TRIUMF

Characterization of Superconductivity in the Antimonide CaSb$_2$ using μSR

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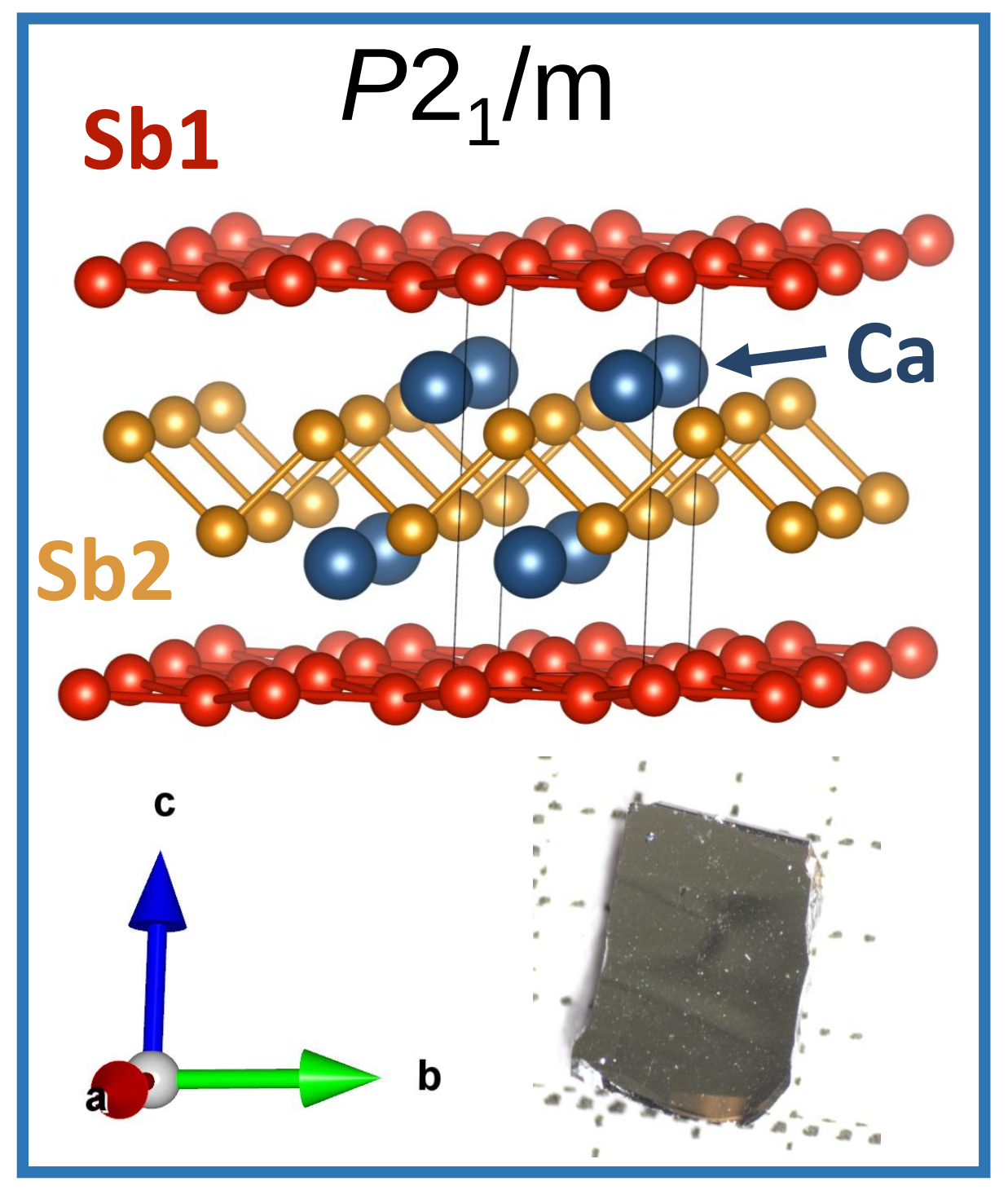
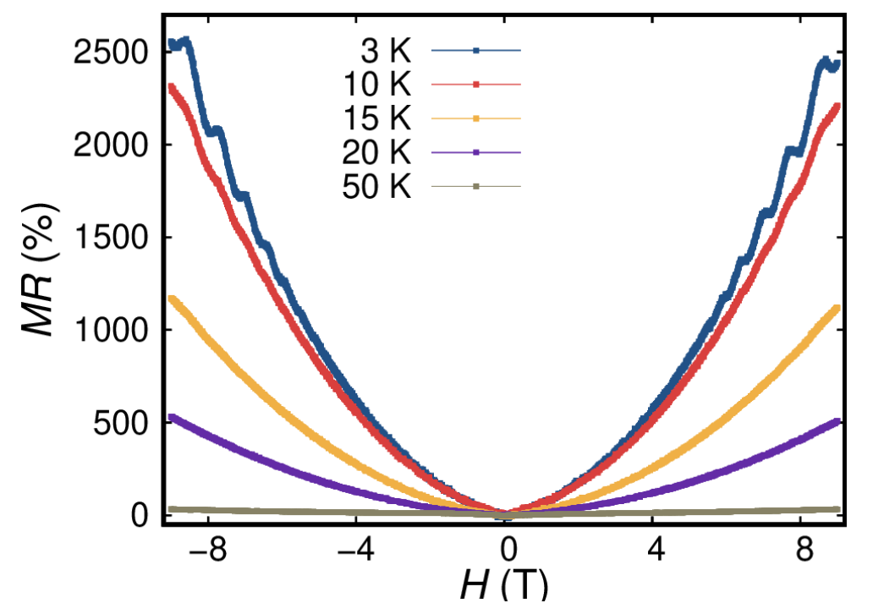
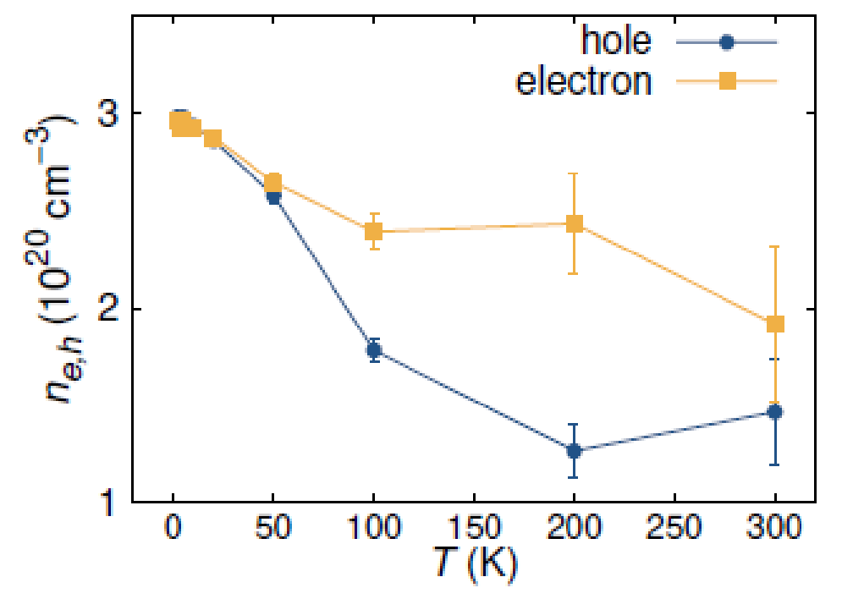
Background

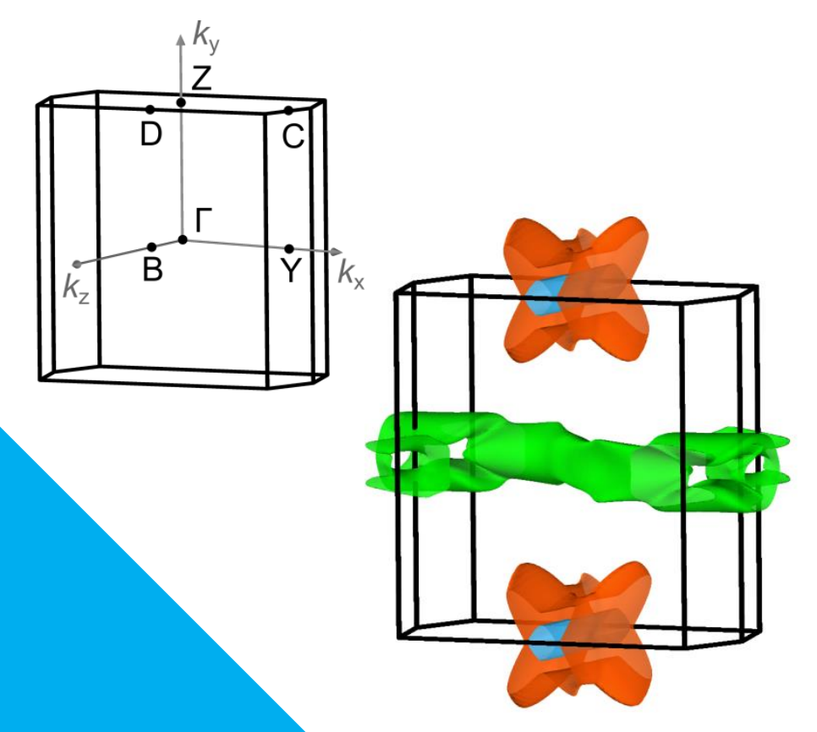
Superconductivity is a quantum state of ~10^{20}-10^{23} electrons, where conventional pairing is expected to preserve time-reversal and inversion symmetries. The absence of these symmetries in a superconductor hints at an unconventional superconducting pairing symmetry. Only a few superconductors have been confirmed with time reversal symmetry breaking (TRSB) and even less superconductors with topological properties.

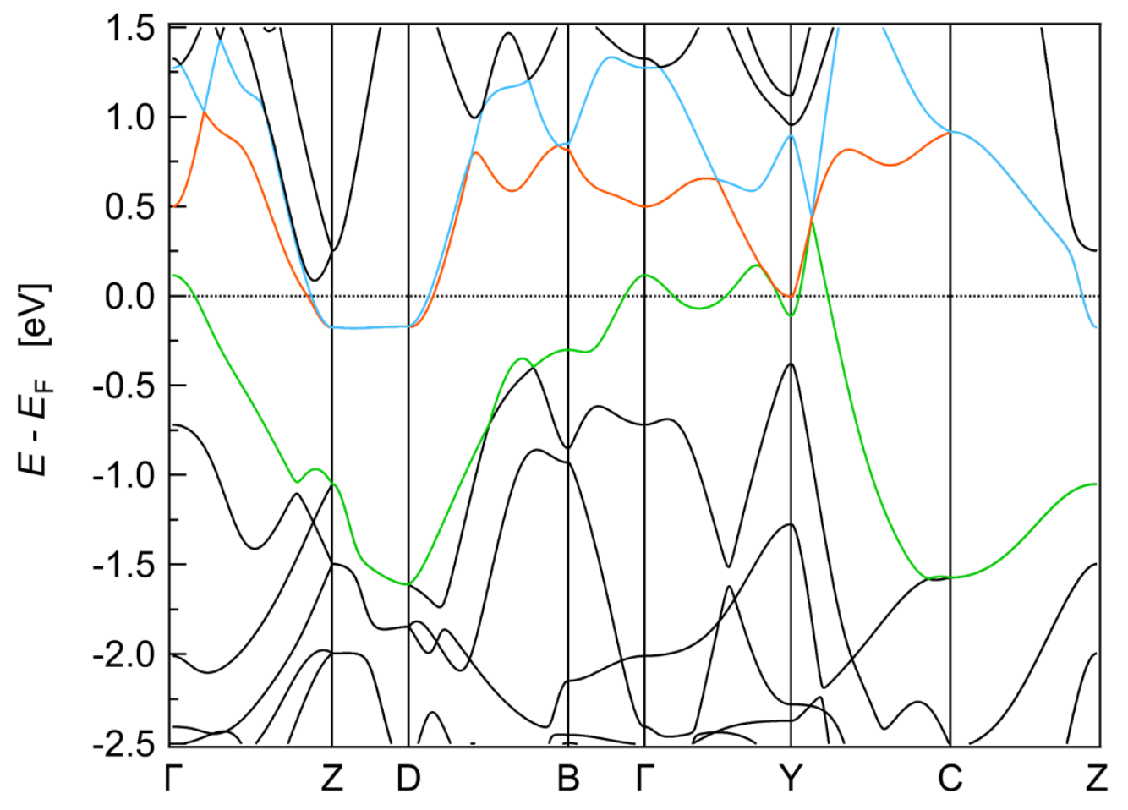
Recent studies on the non-symmorphic CaSb$_2$ show superconductivity below ~1.6 K[1,2] (right), and transport measurements show it is a compensated semimetal in the normal state[1,3] (below). These results are consistent with band structure calculations showing a topological nodal-line semimetal state in CaSb$_2$. The meeting of non-trivial topology and superconductivity in this antimonide can result in novel superconductivity, and low T specific heat data deviates from a conventional gap model. Further measurements of the penetration depth and TRSB are valuable to gain additional insight into the superconducting state of CaSb$_2$.

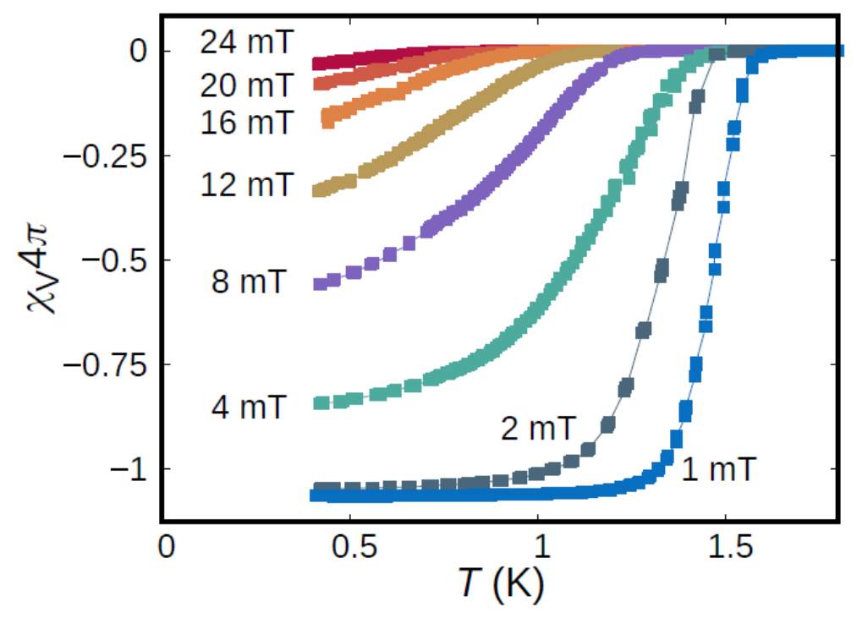


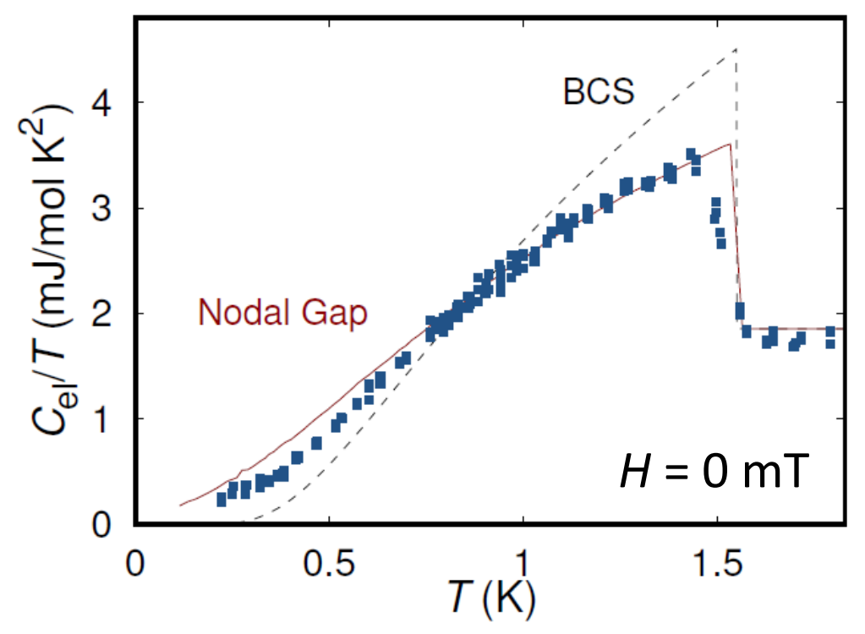


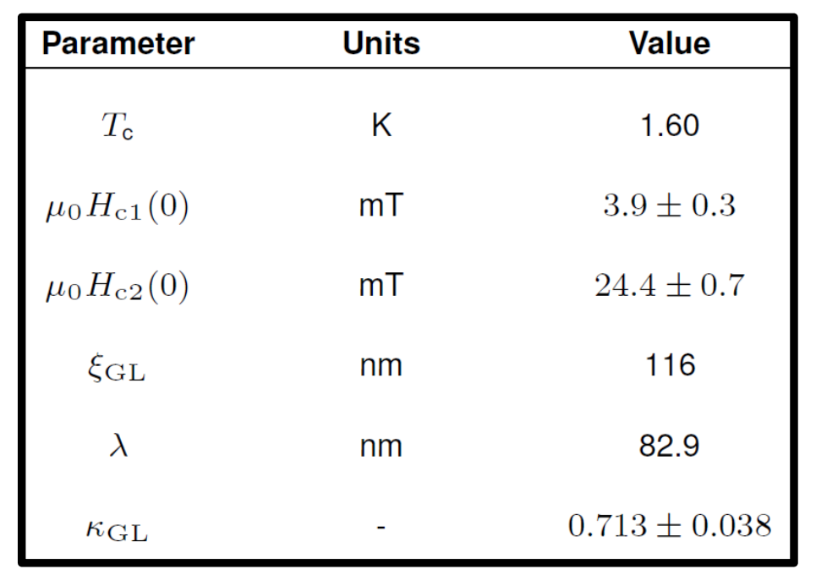




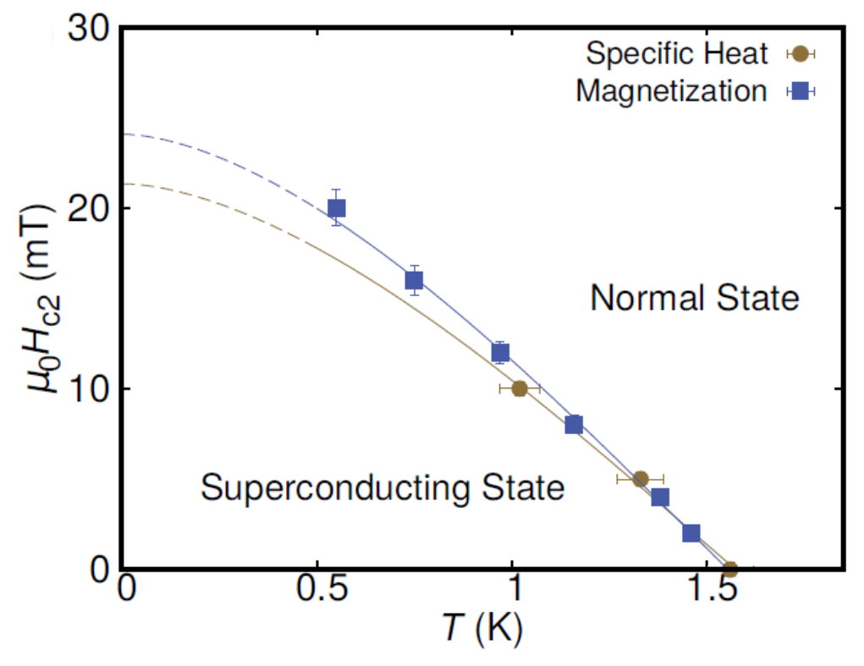








Parameter	Units	Value
T_c	K	1.60
$\mu_0 H_{c1}(0)$	mT	3.9 ± 0.3
$\mu_0 H_{c2}(0)$	mT	24.4 ± 0.7
ξ_{GL}	nm	116
λ	nm	82.9
κ_{GL}	-	0.713 ± 0.038



ZF-μSR

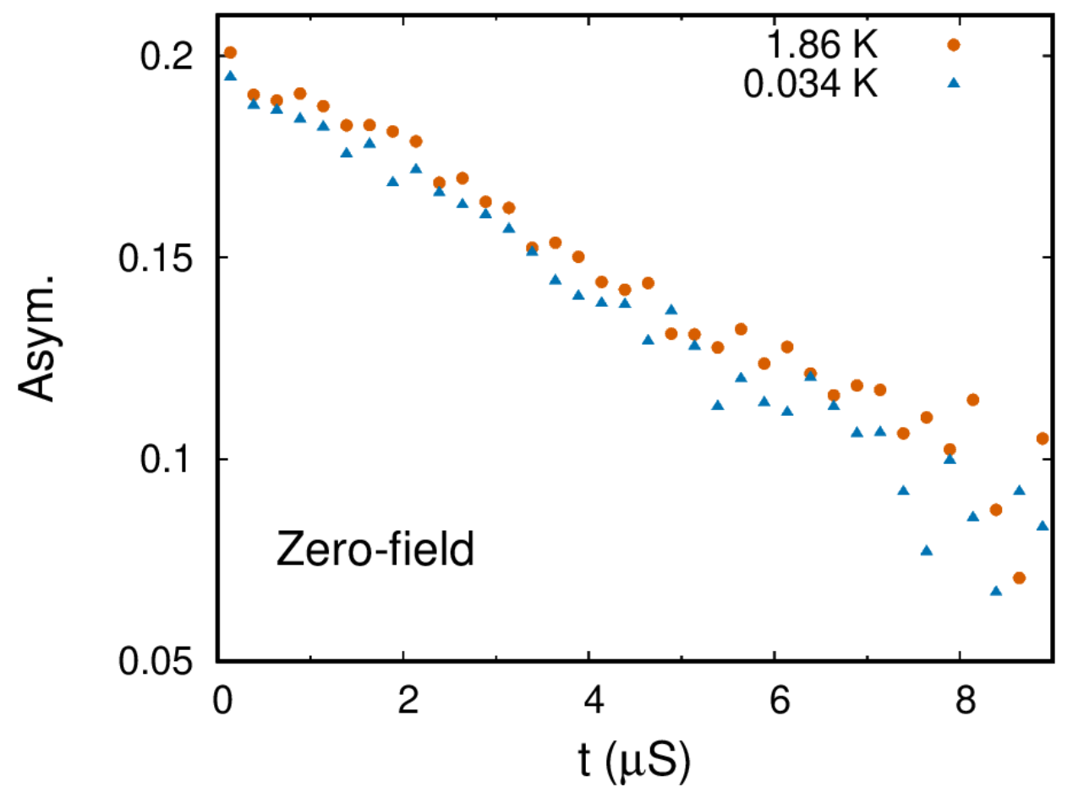
To investigate the possibility of TRSB and its pairing symmetry we performed ZF-μSR measurements.

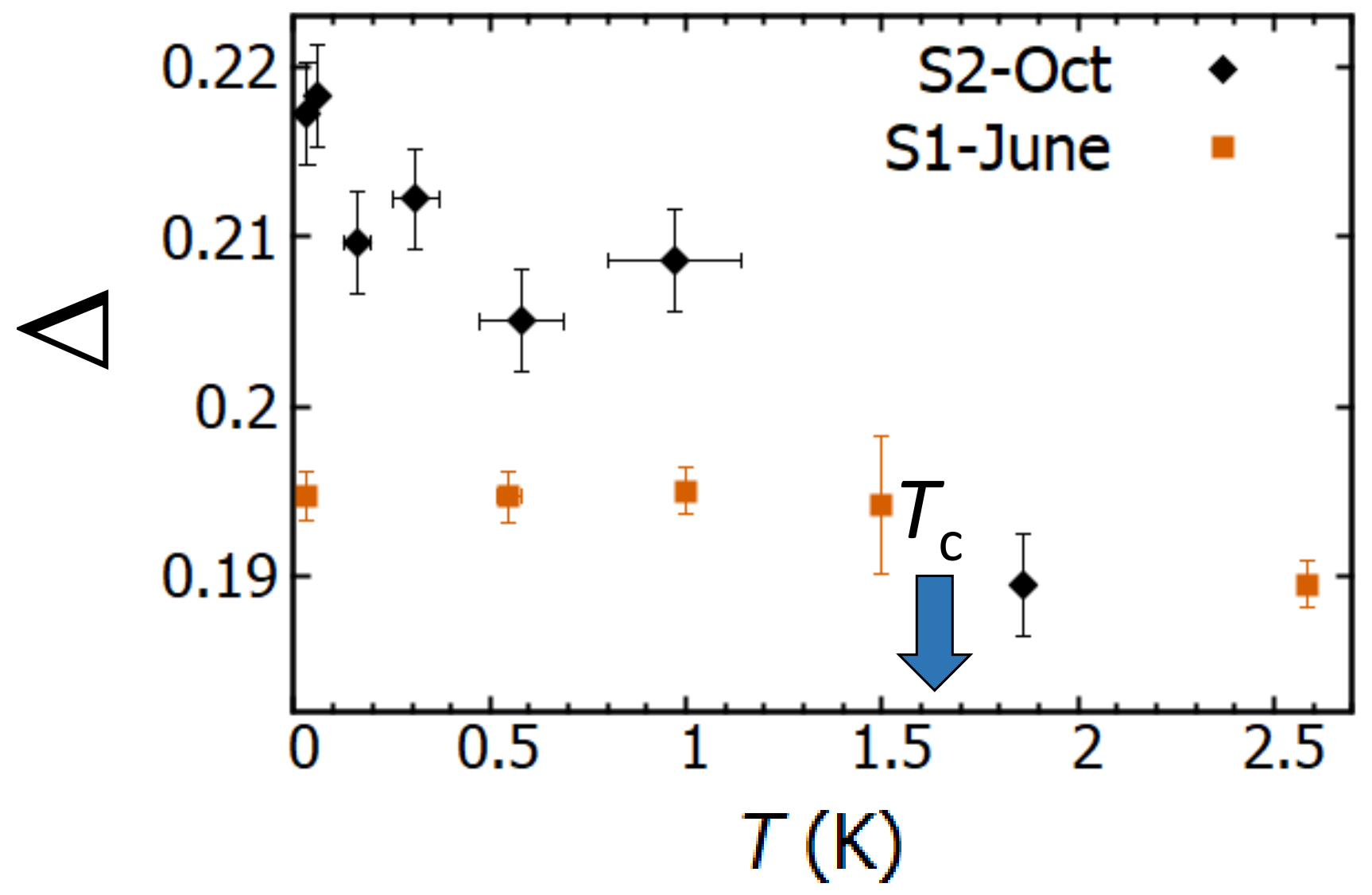
The ZF relaxation rate when crossing the transition temperature will show two different behaviors:

1) the relaxation rate, Δ, due to the normal state from the nuclear dipoles (Gaussian Kubo-Toyabe form)

2) the relaxation rate, λ, due to the TRSB fields which has a multiplicative exponential relaxation.

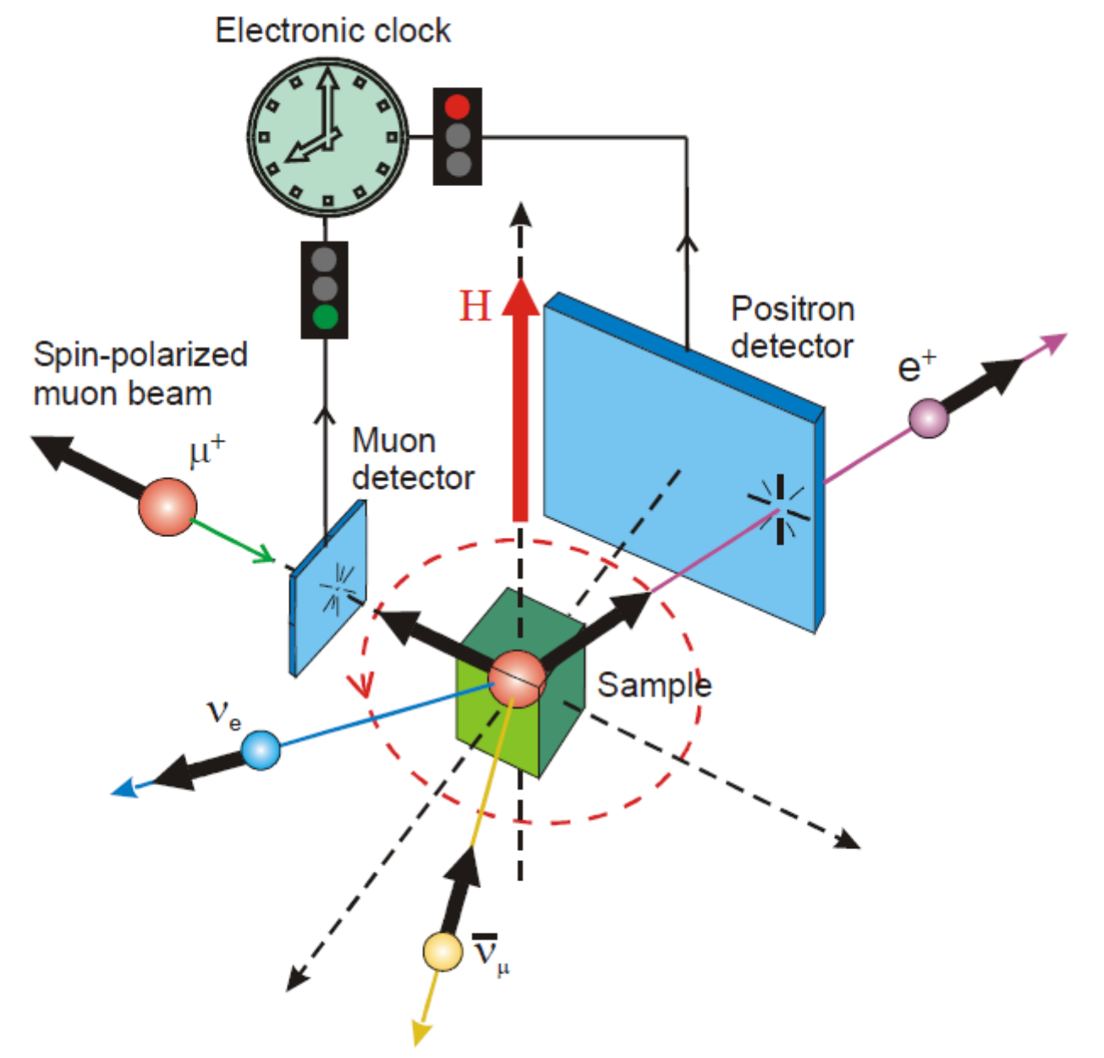
Our results show possible evidence of TRSB.





μSR

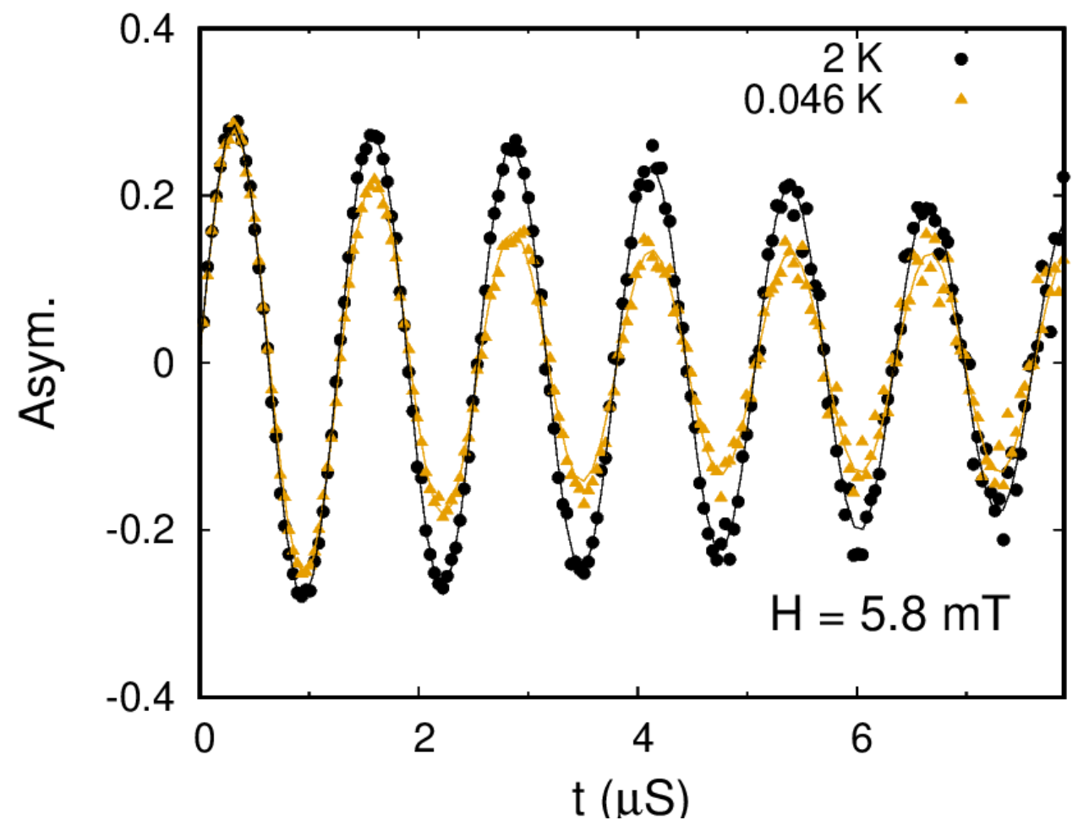
In ZF setup, μSR is the most powerful method to detect weak internal magnetism that arises due to ordered magnetic moments or random fields that are static or fluctuating with time. While in TF setup, it can measure the field distribution, including the vortex lattice in a type-II superconductor.

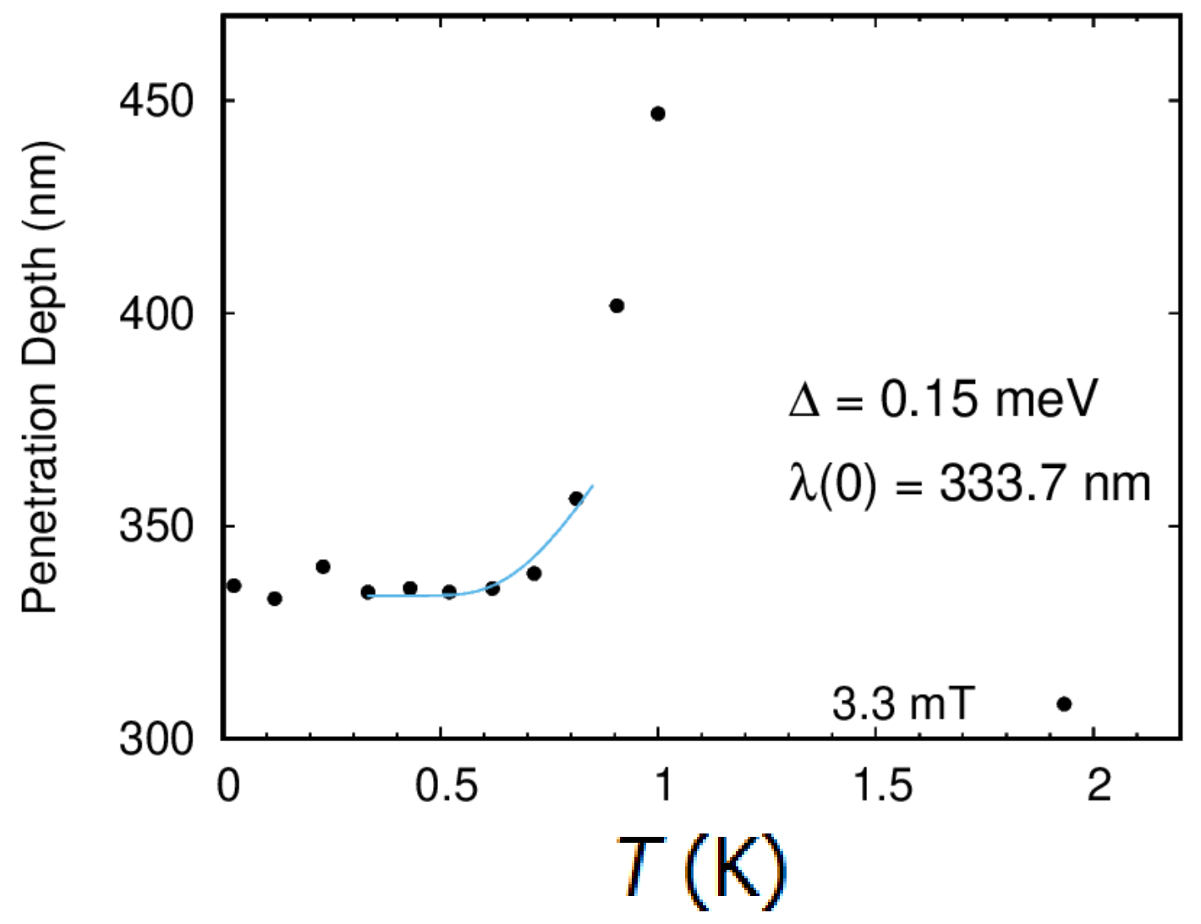


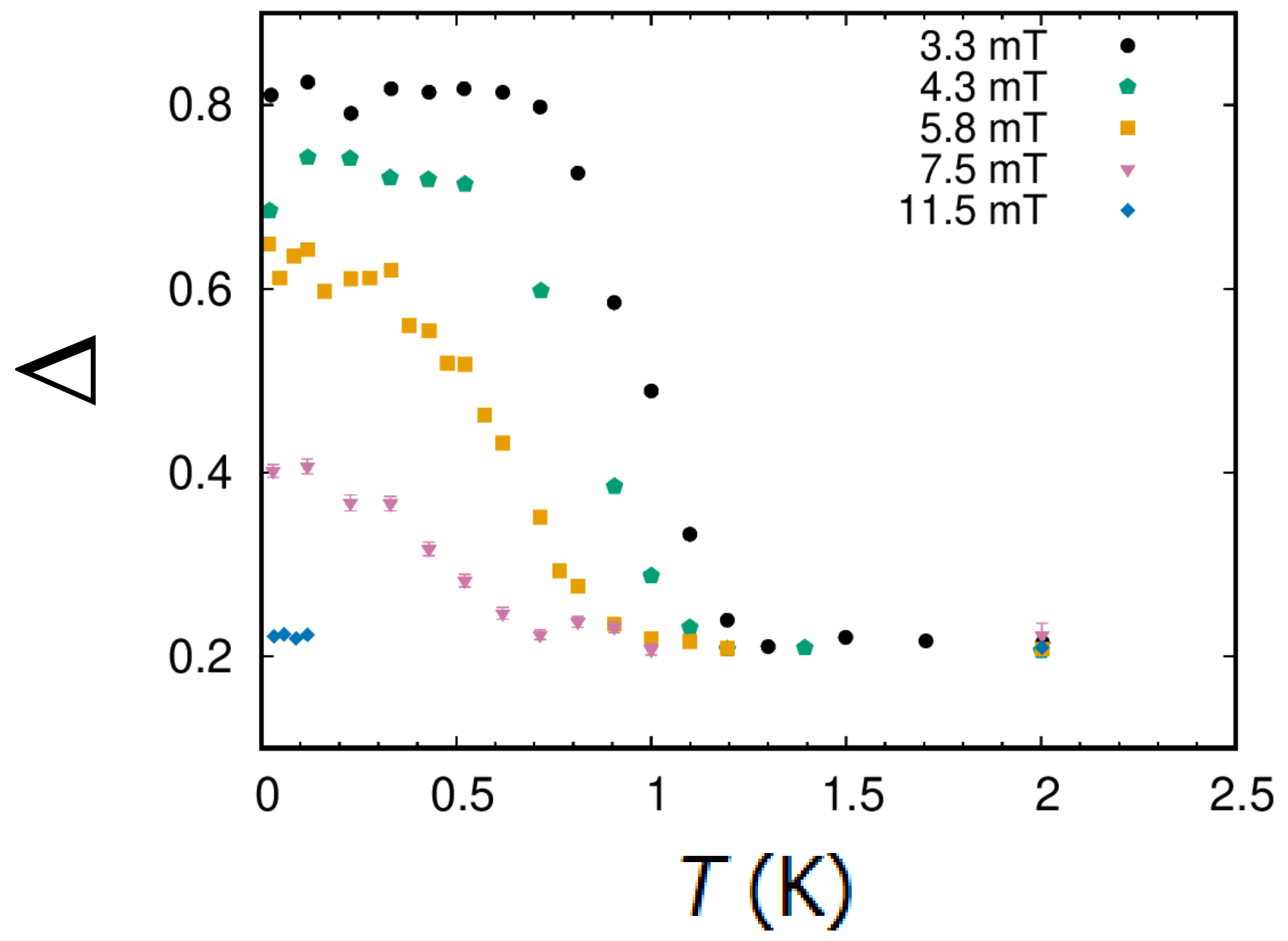
TF-μSR

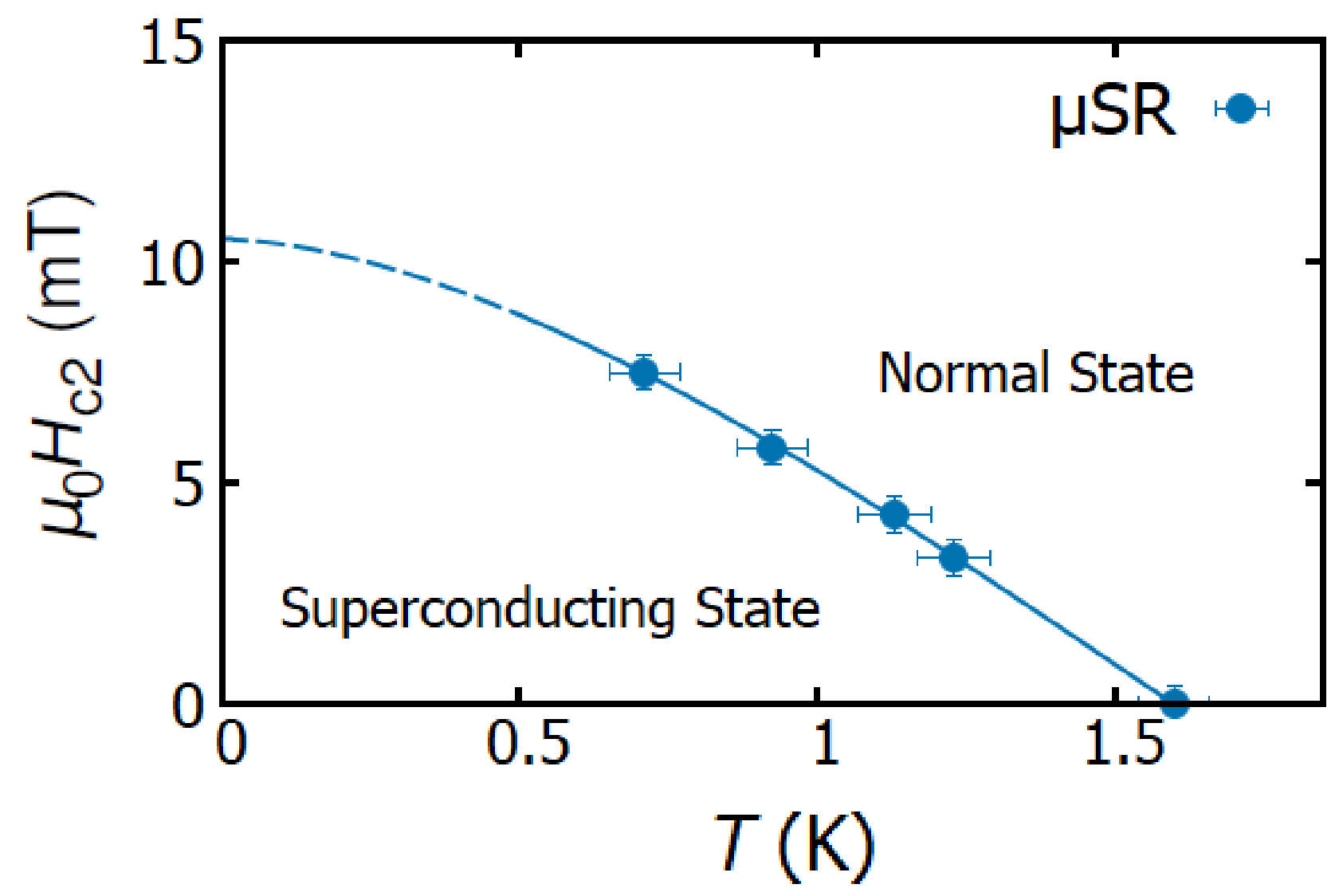
We also performed TF-μSR measurements to study the penetration depth. TF spectra show oscillations as expected for muon precession in applied external field with two components contributing to the asymmetry. Slow relaxing large amplitude comes from muons stopping in the silver sample holder or non-superconducting portions, while the lower field comes from muons stopping in the superconducting sample.

$$A = A_T\left[F\cos(\gamma_\mu B_s t + \phi)e^{-0.5(\sigma_s t)^2} + (1-F)\cos(\gamma_\mu B_{\mathrm{Ag}} t + \phi)e^{-0.5(\sigma_{\mathrm{Ag}} t)^2}\right]$$









Expressing penetration depth as a function of σ yields:

$$\lambda = \xi\sqrt{(1.94\times10^{-2})\frac{\phi_0}{\xi^2}(1 - H/H_{c2})\frac{\gamma_\mu}{\sigma_{SC}} + 0.069}.$$

For further test of the pairing symmetry, we calculated the normalized superfluid density as $n_s/n_0 = \lambda^2(0)/\lambda^2(T)$. Which was well fit by following equation assuming a fully gapped superconductor:

$$\frac{n_s(T)}{n_0} = \left[1 - 2\int_\Delta^\infty dE\left(-\frac{\partial F}{\partial E}\right)\frac{E}{\sqrt{E^2-\Delta^2}}\right].$$

Summary/Conclusion

Our TF-μSR results on CaSb$_2$ suggest that it is a type-II s-wave superconductor. Zero-field μSR measurements show possible hints of TRSB, which requires further investigation. These features are overall consistent with an anisotropic s-wave gap description of CaSb$_2$, and future measurements and calculations will be necessary to clarify the details of the gap structure.

Discovery,
accelerated

[1] Submitted to *PRB* arXiv:2106.06175 [2] *PRM* **4**, 041801(R) (2020) [3] *JPSJ* **88**, 044711 (2019) [4] PhysRevB.103.214508 (2021)