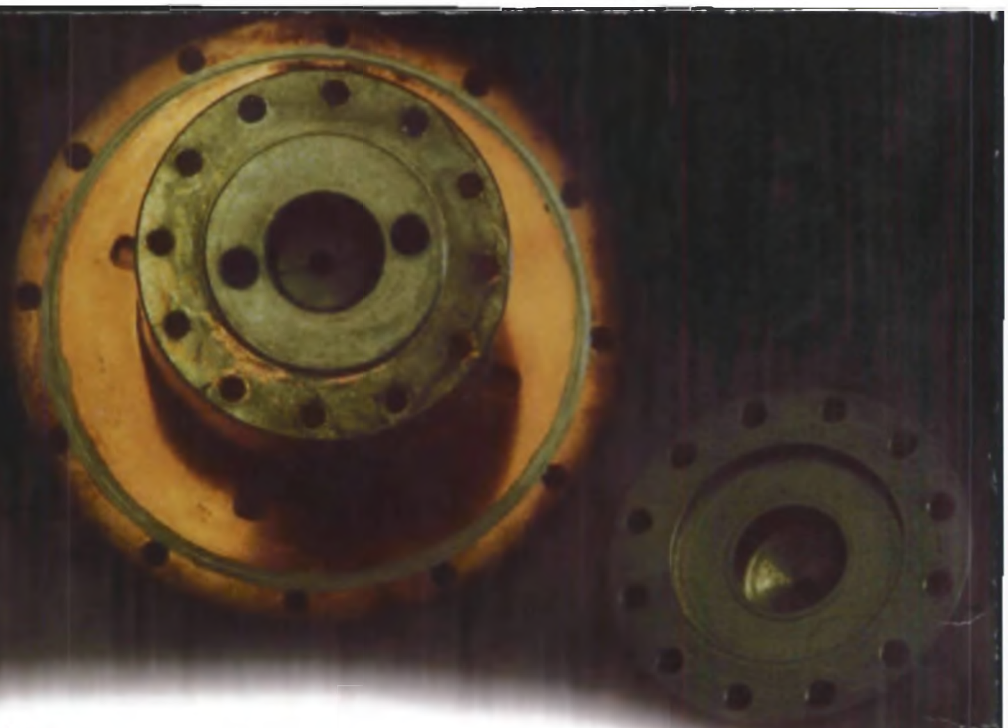
Mathis Instruments Ltd.
MPB Technologies Inc.
National Research Council of Canada
Newport Instruments Canada Corp.
Nortel Technology
Optech Incorporated
Spectra Research Corporation
TRIUMF
Varian Canada Limited

The Canadian Association of Physicists cordially invites interested corporations and institutions to make application for Corporate membership and will welcome the inquiries addressed to the Executive Director, Canadian Association of Physicists, Suite 112, McDonald Building, 150 Louis Pasteur Avenue, Ottawa, ON, K1N 6N5.
Tel: (613) 562-5614; Fax: (613) 562-5615; E-mail: CAP@physics.uottawa.ca ; Website: http://www.cap.ca.

L'Association canadienne des physiciens et physiciennes invite cordialement corporations et institutions à faire partie des membres corporatifs. Renseignements auprès de la directrice exécutive, Association canadienne des physiciens et physiciennes, Bureau 112, Immeuble McDonald, 150 rue Louis Pasteur, Ottawa, ON, K1N 6N5.
Tél. (613) 562-5614; Téléc. (613) 562-5615; Courriel : CAP@physics.uottawa.ca; Internet : http://www.cap.ca.



The Canadian Institute for Advanced Research

Superconductivity

Created in 1988, CIAR's Superconductivity Program seeks to solve one of the most challenging problems facing scientists today: the remarkable electronic and magnetic properties of high-temperature superconductors. Over twenty scientists at eight Canadian institutions collaborate with colleagues abroad to work at the leading edge of the materials, experimental and theoretical fronts.

CIAR has played a major role in developing this tightly interacting network of researchers by fostering numerous links and helping bring to Canada several leading experts and promising young scientists.

The Institute

The Canadian Institute for Advanced Research (CIAR) is Canada's research institution without walls. Its mission is to mobilize and focus the knowledge resources of a vast and thinly-populated country into an international network of highly talented individuals in order to tackle complex problems confronting human society or challenging our understanding of the natural world.

CIAR funds people only, not equipment or bricks and mortar.
Its principal asset is the research and interaction time of the scientists and scholars it supports. By joining them together in research programs, the intellectual foundations of Canadian universities have been significantly strengthened. Furthermore, with CIAR's help, universities are better able to retain some of their best scientists and scholars and attract others.

The Programs

At the heart of the Institute are its eight programs, which fall into three broad categories:

Individual and societal well-being:

- Economic Growth and Policy
- Human Development
- Population Health

Origins and evolution of life:

- Cosmology and Gravity
- Earth System Evolution
- Evolutionary Biology

Science, technology and innovation:

- Nanoelectronics
- Superconductivity

These involve a total of 178 researchers at 25 institutions in Canada, 36 in the United States, 9 in Europe and 6 in other parts of the world.

The Canadian Institute for Advanced Research
L'Institut canadien de recherches avancées