Neutrons Reveal the Secrets of Superconductivity

Thirty years into the investigation and the theory still has gaps – researchers worldwide are still attempting to fathom why some materials suddenly become superconductive at specific temperatures. The PUMA and PANDA experiments at the FRMII research neutron source are among the best in the world for investigating certain aspects of the phenomenon. There, scientists have spent the last ten years or so piecing together the picture.

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Superconductors are crystalline solids with complex lattice structures. Especially high-temperature superconductivity is not yet fully understood. Neutron beam experiments at Heinz Maier-Leibnitz Zentrum (MLZ) in Garching shed light on the phenomenon.

Graphics: ediundsepp

Spin waves seem to be one key to the phenomenon of high temperature superconductivity. They can be measured by means of neutron scattering. The PUMA and PANDA experiments beam neutrons from one side into the crystal and measure how many are scattered by the electron spins and at what angles.

Brigitte Röthlein

Spinwellen als Auslöser für Supraleitung?

Seit vor 30 Jahren Materialien entdeckt wurden, die bei weit höheren Temperaturen supraleitend werden als die bis dahin bekannten Substanzen, versuchen Forscher die Mechanismen zu verstehen, die hinter diesem Verhalten stecken. Die Hoffnung ist, nicht nur endlich eine konsistente Theorie zu finden, sondern auch, weitere Stoffe zu entwickeln, die im besten Falle sogar bei Zimmertemperatur supraleitend werden. Die bisher gültige Theorie, die aber nur konventionelle Supraleiter erklären kann, geht davon aus, dass Gitterschwingungen – Phononen – im Kristall zur Bildung sogenannter Cooper-Paare beitragen, die den verlustfreien Stromtransport bewirken. Dies gilt aber nicht in Bezug auf die neu entdeckten Substanzen.

Da sich in den letzten Jahren herausstellte, dass bei den Hochtemperatur-Supraleitern magnetische Vorgänge im Inneren des Kristalls eine große Rolle spielen, hat sich Neutronenstreuung als das Forschungswerkzeug der Wahl etabliert. Dr. Astrid Schneidewind und Dr. Jitae Park betreuen am Heinz Maier-Leibnitz-Zentrum (MLZ) in Garching die beiden Spektrometer PANDA und PUMA, die als die weltbesten Instrumente ihrer Art gelten. „Neutronen sind elektrisch neutral und können deshalb ins Innere von Kristallen eindringen, haben aber gleichzeitig ein magnetisches Moment, das heißt, sie können an den Elektronen gestreut werden, die ebenfalls magnetische Dipole sind“, sagt Park. Damit lassen sich magnetische Strukturen im Inneren des Kristalls aufklären. Wissenschaftler aus aller Welt kommen seit Jahren ans MLZ und bestrahlen supraleitende Materialien mit den Neutronen aus dem Hochflussreaktor FRM II.

> *„Der Traum ist, Supraleiter zu entwickeln, die sogar bei Zimmertemperatur – also ohne aufwändige Kühlung – funktionieren. Aber bis dahin ist noch ein weiter Weg.“*
>
> *Jitae Park*

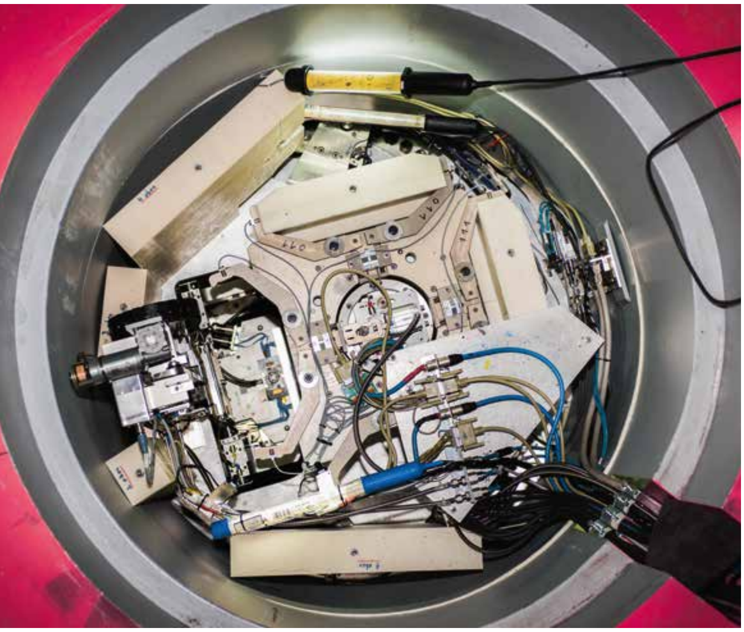
Unter der Mithilfe von Schneidewind und Park sind so inzwischen von Forschern aus der ganzen Welt eine Reihe von Puzzlesteinen gefunden worden, die zu einer kompletten Theorie der Supraleitung beitragen können. Vieles deutet darauf hin, dass dabei Spinwellen eine entscheidende Rolle spielen könnten. □

Graphics: ediundsepp

Rarely are theory, basic physical research and practical applications so closely linked as in the case of superconductivity. If it were possible to explain the physical mechanisms that cause some compounds with complex crystal lattice structures to lose all electrical resistance at a particular critical temperature, we could then set about optimizing this superconductive capability or even identifying completely new contenders. “The dream is to develop superconductors that even work at room temperature – so no need for resource-intensive cooling,” explains Dr. Jitae Park, who is researching superconductivity alongside his colleague Dr. Astrid Schneidewind at the Heinz Maier-Leibnitz Zentrum (MLZ) in Garching, “but we have a long way to go.”

In 1911, Dutch physicist Heike Kammerlingh-Onnes encountered a strange phenomenon that he was unable to explain: if he cooled mercury to below – 269 degrees Celsius, its electrical resistance would drop abruptly to zero and it would conduct electric current without any losses. This discovery was known as superconductivity. Gradually, scientists established that around a dozen elements and well over a hundred alloys display similar behavior. However, the so-called critical temperature below which superconductivity takes place was always only a few degrees above absolute zero, which corresponds to around – 273 degrees Celsius. This is expressed as 0 kelvin and corresponds to the point at which all thermal motion of atoms and molecules stops.

Since the temperature required to induce superconductivity is so very low, liquid helium was required to cool the materials.



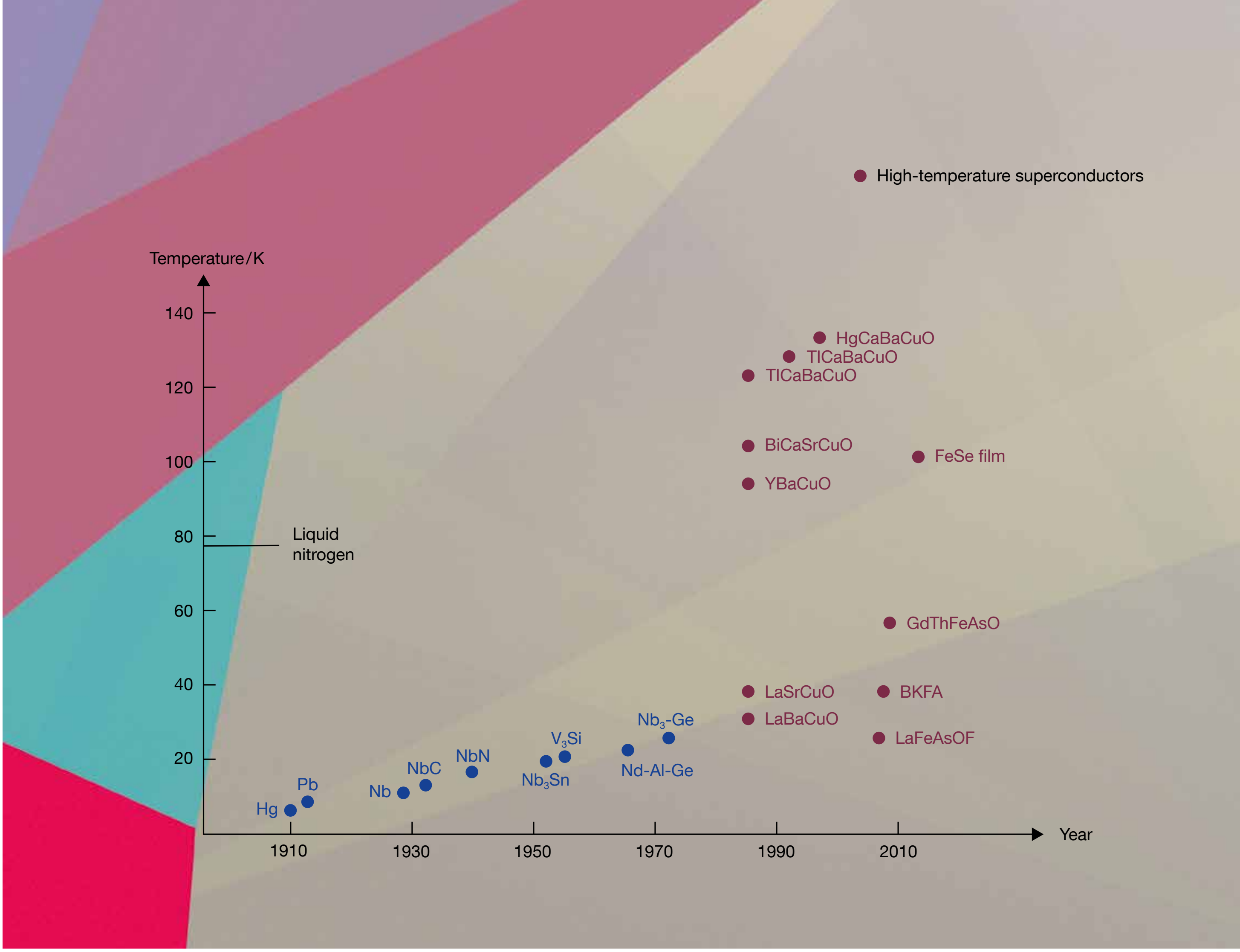
A look inside the monochromator. It offers four monochromators which allow the scientists to select neutrons with certain energy levels for the experiment.

Astrid Schneidewind mounts a high temperature superconductor sample for the neuton scattering experiment. During the measurement itself, the sample is positioned in a cryostat and people are not allowed near the experiment.

The huge effort involved in supplying this gas meant that just a few practical applications were viable – such as superconducting coils to generate extremely strong magnetic fields for accelerator experiments, fusion devices and magnetic resonance imaging (MRI). And for many people, that was the extent of the superconductivity story.

Fresh discoveries widen horizons

It thus caused quite a stir when Swiss and German scientists K. Alexander Müller and J. Georg Bednorz made their announcement at a New York meeting of the American Physical Society in March 1987: they had discovered a material the year before that became superconductive at the relatively high temperature of 35 kelvin. This was the ceramic material lanthanum barium copper oxide (LBCO), which possesses a complex crystal lattice structure and belongs to the cuprate family. The two researchers were awarded the 1987 Nobel Prize in Physics for this breakthrough. This then opened up a new area of research, yielding a raft of new materials with ever-higher critical temperatures. These high-temperature superconductors (HTS) paved the way for totally new



Superconductivity was first discovered in 1911. For decades, all materials found had to be cooled with liquid helium to temperatures just above −273 Celsius, or absolute zero, to trigger superconductivity. Finally, in 1987 the first material was discovered that became superconductive at the relatively high temperature of 35 kelvin.

Picture credits: Filser, Graphics: ediundsepp (source: Keimer PIUZ 201291297 / TUM)

technical possibilities, inspiring utopian visions among engineers. They predicted a revolution in the transfer of energy if they could successfully transport electricity across long distances without losses and with no need for cooling. A pilot project has been running in the German city of Essen since 2014, with one kilometer of superconductive high-voltage cable spanning the distance between two substations, cooled only by liquid nitrogen – which requires a lot less effort than cooling with helium. In the telecommunications sector, too, HTS could play an important role: superconductive components could increase technical performance by enabling component miniaturization, reducing interference and thus dramatically improving transmission quality. Scientists assumed that if they could just work out how these high-temperature superconductors actually work, it should be possible to produce even better ones. But that is proving to be a lot more difficult than it sounds – even today, there is still no generally applicable theory that explains their behavior. The quantum mechanical theory proposed by US researchers John Bardeen, Leon Cooper and Robert Schrieffer towards the end of the 1950s was a significant milestone, explaining the mechanism underlying conventional superconductivity. Known by the initials of its three authors, this BCS theory gained them a Nobel Prize in 1972.

The BCS theory postulates that the electrons in a superconductor form Cooper pairs, which – unlike single electrons – do not collide with one another or interact with the conducting crystal or its defects, thus impeding scattering. They thus experience no resistance as they travel. The fact that electrons, which of course are negatively charged, are able to form pairs without repelling each other in the first place is attributable to a quantum mechanical effect that only arises in solid-state bodies – specifically crystals – and is caused by lattice vibrations (phonons).

The mysterious role of magnetism

The BCS theory may provide an adequate explanation for the processes in conventional superconductors, but it falls rather short when it comes to high-temperature superconductivity. One of the sticking points is behavior in the presence of magnetism. While normal impurity in the crystal lattice has virtually no effect on the conducting state, this

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state is extremely sensitive to foreign atoms, which behave like tiny magnets and are known as dipoles. A small percentage of these atoms distributed in the crystal lattice is enough to suppress conventional superconductivity altogether in standard metals and alloys.

The story is very different when it comes to high-temperature superconductors. Here, researchers have discovered that they can even promote superconductive effects by doping magnetic materials in such a way that they partially lose their magnetism. The assumption today is therefore that the Cooper pairs – which are demonstrably also present in high-temperature superconductors – are held together not by phonons but by spin waves. These magnetic phenomena occur in crystals and are caused by the electromagnetic moment of electrons, known as spin. Many scientists view these spin waves as one of the keys to understanding the mechanism of high-temperature superconductivity. But how can we measure these spin waves? “Neutrons are a particularly good tool for this,” reveals Jitae Park. “They are electrically neutral and can thus penetrate the interior of crystals. At the same time, they have a magnetic moment, meaning that they can be scattered by the electrons that also possess magnetic dipole fields.” This sheds light on magnetic structures in the interior of the crystal.

Small wonder, then, that so many research groups from all over the world have made their way to the MLZ over the past few years, keen to irradiate all manner of exotic crystals with neutrons. The PUMA and PANDA experiments in particular are ideally suited to this type of investigation. Each of these involves beaming neutrons in from one side and counting how many of them are scattered by the electron spins in the crystal and at what angles. The amount of energy lost by each neutron in this process is also resolved. The models that emerge from these days or even weeks of measurements then enable the physicists to draw conclusions about the processes inside the crystals. Schneidewind and Park are on hand to advise and assist them in this endeavor, since it takes a great deal of experience to correctly assign and interpret the numerous measurements obtained.

Astrid Schneidewind, who has been looking after the PANDA spectrometer since 2004, talks about her “60 ton giant” with evident affection and emphasizes the importance of an experienced team that is familiar with every nut and bolt and knows what to tweak and where for any given outcome. Her young Korean colleague, Jitae Park, has been working in this field since his doctorate and has also become an internationally acknowledged expert in performing and interpreting such investigations at the MLZ, especially with PUMA. “We have made many discoveries over the

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“PANDA and PUMA are among the world’s best instruments in their field.”

Jitae Park on the reserach environment at MLZ

Dr. Astrid Schneidewind and Dr. Jitae Park

Research groups come from all over the world to use their instruments

Two career paths that could hardly be more different have ultimately converged in superconductivity research roles at the MLZ. Dr. Astrid Schneidewind began her career at Technische Universität Dresden, where she initially focused on low temperature physics, having always been drawn to research “off the beaten track.” However, the turmoil surrounding German reunification meant she was unable to finish her doctorate. “The wall coming down threw a major spanner in the works, with only half of all positions staffed again afterwards.” She was also expecting the first of her two daughters at the time, so decided to focus on her family for the time being. Four years later she then returned to her old institute, essentially to undertake a second doctorate – which she successfully completed this time. “Doing another doctorate so late has kept me young,” reflects the 51-year-old physicist. “It’s meant I’ve almost always worked with colleagues at least ten years my junior.”

So Schneidewind was unperturbed when she finally arrived at the MLZ after her move to Munich and often found herself working with university graduates. “I see myself in an advising and supporting role where younger people are concerned,” she says. “I’m aware that I can contribute a lot of life experience that others have yet to gain.” She also has a very relaxed relationship with her 34-year-old colleague, Jitae Park.

Park, for his part, was already cultivating an interest in neutron scattering during his studies in Seoul. He therefore decided to pursue his doctorate at the Max Planck Institute for Solid State Research in Stuttgart, where he became interested in superconductivity. His two children were thus born in the heart of Germany’s Swabia region, meaning that his daughter “initially learnt Swabian dialect at kindergarten, while my son tends more towards Bavarian as a result of moving to Munich.” Both children now speak a mixture of German and Korean. Park’s wife also comes from Korea and hopes to resume her training as a fashion designer shortly.

Both Astrid Schneidewind and Jitae Park particularly value the outstanding research environment Munich has to offer. “PANDA and PUMA are among the world’s best instruments in their field,” declares Park – who would, however, also be ready to move elsewhere if conditions were even better. His colleague, though, now takes a more laid-back approach – she is happily settled in the north of Munich, having found a good balance between research, team work, administration and family life. And she doesn’t mind being on call in the evenings or at the weekends, which sometimes means hurrying back into work to rescue a baffled researcher.

Picture credits: Filser

Calls her PANDA experiment a "60 ton giant" with a touch of affection: Astrid Schneidewind and her team know every nut and bolt in their baby and know what to tweak to answer any question a scientist might have.

past few years, including specific energy loss patterns with the neutrons," he reports. "This is known as resonant mode and points to the formation of Cooper pairs." The assumption by both experimental and theoretical physicists is that spin waves play a crucial role in this. "All the materials we investigate here exhibit this type of resonance but we still don't have a precise explanation for it yet – unfortunately nature is just not that straightforward!"

Alongside their services at the MLZ, both scientists are also pursuing their own research interests. Crystal doping is high among them. Whether or not superconductivity can be induced at various temperatures depends on how many excess electrons or distortions the crystal contains. However, they are still some way from explaining this. "We are investigating three different types of material: cuprates, iron-based superconductors and heavy fermions," explains Astrid Schneidewind. "Our aim is to identify a pattern that applies to all three so we can finally find out how they work." The latest measurements suggest that a transition in wave function symmetries might be a condition for the formation of Cooper pairs. "This might hold the key," muses Jitae Park. At just 34 years of age, there is a good chance that he will see the solution to this puzzle in the course of his active research career. Perhaps he himself will play a pivotal role. *Brigitte Röthlein*

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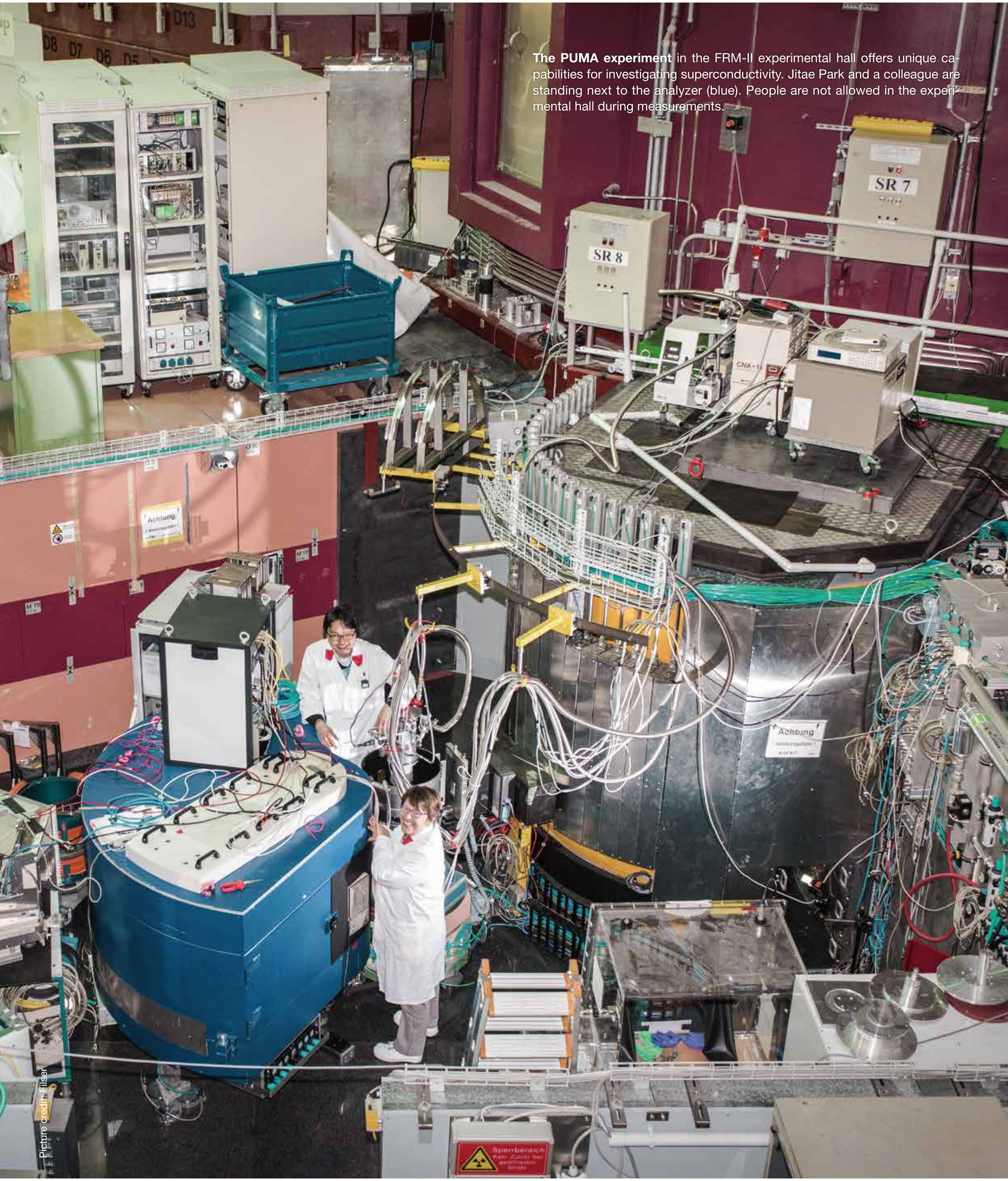

The PUMA experiment in the FRM-II experimental hall offers unique capabilities for investigating superconductivity. Jitae Park and a colleague are standing next to the analyzer (blue). People are not allowed in the experimental hall during measurements.

Picture credit: Filser