10. Occasional challenge inspections of ammunition ships could be used to verify that reloads are not carried with the fleet.
11. A related issue would be to require that nuclear air-launched cruise missiles (ALCMs) are not capable of being fired from existing SLCM launchers. Current U.S. ALCMs meet this condition, but it is not known if this holds for Soviet ALCMs.
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Photoemission Spectroscopy of the High-Temperature Superconductivity Gap

G. MARGARITONDO, D. L. HUBER, C. G. OLSON

Superconductivity is related to the presence of a narrow forbidden gap in the spectrum of the possible energies for the electrons in the material. These "superconductivity gaps" have traditionally been studied with tunneling and infrared absorption experiments. A third, powerful technique has been made possible by the discovery of high–transition temperature materials: the direct observation of the gap in photoemission spectra. The data analysis requires a careful reconsideration of the standard Einstein-Fermi model of the photoelectric effect. The conclusions are surprisingly simple and offer an alternate way to measure superconductivity gaps. This approach can also be used to study the directional properties of the gap, phenomena related to the coherence length, and possible departures from Fermi-liquid behavior.

SUPERCONDUCTIVITY IS CAUSED BY A CHANGE IN THE STATE of electrons that are close in energy to the Fermi level, E_F. In order to clarify the nature of high–transition temperature (high-T_c) superconductivity, it is important to learn as much as possible about these states. A traditional probe used by materials scientists to investigate electronic states in solids is photoemission spectroscopy (*1*). In the past, however, photoemission methods failed to make substantial contributions to superconductivity research.

This situation has been reversed in the past 12 months: photoemission has become one of the leading techniques in high-T_c research (*2*), and the opening of the superconductivity gap has been detected in photoemission spectra (*3–6*). The gap width has been measured in well-characterized samples, with values much larger than the predictions of the conventional Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. Angle-resolved photoemission experiments are exploring directional effects in the gap, which reflect the anisotropic properties of high-T_c materials (*4–6*). Careful studies of the photoemission spectral edge should be sensitive to departures from a basic concept in today's solid-state physics: the Fermi liquid (*7, 8*).

This article describes the rapid progress of photoemission experiments on the superconductivity gap. With photoemission spectroscopy it has also been possible to investigate other aspects of the electronic structure of high-T_c materials. We briefly review the use of photoemission resonances in these studies. We do not, however, describe the many different electron spectroscopy experiments that have been performed on these materials since 1987. Such experiments are described in a number of recent reviews (*2*).

Photoemission experiments on superconductors pose stimulating fundamental questions. The interpretation of solid-state photoemission data is based primarily on the model developed 84 years ago (*9*) by Einstein: an electron inside the solid absorbs the energy $h\nu$ of a photon and is emitted into the vacuum. Consider the case of an ideal Fermi gas model of a metal. Before the process, the electron is an independent particle of energy E_i. After the process, the electron is free and with energy E_p, and the Fermi gas has a hole of energy E_h. Energy conservation requires that $h\nu = E_p + E_h$. In turn, E_h (measured from the Fermi level, E_F) equals $-E_i$; hence, the well-known linear relation between E_p and $h\nu$: $E_p = E_i + h\nu$. This simple model does not account for phenomena caused by particle-particle interactions. In the practice of photoemission spectroscopy, such effects are treated as corrections to Einstein's single-electron picture (*10*).

Once this simple framework of interpretation is adopted, photoemission produces a wealth of information on the electronic states of solids (*10*). For example, the energy distribution of the photoelectrons outside the solid corresponds to the energy distribution inside the solid, shifted to higher values by $h\nu$. One can also retrieve information on the directional (k-space) properties of the electronic states from the direction of emission of the photoelectrons. In the past 30 years, photoemission techniques have been used extensively to investigate the electronic structure of metals, insulators, and semiconductors.

Why, then, have they failed in the case of superconductivity, perhaps the most interesting phenomenon caused by electrons in solids? The main reason is the limited energy resolution. The superconducting state involves electrons close to the Fermi level; the width of their energy range is determined by the magnitude of the

G. Margaritondo and D. L. Huber are in the Department of Physics and in the Synchrotron Radiation Center of the University of Wisconsin–Madison, Madison, WI 53706. C. G. Olson is in the Ames Laboratory–U.S. Department of Energy, Iowa State University, Ames, IA 50011.

superconductivity gap, 2Δ. In conventional superconductors, Δ is at most of the order of a few millielectron volts, beyond the resolution limits of photoemission experiments.

The situation was changed by the discovery of high-T_c superconductors, whose gaps are larger by one order of magnitude. High-T_c photoemission, however, still faced a difficult fundamental problem: the Einstein model of the photoelectric effect is basically flawed in the case of superconductors. The superconducting state is a collective state of all electrons close to E_F; these electrons do not behave like independent particles. Similar problems affect photoemission studies of electrons far from the Fermi level: multielectron-interaction phenomena are quite probable for superconducting materials and cannot be explained by Einstein's model.

Until recently, there was concern that these fundamental problems would make high-T_c photoemission spectra impossible to interpret and therefore useless. Early data reinforced these doubts: for example, the first spectra of $YBa_2Cu_3O_{7-x}$ and other compounds in the same family (referred to as 1-2-3 materials) did not exhibit a Fermi edge (*2*). This was a most disturbing result; after all, a Fermi-gas metal must have occupied electronic states up to the Fermi level. Photoelectrons extracted from these states must have, according to Einstein's model, energy up to $E_F + h\nu$. Thus, the leading edge of the spectra must be observed at $E_F + h\nu$. As seen in the bottom curve of Fig. 1, no such cutoff was found in spectra taken (*11*) early in 1987 on room-temperature $YBa_2Cu_3O_{7-x}$. Features not explained by Einstein's one-electron model had been observed in many other metals, but the absence of the Fermi edge was very surprising.

This dismal situation changed radically with the observation (*12*) of a clear Fermi edge in the photoemission spectra of Bi-Ca-Sr-Cu-O (Fig. 1). This result, obtained by scientists from Wisconsin and Bellcore, demonstrated that the absence of the photoemission Fermi edge in the earlier spectra of 1-2-3 materials was not an intrinsic feature of high-temperature superconductors. Fermi edges have been seen for many of the new materials discovered in the past 12 months. Furthermore, scientists from Los Alamos, Sandia, and Argonne have demonstrated (*13*) that the absence of the Fermi edge from the early spectra of 1-2-3 materials (*11*) was trivially due to loss of oxygen from freshly cleaned surfaces: 1-2-3 specimens cleaved at very low temperature did exhibit clear Fermi-edge cutoffs. The presence of the Fermi edge in good high-T_c photoemission spectra is now firmly established.

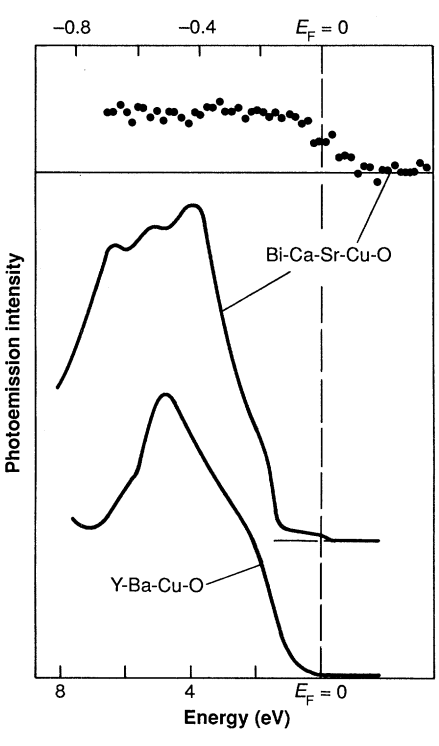

Fig. 1. Photoemission spectra (*12*) taken with a photon energy of 30 eV on $YBa_2Cu_3O_{7-x}$ and Bi-Ca-Sr-Cu-O; in both cases, the specimens were at room temperature. The horizontal scale (for this and all other spectra in the article) has been shifted in energy by $-h\nu$, thus its zero is at the Fermi level, E_F. The spectrum of the Bi compound exhibits a clear Fermi edge at E_F. The edge region is shown in detail in the upper part of the figure.

Direct Detection of the Superconductivity Gap

The search for spectral evidence of the superconductivity gap began immediately after the observation of the Bi-Ca-Sr-Cu-O Fermi edge (*3–6*). What are the spectral fingerprints of the gap? If one could adopt Einstein's model of photoemission, the spectrum would be determined simply by the density of independent electron states. The opening of the gap, however, implies the formation of a collective state for electrons near E_F. The independent-particle model of the photoelectric effect is certainly inadequate for a collective state. What, for example, does energy conservation imply when a photoelectron is extracted from such a state? Simplistic models are not able to answer the question correctly (*14*).

In 1988, a theoretical approach to this problem was developed that was based on a quasi-particle formalism, which is valid in the weak-coupling limit (*3*). The most interesting prediction of this model is derived under the assumption that the distribution in energy of the electrons in the normal state is strictly equal to the Fermi-Dirac function, that is, it is not affected by the specific properties of the sample. Then, the predicted line shape for the superconducting state is the celebrated BCS function:

$$f(E_i) = \frac{|E_i|}{(E_i^2 - \Delta^2)^{1/2}} \tag{1}$$

where the electron energy, $E_i = E_p - h\nu$ is measured from the Fermi level. This function is shown as the solid curve in Fig. 2A for

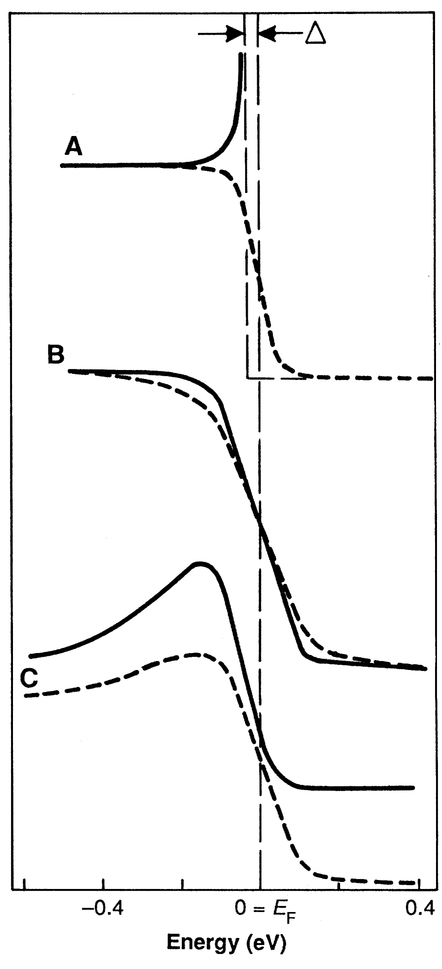

Fig. 2. (**A**) When the temperature of a BCS superconductor is reduced from above to well below the critical value, T_c, the predicted photoelectron energy distribution changes from the Fermi-Dirac function (dashed line, calculated at 300 K) to the BCS function (solid line), reflecting the creation of the superconductivity gap, 2Δ. (**B**) The corresponding photoemission spectral changes observed by Chang *et al.* (*3*) on Bi-Ca-Sr-Cu-O; the curves were taken at 300 and 65 K, with a photon energy of 25 eV and an angle-integrated photoelectron collection geometry, and are affected by instrumental broadening. (**C**) Angle-resolved experiments on the same material [data from Manzke *et al.* (*5*)] exhibit a peak corresponding to the "spike" of the BCS function. These spectra were taken at 125 and 77 K, with a photon energy of 21.2 eV.

the occupied electronic states: note the characteristic divergence for $E_i = -\Delta$ (where, again, 2Δ is the width of the superconductivity gap for $T \ll T_c$).

One could be tempted to adopt a naive interpretation of this result by assuming an independent-electron picture of the photoelectric effect and using the BCS function as the one-electron density of states for the superconductor. This interpretation is fundamentally wrong, as is well known from the analogous phenomenon of superconducting tunneling. Because of the collective character of the electronic state before and after the photoelectric process, the photoemission spectral line shape does not correspond to the density of states of independent electrons. The correct derivation and interpretation of the photoemission spectral line shape of Eq. 1 must be strictly based on treating the initial and final states of the process as collective states of an assembly of interacting electrons (*3*).

The predicted spectral line shape for the BCS superconducting state is quite different from that of a Fermi-gas metal (dashed curve in Fig. 2A), which reflects the Fermi-Dirac distribution function. The differences, however, are strong only for E_i energies not much farther than Δ from E_F; thus, they can be observed only with good energy resolution. The resolution of photoemission spectroscopy is not adequate for the small Δ values of conventional superconductors. The situation is different for high-T_c materials, since Δ increases with T_c. Furthermore, there is evidence (*3–6*) that the $\Delta/k_B T_c$ ratio (where k_B is the Boltzmann constant) is much larger for high-T_c materials than for conventional superconductors.

The temperature changes of the photoemission edge were measured for Bi-Ca-Sr-Cu-O by four groups: Chang *et al.* of Wisconsin and Bellcore (*3*), Imer *et al.* of Neufchatel and Orsay (*4*), Manzke *et al.* of Karlsruhe and Kiel (*5*), and Olson *et al.* of Ames, Argonne, and Los Alamos (*6*). Chang *et al.* reported (*3*) a gap parameter $\Delta = 30$ meV derived from their spectra (Fig. 2B), with an uncertainty of ± 10 meV caused primarily by limited energy resolution. Imer *et al.* (*4*) derived a value $\Delta = 30$ meV from their elegant high-energy resolution experiment (Fig. 3A). A study with high angular resolution (Fig. 2C) was performed by scientists from Karlsruhe and Kiel (*5*), who derived the same value of Δ.

Figure 3B shows results recently obtained with high energy and angular resolution by Ames, Argonne, and Los Alamos scientists at the Wisconsin Synchrotron Radiation Center (*6*). The data of Figs. 2 and 3 provide a direct visualization of the BCS function (Fig. 2A), convoluted with the instrumental broadening. The solid and dashed lines in Fig. 3B show the best fits of the data with broadened Fermi-Dirac and BCS functions. From these fits one derives a Δ value of 24 meV. The gap was observed only in spectra taken below T_c, and it disappears immediately above T_c. Thus, its creation is related to the superconducting transition.

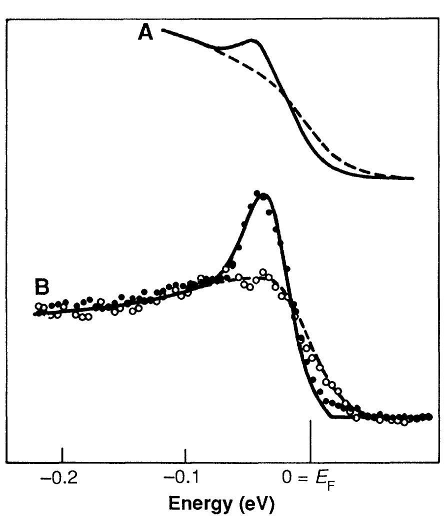

Fig. 3. (**A**) Data obtained in a high-resolution experiment, performed by Imer *et al.* (*4*) on $Bi_2CaSr_2Cu_2O_8$, reveal spectral features corresponding to those of Fig. 2A; the spectra were taken at 15 and 105 K, with 21.2-eV photons. (**B**) Very clear evidence of the opening of the superconductivity gap was obtained by Olson *et al.* (*6*), using high energy and angular resolution. These spectra were taken at 90 and 20 K, with 22-eV photons, at an angle corresponding to the *k*-space region near the $\Gamma - \bar{M}$ direction. The dashed and solid lines are best fits based on the use of Fermi-Dirac and BCS functions, respectively.

The value $\Delta = 24$ meV corresponds to $\Delta/k_B T_c \approx 3.5$, nearly twice the prediction (≈ 1.76) of the conventional BCS theory of superconductivity. The results of Figs. 2 and 3, obtained independently by several groups, leave no doubt that a gap exists in the photoemission spectrum of Bi-Ca-Sr-Cu-O in the superconducting state and that its magnitude is much larger than the predictions of the BCS theory. This large magnitude is also consistent with the value obtained from tunneling experiments (*15*) on Bi-Ca-Sr-Cu-O, $\Delta = 25$ meV. To our knowledge, no infrared data exist for this compound.

Search for the Resonating Valence Bond State

How does the photoemission technique compare with infrared spectroscopy and tunneling, the traditional probes of superconductivity gaps? Photoemission has one disadvantage but several advantages. The disadvantage is that the energy resolution is not yet comparable with that of infrared spectroscopy and tunneling, although it is adequate for the Δ values of high-T_c materials. On the other hand: (i) Photoemission is performed on well-identified solid-vacuum interfaces, which are independently characterized with a battery of sophisticated surface-science techniques. (ii) The energy analysis is performed for each single particle (photoelectron) rather than as the energy derivative of a particle flux (tunneling current). This results in an intrinsically better signal-to-noise ratio than can be obtained in the tunneling experiments. (iii) The trajectory of each photoelectron can be analyzed; this makes it possible to study in detail the directional aspects of the gap formation mechanism. In summary, infrared, tunneling, and photoemission experiments appear to be complementary to each other. The complementarity of tunneling and photoemission extends beyond the mere study of gaps: both techniques can, at least in principle, search in complementary ways for deviations from conventional Fermi-liquid behavior (*7, 8, 16*).

Many theorists believe (*7*) that the explanation of high-T_c superconductivity requires a drastic departure from conventional solid-state physics, which is based on the concept of the Fermi liquid, a generalization of the ideal Fermi-gas model appropriate for an assembly of electrons interacting through Coulomb forces. Noteworthy among the alternative theories is the resonating valence bond (RVB) model (*17*); recently, the evidence for this model has been called (*7*) "compelling." We find instead that the photoemission data are consistent with a well-defined Fermi surface and have failed to provide positive evidence for RVB states (*6, 8*).

In principle, this evidence could be provided by a possible asymmetry of tunneling data with respect to the external bias polarity (*16*). This approach, however, has not produced clear results. Similarly, one could search for asymmetries between normal photoemission and "inverse" photoemission, the technique in which electrons are injected into the sample and photons are emitted. However, the energy resolution of inverse photoemission is not adequate for this approach.

Fortunately, there is a much more direct photoemission test for the existence of RVB states: the normal-state, near-edge photoemission spectral line shape should be quite different for a Fermi liquid and for an RVB system (*18*). The RVB state is based on a decoupling of the spin and charge degrees of freedom of the electrons. Assume complete decoupling; then, the elementary excitations of the system are not holes, as in a Fermi liquid, but new quasi-particles called "holons" and "spinons" (7). The extraction of a photoelectron from an RVB system implies the creation of a holon and a spinon. The energy conservation equation is no longer $h\nu = E_p + E_h$, but $h\nu = E_p + E_H + E_S$. Thus, the energy difference $(h\nu - E_p)$ is not taken by a single particle (hole) but is partitioned between the holon energy E_H and the spinon energy E_S.

This partition is subject (*18*) to geometrical constraints in *k*-space (reflecting the conservation of *k*-vector, which is similar to the momentum conservation in free space). These constraints determine the number of ways in which the partition can occur, and the number increases with the energy difference $(h\nu - E_p)$. The result is a dependence on E_p of the photoemission intensity, which is not present for a Fermi liquid (*18*).

Assume that the near-edge photoemission spectrum of the Fermi liquid simply corresponds to the Fermi-Dirac distribution function, as shown in Fig. 4 (top, solid line). This is quite different from the spectrum of an RVB system, shown by the model calculation of Fig. 4 (top, dashed line) (*18*). The differences are significant only when $(h\nu - E_p)$ is smaller than the maximum possible spinon energy, E_S^{max}; otherwise, the RVB behavior approaches that of a Fermi liquid.

Do these considerations imply that the edge seen for Bi-Cu-Sr-Cu-O in Fig. 1 rules out an RVB state? To answer this question, one must use some prudence, because of the effect of instrumental energy-broadening. A broadened version of the model RVB spectrum of Fig. 4 still resembles a Fermi edge (*8*), but the apparent edge position is shifted to lower energies with respect to E_F. This shift, therefore, would be the experimental fingerprint of the creation of holons and spinons in the photoelectric process. The test of this process cannot rely on the mere observation or absence of the spectral edge: one must check the position of the edge against that of a known Fermi-liquid system (for example, a thick simple-metal overlayer deposited on the superconducting specimen).

This test was performed, first on Bi-Ca-Sr-Cu-O (*6, 8*) and then on other high-T_c materials. No positive evidence of a shift was observed. Rigorously speaking, even within the context of the model, this negative result does not rule out an RVB state, but it sets an upper limit for the magnitude of E_S, if the RVB state exists. The upper limit estimated in the first tests (*8*) was 65 meV. High-resolution results like those of Fig. 4 (bottom), in which the instrumental broadening is comparable to the width of the Fermi-Dirac distribution edge, again fail to provide evidence for the shift and push E_S^{max} down to less than 20 meV.

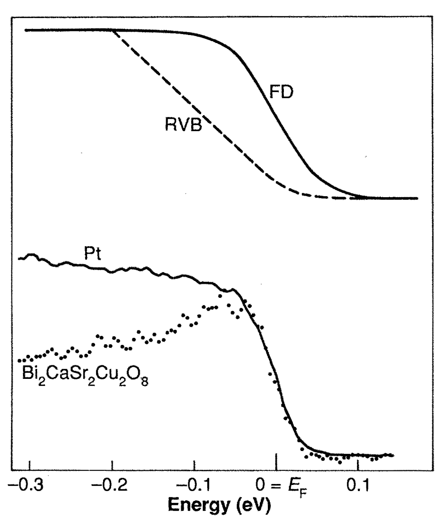

Fig. 4. (**Top**) Calculated photoemission spectra (*8, 17*), for a Fermi liquid at room temperature (solid line) and for a resonating valence bond (RVB) state (dashed line) (FD, Fermi-Dirac distribution function). Calculations were made with the model of Huber (*18*). We calculated the RVB curve by assuming complete decoupling between spin and charge degrees of freedom and a maximum spinon energy of E_S^{max} = 0.2 eV. The two curves are different only within ≈ E_S^{max} of E_F. (**Bottom**) Measured photoemission spectrum of $Bi_2CaSr_2Cu_2O_8$ (T_c = 82 K) at 90 K, compared to that of the metallic Pt Fermi edge [from measurements reported in (*6*)]. The instrumental resolution (32 meV) is comparable to the thermal width of the Fermi edge at 90 K (34 meV).

Such a low value raises serious questions about the existence of an RVB state or at least about the existence of completely decoupled holons and spinons in Bi-Ca-Sr-Cu-O. Further refinements are needed in the RVB theory of photoemission as well as in the experiments if we are to answer these questions and possibly settle the issue. Note, however, that photoemission experiments cannot address the critical point of the lifetime of the quasi-particles, be they holons, spinons, or ordinary holes.

Photoemission Resonances

Our discussion is focused on the near-edge results, which are the most important results produced by photoemission studies of high-T_c materials. These results are accompanied by extensive data obtained in other spectral regions (*2*). The importance of these data should not be overlooked: they provide excellent information on the chemical and electronic structure, which is crucial to the understanding of high-T_c superconductors.

Although a complete review is beyond our scope, we call the reader's attention to one class of very interesting features: the resonating copper satellites (*2, 19*). These satellites are a direct probe of the valence state of the Cu atoms, which is considered by some investigators the essential ingredient of high-T_c superconductivity. They are due to multielectron phenomena, not explained by Einstein's model (*9*).

Consider (*20*) the ground state of a Cu atom in the 1+ valence state (as, for instance, in Cu_2O): $3p^6 3d^{10}$. The excitation of a single photoelectron from the *d* band leaves the atom in the configuration $3p^6 3d^9$. The photoelectric process, however, can also involve the parallel excitation of a second electron to an empty state $n\ell$ (in this case $4s,p$); the final configuration is $3p^6 3d^8 n\ell$. The excitation of the second electron reduces the energy of the photoelectron. Thus, this process produces a low-energy satellite of the main Cu 3*d* photoemission feature (*21*).

Similar phenomena occur for Cu atoms in the 2+ state, such as in CuO. The single electron photoemission process in this case is:

$$3p^6 3d^9 + \text{photon} \rightarrow 3p^6 3d^8 + \text{photoelectron}$$

The satellite occurs when a second 3*d* electron is excited to an $n\ell$ state (in this case, an empty 3*d* state). Because of the different states and configurations involved, the position in energy of this satellite is different from that of Cu^{1+} (*21*). Thus, the spectral position of the Cu satellites can be used (*19*) to identify the valence state of Cu.

The observation of the Cu satellites is made easier by an interesting property of these features, their resonant behavior (*19, 20*). This consists in a large intensity enhancement when the photon energy is close to the optical absorption threshold for Cu 3*p* electrons. Figure 5 shows this enhancement by comparing on-resonance and off-resonance spectra for Eu-Ba-Cu-O (*22*). The cause of the resonance is the quantum interference between two different processes, both of which produce photoelectrons of the same energy (*10, 19*). The first process is the single-step excitation discussed in the previous paragraphs. The second process is a two-step mechanism: threshold excitation of a Cu 3*p* electron, followed by Auger annihilation of the Cu 3*p* core hole, whose energy is used to excite a photoelectron from a Cu 3*d* state.

The resonating behavior is helpful in identifying the Cu satellites of cuprate superconductors. In fact, these compounds contain several different elements, whose contributions produce complex

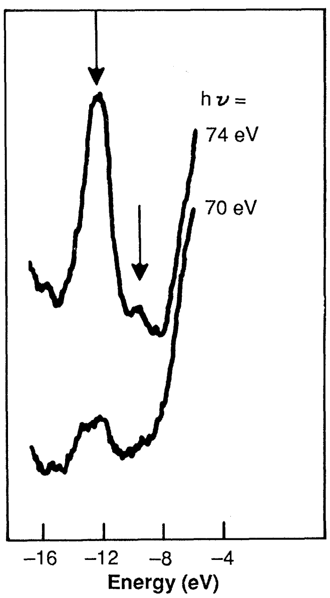

Fig. 5. Spectra taken at photon energies near the Cu 2*p* optical absorption edge on $EuBa_2Cu_3O_{7-x}$ (*22*). The arrows mark resonating Cu satellite peaks.

spectra. Without the help of resonance, the identification of features specifically related to Cu could be quite difficult.

At present, the most exciting question addressed by Cu satellite studies is the existence of high-T_c materials with electrons rather than holes as carriers. The data produced by other techniques are somewhat controversial on this point (*23*). In principle, an increase in the number of free electrons should change the Cu^{1+}/Cu^{2+} ratio, and Cu satellite studies could detect this effect. The results of this approach are expected in the near future.

Looking Forward

The observation of the superconductivity gap establishes photoemission spectroscopy as a full partner of traditional infrared and tunneling experiments. It should be emphasized that this field is still in its infancy. The experiments are difficult and require excellent samples and state-of-the-art instrumentation. In due time, however, they will provide information in areas that cannot be easily investigated by infrared and tunneling experiments.

We have seen, for example, that angle-resolved photoemission experiments can investigate the directional dependence of the superconductivity gap, suggested by recent infrared data in the case of 1-2-3 materials (*24*). Preliminary steps have been described elsewhere (*4–6*); in particular, the Ames–Argonne–Los Alamos study has already explored in detail a region of *k*-space close to a high-symmetry ($\Gamma - \overline{M}$) line. These experiments can be used to directly analyze the anisotropic character of the electronic properties, which is a fundamental issue in high-T_c superconductivity.

Photoemission studies of the superconductivity gap can also be performed with "tunable" surface sensitivity (*10*). This is a well-known technique in other applications of solid-state photoemission: one can control the depth of the region from which photoelectrons are extracted (escape depth) by varying the photoelectron energy. In turn, one can control the photoelectron energy by varying the photon energy with a tunable synchrotron radiation source. This approach can identify surface and bulk phenomena in the opening of superconductivity gaps.

Consider, for example, the possible role of the coherence length. The coherence length is very small ($\ll 10$ Å) for high-T_c materials, in the direction perpendicular to the natural cleavage planes (from which photoelectrons are emitted). The data of Figs. 1 to 3 correspond to escape depths that are larger than the coherence length and are therefore marginally affected by surface effects related to the coherence length. On the other hand, by systematically varying the escape depth one could identify these coherence length effects. This is an interesting possibility, because the ultrasmall value of the coherence length raises fundamental questions about the physical meaning of this parameter in high-T_c materials.

How far can photoemission go in the study of high-T_c superconductivity gaps? The answer probably resides in the development of new experimental techniques. The most exciting news in this area is the recent implementation of photoemission spectromicroscopy, which combines photoemission spectroscopy with high lateral resolution. When applied to high-T_c materials, photoemission spectromicroscopy will make it possible to investigate the lateral dependence of the superconductivity gap and other electronic properties.

Two electron-imaging photoemission spectromicroscopes have been implemented by Pianetta at Stanford (*25*) and by Tonner and Harp of the University of Wisconsin–Milwaukee (*26*). Furthermore, micrographs produced by the scanning photoemission spectromicroscopes MAXIMUM (Multiple-Application X-Ray Imaging Undulator Microscope) and SPM (Scanning Photoemission Microscope) have just been announced by scientists from the University of Wisconsin–Madison, the Berkeley Center for X-Ray Optics, the Brookhaven National Laboratory, Stony Brook, and IBM (*27*). These systems will greatly profit from the advent of ultrabright undulator sources of soft-x-ray synchrotron radiation currently under development, such as the Advanced Light Source (ALS) at Berkeley and ELETTRA at Trieste. With these developments on sight, the future of photoemission spectroscopy of the superconductivity gap appears very bright indeed.

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Fetal Research

JOHN T. HANSEN AND JOHN R. SLADEK, JR.

This article reviews some of the significant contributions of fetal research and fetal tissue research over the past 20 years. The benefits of fetal research include the development of vaccines, advances in prenatal diagnosis, detection of malformations, assessment of safe and effective medications, and the development of in utero surgical therapies. Fetal tissue research benefits vaccine development, assessment of risk factors and toxicity levels in drug production, development of cell lines, and provides a source of fetal cells for ongoing transplantation trials. Together, fetal research and fetal tissue research offer tremendous potential for the treatment of the fetus, neonate, and adult.

HUMAN DEVELOPMENT OCCURS IN TWO ENTIRELY DIFFERent environments, one prenatal and the other postnatal. Prenatal development encompasses the embryonic and fetal periods, whereas postnatal development involves the passage through infancy, childhood, and adolescence to adulthood. These two environments could not be more different. The safe and nutritive environment of the womb predictably yields to the more hostile existence of life after birth. Nevertheless, the relatively short prenatal existence has always held a fascination for us as we marvel at the apparent recapitulation of our developmental history. Advances in scientific understanding now are at the point where the homunculus of our ancestors' imaginations has given way to an appreciation of the intricate patterning faithfully reproduced by our genetic blueprint. Our ability to intervene prenatally when nature's course deviates has long been limited to the physician's crude palpations and auscultations, methods woefully inadequate to diagnose, let alone treat, fetal problems. Only through persistent scientific inquiry, driven by our inherent curiosity about our development, have we now reached the threshold of prenatal diagnosis and treatment necessary to ensure the mother's safety or save an endangered life.

The authors are professors in the Department of Neurobiology and Anatomy, University of Rochester School of Medicine and Dentistry, Rochester, NY 14642.

The fetus, once a captive of its own environment, an enigma to be protected but left untreated, finally has gained the status of patient. Accordingly, fetal research itself enters an important new era.

In this article, we review some of the significant contributions of fetal research and fetal tissue research over the past 20 years. It is important to draw a distinction between fetal research, that is, research performed on the living fetus in utero, versus fetal tissue research that focuses on tissues or cells derived from the dead fetus, obtained as a result of spontaneous or induced abortion (*1*). By its very nature, scientific inquiry that involves fetal research or the use of fetal tissues often is obscured in the larger ethical, moral, and legal questions surrounding the use of fetuses, especially human fetuses, in research of any kind. These concerns are not trivial, for they strike at the heart of our moral dilemma regarding abortion, or the use of invasive procedures on a patient (the fetus) who can neither be informed nor grant consent. The resolution of these concerns and the answers to the ethical and legal questions will require honest, open dialogue from all aspects of society before, and if, a consensus is ever forthcoming. Our intent is not to debate whether fetal research should continue; rather, our focus will be on why fetal research and fetal tissue research are done at all, what procedures are feasible, and how this research benefits mankind.

Prenatal Diagnosis

Fetal research plays a vital role in the continued ability to diagnose a variety of fetal disorders, from genetic inborn errors in metabolism to congenital malformations (Table 1). Approximately 150,000 children in the United States alone, representing 3 to 5% of all live births each year, are born with congenital abnormalities (*2*). Ultrasonography, a noninvasive procedure that permits visualization of the fetus without apparent risk to fetus or mother, is one of the most important diagnostic advances available to the physician (*3*) and is used as an aid for the accurate guidance of instruments. Ultrasonography is also used to assess fetal movements and gross fetal malformations. For example, neurological defects such as anencephaly, spina bifida, and hydrocephalus can be diagnosed with ultrasonography. Heart defects, which occur on the order of 1% of all live births (*4*), and various obstructive disorders of the gastrointestinal