HIGH TEMPERATURE SUPERCONDUCTIVITY: A PERSPECTIVE ON THE CURRENT STATE OF AFFAIRS

P. M. Grant

IBM Research Division
Almaden Research Center
650 Harry Road
San Jose, California 95120-6099

ABSTRACT: In this talk we will trace the important developments in high temperature superconductivity that have occurred since the 9th Winter Meeting on Low Temperature Physics a year ago in Vista Hermosa and identify key frontier areas and issues which are currently attracting attention in high-T_C research.

Introduction

It is now some 28 months since the appearance of the historic Bednorz and Müller paper,[1] published in the September, 1986 issue of Zeitschrift für Physik, announcing the discovery of high temperature superconductivity in copper oxide perovskites. This work presaged the most intense period of worldwide research on any subject whatsoever since modern physics began with Galileo, a trend which continued and increased throughout 1988. Some idea of the depth of activity now being undertaken is given in Table I. More than 1200 institutions (academic, industrial and government) worldwide are carrying out some sort of full-time program in high-T_C. These range from small companies supplying educational kits and materials to major corporations and government labs, most with no previous involvement in superconductivity. Although the number of Japanese institutions may seem a small fraction of the total, a closer examination shows a significantly larger number of people on average at each location than in the USA or worldwide. An example Japanese institution dedicated entirely to superconductivity is the International Superconductivity Technology Center (ISTEC), an innovative attempt to promote collaborative technologically-oriented research by otherwise extremely competitive institutions on an international scale. This interesting experiment will be watched closely, to say the least.

Table I also shows the enormous publication activity in progress as a result of this large body of work throughout the world. At least five new journals have appeared dedicated to superconductivity and numerous other established publications have initiated special sections on the subject, along with several commercial and non-profit high-T_C newsletters, an example of the latter being the very excellent High-T_C Update. Moreover, the proliferation of personal computers running powerful scientific text/graphics processing programs, electronic mail networks, relatively inexpensive worldwide telecommunications facilities and facsimile machines has enabled many institutions to become instant "desktop publishers," printing and distributing the results of their research in parallel to (and sometimes in lieu of) the more traditional channels of the scientific journals. Timely access to new developments has become critical to competing and participating in high-T_c research. This has always been true in science, but whereas in the past a few weeks sufficed, now it is necessary to have almost daily (and, on a few occasions, hourly) contact with colleagues worldwide. Indeed, the principal impediment to effective participation in high-T_c research by institutions in the Third World is generally not lack of good laboratory facilities, or qualified personnel, but rapid and efficient communication with the scientific community in the First World. Many of the scientists in these former countries find themselves more handicapped by poor and expensive government-managed mail and telecommunications systems than by limited talent and equipment resources. The tracking of preprints, publications and patent filings in high-T_c has become an important and essential activity in and of itself. At least one government agency, the US Department of Energy, has recognized this fact and is undertaking the establishment of a national database for high-T_c reports and publications. As mentioned previously, the accumulation and dissemination of knowledge has always been part of the essence of science, yet it has never occurred fast enough. The advent of high-T_c has served to vastly exacerbate this problem and focus attention on it. It may be that the most important short-term consequence of these discoveries, long before practical applications of economic significance are achieved, will be the development of more rapid and effective means of communication of scientific progress of all kinds to researchers throughout the world. Therefore, to improve distribution of, and access to, current research results, should rank equally with scientific investigation on the list of priority matters requiring the attention of the high-T_c community.

Progress in Materials

1988 began with the announcement of the bismuth[2] and thallium[3] layered copper oxide compounds. The current reproducible record transition temperature, 125 K, occurs in the double-TlO, triple-CuO (2223) member of this family.[4] Today, almost a year after their discovery, a number of important questions remain open. It is still not clear why T_c in some cases seems to scale with the number of layers. That such is not universal behavior is evident from the 122 K transition temperature found for the four-CuO layer compound.[5] T_c

does not seem to increase with decreasing CuO interplanar spacing either, inasmuch as this distance is smaller in the two-layer compounds than in the three-layer, yet T_C is higher in the latter. Associated with this issue is the exact transition temperature for the Bi 2021 and Tl 1021 structures. Two groups have reported $T_C \simeq 80$ K for the former compound,[6] yet extensive efforts in other laboratories have failed to confirm these high values, typically obtaining $T_C < 10$ K[7]. Therefore, any intrinsic dependence of T_C on number of layers or layer spacing is not presently obvious and remains an open question. Indeed, can one CuO layer alone sustain superconductivity?

Another mystery surrounding the bismuth and thallium compounds is the source of the carriers producing superconductivity. If one uses the ionic state of Cu as the summand for counting charge within the stoichiometric structures of all these compounds, one obtains exactly Cu^{2+}, thus these materials should ideally be Mott-Hubbard insulators! Whether the carriers originate from subtle conduction band overlap effects, as in semimetals, or, which is much more likely, from cation deficiency and/or oxygen excess, remains to be seen. Structural defects as a source of excess charge is an area of intense current investigation in these materials.

The general role of oxygen content and carrier concentration continued to attract the attention of the high-T_C materials community throughout 1988. This was typified by the work of Torrance, *et al.*,[8] who, through doping La_2CuO_{4-y} to large Sr levels by reacting in a high pressure oxygen environment, found that above a certain carrier concentration, roughly 0.3 holes per CuO_2 plane-molecule, T_C disappeared but the metallic state remained. This finding has potentially important theoretical implications and should receive detailed attention as to whether bulk superconductivity exists over a wide or narrow range of carrier concentration as a universal property of high-T_C materials, and whether the materials involved undergo subtle structural changes at the high doping levels at which these properties are observed.

In this same arena, i.e., the production and role of carriers in CuO high-T_C compounds, several new material developments of interest occurred in 1988. One was the synthesis of $Ca_{0.88}Sr_{0.14}CuO_2$ by Siegrist, *et al.*,[9] a structure consisting of an ideally infinite stack of CuO planes, with no apical oxygens attached, separated by Ca and Sr ions. The formal valence of copper in this structure is 2+ and the material is insulating and has not been doped (with holes) successfully. Could this behavior be due to the lack of an apical oxygen? Precedence can be found for this assertion in the case of the Nd_2CuO_{4-y} class of compounds which differ from their La_2CuO_{4-y} cousin in that in the former no apical oxygen is found and doping with alkaline earths does not produce itinerant carriers.[10] However, Tokura, *et al.*,[11] have recently made the exciting discovery that doping the Nd 2-1-4 system with the tetravalent rare earths Ce and Tb yield superconductors with onset temperatures in the 20-30 K range. The electron donating properties of the dopants would lead one to expect the carriers to be electrons as opposed to holes, and this expectation is indeed supported by the sign observed for the Hall and Seebeck effects. The prospect of n-type superconductivity significantly increases the potential material space that could be explored; however, much experimental work remains to be done on the Nd 2-1-4 systems. The sign of both the Hall and Seebeck effects can be misleading and at best indicate the type of majority normal state carriers and not necessarily whether these, or minority carriers of opposite sign, pair to give superconductivity. Nonetheless, the fact that this class of compounds can now be made to superconduct at all is very interesting and will undoubtedly get lots of attention in 1989.

1988 also saw the discovery of a high-T_C non-copper oxide material, $Ba_{0.6}K_{0.4}BiO_{3-y}$, by Cava, *et al.*,[12] with an onset temperature near 30 K. Interestingly, that this compound might be superconducting was predicted theoretically by Mattheiss, *et al.*,[13] demonstrating that, occasionally, the famous "Matthias Rule" (no superconductor was ever theoretically predicted) can be violated. It appears that $Ba_{0.6}K_{0.4}BiO_{3-y}$ is a structural extension of $BaPb_xBi_{1-x}O_{3-y}$, the prototypical oxide superconductor. The origin of its high transition temperature and pairing mechanism, just as for the copper oxide systems, remains presently unclear. Unlike the latter compounds, no evidence of magnetic activity is found in the BiO materials; however, it has been suggested by Batlogg, *et al.*,[14] that the coupling might originate from charge density wave mediated pairing in analogy to the various spin density wave models proposed for the copper oxide superconductors. Another interesting difference between these two material systems is that the low field properties and flux dynamics in the BiO compounds are quite traditional, in that they resemble much more those of the low-T_C type-II superconductors, than does the copper oxide family.

1988 was thus a very encouraging year for new compounds. Although further increases in T_C did not take place after February, the number of materials discovered continued apace, now totalling, depending on how one defines "new", some 40 - 50 high temperature superconductors. In the long run, sustaining the rate of new materials uncovered may prove more important than incrementally raising T_C. A transition temperature of 125 K, and even 93 K, is sufficient for many applications. However, as the number of new compounds continues to grow, both in quantity and complexity, the basic paradigm of materials science -- synthesis, processing and characterization -- assumes greater and greater importance. Many of the new systems require closer control of these parameters now than previously. At IBM Almaden, we often find the conditions required to repeat the work of others to be quite different than those which were published. For example, frequently we find the stated reaction temperatures to be too high. The way in which furnace temperatures, quenching rates and ambient reaction atmospheres are determined vary from lab to lab. Many processes, such as oxygen annealing, may be quite out of control especially when compared to prevailing standards of, say, semiconductor technology.

Finally, we should discuss briefly a few recent developments in organic superconductors. These were the first class of materials thought likely to yield high transition temperatures, in part motivated by the exitonic pairing models originally proposed by Little.[15] Beginning in the early 1970's, much attention was given to planar π-bonded molecular crystal cyanoquino-dimethanide (TCNQ) and sulfur/selenium fulvalene (TTF, TMTSF) compounds, but it was not until 1980 that superconductivity was discovered in Lewis acid complexes of TMTSF.[16] Until then, various quasi-one-dimensional charge and/or spin instabilities would destroy the metallic normal state at relatively high temperatures, but in these latest compounds, the Fermi surface has sufficient two-dimensionality to maintain the metallic state to temperatures low enough to permit the possibility of superconductivity. At first transition temperatures were of the order 1 K occurring only under 10 kbar pressure, but rapid progress has since been made with existing materials displaying onsets near 12 K at ambient pressure.[17] No universally accepted theory for the pairing mechanism in these organic superconductors exists at the present time; however, spin density wave instabilities are usually present as well as superconductivity and it could be that one of the magnetically mediated pairing models under consideration to explain high-T_C may indeed apply. Plotted against year of discovery, the slope of the rise in T_C for organics is quite dramatic, especially when compared to the traditional low-T_C compounds. Whether this trend will continue is problematic. In the organics, T_C has so far scaled empirically with unit cell volume -- the larger the volume, the higher T_C. In the current record material, the cell volume is around 720 Å^3, a huge size, and it is difficult to conceive a crystallographically stable structure of much larger amount. Further progress in raising T_C in organics will probably depend on discovery of a different class of compounds apart from the current materials, perhaps parallelling the recent history of inorganic superconductors.

Physics of High-Tc -- Experiment

Several key experimental areas developed rapidly in 1988. One of these was the continuing study of optical properties of high-T_C materials from the visible to the far infrared. The issues confronted in attempts to use optical properties as a tool for understanding coupling mechanisms and determining gap energies are summarized in an extensive review article by Timusk and Tanner.[18] The optical data is acquired by indirect near-normal incidence reflectance techniques, is very rich in structure, and requires rather elaborate numerical analysis to extract the underlying dielectric response function which connects to the physics one is trying to understand, and therein lies the difficulty. With so many optical excitation and decay channels open in these materials (electronic, vibronic, magnetic), their optical spectrum is far more complicated than the simple Drude-like response of elemental metals and superconductors. In the near infrared, a uncharacteristically strong frequency dependent dielectric response is observed. Some have interpreted this behavior in terms of an electronic gap which may possibly be mediating an excitonic coupling mechanism,[19] while others have associated it with a frequency dependent itinerant carrier scattering time and effective mass.[20] This latter picture implies there exists strong coupling, or dressing, of the single particle carriers with high energy boson excitations which at sufficiently low temperatures gives rise to pairing. These are quite separate views of the same data. In terms of a BCS-Eliashberg-MacMillan framework, if the spectrum indeed contains a "mid-IR gap," then high-T_C could arise in the weak coupling limit from the large characteristic boson temperature prefactor (Θ in the simple BCS expression $T_c \simeq \Theta \exp(-1/\lambda)$) associated with the large gap. On the other hand, the same spectrum taken as evidence for strong coupling would argue for a high transition temperature resulting from a large λ.

To decide the question of weak *vs.* strong coupling, one usually examines the ratio $2\Delta(0)/kT_c$, where $2\Delta(0)$ is the value of the superconducting gap measured well below T_C by either optical or tunneling methods. For weak coupling, this ratio is approximately 3.5, while for strong coupling, it can be typically 1.5-2.0 times greater. As in the near-IR, reflectance spectra taken in the far-IR in order to obtain 2Δ are complicated by overlapping, and possibly temperature dependent, excitations from similar sources as at higher energies which can mimic a pairing gap. Added to this is the further complication that in an ideal superconductor, the reflectance will not reveal any additional structure arising from the presence of a gap -- one must have a certain amount of impurities (the so-called "dirty limit") for gap transitions to be observed. These difficulties notwithstanding, features which appear at the onset of superconductivity are observed[21], and, when taken as the gap energy, yield values of $2\Delta(0)/kT_c \simeq 7\text{-}8$, in general agreement with tunneling data, in support of a strong coupling viewpoint. However, not all workers agree on this and the optical question is still open.

It is now well known that all the present high-T_C materials are type II superconductors -- a fact dramatically illustrated by the ubiquitous demonstrations of laterally stable levitation of a permanent magnet over (and even under!) a flat surface of the compounds. The study of these type II properties exploded in 1988. Interestingly, these investigations began very early with the third paper published by the IBM Zürich group[22] which contained observations of the time-dependent decay of diamagnetism in the superconducting state. This behavior was originally interpreted in terms of a spin-glass analogy model involving intergranular Josephson tunneling. Much later, in IBM Yorktown,[23] these experiments were repeated and re-examined from the more conventional flux creep viewpoint traditionally applied to explain flux dynamics in type II superconductors. The principal difference found between the old low-T_C materials and the new high-T_C compounds is that the "pinning" force, or resistance to vortex motion in an applied magnetic field, is orders of magnitude smaller for the latter, leading to what has been termed "giant flux creep." This phenomenon may also be responsible for the unusual vortex lattice properties observed as well.[24] This finding has profound consequences for transport and dissipation effects in the new materials. It is responsible for the broadening of the resistive transition and loss of zero resistance in relative modest (2T) magnetic fields and, because such has been observed in untwinned single crystals[25] as well as ceramics, does not appear to arise from sample inhomogeneity. Tinkham[26] has proposed a Ginzburg-Landau based model for the dependence of the flux creep activation energy on the intrinsic depairing critical current (note -- this is not the measured critical current, usually discussed in the press and technical literature). The depairing critical current at zero temperature and zero applied magnetic field, J_{c0}, in the present high-T_C compounds is estimated to be about 10^7- 10^8 A/cm^2. If one assumes the eventual discovery of a material with $T_C = 400$ K, Tinkham's model estimates that, unless concurrent increases in J_{c0} also occur, zero resistance at room temperature would only exist in applied magnetic fields less than 10 T. This limitation would be in addition to the much stricter requirement of a usefully high *extrinsic* critical current. Thus, the nature of the flux dynamics in high-T_C materials may strongly impact the real application of higher transition temperature compounds and the subject certainly deserves the attention it is currently getting.

Physics of High-Tc -- Theory

There is as yet no generally accepted theory of high-T_C. The most one can say is that the majority of models proposed rely on the assumption that the close proximity of the superconducting and antiferromagnetic states to each other in the phase diagram of high-T_C compounds is not simply an accident. Anderson[27] was the first to exploit this observation with his resonating-valence-bond (RVB) picture, essentially involving a Bose condensation of pre-existing normal state charged quasiparticles ("holons"), as a model for high-T_C. Others[28] have followed more traditional Fermi liquid concepts in which the internal antiferromagnetic interaction between Cu^{2+} sites mediates BCS-like pairing of holes in the oxygen ligands. Both lines of thought, particularly the latter, received major focus by theoreticians in 1988. Here we will limit discussion to difficulties faced by each in view of their experimental predictions and existing data.

The RVB model requires no gap and very unusual normal state properties. However, as stated above, current far-IR data, and tunneling results as well, support the existence of a gap and it is likely that this will become even more well established as these experiments are extended and refined. In terms of the normal state, one would expect the absence of the usual metallic Fermi surface if RVB applies. Here the high transition temperatures and upper critical fields involved perversely frustrate attempts to use directly the usual magneto-oscillatory measurement tools, e.g. de Haas-Shubnikov, which require the restoration of the normal state at sufficiently low temperatures in order to reduce carrier scattering. On the other hand, some positron annihilation measurements do suggest the existence of a Fermi wavevector. RVB predicts the universally observed linear temperature dependence of the resistivity in the high-T_C materials. However, it is still open as to whether this cannot be accommodated in an appropriate Bloch-Gruneisen picture. Yet, it is interesting to note that in those CuO perovskites that are metals and not superconductors, e.g. $La_4BaCu_5O_{13+y}$ and heavily doped La_2CuO_{4-y}, this linear dependence is not seen.

The spin-mediated pairing models are also not without problems. The pair wavefunction contained in these theories should have non-s-wave symmetry, but both gap measurements and the temperature dependence of the penetration depth[29] suggest otherwise. Moreover, one would expect that for these models to hold, some remnant of antiferromagnetism should spill over into the metal-superconducting part of the phase diagram. On a local scale, at least the antiferromagnetic coherence length should exceed, by perhaps several times, the Pippard coherence length of the pairs. The evidence is that they are equal or even reversed in magnitude.[30] The accommodation of these data pertaining to the superconducting wavefunction symmetry and the very short range magnetic order are the principal challenges facing the various spin-mediated pairing models.

Thin Films

Thin film activity forms its own separate sub-set of high-T_C research quite apart from the study of bulk properties and the basic nature of high-T_C itself. This is because many projected applications must employ films and the economic incentive, and support, is easiest to rationalize in this area. Table I indicates that the number of thin film publications is rising rapidly compared to bulk, and this is true for patent activity as well. We do not have space here to review the entire field and will just dwell on a few emerging developments.

Methods of depositing metal oxide films of any type has always been tricky in that retaining oxygen in the proper stoichiometric amount in the resulting film is difficult. Usually some sort of post-annealing in an oxygen atmosphere is required. This remains the situation for high-T_C films produced by standard methods such as vacuum deposition and reactive sputtering. These methods have been refined and, when used in conjunction with appropriate post-annealing, yield films of 1-2-3, bismuth and thallium compounds with superconducting properties approaching, and in some aspects, like critical current, exceeding bulk materials. However, these fabrication techniques are still awkward, and recently a new approach, laser ablation, is starting to be used. Here, the source target is stoichiometric bulk material which is subject to bombardment by an intense focused laser beam producing a roughly equally stoichiometric plasma subsequently condensed on a suitable substrate. It will be interesting to see if laser ablation will supplant the more traditional methods of high-T_C thin film deposition.

Substrate properties dominate in enabling the production of high-quality films in at least two ways: 1) by influencing the film micro-structure and crystallinity, and 2) by being sufficiently robust to withstand the high post-annealing temperatures usually required. Right now, the best substrates, e.g., strontium titanate, are expensive and impractical for large area film production and difficult to integrate, or are incompatible with other materials such as semiconductors, where high dielectric constants of the substrate can present problems. Diffusion of substrate elements into the film at the current processing temperatures required remains a major constraint on the choice of substrate material. Lowering of these temperature is one of the major challenges in this field today, and perhaps new deposition techniques, such as laser ablation, will help ameliorate this problem.

We pointed out earlier that current research in flux dynamics suggests the intrinsic zero resistance state in high-T_C materials might be quite fragile. On top of this is the question of the transport critical current at a given temperature and applied magnetic field. In practice, J_C is always determined by extrinsic material conditions, and for this reason one should not be overly pessimistic concerning the findings from flux dynamics studies. The nature of the pinning centers is one of the major open issues not only for thin films, but bulk material as well. In the old low-T_C materials with reasonably large coherence lengths, pinning could occur on dislocations or any other imperfection with length scale on the order of ξ. In high-T_C compounds, however, pinning might be occurring on point defects due to the extraordinarily small values of ξ. This could, in principle, result in greater flexibility to "engineer" high values of transport critical current through implantation techniques.

Applications

Exceedingly high expectations were raised in the public mind at the time of the initial high-T_C discoveries regarding their eventual application, both temporally and in magnitude. In the euphoria of those times, even scientists with wide experience in the field of superconductivity were guilty of broadly misleading statements. 1988 was a year of sobering up. Forgotten had been the fact that for many past proposed applications of superconductivity, liquid helium refrigeration was never a problem. Digital logic technology in high-speed computers is an excellent example. Superconductivity above liquid nitrogen offers no significant advantages in performance for digital Josephson devices; in fact, there are a number of distinct disadvantages to operation at higher temperature, and one is better off for this particular application using conventional materials such as Nb and Sn. Moreover, the task of preparing massively-replicated micron-scale Josephson logic with low individual device margin limits has up to now proved to be a showstopper for this technology even using these traditional metals, yet those past difficulties seem almost trivial when one contemplates trying the same feat with ceramic perovskites. One can safely say that, if superconductivity using low-T_C materials had offered a clear and significant cost/performance advantage over current, or even projected, semiconductor and magnetic technologies, it would have been already applied commercially to computers by somebody somewhere today.

What about the possibilities of integrating superconductivity with conventional computer technology? At first sight, it would seem advantageous to have superconducting transmission lines between active elements on a chip -- after all, zero resistance would imply no pulse shape distortion. It turns out that the major performance aspects of transmission lines are determined by their inductance and capacitance, whereas the resistive component is dominated by the impedance characteristics of the active elements themselves, especially if they are CMOS devices. To truly utilize the benefits of a zero resistance transmission line in CMOS logic, which is seen as the emerging dominant semiconductor technology, would require the use of appropriate impedance matching devices, thus increasing overall circuit complexity. There does appear to be one window of opportunity opened by advent of high-T_C. This is in the area of high-end packaging to interconnect highly integrated logic modules, a function currently served by large laminated copper printed circuit boards of order one square meter in size, containing nearly 20 kilometers of wiring. Here the distances involved, with their attendant large resistance, might justify the additional driving circuitry that would be needed. However, most importantly, since future supercomputer technology will almost certainly utilize liquid nitrogen cooled CMOS, packaging employing high-T_C printed circuitry could piggyback on the same refrigeration system. Nevertheless, a formidable amount of work needs to be done to even assess the feasibility of such a concept, and to approach the current densities and reliability provided by the present technology.[31]

Computer applications, like those discussed above, rely mainly on thin film embodiments of high-T_C. There are a number of applications which use superconductors in bulk form -- mainly in the shape of wires -- which could be potentially impacted by high T_C. Primary among these are long-distance power transmission and high-field electromagnets. It took over 20 years to enable the economic manufacture of low-T_C wires, a particularly uncomfortable reflection when one recalls that high critical currents at high magnetic fields for NbTi and Nb_3Sn were achieved on a laboratory scale almost immediately after their discovery, as opposed to the present situation for the new high-T_C compounds. Time does not allow a complete discussion of superconducting wire applications here. Suffice it to point out that even if all problems regarding critical properties, large scale manufacture, and cost of high-T_C (perhaps even room temperature) wire were solved, its actual application would involve peripheral political, economic and social factors of greater magnitude than the mere technological achievement. For example, a decision to implement the wide-scale installation of a superconducting transmission line network would be governed principally by capital investment in the existing power grid, its efficiency, and the current and projected cost of source energy, as opposed to the cost of replacing it by the new technology. The solution to this economic equation would vary from society to society. It is doubtful that First World nations would find such replacement attractive for a very long time, whereas certain

Third World countries of large land area with minimal power distribution facilities in place may find superconducting technology a very economic growth path. Similar arguments can be made for high-speed levitated locomotion.

The foregoing comments may seem very pessimistic, and even iconoclastic, regarding the future for applications of high-T_C. Not at all -- it is just that a large dose of realism needs to be injected into current popular thinking and expectations. An appropriate perspective is given in the thoughtful and insightful review, *Superconductors: The Long Road Ahead*, by Foner and Orlando,[32] of the prospects for, and problems involved in, applications of high temperature superconductivity. They sum up with the following thought: "Despite the many challenges on the road to practical superconducting technologies, the recent scientific breakthroughs in the field remain extremely important. They are the prelude to the continuing development that will make widespread superconducting applications possible...but a great deal remains to be done." Certainly it would be very foolhardy to propose at this time that these discoveries are bound to make great changes in the way we live, but it would be even more of a mistake not to put in the hard work to find out if they indeed will.

Also, unlike the topics discussed above, the first applications to emerge are likely to have more social than economic impact, in that they will indirectly affect areas like medical research and education, rather than overturn entire technologies thereby producing large revenue returns. For example, dc SQUIDS made from thallium 2223 films[33] are, at least on a laboratory scale, approaching commercially available devices fabricated from low-T_C materials in their sensitivity and noise properties. The availability of high-T_C SQUIDS may enable significant advances in the *in vivo* detection of minuscule magnetic fields emanating from nerve tissue. Here, the proximity of the detector to the magnetic field source is an important factor which is ameliorated by the simplicity of liquid nitrogen refrigeration and subsequent insulation requirements as compared to liquid helium. In general, these considerations would apply to any situation requiring the detection of low magnetic fields where convenience of SQUID refrigeration was a prime factor, such as geological exploration for oil reserves in remote areas, antisubmarine early warning stations, or outer space, where, in fact, "room temperature" is below that of liquid nitrogen. Having brought up the subject, let me make a brief remark about military applications. It used to be that military applications drove later development of a given technology in the private sector. In recent years, this trend has reversed, with new developments made by commercial industries being subsequently transferred to the military. Computer technology is an excellent example. This has lead some First World countries, like the United States, to restrict transfer of certain privately developed technologies abroad. It remains to be seen whether this practice will continue as high-T_c applications are developed.

Finally, let me mention one application of the new discoveries that was totally unanticipated -- the introduction of the subject of superconductivity as part of the experimental science curriculum at the primary and secondary school level worldwide, and the consequent renewed interest by youth in science as a whole by allowing them to participate directly in an activity at the forefront of modern research. The new high-T_c superconductors, by virtue of their ease of synthesis and low-cost refrigeration, are readily available to schools in nations at every economic level and provide excellent tools with which to teach fundamental principles of solid state chemistry and the physics of electricity and magnetism. It all began with the fabrication and testing by magnetic levitation of 1-2-3 by a high school chemistry class in Gilroy, California,[34] in late May, 1987, four months before Bednorz and Mueller were awarded the Nobel Prize in Physics for the basic discovery! Since then, thousands of students throughout the world, not only in large countries, but also in small nations, some with political difficulties and others economically isolated (Northern Ireland and Cuba are two recent examples!), have repeated similar experiments as science projects. Perhaps, instead of any of the possibilities we have discussed here, the truly large applications of high-T_c will occur in entirely unforeseen areas uncovered by this soon-to-emerge generation of young scientists unfettered by the preoccupation of the present one with the old past concepts.

Summary

In this talk we have attempted to review important developments over the past year and point out topics likely to receive focus in the near future. Such an effort is by necessity subjective. The advances made in materials, especially the continuing discovery of new compounds, we find very encouraging. The physics of high-T_C is turning out to be extremely rich. The nature of the pairing mechanism still eludes us, but very rapid progress is being made in understanding the peculiar flux behavior in the copper oxide compounds. On the application front, developments of major economic consequence are still far in the future, but potential impact on narrower markets, such as magnetic field sensors, appears imminent.

Finally, I would like to thank the Instituto de Investigaciones en Materiales, UNAM, for their hospitality during the conference, and my friends and colleagues in Mexico, as well as those at the IBM Almaden Research Center, for numerous helpful discussions on the topics covered in this talk. I also want to thank Jim Russel, Ellen Feinberg and Paul Berdahl for providing the data contained in Table I.

TABLE I Summary of Worldwide High-T_C Institutional and Publication Activity as of December, 1988.

- Institutions carrying out full-time activity involving two or more people†.
  - USA: $\simeq$400
  - Non-USA: 800-900
  - Japan: $\simeq$100
- Publication submission and appearance activity (all figures approximate)‡.
  - High-T_C Update
    - 2700 addresses on direct mailing list, of these, 500 non-USA to more than 50 countries
    - > 300 addresses on electronic mail USA and worldwide
    - Currently receiving about 50 preprints per week, 50% from non-USA (represents a 45% increase over average rate of reception during first six months of 1988)
  - Westinghouse Bibliography of High-T_C Publications
    - > 5000 publications in open literature
    - Of these, $\simeq$750 are thin film related and their number is increasing faster than those on bulk materials.

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†Source: Jim Russel, Superconductivity Report.
‡Sources: Ellen Feinberg, High-T_C Update; Paul Berdahl, Lawrence Berkeley Laboratory.

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