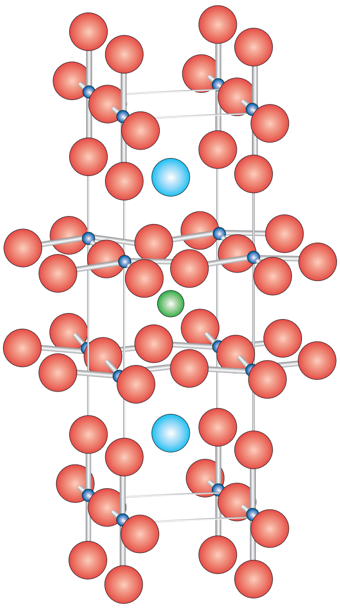
nature materials Vol.5 No.6 June 2006 www.nature.com/naturematerials

Hot superconductors, 20 years on



THE STRUCTURE OF THE CLASSIC HIGH-TEMPERATURE SUPERCONDUCTOR $YBA_2CU_3O_7$. YTTRIUM IS GREEN, BARIUM LIGHT BLUE, COPPER DARK BLUE AND OXYGEN RED.

Most Nobel prizes are awarded long after the dust has settled. That Georg Bednorz and Alex Müller won theirs just a year after their crucial breakthrough was a testament to the profound significance of their work. Twenty years ago this spring, they discovered that a crystalline compound of lanthanum, barium, copper and oxygen becomes superconducting at a temperature 12 K higher than any material known previously.

12 K may not sound like much, particularly when the absolute temperatures involved are near absolute zero — the superconducting transition temperature (T_c) of Bednorz and Müller's $La_{1.85}Ba_{0.15}CuO_4$ was just 35 K. But arguably more significant than this being the biggest leap in T_c ever reported was the composition of their 'high-T_c' superconductor. Most previous superconductors had been metal alloys, but this one was a ceramic, an oxide. Its layered, 'perovskite' structure — the Cu and O atoms form sheets — offered plenty of scope for fine-tuning the composition, and by the time the Nobel was awarded, the T_cs of copper-oxide superconductors had already jumped to 90 K in the classic yttrium barium copper oxide (YBCO).

That was the vital step for applications, because if T_c exceeds the boiling point of nitrogen (77 K), relatively cheap liquid-nitrogen cooling can be used rather than costly liquid helium. Although T_cs of up to 133 K have been attained, YBCO's low cost and non-toxicity continues to make it the favourite for potential applications such as superconducting coils in generators, transformers and motors. Yet despite the initial excitement, those applications have been slow to arrive, largely because of the difficulty of making high-quality wires that sustain large current densities in magnetic fields. Recent developments in this direction give cause for cautious optimism (J. L. Macmanus-Driscoll *et al. Nature Mater.* **3,** 439–443; 2004).

But the technical obstacles take away nothing from Bednorz and Müller's discovery. The two researchers, based at IBM's research labs in Zürich, bucked conventional wisdom about what makes a material superconducting, not through sheer good fortune but by solid reasoning, showing the value of intuition about materials chemistry even (perhaps especially) when the physics is not fully understood. And it still isn't — it has long been suspected that another Nobel awaits for a complete explanation of the mechanism of high-T_c superconductivity, just as one went to the architects of so-called BCS theory that explained conventional superconductivity in the 1950s.

Bednorz and Müller were drawn to the copper oxides by the ferroelectric behaviour of similar metal oxides, such as $SrTiO_3$. It had been known since 1967 that oxygen-deficient $SrTiO_3$ was superconducting, but only at 0.3 K, which scarcely seemed very promising. Nonetheless, Bednorz began investigating this phenomenon under the supervision of Gerd Binnig at Zürich, who later transferred his interest to work on the scanning tunnelling microscope (which won Binnig the 1986 Nobel). Bednorz returned to the topic in 1983 under Müller's guidance. Building on the idea of BCS theory that superconductivity comes from coupling of electron motions to crystal lattice vibrations, they figured that this coupling would be enhanced in related oxide materials with strong Jahn–Teller distortions to the geometry of the metal–oxygen octahedra. That included copper oxides.

In late 1985 Bednorz became aware of the Ba-La-Cu-O system, which seemed to meet the requirements he and Müller had identified. Thus, sound crystal-chemical reasoning led them to their prize-winning material. What is more, the ability to fine-tune the crystal structure and charge-carrier concentrations in these materials by varying the metal-ion ratios and oxygen content gave plenty of room for manoeuvre to optimize T_c.

That is why subsequent work on the high-T_c compounds became an exercise in inorganic chemistry, with the facility to draw on decades of experience with these perovskite oxides. It is notable that, despite the absence of a theory (BCS does not, after all, work in this case), all the most important high-T_c superconductors were found, not through random combinatorial searches, but via rational exploration of the materials options. For all that high-T_c was celebrated as a triumph of physics, it remains at this stage a success story in materials science.