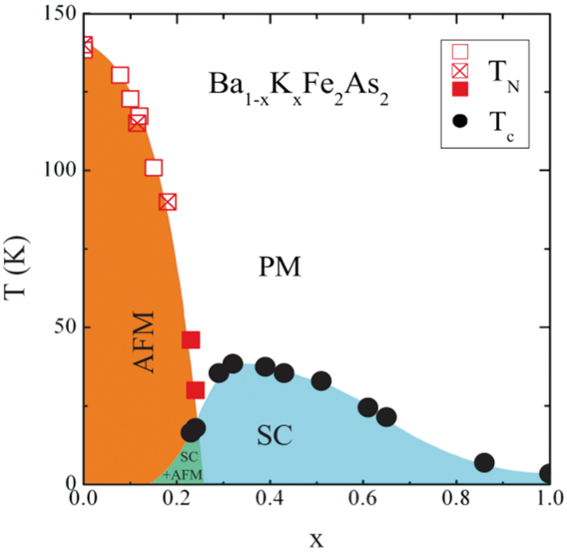
Antiferromagnetic Order Coexisting with Superconductivity in $Ba_{0.77}K_{0.23}Fe_2As_2$

By SONG Jianlan (Staff Reporter)

Ensuing previous breakthroughs in the field of iron-based superconductivity achieved by their colleagues at the Institute of Physics and the Beijing National Laboratory for Condensed Matter Physics under CAS, a group of physicists led by Prof. ZHENG Guoqing recently obtained unambiguous evidence for a microscopic coexistence of antiferromagnetic order and superconductivity in a high-quality crystal of $Ba_{0.77}K_{0.23}Fe_2As_2$, revealing a new episode of the mystery of unconventional superconductivity.

The group's report has recently been selected as a highlighted article in *Physical Review B*, an international journal focusing on condensed matter and materials physics. This, however, is actually a newly emerged wave in the tide of studies on iron pnictides, a new class of superconductors. And iron pnictides, the leading roles in the serial stories of high temperature superconductivity, came into the view of physicists a number of years ago with groundbreaking news, due to their inherent subversive nature.



Coexistence of antiferromagnetism and superconductivity in $Ba_{0.77}K_{0.23}Fe_2As_2$: ZHENG's group successfully observed clear evidence showing AFM and SC coexisted below temperature 16 K. (Image: By courtesy of Prof. ZHENG Guoqing)

"Thrilling" Breakthroughs in 2008

Back in 2008 the successful induction of high-temperature superconductivity (HTS) in ferrous materials thrilled the physical community and inspired a big wave of explorations into the mechanism of superconductivity in microscopic world. This is not just because of the unprecedentedly high transition temperature, but also because of the surprising occurrence of HTS in a seemingly impossible family of materials: iron pnictides.

At that time iron-based materials were never considered promising candidates for superconductors, as the element iron was widely believed to be at odds with superconductivity (SC) due to its ferromagnetism, a "natural foe of superconductivity".

What has made the two "natural foes", magnetism and SC tolerate each other so well in iron pnictides? This fascinates physicists, in that it might shed some new light on the physics underlying the mysteriously high transition temperature of this type of superconductivity.

"For a very long time people had believed that magnetism (regardless of ferromagnetism (FM) or antiferromagnetism (AFM)) was incompatible with SC. This belief was subverted by the discovery of high temperature superconductors, and people realized that the fluctuation of magnetism might produce superconductivity," Prof. ZHENG told the reporter. "In the case where the SC is induced by fluctuation of magnetism, the electron pairing symmetry is different from that of a conventional BCS superconductor, which is caused by the vibration of crystal lattice," he continued.

BCS superconductors refer to the superconductive materials that conform to the theory established by John Bardeen, Leon Neil Cooper and John Robert Schrieffer in 1957 concerning the mechanism of SC. Yet the new family of superconductors, iron pnictides posed a big challenge to BCS theory, as their transition temperatures exceed the limit predicted by the theory.

Inspired by this envision physicists endeavor to understand the fluctuation of magnetic field in iron pnictides.

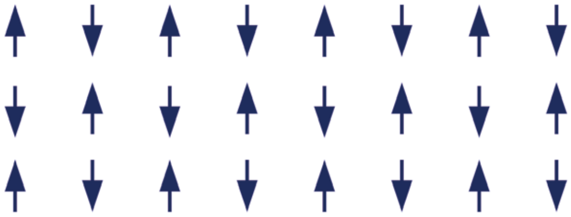
An important issue is whether AFM, a kind of ordered magnetism in materials, and SC can coexist in iron-based materials at a microscopic scale.

AFM Order and Superconductivity

It would be very interesting to see whether or not such coexistence is possible, as it may give some clues about whether fluctuation of magnetism — which is demonstrated by three forms of ordered magnetism, namely the FM, AFM and ferrimagnetism — can lead to emergence of superconductivity.

Unlike FM, the concept AFM is not so familiar to general people, since it is not quite visible in daily life. It is well known that a ferromagnetic material can attract small irons, yet its opposite, AFM might be a bit comprehension resisting. In a ferromagnetic material like magnetite, the neighboring magnetic moments (caused by the electron spin of atoms or molecules) within a magnetic domain (a magnetism unit) align along the same direction. In a material exhibiting AFM, however, neighboring units of magnetic moments align against each other. In other words, in a compound that exhibits AFM, the magnetic moments of atoms or molecules distribute in a special matrix in which every unit of magnetic moment is surrounded by neighbors pointing to an opposite direction. This regular matrix is called AFM order. A compound exhibiting AFM order cannot be magnetized, as the net magnetic moment of the bulk material is zero. However, an internal magnetic field can be produced inside an AFM material.

AFM might emerge in a material when it is cooled to a threshold temperature called Néel temperature, which is named after Louis Néel, the physicist who first identified AFM order. Once it is warmed up to the Néel temperature, AFM will be suppressed and paramagnetism will take an upper hand again, forming a fluctuation of magnetism.



A schematic view of the spins in a material with an antiferromagnetic order. (Image by Michael Schmid, quoted from en.wikipedia.org)

A decade or so ago scientists managed to obtain evidence for a homogeneous coexistence of AFM and SC in heavy fermion compounds, a special type of intermetallic compound, at microscopic scale. However whether such coexistence is possible for iron pnictides remained unknown, though superconductivity emerges in the vicinity of AFM in this family of materials.

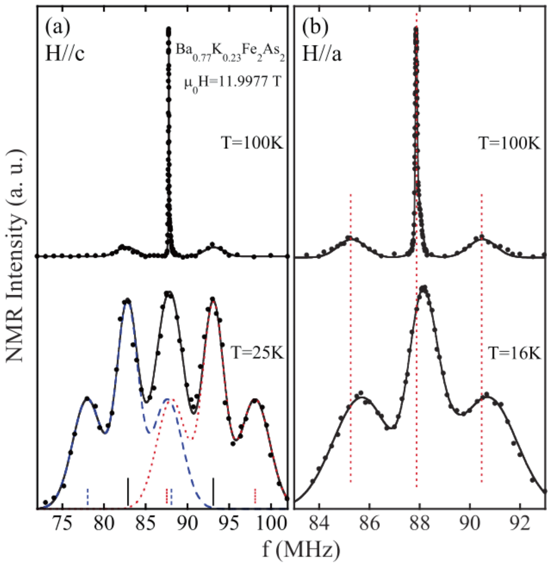
Eventually this gap was bridged by the work of ZHENG's group, together with their collaborators in Germany. Their experimental observations clearly demonstrated that AFM order and SC could microscopically coexist in under-doped iron pnictide crystals of $Ba_{0.77}K_{0.23}Fe_2As_2$, at temperatures low enough — below 16K.

"There were expectations that AFM might microscopically coexist together with superconductivity in all the iron- and arsenic-based superconductors. However, no one observed firm evidence for this envision before, due to the lack of suitable experimental probes and high-quality single crystals of the material," ZHENG said: "for the first time ever our group reported unambiguous evidence."

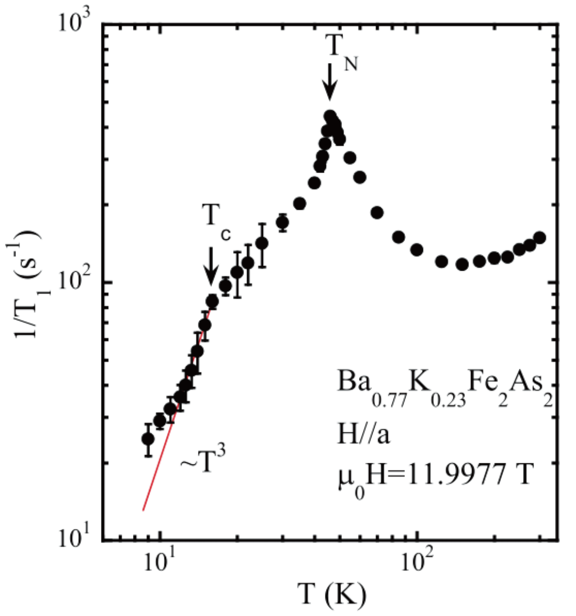
Success

At the early stage of the iron-pnictide study, some experiments suggested that AFM and SC were both temporally and spatially separated when they occurred in the same sample: they occurred at different parts of the material as separated phases. Later on, in the crystals with improved quality, researchers found indications that AFM and SC might reside in the same place. However, there was a setback of those experiments: the onset of SC was only indicated by a susceptibility measurement, which is not a microscopic indicator. Therefore, the relationship between AFM and SC in iron pnictides remained controversial.

The team used nuclear magnetic resonance (NMR) measurements in their experiments and smartly established the



The group obtained the NMR spectra of ^{75}As in an under-doped single crystal $Ba_{0.77}K_{0.23}Fe_2As_2$ under a fixed magnetic field along the *a*- and *c*- axis, and observed changes in their peaks. (Image: By courtesy of Prof. ZHENG Guoqing)



The spin-lattice relaxation rate $1/T_1$ shows a peak at Néel Temperature T_N and a drop at the superconducting transition T_c within the AFM state. (Image: By courtesy of Prof. ZHENG Guoqing)

relationship between AFM order and SC via a combination of microscopic experimental measurements. In an under-doped single crystal $Ba_{0.77}K_{0.23}Fe_2As_2$, firstly they obtained the ^{75}As NMR spectra under a magnetic field, respectively along the *a*- and *c* -axis. Then they observed that under a Néel temperature of 46K, sharp changes occurred to two physical parameters: the NMR peaks along the *c*-axis split, and those along the *a* -axis shifted to higher frequencies, indicating that an internal magnetic field had developed. More importantly, the nuclear spin-lattice relaxation (SLR) rate measured at the shifted peak decreased distinctively at 46K and 16K, latter of which is the critical temperature at which SC occurred in the crystal. As interpreted by the authors, this combination of changes in measurements clearly and incontrovertibly indicated the coexistence of AFM order and SC below 16K.

"Our result suggests that the SC in this iron pnictide is caused by the fluctuation of magnetism instead of the vibration of crystal lattice. It also implies that this type of SC is unconventional, otherwise such coexistence will not be possible," ZHENG explains. "Our work also suggests that properly manipulating the fluctuation of magnetism can be a good approach to further raising the transition temperature of the iron-pnictide superconductors," he proceeds.

New Opportunity for Quantum Critical Phenomena

Another reason that the group's work has attracted so much attention is the connection of the iron-based superconductors to another important issue in physics, the quantum critical phenomena, which occur around a critical point of a quantum phase transition. "Some very unusual, abnormal things have been found to take place around a quantum critical point (QCP)" ZHENG introduces: "hence this issue has been studied extensively in the past two decades, but up to now no common agreement has been achieved on what role a QCP plays in producing new states of matter."

In a material, the critical temperature of an order could be driven to absolute zero through applying a pressure, a field or doping. "AFM could be suppressed by chemical doping or applying an external pressure. The doping rate or pressure where the AFM vanishes is a QCP. For a low-doping system like the crystal we studied, the coexistence of AFM order and SC is a necessary condition for a QCP to exist," explains ZHENG.

The verification of the coexistence of AFM order and SC in the $Ba_{0.77}K_{0.23}Fe_2As_2$ hence will provide a new opportunity for further investigations of quantum critical phenomena.

"Unusual" Superconductivity

Their discovery might also help determine the disputed pairing symmetry, on which Prof. ZHENG has been working for decades.

For iron pnictides, both conventional pairing symmetry (called *S*-wave) and unconventional symmetry such as an S^{+-}-wave gap, which changes sign on different Fermi surfaces, have been proposed. According to previous theoretical work, when AFM order coexists with SC, the conventional *S* -wave will become unstable, whilst the new type of gap, the S^{+-}-wave gap, can maintain easily. The S^{+-}-wave gap is realized because of the fluctuations of AFM. The team's latest results strongly suggest that such unconventional pairing symmetry occurs in iron-pnictides.

Other signs also indicate that what ZHENG's team has observed was an "unusual" type of SC.

"For a pure SC state without a coexisting AFM order in a highly-doped iron pnictide, the energy gap is isotropic. Accordingly the SLR changes exponentially with temperature, as we first discovered in a previous work. However, in the case where an SC state coexists with AFM order, we found that the SLR changed very slowly with temperature. This means that there existed some kind of excitations there. What exactly is it? We do not know yet. I think it is worthwhile delving into that issue in detail," ZHENG told the reporter.

It seems that the solution of one issue has just led to the rise of more questions. But that is science. Who knows what the pursuit of this unknown excited state will lead to? Get ready: We might be surprised again.