Strike while the iron is hot

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It is a glorious period for science. It is progressing in leaps and bounds. Science has also become a collective exploration of the material universe. Countries like USA, Russia, UK, Germany, France, etc. partly for historical reasons, have a strong base in science and are major beneficiaries of the ongoing revolution. Japan, a relatively late entrant, also has a strong base. Among the scores of developing countries which got independence in the last century, India was somewhat unique in recognizing the importance of science and technology (S&T) as a 'saviour' at the time of independence. In spite of several social and political problems at hand, it did focus on S&T at the beginning. The 'modern science' tradition and expertise that already existed in Indian universities helped significantly in the initial efforts.

In the last 60 years, science has progressed much faster at the global level. Big nations like India and Brazil are struggling hard to catch up. Smaller nations such as Korea, Taiwan and Singapore that have a new economic edge are showing fast progress. The case of China is fascinating. It started investing in science perhaps later than India. China is now showing signs of becoming a major participant in world science in the coming decades.

Here I discuss a discovery, that is hardly three months old, of a new family of iron-based superconductors. We will briefly touch upon the interesting basic science in this new superconductor. This article may also be viewed as a case history of China's emerging strength as a global player in science. India and other developing nations have lessons to learn from China.

In 1911, Kamerlingh Onnes discovered that mercury offers no resistance to the flow of electric current at temperatures below about 4.2 K. This was the beginning of the field of superconductivity. In the next seven decades, new materials with superconductivity occurring at temperatures as high as 23 K were synthesized. In 1986, a revolutionary development was initiated by Bednorz and Muller from IBM Laboratory at Zurich, when they discovered superconductivity in $La_{2-x}Ba_xCuO_4$, an oxide ceramic. This discovery lead to the synthesis of many cuprate superconductors, in a short span of time, some of which become superconducting at temperatures as high as 163 K, well above liquid nitrogen temperatures.

It is also well known that Partho Ganguly and C. N. R. Rao, then at the Indian Institute of Science, Bangalore, were pioneers in the synthesis and study of La_2CuO_4, the Nobel Prize compound. Among other things, they had done some important magnetic susceptibility measurements, before the work of Bednorz and Muller. P. W. Anderson, a Nobel Laureate from Princeton, became familiar with this work at the Valence Fluctuation conference in December 1986 at Bangalore. An unexpected behaviour of the spin susceptibility, as observed by Ganguly and Rao, gave Anderson confidence and the opportunity to sharpen his intuitive ideas and propose the famous resonating valence-bond mechanism of superconductivity in cuprates at the same conference. It is a good example of the emergence of a new field, through a true international cooperation, at a first-rate conference. More interestingly, it was a developed country–developing country cooperation, which is becoming rare these days. It turns out that another such interaction began at Princeton at the same time. I was a young visiting research staff in the group of Anderson at Princeton during 1984–87. Anderson, Zhou Zou (then a Chinese graduate student) and I developed the RVB proposal into the RVB theory, in a series of influential papers starting early 1987.

Cuprates have dominated the field of superconductivity for the last 22 years. There have been new entrants such as K-doped $BaBiO_3$, doped C_{60}, $LaNi_2B_2C$ (TIFR compound), MgB_2, $Na_xCoO_2{\cdot}yH_2O$ and organics. But superconductivity in them occurs at lower temperatures compared to the best cuprates. Superconducting LaOFeP and LaOFeAs are two new entrants that might change the dominance of cuprates! This discovery came from Japan[1,2]. Hideo Hasano, a materials scientist from Tokyo Institute of Technology is the leader of the group. This discovery coming from Japan is not surprising, as it has an excellent and expanding base in modern materials science that intimidates even American materials scientists. Even before Bednorz and Muller's discovery, Hide Fukuyama and S. Tanaka from Japan had realized the importance of search for new superconducting materials and started research programmes from the late 70s. It has paid them well over the years.

It is the Chinese who have struck while the iron is hot and are shaping this field. Hai-Hu Wen, a physicist at the Institute of Physics (IOP), Chinese Academy of Sciences, Beijing, synthesized and confirmed the Japanese results in a matter of 3–4 days and also made important thermodynamic and transport measurements[3]. On 25 March, Xianhui Chen, University of Science and Technology of China in Hefei, reported that $SmO_{1-x}F_xFeAs$ superconducts at 43 K. A few days later, Zhong-Xian Zhao (IOP) reported that $PrO_{1-x}F_xFeAs$ superconducts below 52 K. On 13 April, Zhao's team showed that the samarium compound becomes a superconductor at 55 K, if it is grown under pressure. Dozens of papers have come from China, from at least four different groups, pushing superconducting temperatures and also making good basic science measurements that are key to understanding the mechanism of superconductivity.

A couple of neutron scattering results and muon spin resonance experiments have come from USA and Europe. They have clarified the nature of phase transition in the parent compound, LaOFeAs.

On the theory front, where I have interest and some insights, things are pretty exciting too. It is rather clear that the mechanism of superconductivity in this system is far from conventional and electronic in origin. There is a smell of resonating valence-bond physics at work, which I have elaborated in my recent theory[4]. Briefly, LaOFeAs is a layered system. A square lattice of mono atomic layer of Fe^{2+} ions and LaO/As layers are alternately stacked. Electrical conductivity is confined to the Fe layers and makes it a quasi two-dimensional metal. This makes it similar to cuprates. However, the valency of iron is Fe^{2+}, with an electronic configuration $3d^6$. This is different from the $3d^9$ configuration of Cu^{2+} in cuprates.

In the superconducting state, electrons are paired and there is a quantum mechanical condensation of the pairs into a resistanceless coherent state. In conventional superconductors, quanta of lattice vibrations called phonons mediate a rather weak pairing. On the other hand, in the RVB mechanism, electrons are paired rather strongly through covalent-like bonds. The resonance of the valence bonds leads to a superconducting state. The quantum chemical origin of electron pairing makes the superconducting temperatures considerably higher than the average conventional superconductors. For RVB mechanism to be operative we need a template, which is called a Mott insulator. In the case of cuprates, La_2CuO_4, the parent compound is a Mott insulator.

What is interesting is that there are experimental signals that indicate LaOFeAs is close to a Mott insulating state. An antiferromagnetic metallic state disappears and gives way for superconductivity on doping in the compound $LaO_{1-x}F_xFeAs$. There is also a remarkable electron–hole symmetry as a function of doping. There have been many electronic structure calculations and attempts to build a theory in the last two months. The theory I have proposed claims that there are two coupled resonating valence-bond systems in LaOFeAs. It is indeed interesting that $A + A \neq 2A$. The coupled RVB systems lead to what I have called 'quantum string liquid', a condensed matter realization of a specific form of string field theory!

What is exciting is that this mechanism holds promise for higher temperature superconductivity and in fact, provides a new route which I call the 'iron route'.

As for the lessons we have to learn from the Chinese example, perhaps there are many. The present dominance of China in this corner of condensed matter physics cannot be an accident. It must be a consequence of hard work, long preparation of the soil and sowing the seeds of science. Arunachalam[5] has been writing, contrasting and quantifying for more than 10 years about the Chinese efforts in science and where they are going.

Postscript: As I was finishing this note, it was gratifying to see the first experimental result from India (as reported in the arXiv), from the group of Awana[6] at National Physical Laboratory, New Delhi. In a key step, they report the discovery of a single-step solid-state reaction method, as opposed to the existing high pressure or multistep solid-state reaction methods, to synthesize the parent compound, LaOFeAs.

1. Kamihara, Y., *J. Am. Chem. Soc.*, 2006, **128**, 10012.
2. Kamihara, Y. *et al.*, *J. Am. Chem. Soc.*, 2008, **130**, 3296.
3. Hai-Hu Wen *et al.*, cond-mat/0803.1288. Most of the papers in this field are posted in the arXiv, which makes communication and progress remarkably fast and convenient.
4. Baskaran, G., cond-mat/0804.1341.
5. Arunachalam, S., *Curr. Sci.*, 2002, **83**, 108.
6. Awana, V. P. S. *et al.*, cond-mat/0804.0214.

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