Experimental Evidence for Current Suppression in Superconducting Heterostructures

Md Asaduzzaman (Asad)

Ph.D. Candidate

Department of Physics & Astronomy, University of Victoria, BC, Canada

TRIUMF, BC, Canada

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Direct measurement of the Meissner screening profile in superconductor-superconductor bilayers using low-energy muon spin rotation

Md Asaduzzaman, Ryan M.L.McFadden, Anne-Marie Valente-Feliciano, David R. Beverstock, Andreas Suter, Zaher Salman, Thomas Prokscha, Tobias Junginger

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Agenda

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- Motivation
  - Experimental evaluation of Meissner current suppression (due to a counter-current flow) in superconductor-superconductor (SS) bilayers to overcome Nb's fundamental field limits.
- Measurement of microscopic properties of layered superconductors
  (Using direct observation of depth resolved magnetic field profile)
  - Low energy muon spin rotation (LEμ-SR) technique
- Experimental results
- Summary

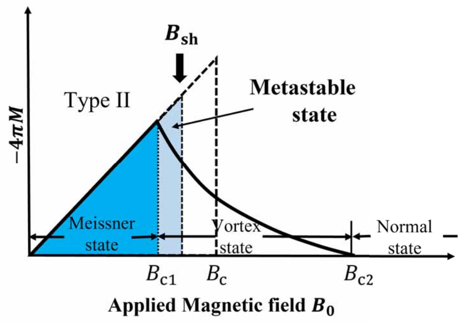
Maximum field in the Meissner state of a semi-infinite superconductor?

- In a type-II superconductor Meissner state can persist as a metastable state up to a maximum field above B_{c1} named by superheating field (B_{sh}).
- Superheating field (B_{sh}) at $T << T_c$:

$$B_{sh} \propto B_c \propto J_{max}$$

Here, J_{max} is the maximum screening current that can withstand against vortex penetration.

Magnetization response of a type-II superconductor



Catelani. G. et al. (2008)

F. Pei-Jen Lin et al. (2012)

Counter current flow modifies the Meissner screening profile in SS bilayers

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- The surface current is reduced in the $Nb_{1-x}Ti_xN$ layer due to the counter current flow in the Nb layer.

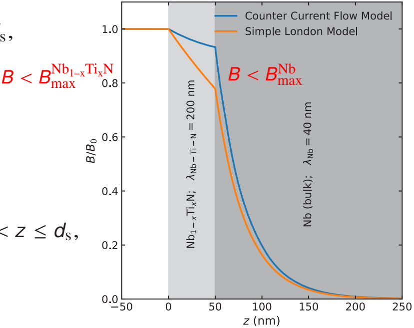
- Simple London model for an SS bilayer:

$$B(z) = B_0 \times \begin{cases} \exp\left(-\frac{z}{\lambda_s}\right), & 0 \le z < d_s, \\ \exp\left(-\frac{d_s}{\lambda_s}\right)\exp\left(-\frac{z-d_s}{\lambda_{sub}}\right), & z \ge d_s, \end{cases}$$

- Counter current flow model for an SS bilayer:

$$B(z) = B_0 \times \begin{cases} \dfrac{\cosh\frac{d_s - z}{\lambda_s} + \left(\frac{\lambda_{sub}}{\lambda_s}\right)\sinh\frac{d_s - z}{\lambda_s}}{\cosh\frac{d_s}{\lambda_s} + \left(\frac{\lambda_{sub}}{\lambda_s}\right)\sinh\frac{d_s}{\lambda_s}}, & 0 < z \le d_s, \\ \dfrac{\exp\left(-\frac{z-d_s}{\lambda_{sub}}\right)}{\cosh\frac{d_s}{\lambda_s} + \left(\frac{\lambda_{sub}}{\lambda_s}\right)\sinh\frac{d_s}{\lambda_s}}, & z > d_s, \end{cases}$$

Illustration of field screening with different screening model in an SS bilayer.

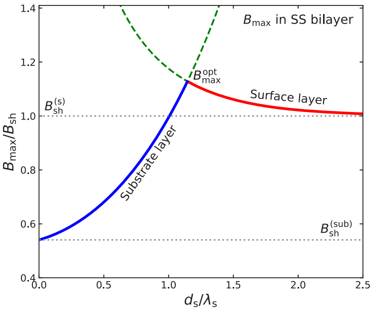


T. Kubo (2017)

How max B_0 can go in the Meissner state in an SS bilayer?

- B_{max} increased in the substrate layer because it needs to be attenuated while reaching at the SS interface.
- In the surface layer B_{max} increased due to the counter current flow in the substrate layer.

The prediction of maximum applied field, B_{max} in an SS bialyer as a function of surface layer thickness (d_s).

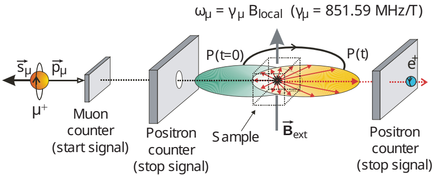


Measurement of a depth-resolved field profile using LEμ-SR

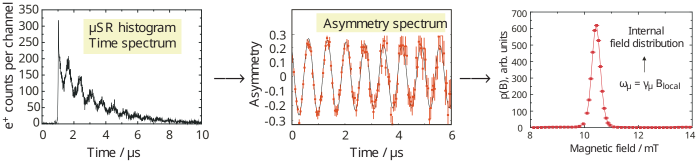
Principle of a muon spin rotation (μ-SR) technique in an externally applied transverse magnetic field (B_{ext}).

- **Frequency** $\longrightarrow$ Average local magnetic field
- **Damping rate** $\longrightarrow$ The width of the magnetic field distribution

P Bakule et al. (2004)



The transformation of asymmetry from time to frequency domain allows measurement of the local fields experienced by the muons at their stopping site.

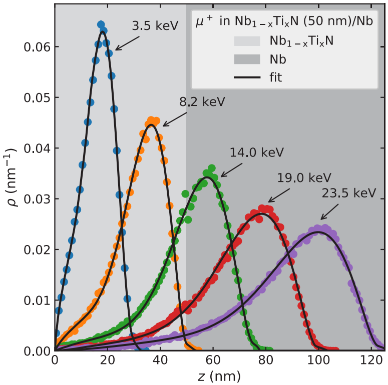


- In case of LEμ-SR, a range of implantation energies (~2 keV–~30 keV) of μ^+ were used, providing depth-resolution on the nm scale (i.e., ~10 nm–~150 nm).

LEμ-SR has depth resolution over the Meissner screening profile

μ^+ stopping profile in $Nb_{1-x}Ti_xN$ (50 nm)/Nb SS structure simulated using the Monte Carlo code TRIM.SP.

- LEμ-SR has depth resolution and can thus measure the depth dependent field profile

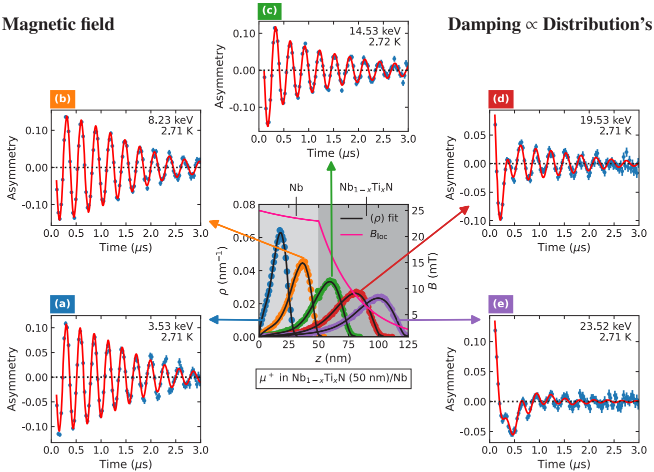


Results: LEμ-SR time spectra in the Meissner state in SS bilayers

- Time spectra, $A(t) = A_0 P(t)$ in $Nb_{1-x}Ti_xN$ (50 nm)/Nb at $B_0 = 25$ mT in the Meissner state.
- The asymmetry signal is more strongly damped at high implantation energies in SS bilayers.

Frequency ∝ Magnetic field

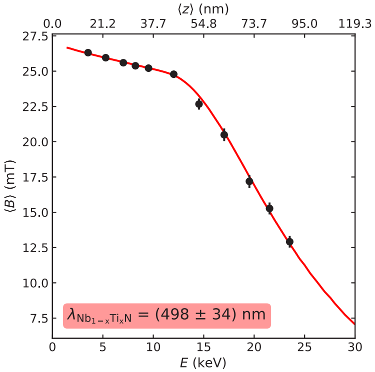
Damping ∝ Distribution's width



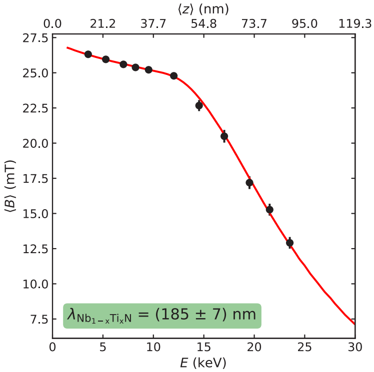
Does the counter current flow model validate the value of $\lambda_{Nb_{1-x}Ti_xN}$?

The screening profile of $Nb_{1-x}Ti_xN$ (50 nm)/Nb fitted with different models.

Simple London model.



Counter current flow model.



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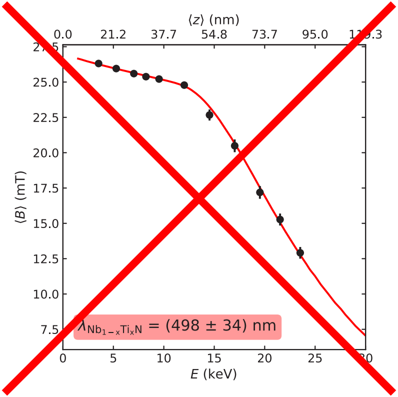
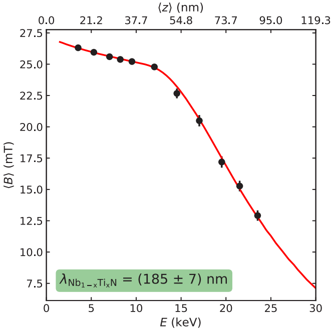
The screening profile of $Nb_{1-x}Ti_xN$ (50 nm)/Nb fitted with different models.

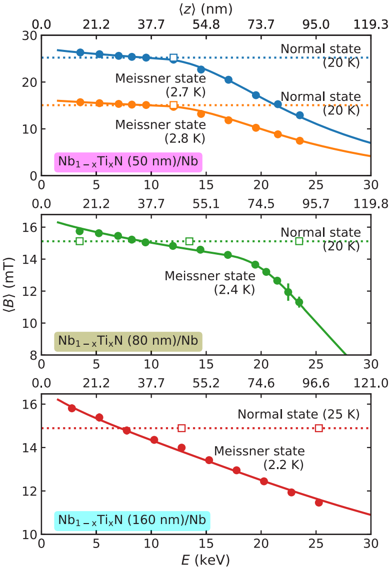
Simple London model.
$\lambda_{Nb_{1-x}Ti_xN} \rightarrow$ too large by a factor of ~ 2.5!



Counter current flow model.
$\lambda_{Nb_{1-x}Ti_xN} \rightarrow$ Agrees with the literature!



Global fit to the counter current flow model with independent fit parameters



Global fit to the Meissner screening profiles as a function of energy, E:

- Three different thicknesses of $Nb_{1-x}Ti_xN$ (d_s nm)/ Nb samples:
  - d_s = 50 nm
  - d_s = 80 nm
  - d_s = 160 nm
- Extracted penetration depth of $Nb_{1-x}Ti_xN$ is at 0 K:
  - $\boldsymbol{\lambda_{Nb_{1-x}Ti_xN} = (182.5 \pm 3.1)}$ **nm**
- $\boldsymbol{\lambda_{Nb_{1-x}Ti_xN}}$ → **Agrees with the literature!**

Predicted B_{max} in our SS bilayer sample

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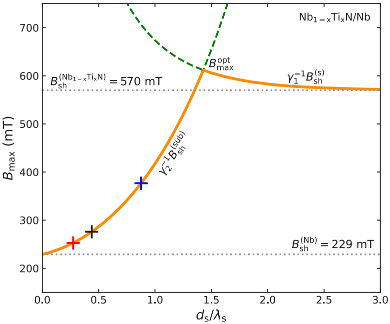
B_{max} as a function of surface layer $Nb_{1-x}Ti_xN$ thickness d_s.



- B_{max} of our measured $Nb_{1-x}Ti_xN$ (d_s nm)/ Nb samples using measured λ:
  - + (red) = (253 ± 5) mT for d_s = 50 nm
  - + (black) = (276 ± 5) mT for d_s = 80 nm
  - + (blue) = (377 ± 5) mT for d_s = 160 nm
- For our $Nb_{1-x}Ti_xN$ (d_s nm)/Nb:
  - B_{max}^{opt} = (610 ± 40) mT corresponding to
  - $d_s \sim 1.14\lambda_{Nb_{1-x}Ti_xN}$ = (261 ± 14) nm.
- Since $d_s > \lambda_{Nb_{1-x}Ti_xN}$, multilayer superconductor with alternating interface layer are required to protect vortex penetration into the substrate layer in order to reach at B_{max}^{opt}.

Summary

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- We used LEμ-SR to measure the Meissner screening profile into SS bilayers.
- Fits of our data to Kubo's counter current flow model yielded $\lambda_{Nb_{1-x}Ti_xN}$ in good agreement with the literature in contrast to a simple London model.
- The results from LEμ-SR imply the validity of Kubo's counter current flow model in SS bilayers and that they are a viable means of exceeding the Nb field limits.
- This result suggests strong suppression of Meissner current in the surface layer therefore multilayer with alternating insulating layers are ideal to stop vortex penetration.
- We will measure the vortex penetration field in superconducting hetero structures using (~200 mT surface parallel field) β-NMR spectrometer in order to observe a layer specific transition from Meissner to vortex state.

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Thank You!