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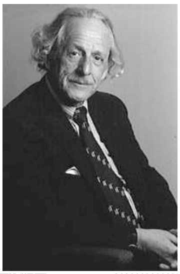

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EUGENE GARFIELD
INSTITUTE FOR SCIENTIFIC INFORMATION®
3501 MARKET ST., PHILADELPHIA, PA 19104

The 1987 Nobel Prize in Physics: Citations to K.A. Müller and J.G. Bednorz's Seminal Work Mirror Developments in Superconductivity

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The 1987 Nobel Prize in physics was awarded to two researchers, Karl Alex Müller and Johannes Georg Bednorz, in the field of superconductivity. According to ISI® data, their key paper, which has garnered them much acclaim as well as the award, shows an unusually rapid citation accumulation. Other aspects of this field are covered, including previous Nobels awarded for work in superconductivity, and a *Citation Classic®* commentary by Soviet physicist A.A. Abrikosov on type II superconductors.

For the seventh time in over 40 years, the physics prize has been awarded within two years of completion of the research recognized by the award. A scant five months elapsed between the publication of Johannes Georg Bednorz and Karl Alex Müller's seminal paper, "Possible high T_c superconductivity in the Ba—La—Cu—O system,"[1] and their Nobel nomination;[2] eight months later these two scientists from the IBM Zurich Research Laboratory, Rüschlikon, Switzerland, received the 1987 physics prize—the shortest time lag in Nobel history.

According to the Nobel committee, when Bednorz and Müller

> at last broke through all existing limits for superconducting materials, it was as a result of systematic work, deep insight and experience of structural problems in the physics and chemistry of the solid state (plus, one may assume, the intuition characteristic of the true scientist). Besides this, they had the audacity to concentrate on new paths in their research.[3]

The 1987 award has highlighted an extraordinary year in this area of physics. Bednorz and Müller's work has electrified the low-temperature research community—for it took scientists 62 years (from 1911 to 1973) to raise the temperature of superconducting materials 19.3 kelvin (K), from 4 to 23.3. Absolute zero on the Kelvin scale is equivalent to minus 273.15 degrees Celsius.

The 1973 achievement by J.R. Gavaler, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania,[4] remained unsurpassed until Bednorz and Müller's January 27, 1986, discovery.[5] The two researchers worked with a new class of superconductors (involving oxide-ceramic materials that are usually semiconductors) that hastened a further breakthrough to the 30 K plateau; less than a year later, in 1987, physicists measured temporary superconductivity phenomena between 200[6] and 500[7] K.

The 1987 physics prize marks the second year in a row that Nobel Prizes have been awarded to personnel at the IBM Zurich Research Laboratory. In 1986 Gerd Binnig and Heinrich Rohrer won for their 1981 invention of a tunneling electron microscope.[8]

The discovery of higher-temperature superconductors widens their use in diverse applications—such as medicine, transportation, oil exploration, energy storage, nuclear research, and computers.

Citations to Bednorz and Müller's most-cited work mirror closely the relative calm

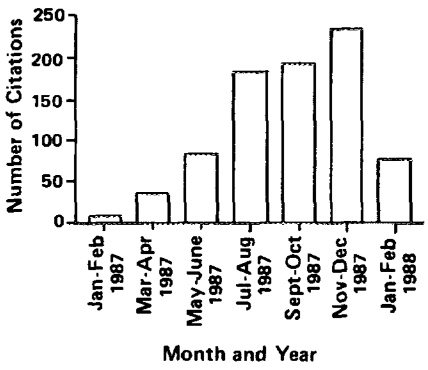


Figure 1: MOST-CITED PAPER. Bimonthly citations to J.G. Bednorz and K.A. Müller's "Possible high T_c superconductivity in the Ba—La—Cu—O system," *Z. Phys. B—Condens. Matter* 64:189-93, 1986.

and the subsequent explosive advancements in this specialized field of physics over the past two years. As of early 1988 their paper has garnered over 800 cites. Figure 1 depicts the growth of citations to their paper over a 14-month period.

"It is very satisfying that our work has generated so much interest and has been recognized by the Swedish committee.... We never thought about the prize," commented laureate Müller in a *Physics Today* interview. "We only wanted to go beyond the intermetallic A15 compounds."[9] Table 1 lists their most-cited works.

Bednorz and Müller's breakthrough came from a "small science" project in an era of multimillion-dollar, frequently government-sponsored efforts. Their tools were simple, consisting of a standard cooling flask, mortar and pestle, a scale, a high-temperature oven, some voltameters, and a personal computer. For scientific establishments in developing Third World countries, this is a heartening example of world-class research on a limited budget. According to Nobel laureate Abdus Salam of the Third World Academy of Sciences, Trieste, Italy, "Any nation can still join this potentially rich yet still-open quest if it can afford just $30,000 for equipment and money for the physicists' salaries."[10]

The portent of this discovery for small science is significant. Even laboratories in small schools and institutions everywhere can conduct basic research that has direct relevance to new technology.

Biographical Sketches of the Nobel Laureates

Müller was born in 1927 in Switzerland and received his PhD in physics at the Swiss Federal Institute of Technology, Zurich, in 1958. He joined the IBM Zurich Research Laboratory in 1963, where he presently works in solid-state physics.

Bednorz was born in the Federal Republic of Germany (FRG) in 1950. In 1982 he also received his doctorate from the Swiss Federal Institute of Technology. In that same year he joined the IBM lab at Rüschlikon.

The two are corecipients of several prestigious awards, including the 1987 Fritz London Memorial Award of the University of California, Los Angeles; the 1987 Dannie Heineman Prize of the Göttingen Academy of Sciences, FRG; the 1987 Robert-Wichard-Pohl Prize of the German Physical Society; the 1988 Hewlett-Packard Europhysics Prize; the 1986 Marcel Benoist Foundation Prize of the Marcel Benoist Foundation for the Advancement of Scientific Research; and the 1987 Viktor-Moritz-Goldschmidt Prize of the German Mineralogical Society.

Physics Phenomenon

Superconductivity remains an only partially understood effect—despite its discovery in the early twentieth century. Basically, superconductivity is a phenomenon in which materials lose all their resistance to electricity. Therefore, such materials can carry current without producing any wasteful heat. Scientists have compiled a list of four criteria that help identify a superconducting material: (1) a total loss of resistance to a direct current; (2) expulsion of a magnetic field from the material's interior (also called the "Meissner/Ochsenfeld effect" after its discovery in 1933 by Walter Meissner and R.

Table 1: HIGHLY CITED WORKS OF MÜLLER AND BEDNORZ. Papers with Karl Alex Müller and/or Johannes Georg Bednorz as first author or coauthor. A = number of citations. B = bibliographic citation. The *SCI*® research fronts to which the paper is core are included in parentheses.

A	B
806	**Bednorz J G & Muller K A.** Possible high T_c superconductivity in the Ba—La—Cu—O system. *Z. Phys. B—Condens. Matter* 64:189-93, 1986. (87-0892)
151	**Muller K A & Berlinger W.** Static critical exponents at structural phase transitions. *Phys. Rev. Lett.* 26:13-6, 1971. (73-0957)
143	**Brout R, Muller K A & Thomas H.** Tunnelling and collective excitations in a microscopic model of ferroelectricity. *Solid State Commun.* 4:507-10, 1966.
128	**Simanek E & Muller K A.** Covalency and hyperfine structure constant A of iron group impurities in crystals. *J. Phys. Chem. Solids* 31:1027-40, 1970. (85-6017, 84-7549)
125	**Muller K A, Berlinger W & Waldner F.** Characteristic structural phase transition in perovskite-type compounds. *Phys. Rev. Lett.* 21:814-7, 1968.
101	**Bednorz J G, Takashige M & Muller K A.** Susceptibility measurements support high-T_c superconductivity in the Ba—La—Cu—O system. *Europhys. Lett.* 3:379-85, 1987. (87-0892)

Ochsenfeld, Physical-Technology State Institute, Berlin, Germany);[11] (3) high reproducibility of the phenomenon; (4) high stability of the phenomenon (superconductivity observed in the sample for periods of days or weeks in the proper environment).

All four of these criteria have been met in some of the new copper oxides[12] (with combinations of barium, strontium, fluorine, lanthanum, yttrium, and oxygen) at the 90 to 100 K range; zero resistivity and a partial Meissner/Ochsenfeld effect have been seen at 225 K; partial resistivity has been seen at 290 K; a drop in resistance and some other faint indications of superconductivity have been observed at 360,[13] 400,[14] as well as 500[7] K. The new oxide superconductors, such as those discovered by Bednorz and Müller, are type II superconductors (materials that exhibit two separate threshold levels in the expulsion of an applied magnetic field)—always alloys and compounds, excepting the rare-earth elements niobium and vanadium.[15]

The current focus on oxide-ceramic materials is only a small part of a very large field that encompasses research in superconductivity. Table 2 lists the 1986 research fronts explicitly related to the subject. The C2-level multidimensional scaling map on superconductivity in Figure 2 shows clusters of research fronts, rather than clusters of journal papers, as would be the case in a C1-level map. Twenty-six research-front clusters on this map show the state of superconductivity research during the year of Bednorz and Müller's breakthrough. This map demonstrates that most of the research emphasis was on theories of how particles (such as electrons, protons, and neutrons) interact during the superconducting state. The map's center is defined by research front #86-0707, entitled "Heavy fermion superconductors, heavy fermion superconductivity, and superconducting UBe_{13}." A fermion is an atomic particle whose spin quantum number is an odd multiple of one-half.[16]

How Superconductivity Heated Up

There have been three antecedent Nobel awards in physics concerning superconductivity. It is interesting to note that low-temperature research dates from the nineteenth century, but it wasn't until the early part of the twentieth century that scientific methods and apparatus allowed for the intense study of phenomena occurring near absolute zero.

Kamerlingh-Onnes

One of the premier researchers in low-temperature physics at the turn of the century was Heike Kamerlingh-Onnes (1853-1926), University of Leiden, The Netherlands. He is widely regarded as the grandfather of superconductivity. He and his associates discovered the phenomenon in April 1911 while working with a sample of supercooled mercury at 4 K (usually liquid at room temperature, the sample was frozen

Table 2: SUPERCONDUCTIVITY RESEARCH FRONTS. The 1986 *SCI®/SSCI®* research fronts on superconductivity. A = number of core papers. B = number of citing papers.

Number	Name	A	B
86-0128	Heavy fermion superconductivity and anisotropic magnetic behavior	9	91
86-0130	Magnetic field penetration depth in superconducting UBe_{13} and magnetic superconductors	10	63
86-0424	Superconducting transition region in $TaSe_3$, superconductivity in amorphous Cr films, and quasi one-dimensional conductors	2	11
86-0522	Superconducting networks, phase transitions in a disordered granular superconductor, and two-dimensional array of Josephson junctions	2	17
86-0524	Superconducting $BaPb_{1-x}Bi_xO_3$ (BPB) thin films, bipolaronic superconductivity, and defects in amorphous selenium	21	173
86-0594	Heavy fermion superconductivity and heavy fermion behavior	3	33
86-0600	Electron-phonon superconductors and electron-phonon interaction in metals	8	125
86-0616	Enhanced superconductivity in quasi two-dimensional systems	2	26
86-0707	Heavy fermion superconductors, heavy fermion superconductivity, and superconducting UBe_{13}	49	462
86-0727	Superconductivity in granular films and electric conduction in copper gallium telluride thin films	4	85
86-0889	Thin superconducting Nb films and two-dimensional superconductivity	2	30
86-1191	Superconducting films and nonequilibrium superconductors	4	30
86-1467	High T_c A15 materials, superconducting NbN, and universal disorder-induced transition in the resistivity behavior	14	68
86-2094	Organic conductors and superconducting BEDT-TTF salts	45	293
86-2449	Antiferromagnetic phase transition and superconducting ternary compounds	5	29
86-3238	Fine-grained Pb alloy films for Josephson integrated circuits	6	36
86-3311	Magnetic heavy fermion superconductor URu_2Si_2	4	30
86-3470	Layered metals and upper critical field in superconducting superstructures	3	20
86-3678	Superconducting vibrating reed in a longitudinal magnetic field and flux-line lattice in type II superconductors	5	24
86-4044	Superconducting ternary molybdenum chalcogenides and phase field of the chevrel phase $PbMo_6S_8$	3	44
86-4118	Superconducting superlattices, upper critical field, and quasiperiodic metallic multilayers	7	61
86-5081	Rare earth metals, electronic structure of solids, and heavy fermion superconductor UPt_3	4	36
86-5161	Superfluid He-3, and thin superconducting films	6	39
86-5241	One-dimensional metals, 2-band Anderson type model, and electron-electron interaction	4	40
86-5553	Tunneling systems in metals and superconducting temperature in BCC niobium-titanium alloys	10	76
86-6470	Upper critical field, thin superconducting films, and magnetic heavy fermion superconductor URu_2Si_2	4	56
86-6947	Josephson tunnel junctions and quantum mechanical flux band dynamics of a superconducting weak link constriction ring	2	22
86-6992	Superconducting tunnel junctions and nonequilibrium superconductors	3	23
86-7284	Superconducting films and Josephson point contact	2	17
86-7467	Superconducting heavy fermion systems, magnetic field-induced superconductivity, and antiferromagnetic superconductors	2	26
86-8182	Heavy fermion superconductivity and magnetic field penetration depth in the heavy electron superconductor UBe_{13}	2	34
86-8235	Superconductivity in Pd-Ag-H alloys	2	12
86-8311	Molybdenum cluster chalcogenides and superconducting chevrel phases	2	13

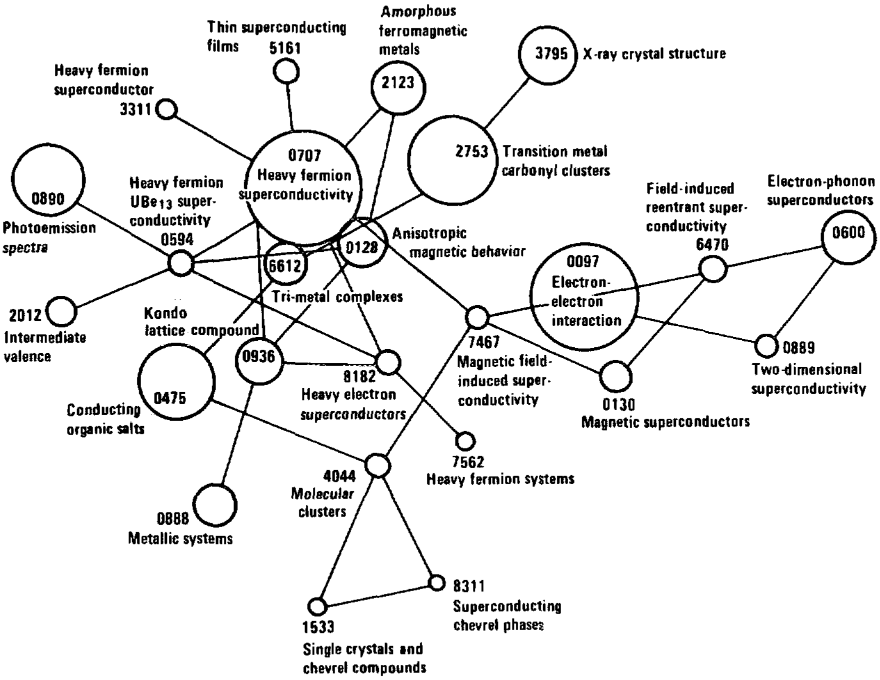
solid).[17] Kamerlingh-Onnes was awarded the Nobel Prize in 1913 for his low-temperature research.

From the 1930s into the early 1950s scientists were able to raise the superconducting temperature of materials to 18 K. Developments in the understanding of the how and why of superconductivity reached a milestone in 1957 with two papers presenting two major breakthroughs: the Bardeen-Cooper-Schrieffer (BCS) microscopic theory of the superconducting state in terms of "Cooper pairs" of electrons[18] and the Abrikosov theory of type II superconductivity.[19]

Bardeen—Cooper—Schrieffer

In 1972 John Bardeen, University of Illinois, Urbana; Leon N. Cooper, Brown Uni-

Figure 2: SUPERCONDUCTIVITY RESEARCH. A multidimensional scaling map for C2-level research front #86-0057. The size of the circles is determined by the total number of cites received by the core papers in the research front.

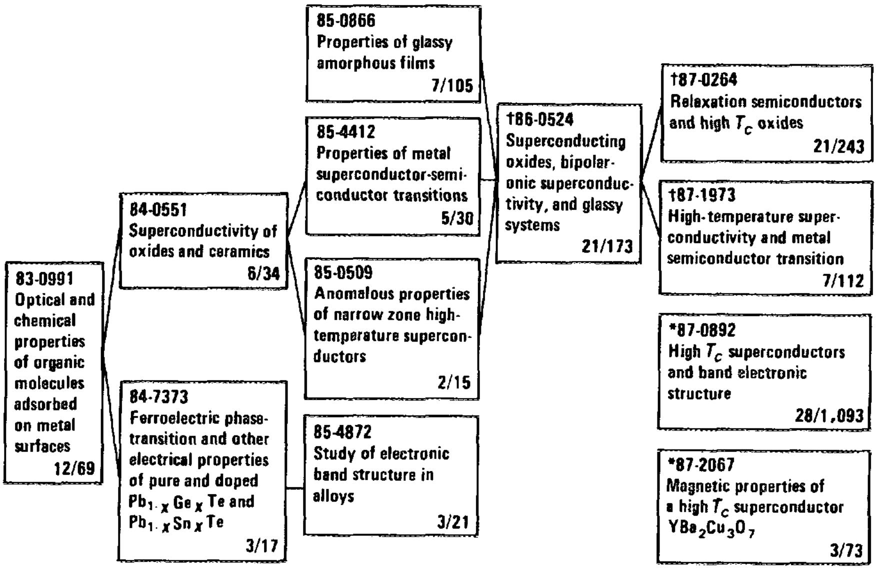


versity, Providence, Rhode Island; and Robert J. Schrieffer, now at the Institute of Theoretical Physics, University of California, Santa Barbara, were awarded the physics prize for their famous "BCS" theory. This hypothesis contains a general theoretical framework that describes superconductivity in terms of a condensation of electron pairs, and thus the theory is independent of the specific nature of the attractive forces involved. Indeed, the BCS theory applies not only to conventional superconductors, but also applies to superfluid helium 3, to superconductivity in neutron stars as well as in atomic nuclei. In each of these cases, the transition temperatures (when the material goes superconductive) vary from millidegrees to millions of degrees kelvin.[20]

For superconducting metals the BCS theory basically posits that an electron moving through a metal's crystal lattice tends to distort or "pucker" the elastic lattice slightly because the negatively charged electron attracts nearby positively charged nuclei of the lattice. A second passing electron will be attracted to the excess positive charge created by the higher density of ions in this puckered region and is thereby indirectly attracted to the first electron. This weak attractive force binds the two electrons into a so-called "Cooper pair." The paired electrons have opposite spins and equal and opposite momenta, so that the net spin and net momentum are both zero. One result of this is infinite electrical conductivity—a superconductive current carried by Cooper pairs is believed to persist forever.[21] This classic paper, entitled "Theory of superconductivity,"[18] has been explicitly cited over 2,800 times since its publication in 1957.

The BCS theory, prior to Bednorz and Müller's discovery of superconductivity in basically semiconducting materials, was thought to be correct for all materials. The theory now seems to hold for those materials that are superconductive below 50 K, but

Figure 3: RECENT DEVELOPMENTS IN SUPERCONDUCTING MATERIALS. Historiograph showing developments in this research. Numbers of core/citing papers are indicated at the bottom of each box. Asterisks (*) indicate research fronts in which Bednorz and Müller have core papers; research fronts that they cite into are indicated by daggers (†).



for those materials that show superconductivity above 90 K, a different, unknown mechanism appears to be operating.[21] However, Schrieffer disagrees with this assessment:

> There is growing evidence that the so-called BCS theory is likely to apply for the oxide high-temperature superconductors such as that discovered by Bednorz and Müller as well as the higher-temperature oxides that have been discovered more recently. At issue here is, what is the specific mechanism of attraction between the electrons? It is my belief that the antiferromagnetic correlations in the copper-oxide plane play a crucial role in providing the attraction. However, regardless of what the attraction might be, a condensation as in the original BCS theory, I believe, is still fundamentally the underlying mechanism producing the effect. Thus, it is essential [to] distinguish between the general theory of superconductivity provided by our original work and the specific mechanism of attraction which can be encompassed by the general theory. This distinction has often been ignored or confused in the literature for more than 25 years.[20]

Abrikosov

The second key paper that appeared in 1957 was authored by A.A. Abrikosov, L.D. Landau Institute of Theoretical Physics, Academy of Sciences of the USSR, Moscow. Entitled "On the magnetic properties of superconductors of the second group,"[19] this paper has garnered 1,300 cites to date. In a *Citation Classic®* commentary[22] on this work, Abrikosov writes that

> My article was published in 1957. But it was only in the early 1960s that it was "discovered" by physicists in connection with the creation of high critical field alloys. I am not surprised by the frequent citation of my article. The superconductors of the second kind with high critical fields are the basis for the construction of

superconducting magnets, which are at present the main technical application of superconductivity.

Josephson

In 1962 Brian D. Josephson, University of Cambridge, UK, published a paper entitled "Possible new effects in superconductive tunnelling."[23] This work, cited in over 650 subsequent publications, presented his theory of how electrons tunnel through conductors to become superconductors. One of the theory's tenets is that if two superconductors are separated by an insulating film that forms a low-resistance junction between them, Cooper pairs can tunnel from one side of the junction to the other. This theory has great import in the computer industry where superfast switching elements exhibit the "Josephson effect." Josephson won the Nobel Prize in 1973 for this work. However, the eponym attributed to this phenomenon undoubtedly will be remembered long after the award is spent.[24]

Goldanskii

Tunneling in temperatures near absolute zero is not a phenomenon singular to superconductivity but also occurs in chemical reactions. Vitali I. Goldanskii, Institute of Chemical Physics, Academy of Sciences of the USSR, recently reviewed this subject in *Scientific American* in a paper entitled "Quantum chemical reactions in the deep cold."[25]

The idea of looking for superconductivity in the class of ceramics called perovskites (a structure type in which physicists have great interest, since slight distortions away from its standard cubic symmetry by outside influences may result in ferroelectric properties) occurred, according to Müller, while he was sitting in the garden of a medieval monastery in Sicily during the summer of 1983.[26] Müller's moment of inspiration led to his work with Bednorz on various oxide materials in late 1983. These efforts, however, did not yield immediate results.

Their breakthrough came later, from Bednorz reading about ceramic experiments, published in 1985, by the chemists Claude Michel, L. Er-Rakho, and Bernard Raveau, Laboratory of Crystallography, Chemistry, and Physics of Solids, Caen University, France.[27] They created and studied a compound of lanthanum, barium, copper, and oxygen. However, the French researchers did not study the sample for superconductivity.[28] In January 1986 Bednorz and Müller did so and discovered that it had superconductive properties—although it took an improved version (using different proportions of the elements[29] as well as a different manufacturing process[26]) in April 1986 for the sample to exhibit superconductivity at the then-unprecedented temperature of 35 K. Figure 3 is a historiograph highlighting research activity in metal-oxide ceramics from 1983 on. It is interesting to note that Bednorz and Müller's "superstar" paper appears as a *citing* work rather than a *cited* one in 1986. The full impact of the journal article on the field of superconductivity came later, in 1987.

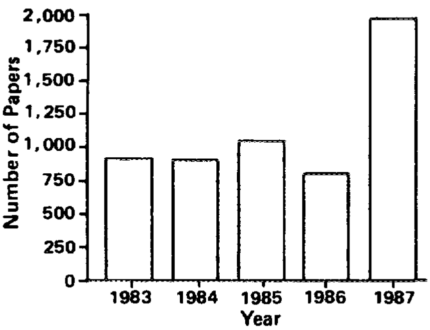
Worldwide Impact of Bednorz and Müller's Paper

When the *Zeitschrift für Physik B—Condensed Matter* published their paper, it was first greeted with widespread skepticism. The physics literature is cluttered with preliminary and unsubstantiated claims for high-temperature superconductivity. However, in the words of the Nobel committee, this paper "was the start of an avalanche. Hundreds of laboratories all over the world were soon at work with materials similar to those of Bednorz and Müller."[3]

We can trace the influence of Bednorz and Müller's classic paper directly to superconductivity research efforts taking place at centers all over the world.

Since January 1987 temperature achievements have exploded, with monthly press conferences reporting preliminary experimental results. The press conferences are held because the flurry of experiments has outpaced the rate of publication for tradi-

Figure 4: SUPERCONDUCTIVITY PAPERS. Annual distribution of papers reporting on superconductivity over the past five years.



tional journal articles, which often take a year or more to see print. Instead, researchers are sending papers—"preprints"—directly to each other. In response there have been initial efforts to publish solid-state physics journals more quickly. I might add, however, that the preprint phenomenon is not new to physics—it is accepted practice.

To ascertain the impact of Bednorz and Müller's discovery on the superconductivity literature, we used ISI®'s *SCISEARCH®* database. Figure 4 depicts our findings—it shows that from 1983 to 1986 an average of 900 papers were published; in 1987 that figure zoomed to 2,000—spurred, in part, by Bednorz and Müller's primordial paper.

Research laboratories in over 40 nations on all continents (excepting Antarctica) have progressively raised the temperature for superconductivity. According to ISI data, the top 10 countries that have published papers on superconductivity are (in descending order) the US, Japan, the USSR, the FRG, the People's Republic of China, France, India, Switzerland, the UK, and Canada. Other nations include South Korea, Israel, Belgium, Egypt, Brazil, Taiwan, Libya, Greece, Argentina, Poland, South Africa, Yugoslavia, Mexico, Sweden, Saudi Arabia, and Hungary.

Superconductivity's Warm Future

One benefit of the almost fourfold increase in the threshold temperature for the onset of superconductivity is that the new materials are now more accessible and less costly to use. In the past superconductors had to be cooled to much lower temperatures with liquid helium, which costs about $2.90 (US) per liter. The new metal oxides are able to use the more abundant, and cheaper, liquid nitrogen, which is about 6 cents per liter.[30] Despite difficulties with the fragility and brittleness of the new oxide-ceramic materials, scientists are making progress in the manufacture of flexible wire, the use of the superconducting new materials as coatings,[31] as well as the use of explosively generated shockwaves in the creation of ceramic/metal alloys.[32]

If 1987 activities are any indication, 1988 will see advances in superconductivity of similar magnitude. Already in the early months of this year laboratories in Japan, the US, and Europe have achieved a further temperature breakthrough to 120 K using copper oxides that contain the elements bismuth, calcium, and thallium.[33]

This essay illustrates what can happen when two scientists think unconventionally. However, this is just one of numerous examples where researchers defied the assumptions of their day. One old myth that comes to mind is that the noble gases are inert. Neil Bartlett and N.K. Jha, University of British Columbia, Vancouver, Canada, discovered in 1962 that xenon was reactive with fluorides.[34] Bednorz and Müller's decision to look into semiconducting materials for superconductivity phenomena reminds us again that today's common wisdom was yesterday's folly.

* * * * *

My thanks to Peter Pesavento for his help in the preparation of this essay.

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