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The Most-Cited 1987 Physical-Sciences Articles: Superconductivity Supersedes Superstrings

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This study of the 100 physical-sciences papers published in 1987 and most cited in 1987 and 1988 reveals a near total preoccupation with the revolutionary advances in superconductors and superconductivity reported that year. The level of activity in this field was so high that it virtually excluded other fields of study from our Bibliography. The subjects that ordinarily appear in our physical-sciences studies—such as superstring theory, high-energy physics, and planetary sciences—are not present in great numbers. In some fields, such as studies of the ozone layer, papers in this year's Bibliography are wholly absent.

Superconductivity Takes Charge

As regular readers of *Current Contents*® know, ISI® annually identifies papers in chemistry, the physical sciences, and the life sciences that become highly cited within one to two years after publication. The 1987 life-sciences articles most cited in 1987 and 1988 was the latest essay in this series.[1] Many of these papers are also reviewed individually in *The Scientist*®'s "Hot Articles" feature, which tracks publications that are highly cited in their first year. All such "instant" *Citation Classics*® are usually indicators for new, rapid-growth fields.

Since the series began about 19 years ago,[2] we've found that the top 50-100 papers with immediate high impact in a given field have pointed to a number of major developments during the year examined. Areas new to these lists emerged gradually, and familiar areas were slow to be displaced. But this comfortable and predictable pattern has been dramatically overturned by the top 1987 physical-sciences papers. They show an explosion of activity and interest in a single area—superconductivity—that is unmatched in previous studies. Like the new materials with remarkable electrical properties they describe, these papers seem to have lost all resistance to citation!

Of the 100 listed in the Bibliography, 87 were on superconductors and superconductivity. Even when we examine the next 50 most-cited papers, superconductivity still dominates with another 38 papers. The *non*superconductivity papers in this study deal with a variety of subjects that have been identified in previous essays, including string theory, high-energy physics, and supernovas, which are discussed below.

In our study of the 1986 physical-sciences papers most cited in 1986 and 1987,[3] only one paper on superconductivity appeared. Incidentally, it was the one describing the Nobel Prize winning breakthrough by Johannes G. Bednorz and Karl A. Müller, IBM Zurich Research Laboratory, Rüschlikon, Switzerland.[4] At the time, its two-year citation count of 664 was the highest ever recorded for a paper included in our annual physical-sciences survey. That record was surpassed by the top *three* papers in this year's study!

Higher Citation Levels for Superconductivity Research

Another interesting difference between this year and last year's study of 1986 papers is the average number of citations the articles in the study received. In this year's list, they were cited about 165 times each—62 times in 1987 and 103 times in 1988. Additionally, the papers received an average of 79 citations in 1989.

In comparison, the average citations per paper in last year's survey was 66 (14 citations in 1986 and 52 in 1987). Figure 1 shows a graph comparing the average in this year's study to previous years. The median in this study is 121 citations, compared with 51 last year.

Thus, it is necessary to remind readers that the top papers ranked solely by total citations are obviously not the *only* ones of significance produced within this time frame. For example, in the list of hot 1986 papers,[3] superstring theory was the dominant subject, although it accounted for only 38 of 106 papers (about 35 percent). The "String Quartet" of Joseph Henry Laboratories, Princeton University, New Jersey—David J. Gross, Jeffrey A. Harvey, Emil Martinec, and Ryan Rohm—contributed four of these papers, which received over 490 citations. This year, only five articles on superstrings appear, two of which are by Martinec.

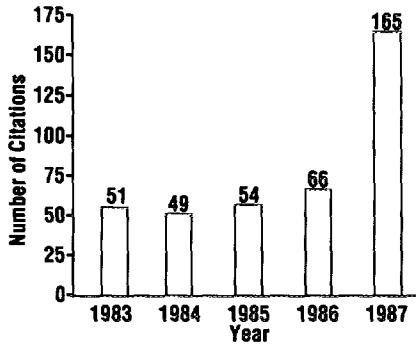
The markedly high citation thresholds achieved by supercited superconductivity research has excluded string theory and other important subjects in the physical sciences that typically appear in our studies. Of course, these research areas still produce high impact work, and these would be represented on a longer list of the top 250-500 most-cited physical-sciences articles of 1987.

Superconductivity Heats Up

Superconductivity is a phenomenon in which materials lose their resistance to the conduction of electricity. Known since the early years of this century, the features that characterize this phenomenon have always been thought to exist only at exceedingly low temperatures—just a few degrees above absolute zero (−273.15 degrees Celsius).

In fact, prior to the work of Bednorz and Müller, the "high-temperature record" for superconducting was 19.3 kelvin (K), achieved in 1973 by J.R. Gavaler, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.[5] Bednorz and Müller's work led to materials that become superconductors at 30 K,[6] while more recent work has described temporary superconducting phenomena at temperatures as high as between 200[7] and 500 K.[8] A more in-depth discussion of the development of superconductivity research may be found in our discussion of the 1987 Nobel Prize in physics.[9]

Figure 1: Average number of two-year citations to the most-cited physical-sciences papers, 1983-1987.



Both Bednorz (with three papers) and Müller (with four) are represented several times in this year's Bibliography. Another Nobelist whose work appears this year is Philip W. Anderson, Department of Physics, Princeton University, who was awarded the physics prize in 1977. Of Anderson's three papers, "The resonating valence bond state in La_2CuO_4 and superconductivity" is the fourth most-cited paper in the Bibliography, with 653 citations (211 in 1987 and 442 in 1988).

Highest Impact Papers and Most Prolific Authors

The most-cited paper is by M.K. Wu and colleagues, Department of Physics, University of Alabama, Huntsville, and by P.H. Hor and colleagues at the Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Texas. Their paper received 758 citations in 1987 and 1,096 more in 1988 for a two-year total of 1,854. In 1989, it received 711 citations. The authors report the observation of superconductivity in a new yttrium-barium-copper-oxygen compound at 93 K at ambient pressure in what they refer to as "a simple liquid-nitrogen Dewar" jar.

C.W. Chu, Hor's coauthor and colleague at the University of Houston, was also the

primary author on the third most-cited paper, which reported "Evidence for superconductivity above 40 K in the La-Ba-Cu-O compound system." It was cited 684 times (400 in 1987 and 284 in 1988). And, with six papers in the Bibliography, Hor and another University of Houston coauthor, R.L. Meng, were among the most prolific authors in this year's study.

One of the "superstars" of previous physical-sciences studies—at least in terms of number of papers—is virtually absent from this year's Bibliography: Edward Witten, Joseph Henry Laboratories, Princeton University. A 1982 MacArthur fellow, Witten has written extensively on superstring theory and has consistently been among the most prolific authors in our physical-sciences studies over the last few years. Last year's study,[3] which included eight of his papers, was no exception. But this year's Bibliography includes just one paper by Witten—on toroidal compactification of heterotic string theory—coauthored with K.S. Narain and M.H. Sarmadi, Rutherford Appleton Laboratory, Chilton, UK.

It was R.J. Cava and colleagues, AT&T Bell Laboratories, Murray Hill, New Jersey, who published the most papers this year (10). The paper by Cava and colleagues on "Bulk superconductivity at 91 K in single-phase oxygen-deficient perovskite $Ba_2YCu_3O_{9-\delta}$," was the second most cited, with 835 citations (391 in 1987 and 444 in 1988). Their paper on "Bulk superconductivity at 36 K in $La_{1.8}Sr_{0.2}CuO_4$" was the fifth most-cited paper, with 403 citations in 1987 and 166 in 1988.

Astronomy and High-Energy Physics

Other papers of interest in this year's study involve theoretical and experimental high-energy physics and some astronomical observations concerning the nearby supernova that took place in 1987.

The paper reporting "Observations of B^0-$\bar{B}^0$ mixing," by H. Albrecht, German Electron-Synchrotron (DESY), Hamburg, Federal Republic of Germany, and colleagues, received 91 citations (15 in 1987, 76 in 1988). The decay of B mesons were produced using the ARGUS detector at the DORIS II storage ring at DESY. The group's observations support the conclusion that the mixing of B mesons is "substantial," a result that has been labeled "one of the most surprising experimental particle-physics results in the last few years" by Paula J. Franzini, European Organization for Nuclear Research (CERN), Geneva, Switzerland.[10] Franzini speculates that the results could imply the existence of a whole new family of subatomic particles.

A paper by R. Machleidt, Los Alamos National Laboratory, New Mexico, and the University of California, Los Angeles, and colleagues concerned "The Bonn meson-exchange model for the nucleon-nucleon interaction." Cited 101 times (23 in 1987 and 78 in 1988), the model yields definite predictions concerning meson-nucleon interaction and is of great value in quantum chromodynamics and the behavior of various particles.

Moving from subatomic particles to exploding stars, some of the papers in this year's Bibliography dealt with the supernova observed on February 24, 1987, in the Large Magellanic Cloud, a companion galaxy to our own Milky Way. In a paper that was cited 157 times (59 times in 1987 and 98 times in 1988), R.M. Bionta, Lawrence Livermore National Laboratory, Livermore, California, and colleagues described their "Observation of a neutrino burst in coincidence with supernova 1987A in the Large Magellanic Cloud." The authors report that the Irvine-Michigan-Brookhaven water Cherenkov detector, located deep within the Morton-Thiokol salt mine in Fairport, Ohio, signaled the release of a burst of neutrino radiation coinciding with the explosion of the star Sk-69 202 (later dubbed SN 1987A, for "the first supernova of 1987").

The same neutrino burst was also recorded by the Kamiokande-II water Cherenkov detector in Tokyo, Japan. K. Hirata, University of Tokyo, and colleagues reported their findings in a paper entitled "Observation of a neutrino burst from the supernova SN1987A," which was cited 183 times (71 in 1987 and 112 in 1988). Both groups detected the neutrino burst on February 23—*before* the supernova was sighted optically.

Institutions and Journals of the Supercited Papers

Owing in part to the prolific output of Cava and colleagues, AT&T's Bell Laboratories was the institution with the most papers listed (20). IBM's various laboratories and research centers are represented by 13 papers, while the Argonne National Laboratory, Illinois, was third with 7. As one might expect, given the virtual absence of string research from this year's list, the institution that topped last year's chart of 1986 papers on the strength of its superstring research, Princeton University, had "just" six papers a year later.

In fact, the displacement of superstrings by superconductivity had a number of effects on this year's statistics. Last year, for the first time ever, *Physical Review Letters* appeared in second place in our journal rankings. It was replaced in first place by *Nuclear Physics B*, which published most of the work on superstrings that so dominated last year's study. This year, however, *Physical Review Letters* has regained its customary first-place position, having published 34 of the papers listed. *Nuclear Physics B*, which had 26 papers last year, has just 6 this year. Table 1 lists all 18 journals that published the papers in this year's Bibliography.

Interestingly, the *Japanese Journal of Applied Physics Part 2* was third in this year's list with eight papers, all on superconductivity. This English-language journal has appeared only once before, in our study of the most-cited 1980 physical-sciences papers. Thus, its appearance in this study perhaps indicates Japan's strengths in superconductivity research. This can also be seen in Table 2, which lists the nationalities of the 100 papers in the Bibliography, defined by the institutional addresses of the authors. Although the US occupies its customary place at the top of the rankings with 79 papers, Japan is second with 12; last year, Japan had 4 papers on the list.

The USSR is represented by one paper on B meson mixing. Last year, it was represented by nine papers, most of which were on Halley's comet and string theory. As we've stated, these and other physical-sciences subjects have been overshadowed in this study by 1987 superconductivity studies, none of which listed authors from the USSR.

Table 1: The 18 journals that published the papers listed in the Bibliography. The numbers in parentheses are the 1987 impact factors for the journals. (The 1987 impact factor equals the number of 1987 citations to a journal's 1985-1986 articles divided by the total number of articles published by the journal during that same period.) Data were taken from the 1987 *JCR®*. The figures at the right indicate how many papers from each journal appear in the Bibliography.

Journal	Number of Papers
Phys. Rev. Lett. (6.5)	34
Phys. Rev. B—Condensed Matter (3.0)	18
Jpn. J. Appl. Phys. Pt. 2 (N/A)	8
Nature (15.0)	7
Nucl. Phys. B (6.1)	6
Solid State Commun. (1.7)	5
Appl. Phys. Lett. (3.2)	4
Science (14.3)	4
Europhys. Lett. (3.0)	2
Mater. Res. Bull. (0.9)	2
Phys. Lett. A (1.6)	2
Z. Phys. B—Condens. Matter. (3.6)	2
J. Amer. Chem. Soc. (4.3)	1
Phys. Lett. B (3.6)	1
Phys. Rep.—Rev. Sect. Phys. Lett. (9.7)	1
Phys. Rev. D—Part. Fields (2.4)	1
Physica A (1.0)	1
Rev. Mod. Phys. (16.2)	1

The number of authors per paper was also affected by the lack of superstring research. As we noted last year, papers on string theory usually have only a handful of authors. The dearth of such papers this year, as well as the appearance of a few high-energy physics papers—which can have as many as 100 or more authors—brought the average number of authors per paper up.

As Table 3 shows, one paper each had 79, 37, 23, and 15 authors, respectively. Two had 13. On the other end of the scale, 44 papers had four authors or less; that's only about half the number of papers that had four authors or less last year. Although the average number of authors per paper had been steadily declining since its peak of 11 for the 1983 study, the average of 7 for this year is nearly double last year's average.

Table 2: National locations of the institutional affiliations listed by authors in the Bibliography, according to total papers (column A). B=number of papers coauthored with researchers from institutions in other countries. C=national locations of institutions listed by coauthors.

Country	A	B	C
US	79	14	Belgium, Canada, France, FRG, Japan, Poland, Sweden, Switzerland, UK, USSR, Yugoslavia
Japan	12	2	US
Switzerland	8	5	France, FRG, Israel, US
France	5	3	Switzerland, US
Canada	4	3	FRG, Sweden, US, USSR, Yugoslavia
FRG	4	4	Canada, Sweden, Switzerland, US, USSR, Yugoslavia
UK	3	3	Poland, US
Belgium	1	1	US
India	1		
Israel	1	1	Switzerland
Poland	1	1	UK, US
Sweden	1	1	Canada, FRG, US, USSR, Yugoslavia
USSR	1	1	Canada, FRG, Sweden, US, Yugoslavia
Yugoslavia	1	1	Canada, FRG, Sweden, US, USSR

Table 3: The number of authors per paper for the 1987 physical-sciences articles most cited in the *SCI®*, 1986-1988.

Number of Authors per Paper	Number of Papers
79	1
37	1
23	1
15	1
13	2
11	2
10	6
9	6
8	10
7	9
6	6
5	11
4	15
3	17
2	4
1	8

Research Fronts

Further proof that the papers in this year's list are on the cutting edge of research is shown in Table 4, which lists the 1987 and 1988 research fronts that have at least four of the papers from the Bibliography among their core documents. ISI's research fronts are identified when pairs of core papers (from any year) are cited together by papers from the current year.

There are 45 papers listed that are core to both 1987 and 1988 research fronts; 3 are core to 1987 research fronts only, while 41 papers are core only to 1988 research fronts. The code numbers for these research fronts follow the references in the Bibliography. Only 11 papers are not included in the core of any research front.

Unsurprisingly, Table 4 is dominated by superconductivity: 12 of the 13 fronts include the term in their titles. Only one front is concerned with superstrings, down from four fronts last year. One of the largest fronts both in terms of citing and core documents is the 1987 front on "High T_c superconductors, band electronic structure, and doped orthorhombic La_2CuO_4" (#87-0892). Twenty-four of the 28 papers forming the core of this front, identified by over 1,093 published (citing) papers, are found in the Bibliography.

Although this is certainly a large research front, it is not unusual in this study. For example, "High T_c superconductivity, pairing interaction in two-dimensional CuO_2, and antiferromagnetic spin fluctuations" (#88-0934) comprises 843 citing papers (10 of its 17 core papers appear in the Bibliography); "High T_c superconducting thin films, pulsed laser deposition, and RF magnetron sputtering using single CO" (#88-0179) has 802 citing papers (8 of its 43 core papers are listed). Four of the other superconductivity fronts each include 500 or more current papers.

The only research front in Table 4 that does not concern superconductivity is the 1988 front entitled, "Four-dimensional heterotic string models, superstring solutions, and multi-loop twist field correlation-functions for Zn orbifolds" (#88-1072). The most-cited of these papers, with 95 citations (15 in 1987 and 80 in 1988), is entitled "Four-dimensional superstrings," by I. Antoniadis, CERN, and colleagues.

Table 4: The 1987 and 1988 ISI® research fronts that include at least four of the most-cited 1987 physical-sciences papers as core documents. A = number of Bibliography papers that are core to each research front. B = total number of core documents. C = total number of citing papers published for the year designated by the prefix.

Number	Name	A	B	C
87-0891	High-T_c superconductivity and two-dimensional antiferromagnetic quantum spin-fluid state in La	5	5	81
87-0892	High-T_c superconductors, band electronic structure, and doped orthorhombic La_2CuO_4	24	28	1,093
87-1972	High-T_c superconductors, Y-Ba-Cu-O thin-films, and single-crystal $YBa_2Cu_3O_{7-\delta}$	5	11	154
87-3719	Superconducting ceramics, high-resolution electron microscopy, and oxygen stoichiometry	4	6	136
88-0179	High-T_c superconducting thin films, pulsed laser deposition, and RF magnetron sputtering using single CO	8	43	802
88-0693	High-T_c superconductors, Cu L_3 x-ray absorption, oxygen sites, and electronic structure of $YBa_2Cu_3O_{7-\delta}$	4	25	500
88-0934	High-T_c superconductivity, pairing interaction in two-dimensional CuO_2, and antiferromagnetic spin fluctuations	10	17	843
88-1072	Four-dimensional heterotic string models, superstring solutions, and multi-loop twist field correlation-functions for Zn orbifolds	5	31	540
88-1641	Oxygen ordering in the $YBa_2Cu_3O_{7-\delta}$ basal-plane, high-T_c superconductors, and structural phase transition	5	22	564
88-2028	High-T_c oxide superconductors, oxygen isotope effect in $La_{1.8}Sr_{0.15}CuO_4$, and phonon-mediated pairing interaction	4	5	209
88-2172	High-T_c superconductors, effects of oxygen atom vacancies, and excitement in solid-state physics	6	7	2,099
88-2173	High-T_c superconductor $YBa_2Cu_3O_7$, empirical atom potentials, and neutron powder diffraction study	11	13	710
88-5913	High-T_c superconductors, doped La_2CuO_4, and spin fluctuation coupling	4	7	490

String theorists conceive of elementary particles as extended curves and loops instead of as spatial points. As they vibrate, the resonances of these superstrings produce the differences between subatomic particles that we perceive. Through superstring theories, physicists hope to include gravity within a mathematical framework that also encompasses quantum chromodynamics and the electroweak theory.[11,12]

Will Superconductivity Charge into the Future?

Given the extraordinary level of interest and activity in superconductivity shown in this study, it seems reasonable to assume that superconductors will continue to play a major role in future analyses of the most-cited contemporary papers in the physical sciences. Indeed, reports in *Science Watch*™, ISI's new monthly newsletter that tracks trends and performance in basic research,[13] indicate that superconductivity remains one of the "hottest" research areas in current science.

For example, a prepublication sample issue of *Science Watch* listed the top 20 fields in the 1988 research-front database by "immediacy"—the percentage of core papers that were published during 1986-1988. Fields with high immediacy are undergoing rapid change, in which the majority of current research is based on findings only a few years old. Superconductivity dominated this list with 11 research fronts that averaged 90.7 percent immediacy. The hottest of these focused on thallium and bismuth copper oxide compounds.[14] These compounds were discovered in 1988, and the high impact papers describing them will likely appear on our upcoming list of the 1988 physical-sciences papers most cited in 1988 and 1989.

The same issue of *Science Watch* also identified the 10 hottest physical-sciences papers that were most cited in July and August of 1989.[15] All but one were on superconductivity, and basically the same set of papers was the hottest in the previous two-month period examined (May-June 1989).

Assuming that superconductivity does indeed maintain its current high level of pub-

lication output and impact, we will change our method for identifying the most-cited physical-sciences papers. That is, rather than list only the top 100 based on total citations alone, we will compile supplementary lists of high impact papers from other fields *exclusive* of superconductivity. This method will give more balanced coverage of significant work in string theory, high-energy physics, astrophysics, geosciences, and other key research areas. It will be interesting to discover whether an important topic from past studies—the deterioration of the ozone layer in the Earth's atmosphere—will make a "comeback" in future essays with a broader view on the physical sciences.

* * * * *

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13. **Garfield E.** Announcing *Science Watch*: a unique newsletter tracking trends and performance in scientific research. *Current Contents* (4):3-6, 22 January 1990.
14. **Pendlebury D.** Superconductivity studies continue at record rate, while new DNA technique speeds discoveries in biomedicine and forensics. *Science Watch* (Sample Issue):1-3, November 1989. (Newsletter.)
15. ----------. Bismuth focus of hot high-T_c papers. *Science Watch* (Sample Issue):6, November 1989. (Newsletter.)

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Citations				Bibliographic Data
'87-'88	'87	'88	'89	
91	15	76	88	**Albrecht H, Andam A A, Binder U, Böckmann P, Gläser R, Harder G, Nippe A, Schäfer M, Schmidt-Parzefall W, Schröder H, Schulz H D, Wurth R, Yagil A, Donker J P, Drescher A, Kamp D, Kolanoski H, Matthiesen U, Scheck H, Spaan B, Spengler J, Wegener D, Ehmann C, Gabriel J C, Ruf T, Schubert K R, Stiewe J, Strahl K, Waldi R, Weseler S, Edwards K W, Frisken W R, Gilkinson D J, Gingrich D M, Kapitza H, Kim P C H, Kutschke R, MacFarlane D B, McKenna J A, McLean K W, Nilsson A W, Orr R S, Padley P, Parsons J A, Patel P M, Prentice J D, Seyweld H C J, Swain J D, Tsipolitis G, Yoon T-S, Yun J C, Ammar R, Coppage D, Davis R, Kanekal S, Kwak N, Boštjančič B, Kernel G, Pleško M, Jönsson L, Babaev A, Danilov M, Fominykh B, Golutvin A, Gorelov I, Lubimov V, Matveev V, Nagovitsin V, Ryltsov V, Semenov A, Shevchenko V, Soloshenko V, Tchistilin V, Tichomirov I, Zaitsev Y, Childers R, Darden C W, Oku Y & Gennow H.** Observations of B^0-$\bar{B}^0$ mixing. *Phys. Lett. B* 192:245-52, 1987. 88-0440

Citations				Bibliographic Data
'87-'88	'87	'88	'89	
75	5	70	101	**Amaldi U, Böhm A, Durkin L S, Langacker P, Mann A K, Marciano W J, Sirlin A & Williams H H.** Comprehensive analysis of data pertaining to the weak neutral current and the intermediate-vector-boson masses. *Phys. Rev. D—Part. Fields* 36:1385-407, 1987. 88-0252
653	211	442	440	**Anderson P W.** The resonating valence bond state in La_2CuO_4 and superconductivity. *Science* 235:1196-8, 1987. 87-0892, 88-0934
270	48	222	140	**Anderson P W, Baskaran G, Zou Z & Hsu T.** Resonating-valence-bond theory of phase transitions and superconductivity in La_2CuO_4-based compounds. *Phys. Rev. Lett.* 58:2790-3, 1987. 87-0891, 88-0934
95	15	80	59	**Antoniadis I, Bachas C P & Kounnas C.** Four-dimensional superstrings. *Nucl. Phys. B* 289:87-108, 1987. 88-1072
135	14	121	123	**Baskaran G, Zou Z & Anderson P W.** The resonating valence bond state and high-T_c superconductivity: a mean field theory. *Solid State Commun.* 63:973-6, 1987. 88-0934
208	89	119	64	**Batlogg B, Cava R J, Jayaraman A, van Dover R B, Kourouklis G A, Sunshine S, Murphy D W, Rupp L W, Chen H S, White A, Short K T, Mujsce A M & Rietman E A.** Isotope effect in the high-T_c superconductors $Ba_2YCu_3O_7$ and $Ba_2EuCu_3O_7$. *Phys. Rev. Lett.* 58:2333-6, 1987. 87-0892, 88-2028
153	110	43	28	**Bednorz J G, Takashige M & Müller K A.** Susceptibility measurements support high-T_c superconductivity in the Ba-La-Cu-O system. *Europhys. Lett.* 3:379-85, 1987. 87-0892, 88-0520
127	33	94	38	**Beech F, Miraglia S, Santoro A & Roth R S.** Neutron study of the crystal structure and vacancy distribution in the superconductor $Ba_2YCu_3O_{9-d}$. *Phys. Rev. B—Condensed Matter* 35:8778-81, 1987. 87-2140, 88-2173
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