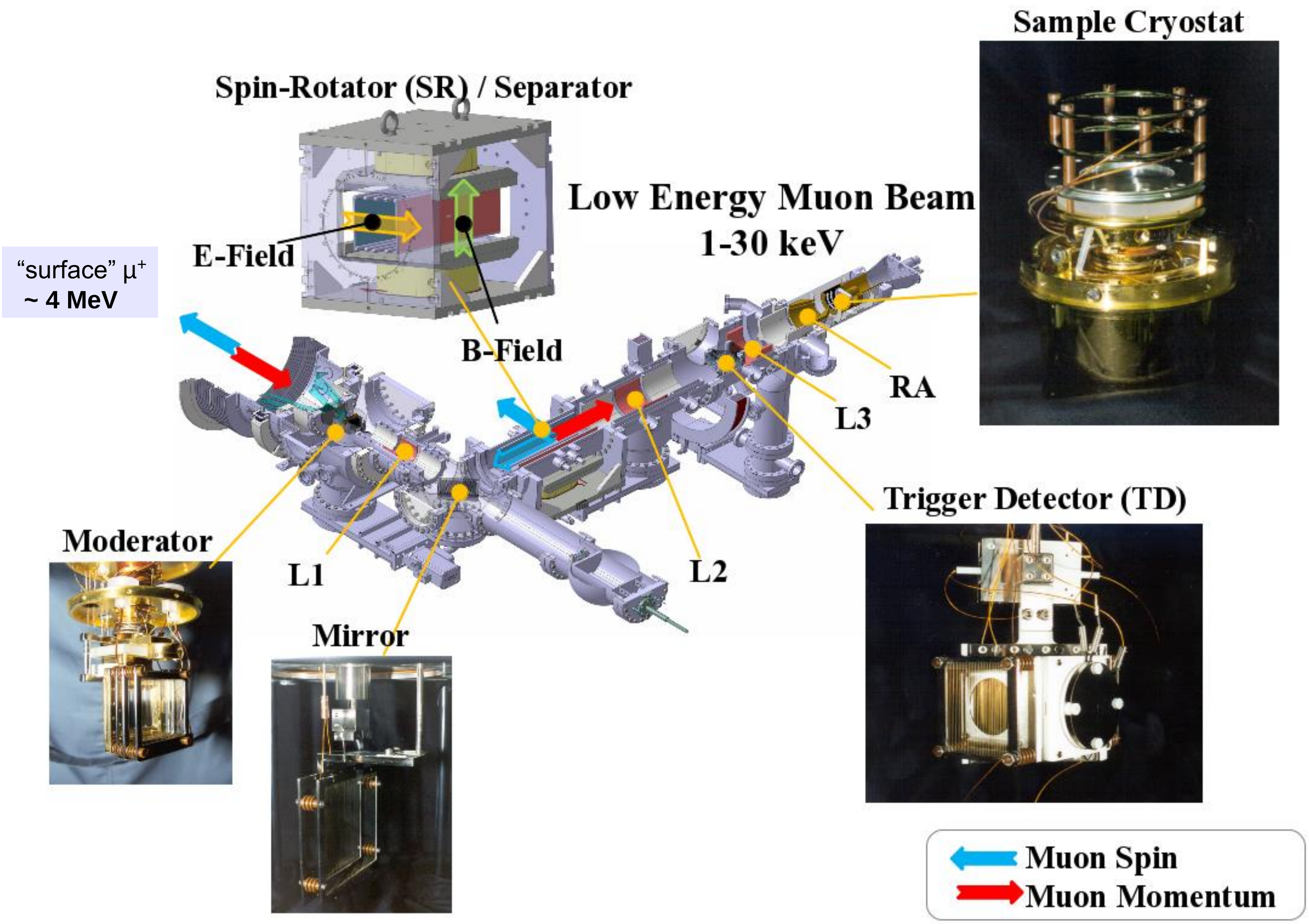
Low-energy muons

- Low energy μ^+ beam and instrument for LE-µSR
- LE-µSR data collected on single-layer FeSe
- Practicalities

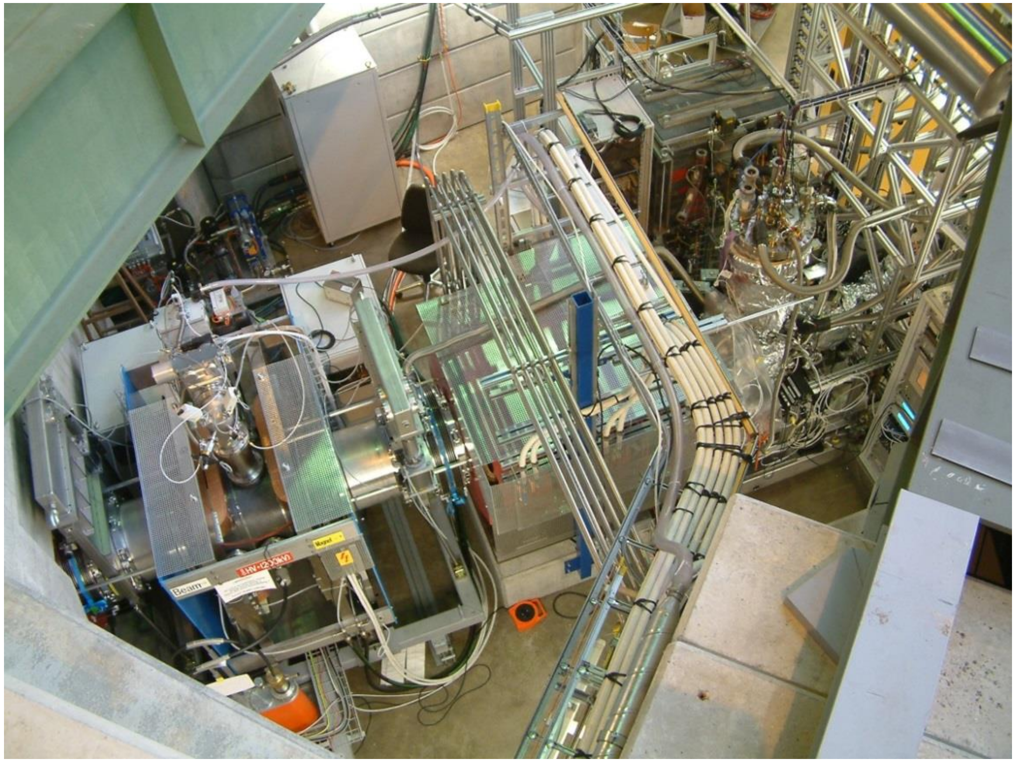
Pabitra Biswas, ISIS Muon Group

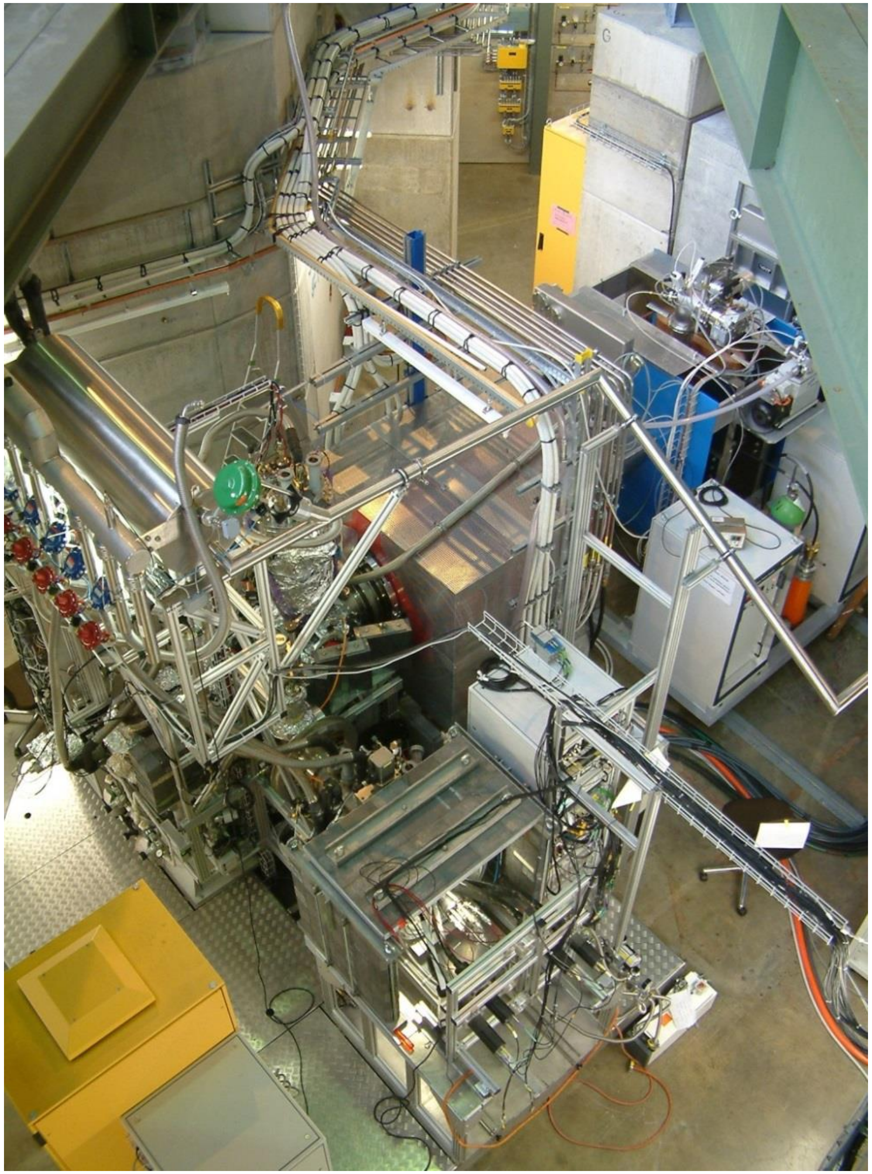
Low energy μ^+ beam and instrument for LE-μSR at PSI



https://www.psi.ch/smus/lem

LE-μ+ Apparatus @ μE4 beamline

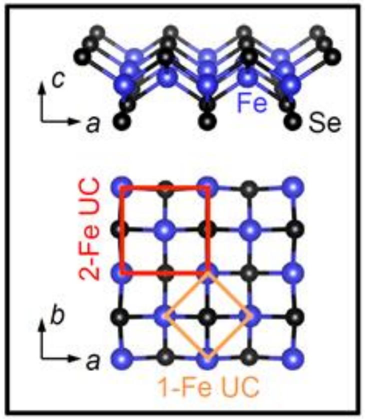


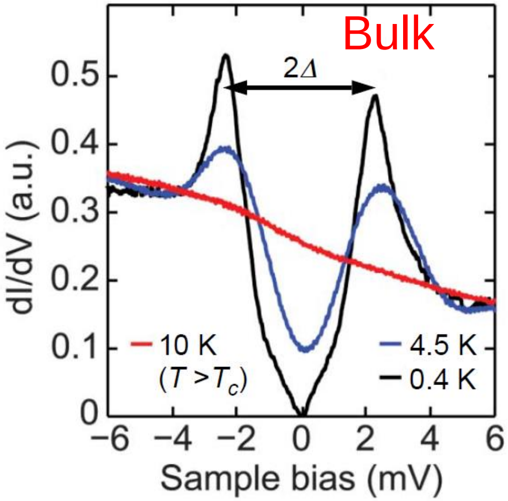


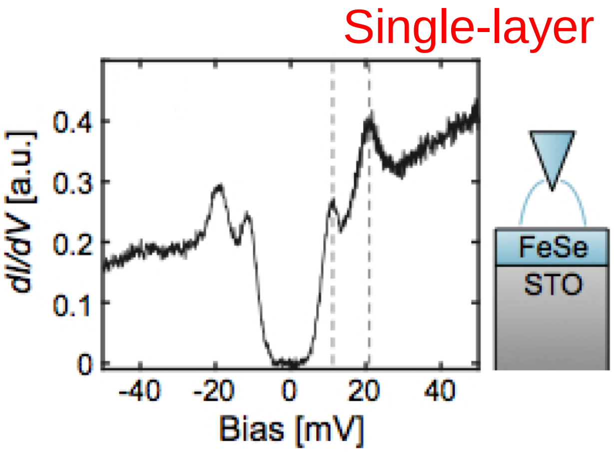
- ~ 6 x10^8 μ^+/s total
- ~ 1.9 x10^8 μ^+/s on LEM source
- ~ 1.1 x10^4 μ^+/s LEM

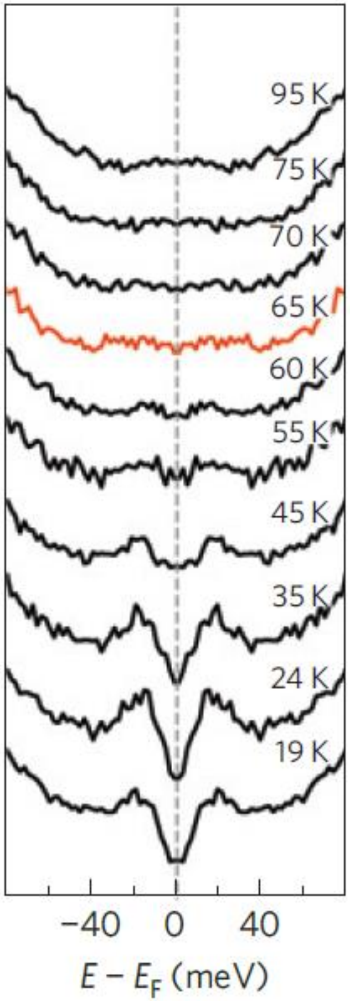
Th. Prokscha, E. Morenzoni, K. Deiters, F. Foroughi, D. George, R. Kobler, A. Suter and V. Vrankovic
Physica B 374-375, 460-464 (2006)
and Nucl. Instr. Meth. A 595, 317-331 (2008)

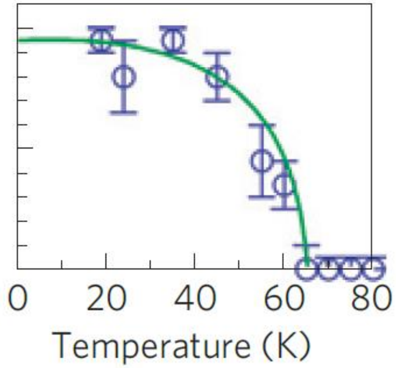
Introduction: Single-layer FeSe

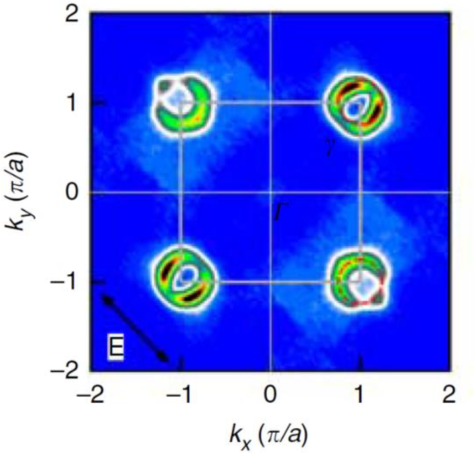










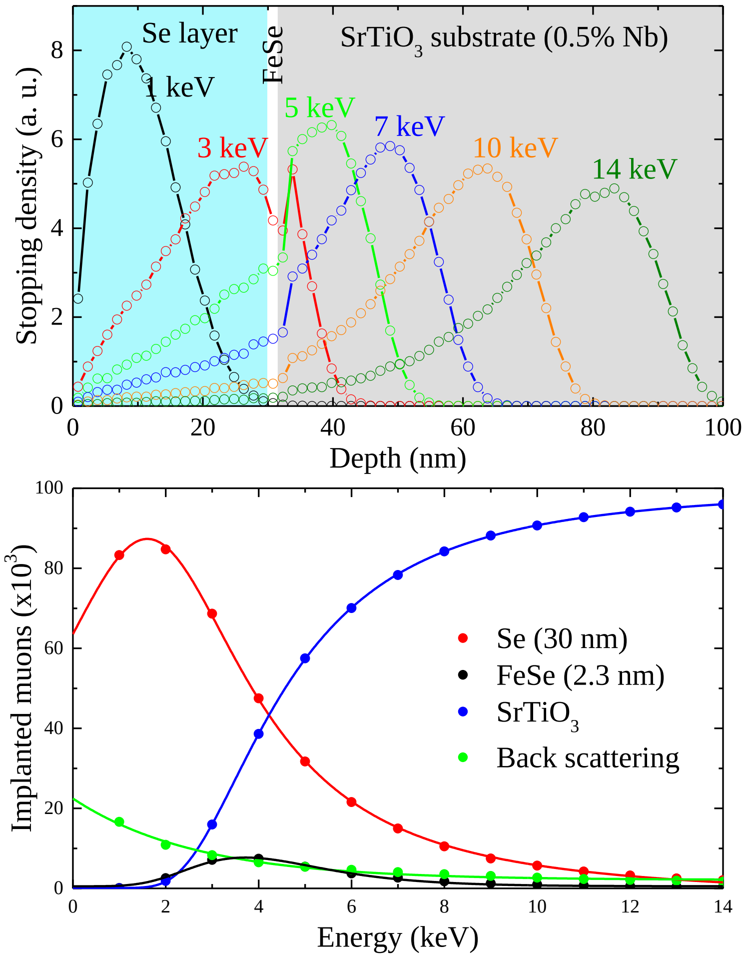


FS mapping of single-layer FeSe at 20 K that consists only of the electron-like Fermi-surface sheet around M (π,π).

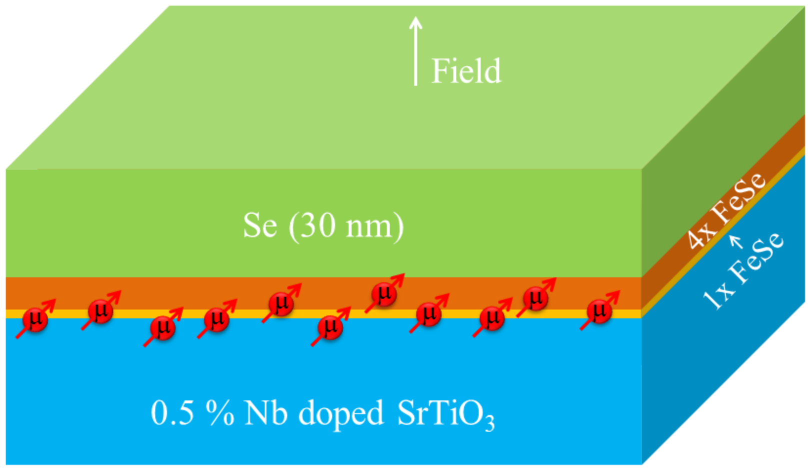
S. He, *et al.*, Nature Materials 12 605 (2013).

D. Liu, *et al.*, Nat. Commun. (2012). DOI: 10.1038/ncomms1946

Evidence of superconductivity in monolayer FeSe

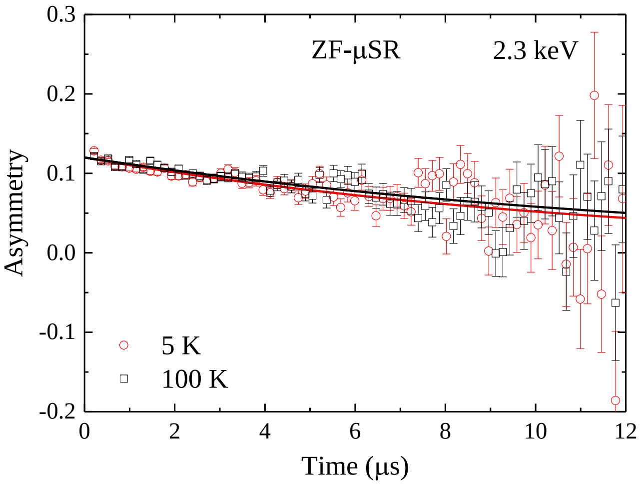


Simulated muon implantation profiles in the single-layer FeSe films grown on SrTiO3 substrate, using the program TRIMSP which has been shown to calculate the stopping profile of the implanted muons with sufficient accuracy.



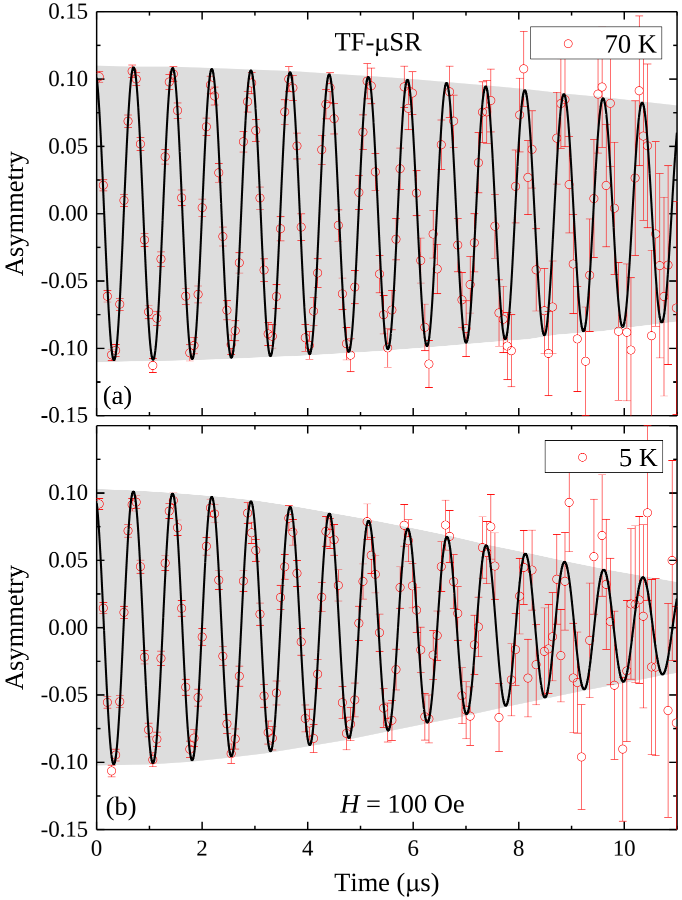
Schematic diagram of the heterostructure films of the single-layer FeSe films grown on SrTiO3 substrate.

Evidence of superconductivity in monolayer FeSe



ZF-μSR time spectra collected at 5 and 100 K show no sign of magnetism in single-layer FeSe.

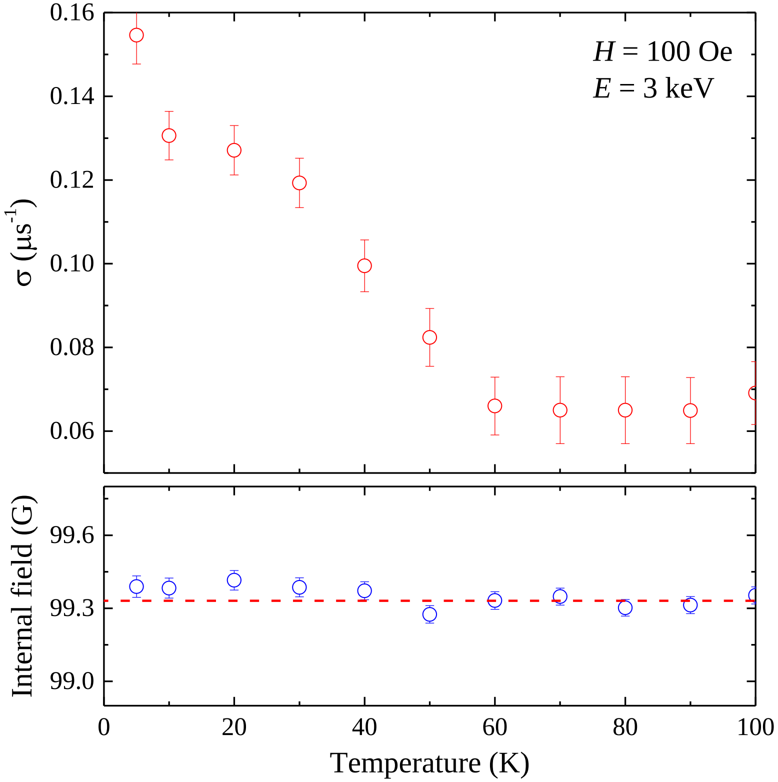
$$A_t = A_0\left\{\frac{1}{3}+\frac{2}{3}(1-\Lambda^2t^2)exp\left(-\frac{\Lambda^2t^2}{2}\right)\right\}$$



TF-μSR time spectra of single-layer FeSe, collected at 5 K, shows higher damping than the 100 K data due to the formation of FLL.

$$G_x(t) = A_0e^{-\sigma^2t^2}\cos(\gamma_\mu B_{int}t+\varphi)+A_{bg}\cos(\gamma_\mu B_{bg}t+\varphi)$$

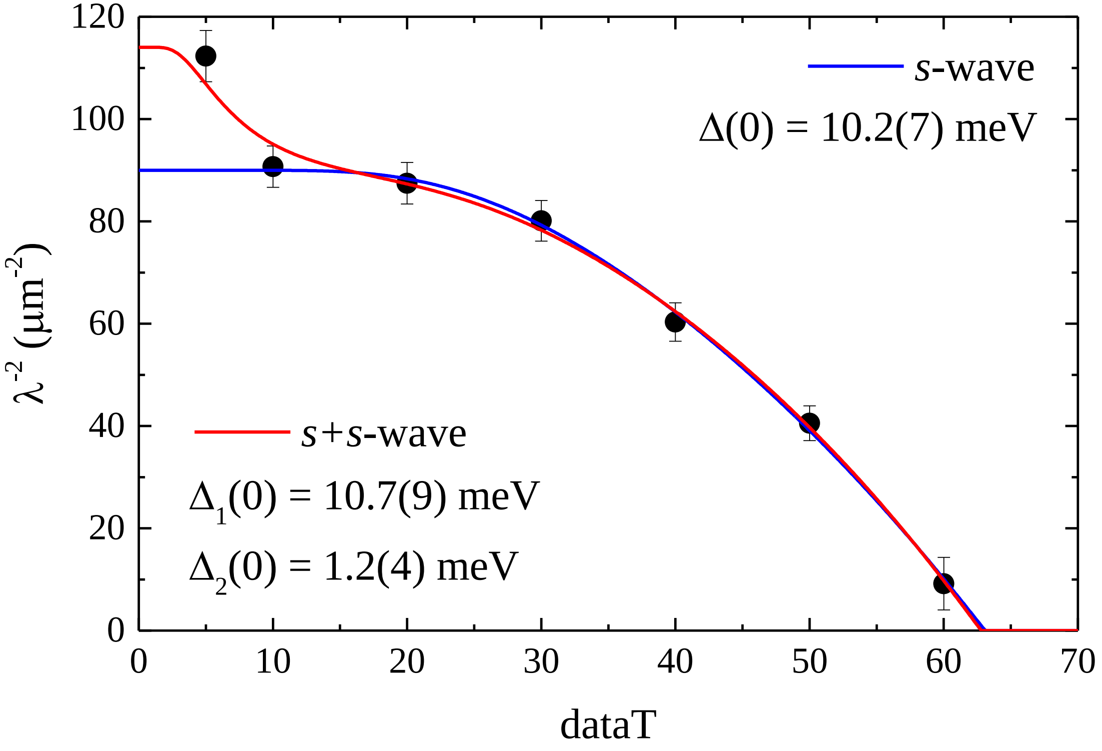
Evidence of superconductivity in monolayer FeSe



$$\frac{\sigma_{sc}{}^{2}(T)}{\gamma_{\mu}{}^{2}} = 0.00371\frac{\varphi_{0}{}^{2}}{\lambda^{4}(T)}$$

Temperature dependence of muon spin relaxation rate σ which increases below 60 K due to superconductivity in single-layer FeSe. Internal field however showing nearly temperature independent nature.

Evidence of superconductivity in monolayer FeSe



Temperature dependence of superfluid density of single-layer FeSe, showing nodeless superconductivity like bulk FeSe superconductor.

$$\frac{1}{\lambda^2} \propto \frac{\mu_0 e^2}{m} n_s$$

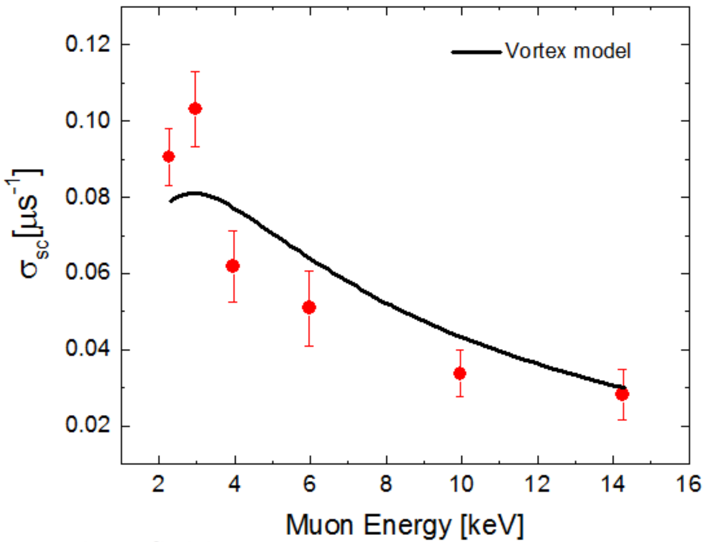
BCS *s*-wave model:

$$\boxed{\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = 1 + 2\int_{\Delta(T)}^{\infty}\left(\frac{df}{dE}\right)\frac{EdE}{\sqrt{E^2-\Delta(T)^2}}}$$

$$f = \frac{1}{1+e^{E/k_B T}}$$

$$\boxed{\Delta(T) = \Delta(0) tanh\left\{1.82\left[1.018\left(\frac{T_c}{T}-1\right)\right]^{0.51}\right\}}$$

Single-layer FeSe/STO: superfluid density and gap



Fitting the energy (depth) dependent field broadening:

$$\Lambda_P(0) \equiv \frac{2\lambda^2}{d} \approx 2.5(5) \cdot 10^4 \text{ nm}$$

$\rightarrow$ Sheet supercarrier density:

$$\mathbf{n_s^{2D}(0)} = \frac{2m^*}{\mu_0 e^2 \Lambda_P} \mathbf{< \approx 6 \cdot 10^{14}\ cm^{-2}}$$

$(\mathrm{m}^* = 2.7\ \mathrm{m_e})$

$\lambda(0) \approx 112(5)$ nm

- Large superfluid density: more than one layer contributing?, proximity (ARPES ≈ 0.1 electron/Fe → $\mathbf{1.3 \cdot 10^{14}\ cm^{-2}}$)

- $\mathrm{n_s^{2D}(T)}$ → s-wave gap: $\mathbf{\Delta(0) = 10.2(7)\ meV}$ (ARPES/STM 10-15 meV)

- Superconductivity found across most of the buried layer ($\mathrm{cm^2}$) (no phase separation)

Practicalities

- Measure a sample in 1-2 days
- Field range: 0-35 mT
- Temperature range: 2.5 – 350 K
- Depth range: 2 -200 nm
- Depth resolution: ~ 10nm
- Sample size: 1-9 cm^2

Summary

- We use the **LE-μSR technique** to detect and quantify the superfluid density and determine the gap symmetry in a **single-layer of FeSe grown on STO (100)** buried in a heterostructure consisting of Se(25nm)/4 ML FeSe/1 ML FeSe/Nb 0.5% doped STO(substrate).
- Measurements in the applied field show a **temperature-dependent broadening of the field distribution below 60 K**, reflecting the formation of a vortex state.
- **Zero field measurements rule out the presence of magnetism** of static or fluctuating origin.
- We determine a superconducting sheet **carrier density of up to 6 x10^{14} cm^2** at T=0 K which is 4 times higher than the excess electrons in single-layer FeSe obtained from ARPES measurements. This may suggest that the **additional FeSe layers or STO contribute to superconductivity of ML FeSe/STO**, possibly via a proximity effect.
- Transverse-field (TF)-μSR results reveal that the observed **superfluid density can be well described by a simple BCS *s*/*s*+*s*-wave model**, indicates for nodeless superconducting state in the single-layer FeSe and is consistence with its bulk counterpart.

Acknowledgements

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Thank you very much for your attention ☺