Probing the Gap Structure of Unconventional Superconductors

EPSRC Engineering and Physical Sciences Research Council
Centre for Doctoral Training in Condensed Matter Physics
University of Bristol
ces

J. A. Wilcox

H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom

Superconductivity and the Magnetic Penetration Depth

Superconductors are materials that exhibit the Meissner effect (perfect diamagnetism and perfect direct-current conduction) below a characterstic temperature, T_c. This occurs due to an attractive interaction between the electrons, causing them to form so-called Cooper pairs, resulting in a single macroscopic wavefunction, coherent throughout the material. [1]

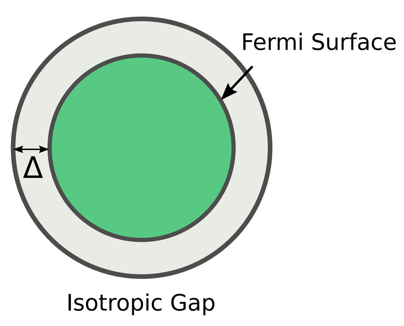
In conventional superconductors, the pairing mechanism is due to phonon exchange between electrons. The pairing mechanism in unconventional superconductors, however, is not well understood. It is not clear whether the mechanism should be the same for all families of unconventional superconductors.

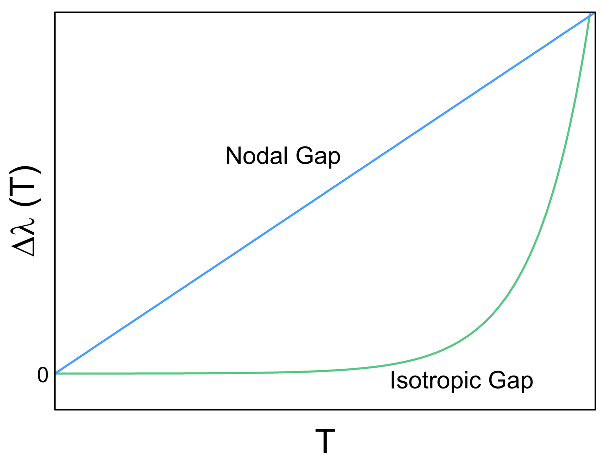
$$\Delta(k) = -\frac{1}{2}\sum_{k'} \frac{\Delta_{k'}}{E_{k'}} V_{kk'}$$

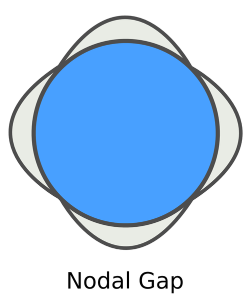
Below T_c a gap, Δ(k), is left in the quasi-particle density of states around the Fermi surface. The structure of the gap is closely linked to the pairing potential.

$$\Delta\lambda(T) \propto \int \mathrm{d}S \int_{\Delta_k}^{\infty} \mathrm{d}E_k \left(-\frac{\partial f(E_k)}{\partial E_k}\right) \frac{E_k}{\sqrt{E_k^2 - \Delta_k^2}}$$

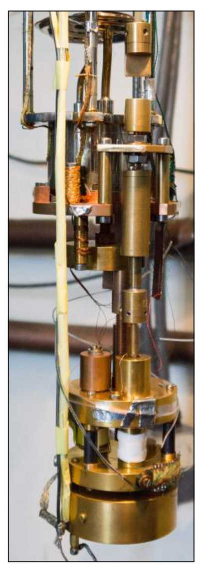
The magnetic penetration depth, λ(T), is a measure of how far a magnetic field penetrates a superconductor, and is closely related to Δ(k). It is difficult to measure the absolute value of λ(T), but measuring the relative change, Δλ(T), in reference to the base temperature of the system, is more achievable. The gap function is reflected in the temperature dependence of λ(T), rather than the absolute value. [2]

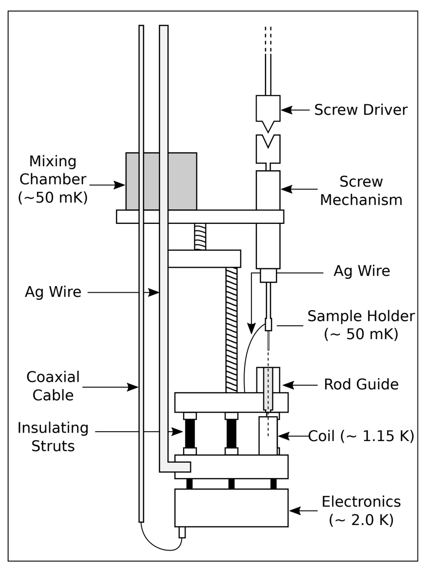






Experimental Approach

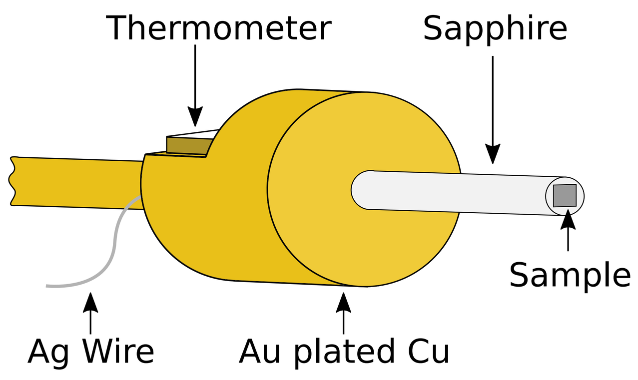




The experiment is built onto a $^3He/^4He$ dilution refrigerator, capable of a base temperature of ~50 mK. (Photo and schematic *left*).

The technique used to measure the penetration depth is based on a tunnel diode oscillator with a resonant frequency of ~15 MHz, stable to < 1 ppb. [3]

The superconducting sample is placed at the tip of a sapphire rod, which itself is located within an inductive coil, part of the resonant LC portion of the TDO. The variation of Δλ(T) is seen as a change the resonant frequency of the circuit.



Schematic of the sample holder

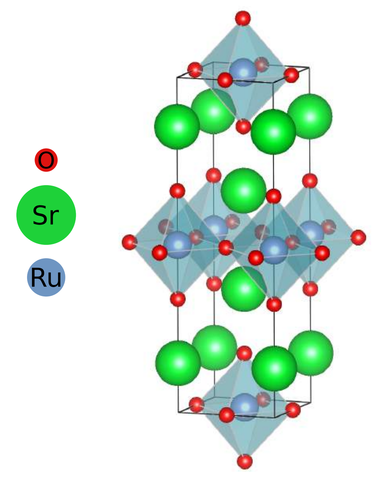
$$\Delta\lambda(T) \propto \Delta f(T)$$

The change in λ is related to the frequency shift through a calibration factor that is dependent on the orientation and geometry of the sample. [4] This can be inferred by measuring the shift in frequency when the sample is fully extracted from the coil.

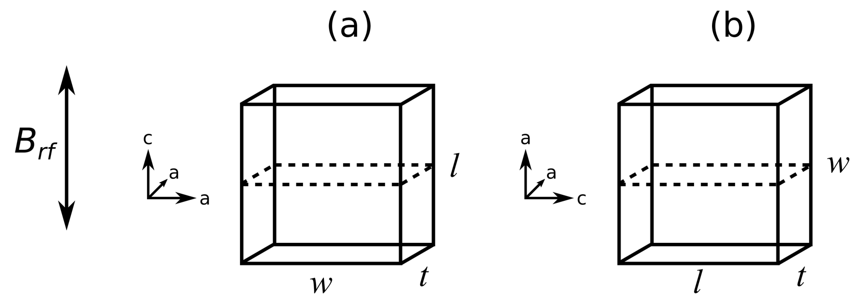
Results

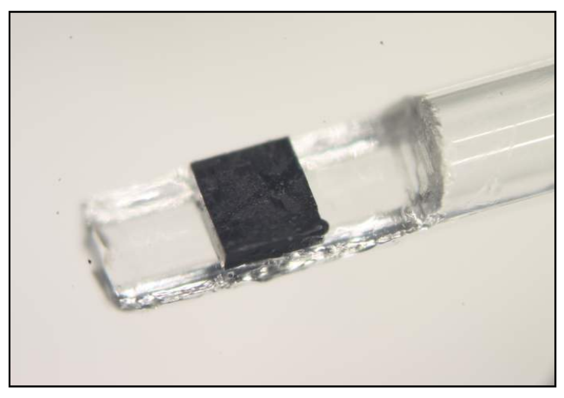
Sr_2RuO_4

Sr_2RuO_4 is a rare example of a candidate p-wave superconductor. It has a quasi-cylindrical Fermi surface, extending along the c-axis, and a T_c of ~1.5 K. The p-wave pairing state restricts the possible shape of the gap function; a horizontal line node on the main Fermi surface sheet would be forbidden. Determining $\Delta\lambda_c(T)$ will help to rule out some potential gap structures, and help to resolve whether Sr_2RuO_4 is p-wave or not.



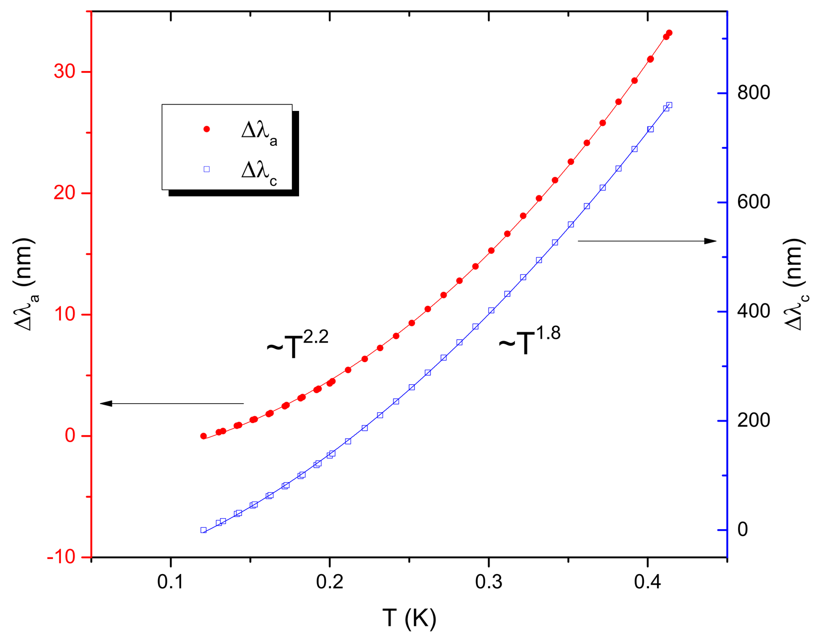
Tetragonal crystal structure of Sr_2RuO_4





Schematic showing the two orientations of the sample and the respective screening currents, and photo of a sample mounted on the sample holder.

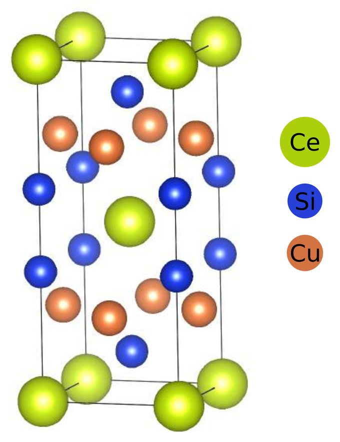
In order to determine $\Delta\lambda_c(T)$, a sample was cut in a desired geometry, and measured in two orientations: (a) screening currents running along both a-axes and (b) screening currents along the a- and c-axes.



The measurement revealed power-law type behaviours in both directions, and the exponent for $\Delta\lambda_a$ was larger than in previously reported measurements. [5]

The power law behaviour is not what is expected for candidate gap functions, suggesting additional factors must be taken into account, e.g. impurities, non-locality and strain.

$CeCu_2Si_2$

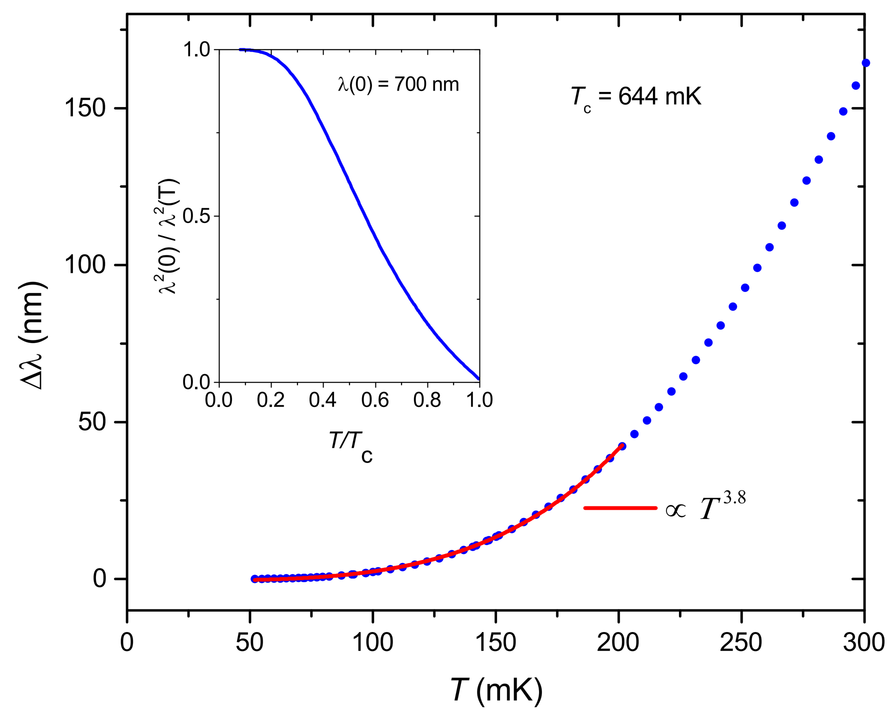


Tetragonal crystal structure of $CeCu_2Si_2$

$CeCu_2SI_2$ is notable for being the very first unconventional superconductor to be discovered. It is a member of the heavy fermion family of materials, and has a T_c of ~ 0.65 K. It is typically thought to have d-wave pairing, but the absence of high-quality crystals has made this a topic for debate.

Recent measurements of the low temperature heat capacity claimed the absence of nodes in the gap function, in contrast to conventional wisdom.[6]

The measurement was performed on a high-quality single-crystal of $CeCu_2Si_2$ (T_c~0.64K). The temperature dependence of Δλ does not display either linear or T^2 behaviour associated with clean or dirty d-wave cases. The high value of the exponent suggests a fully gapped situation.



Acknowledgements

I would like to thank Prof. A. Carrignton and Dr. C. Putzke for their continued help, with both the measurements and understanding the physics.
Thanks also go to T. Croft for preparation of the samples of Sr_2RuO_4.
Work on $CeCu_2Si_2$ was initiated and performed in conjuncion with the Shibauchi group at Tokyo University.

References

[1] Tinkham, M., "Introduction to Superconductivity", Courier Corporation, 1996.
[2] Chandrasekhar, B. S., and D. Einzel. "The superconducting penetration depth from the semiclassical model." Annalen der Physik 505.6 (1993): 535-546.
[3] Craig T. Van Degrift, "Tunnel Diode Oscillator for 0.001 ppm Measurements at Low Temperatures", 1974, Rev. Sci. Instrum., **46**, 599
[4] Prozorov, R., et al. "Meissner-London state in superconductors of rectangular cross section in a perpendicular magnetic field." Physical Review B 62.1 (2000): 115.
[5] Bonalde, I., et al. "Temperature dependence of the penetration depth in Sr 2 RuO 4: evidence for nodes in the gap function." Physical review letters 85.22 (2000): 4775.
[6] Kittaka, Shunichiro, et al. "Multiband Superconductivity with Unexpected Deficiency of Nodal Quasiparticles in CeCu 2 Si 2." Physical review letters 112.6 (2014): 067002.