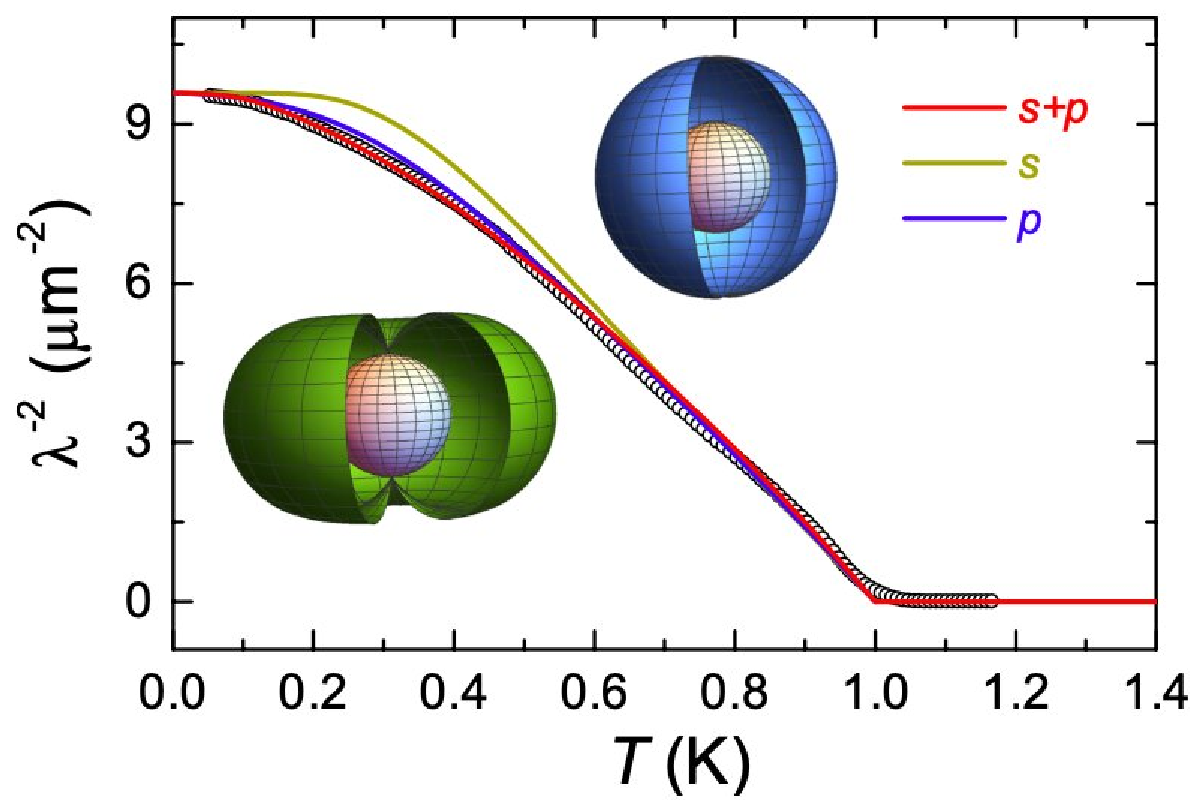
Simultaneous nodal superconductivity and broken time-reversal symmetry in CaPtAs

June 17 2020, by Ingrid Fadelli



The temperature dependence of inverse square of the magnetic penetration depth, which is proportional to the superfluid density, measured using the tunnel-diode oscillator method. The lines show fits to the data using various models, where it can be seen that the s¬-wave model with a fully open gap does not agree with the data, but the nodal 's+p' model can well describe the results. Credit: Shang et al.

In the vast majority of superconducting materials, Cooper pairs have what is known as even parity, which essentially means that their wave function does not change when electrons swap spatial coordinates. Conversely, some unconventional superconductors have been found to contain odd-parity Cooper pairs. This quality makes these unconventional materials particularly promising for quantum computing applications.

Past studies have predicted that noncentrosymmetric superconductors, which have a crystal structure with no center of inversion, could exhibit unique and unusual properties. In recent years, noncentrosymmetric superconductors have become a popular topic of research due to the structure of the Cooper pairs contained within them, which have a mixture of odd and even parity.

CaPtAs is a new noncentrosymmetric superconductor discovered by researchers at Zhejiang University. Together with scientists at the Paul Scherrer Institut and other institutes worldwide, these researchers have recently carried out a study investigating unconventional superconductivity in this compound. Their paper, published in *Physical Review Letters*, offers evidence that in its superconducting state, CaPtAs simultaneously exhibits both nodal superconductivity and broken time-reversal symmetry (TRS).

"The crystal structure of CaPtAs was known to be noncentrosymmetric, and therefore, we thought that it would be interesting to determine whether it is also a superconductor," Huiqiu Yuan, one of the researchers who carried out the study, told Phys.org. "In a paper published earlier this year, we reported that CaPtAs is indeed a non-centrosymmetric superconductor, which becomes superconducting below 1.5 K. We also saw hints of unusual superconducting properties, namely a nodal superconducting gap."

The observations gathered in their previous work inspired Yuan and his colleagues to collect advanced measurements that would allow them to examine the unconventional superconducting properties of CaPtAs more in-depth. The key objective of their recent study was to determine whether when CaPtAs is in its superconducting state time reversal symmetry is broken.

The researchers also measured the magnetic penetration depth of the noncentrosymmetric superconductor at very low temperatures, to better understand the structure of its superconducting gap. More specifically, they wanted to determine whether the material's superconducting gap presented so-called 'nodes," points at which the gap amplitude is equal to zero.

"In our study, the evidence for time-reversal symmetry breaking came from using the muon spin relaxation/rotation (μSR) technique, while the evidence for nodal superconductivity came from both μSR, the tunnel diode oscillator (TDO) method, as well as the specific heat," Yuan said.

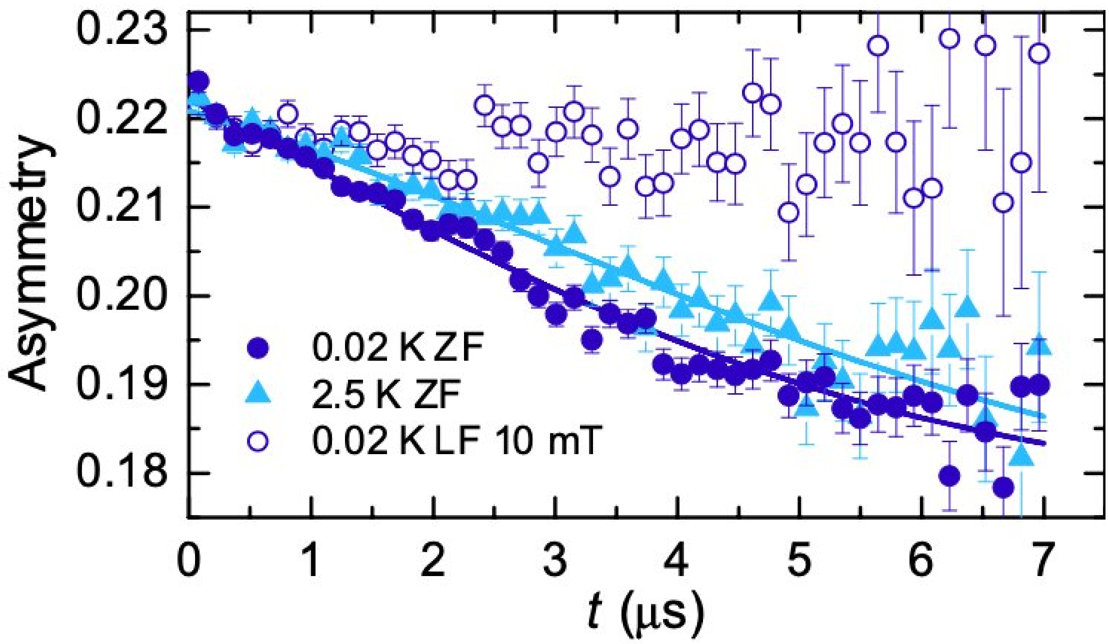
Muon spin relaxation/rotation (μSR) is a powerful method for precisely measuring magnetic fields inside a material, which uses positively charged anti-muons as a probe. A signature of time-reversal symmetry breaking in a superconductor is that very small magnetic fields spontaneously appear when the superconductor is cooled to its critical temperature. μSR is one of the few existing techniques sensitive enough to detect such small magnetic fields inside materials.

"We implanted the spin-polarized muons into the superconductor," Tian Shang at Paul Scherrer Institut explained. "The positive muons are generated at specialized measurement facilities by colliding a proton beam with a carbon target. Our μSR experiments were performed at the Paul Scherrer Institute in Switzerland."

Muons are highly unstable elementary particles that rapidly decay, exhibiting a half-life of 2.2µs, into a positron and two neutrinos. The spin of a muon is typically affected by magnetic fields inside a material. Therefore, implanting muons inside a material allows researchers to reconstruct the nature of these magnetic fields, simply by measuring the distribution of positrons emitted over time.

"In particular, one typically counts the number of positrons at opposite ends of the sample, and how the difference between these numbers, the 'asymmetry," changes over time can be used to detect the tiny extra magnetic fields when time reversal symmetry is broken," Shang said.

The physics term 'nodal superconductivity' refers to the nature of the energy gap inside a superconductor, which is the threshold energy required to break a Cooper pair apart. In nodal superconductors, this energy gap is zero for Cooper pairs moving in certain directions. This means that the thermal energy can break Cooper pairs apart even at very low temperatures.



The asymmetry as a function of time from muon-spin relaxation measurements of CaPtAs in zero-field (ZF) and a small field applied along the initial muon spin direction (LF). The ZF asymmetry decreases more rapidly with time below the superconducting transition at 0.02K than at 2.5 K, which shows that there are extra magnetic fields emerging in the superconducting state, which is a signature of broken time reversal symmetry. Credit: Shang et al.

Nodal superconductivity can thus be detected by counting the amount of Cooper pairs within a material. If the number of Cooper pairs inside a superconductor continues to increase as the temperature is lowered far below the superconducting critical temperature, one can expect that the material exhibits nodal superconductivity.

"We measured the magnetic penetration depth of CaPtAs as a function of temperature down to very low temperatures (less than 0.1 K) using two methods, from which it is possible to determine how the number of

Cooper pairs changes with temperature," Michael Smidman at Zhejiang University said. "One method of doing this is μSR, where a magnetic field is applied to the material. Since CaPtAs is a type-II superconductor, the field will penetrate the material via lines of magnetic flux to form a vortex lattice and the distribution of these flux lines can be detected using μSR. The distribution depends on the magnetic penetration depth, so the quantity of Cooper pairs is then easy to determine."

Yuan and his colleagues also used a further measurement tool known as tunnel diode oscillator (TDO). TDOs are very sensitive instruments for measuring the temperature dependence of the magnetic penetration depth.

Essentially, the researchers placed CaPtAs in a coil, which is part of an LC circuit. The current in this coil generates a very small magnetic field that cannot penetrate deeply into the superconductor due to the so-called Meissner effect, yet it can still reach a certain distance below its surface.

"This distance is characterized by a quantity known as the magnetic penetration depth," Yuan explained. "If the penetration depth of the superconductor changes with temperature, then the inductance of the coil also changes, and this can be detected by measuring the change of the resonant frequency of the LC circuit."

By applying these techniques to the superconductor CaPtAs, the researchers gathered evidence of its nodal superconductivity. More specifically, when they calculated the number of Cooper pairs in the material, they found that their results could be explained by models in which the gap in the superconductor is nodal.

"This was particularly evident from the fact that as the temperature decreased, the superfluid density continued to increase," Smidman said.

"If CaPtAs was a fully gapped superconductor, the superfluid density would saturate at low temperatures."

While many researchers previously predicted the presence of unusual superconducting characteristics in noncentrosymmetric superconductors, this was not always confirmed experimentally. Past studies identified a handful of magnetic noncentrosymmetric superconductors with a superconductivity that clearly differs from the conventional electron-phonon mechanisms outlined by Bardeen-Cooper-Schrieffer (BCS) theory, which manifested in unusual physical phenomena. However, many noncentrosymmetric superconductors with no magnetic ions were found to exhibit similar properties to their conventional centrosymmetric counterparts.

"In some cases, broken time-reversal symmetry is found in noncentrosymmetric superconductors, yet their other properties are still much like conventional superconductors," Yuan said. "In particular, they generally have fully open superconducting gaps. Our findings providing evidence of nodal superconductivity and time reversal symmetry breaking in CaPtAs, and thus allow us to draw a link between what had generally been distinctly different types of noncentrosymmetric superconductors."

Yuan and his colleagues found that the nodal superconductivity in CaPtAs resembles that observed in magnetic noncentrosymmetric superconductors. This means that CaPtAs could be a prime candidate for investigating the mixed singlet-triplet pairing that one would expect to find in these systems.

The study also offers valuable insight about the possible mechanisms behind the breaking of TRS in a wide range of superconductors. In the future, other research teams could draw inspiration from their work and use CaPtAs to investigate mechanisms of topological superconductivity and TRS.

"Although we have evidence for an unusual superconducting state in CaPtAs with both nodal superconductivity and broken time reversal symmetry, the detailed structure of the superconducting gap and underlying mechanisms giving rise to these behaviors still need to be determined," Yuan added. "In our next studies, we are interested in identifying a specific form of the superconducting pairing which can explain both of these results, and then to understand on a microscopic level what it is about CaPtAs that brings about this novel superconductivity. We would also like to determine whether topological superconductivity can be realized in CaPtAs."

More information: T. Shang et al. Simultaneous Nodal Superconductivity and Time-Reversal Symmetry Breaking in the Noncentrosymmetric Superconductor CaPtAs, *Physical Review Letters* (2020). DOI: 10.1103/PhysRevLett.124.207001