Local spectroscopy of hybrid superconducting nanostructures

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Outline

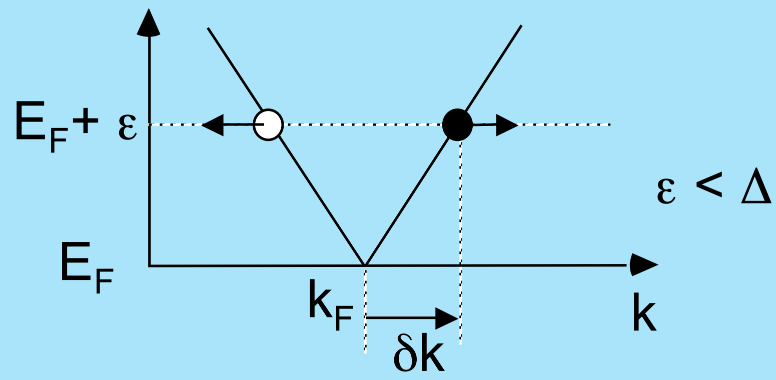
- Andreev reflection, proximity effect
- Very low temperature STM and STS
- F-S junctions made of a diluted alloy
- Combined AFM-STM microscopy

Proximity superconductivity

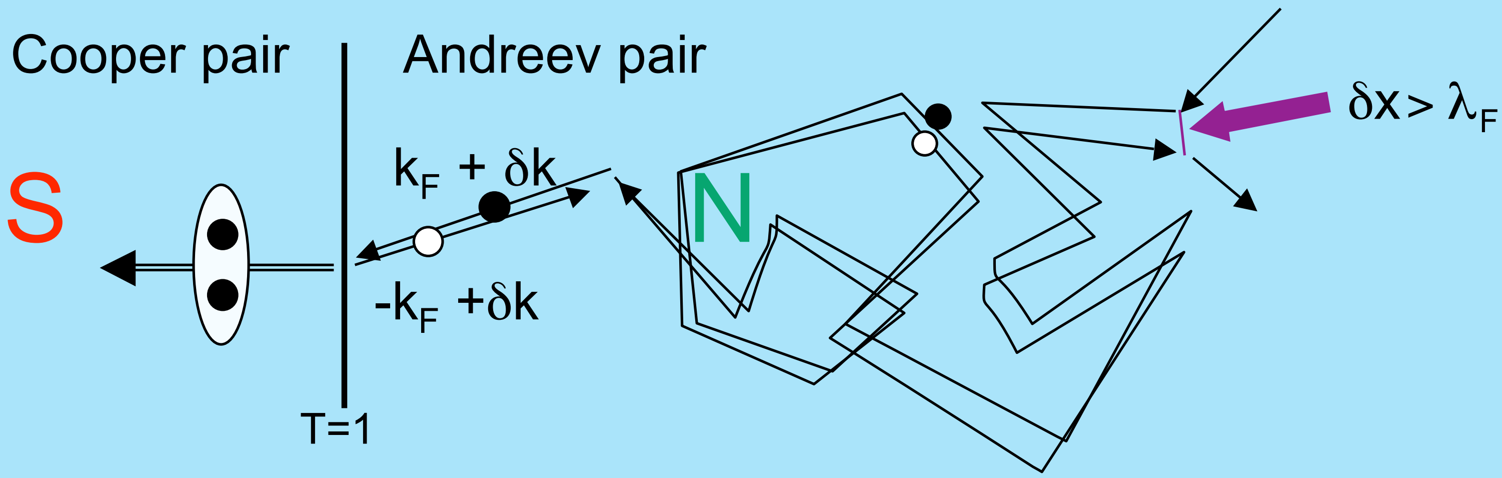
The Andreev reflection

No energy transfer

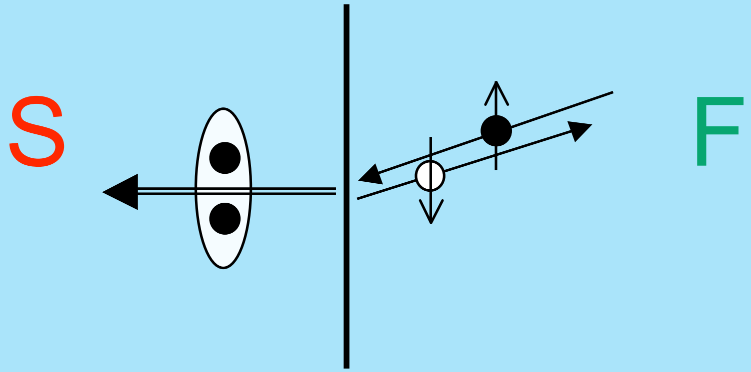
Retro-reflection, perfect only at E_F

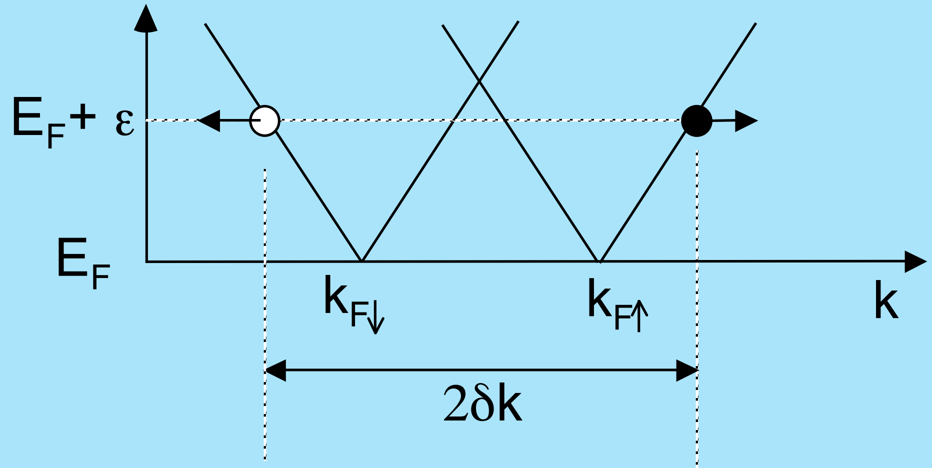


Wave-vector mismatch : $\delta k = k_F \dfrac{\varepsilon}{E_F}$



The Andreev reflection

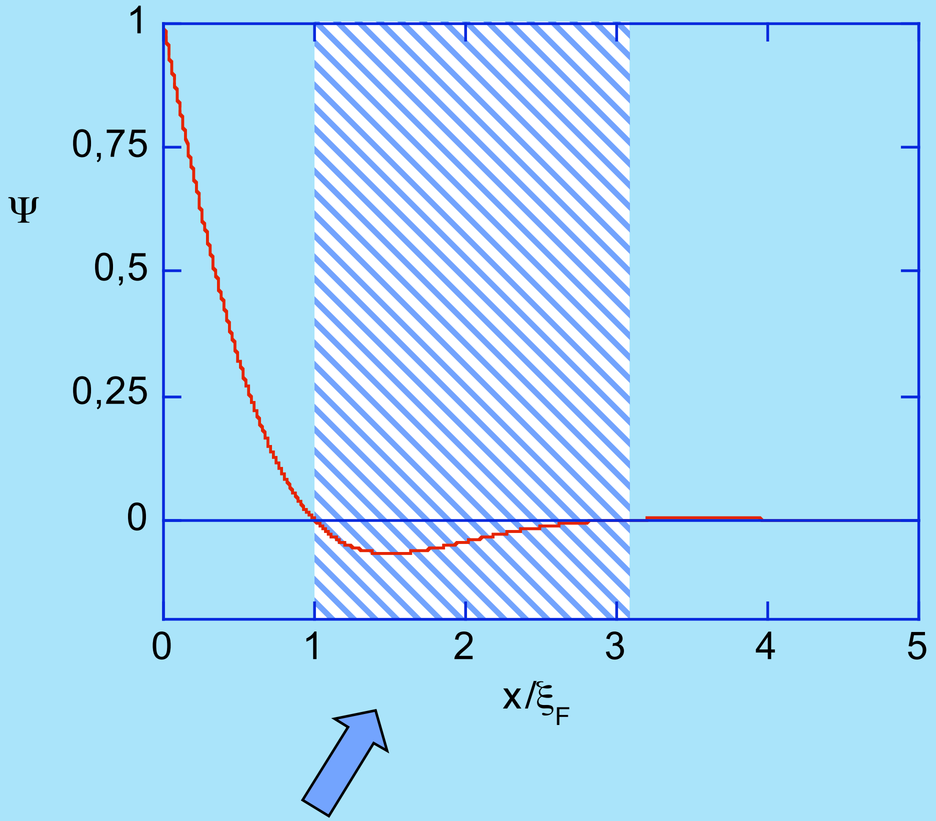


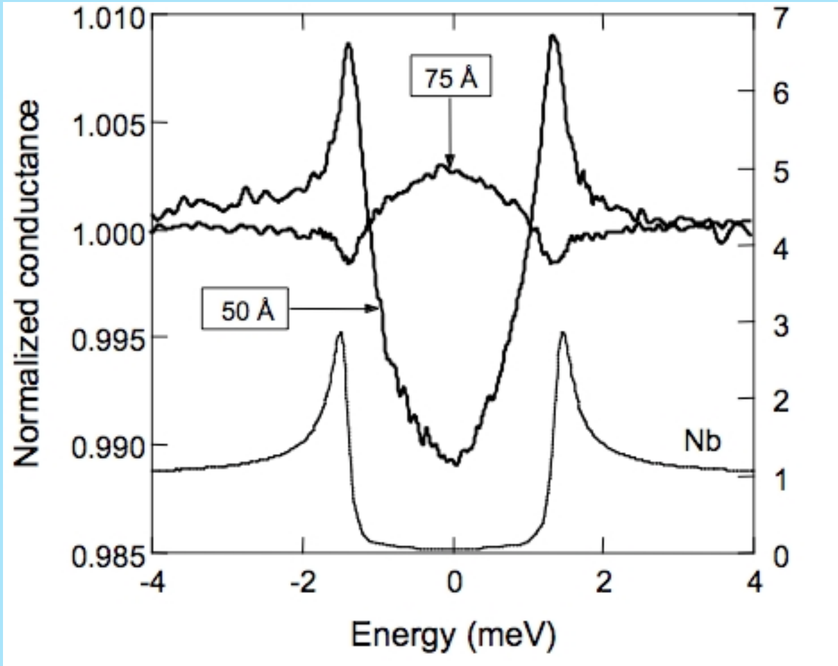


Wave-vector mismatch : $\delta k = k_F \frac{\varepsilon + E_{ex.}}{E_F} \approx k_F \frac{E_{ex.}}{E_F}$ $(\varepsilon < E_{ex.})$

➡ $\delta\varphi = \delta k . d \approx \pi \left(\frac{x}{\xi_F} \right)^2$ where $\xi_F = \sqrt{\frac{\hbar D}{E_{ex.}}}$

The π junction



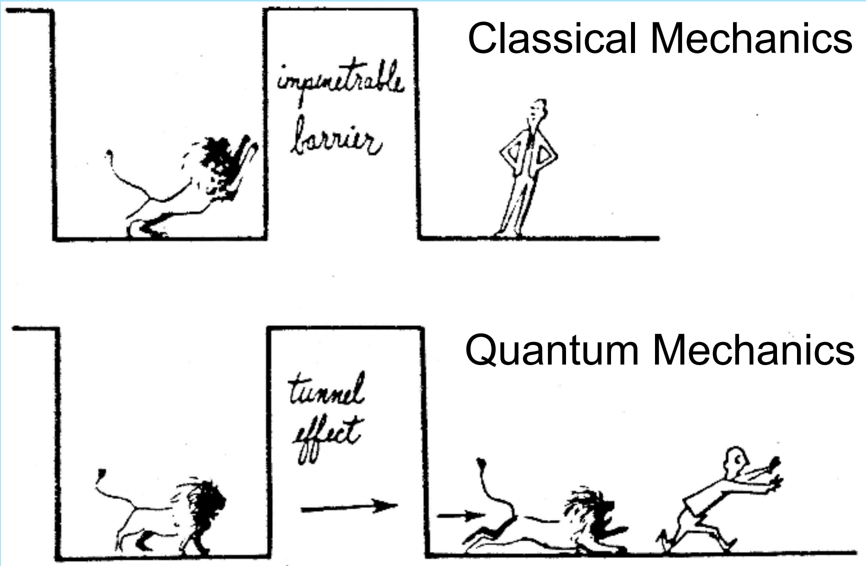


T. Kontos et al., Phys. Rev. Lett. 86, 304 (2001)

Pi-junction regime : occurs at $\xi_F < x < 3\xi_F$

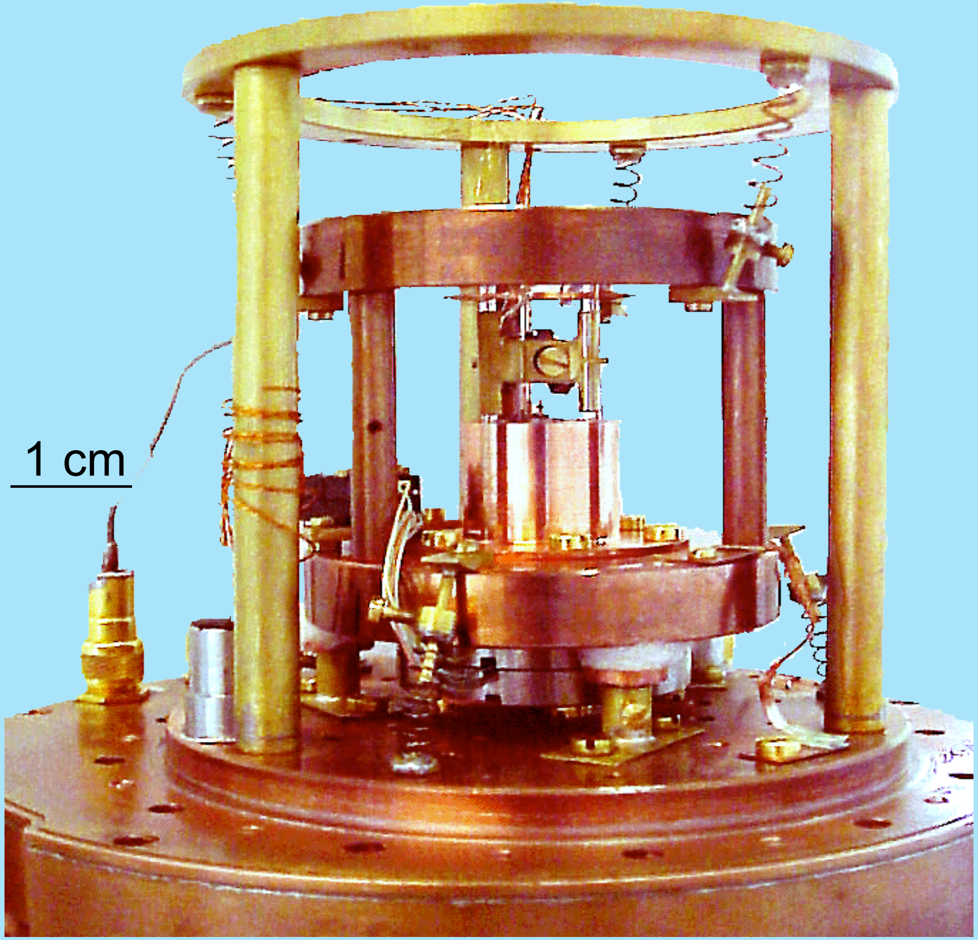
Observed in DOS, Josephson current, critical temperature …

Very low temperature Scanning Tunneling Microscopy / Spectroscopy

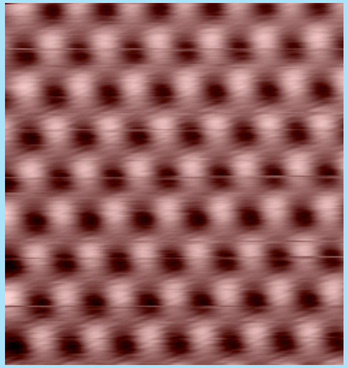


Van Vleck 1979

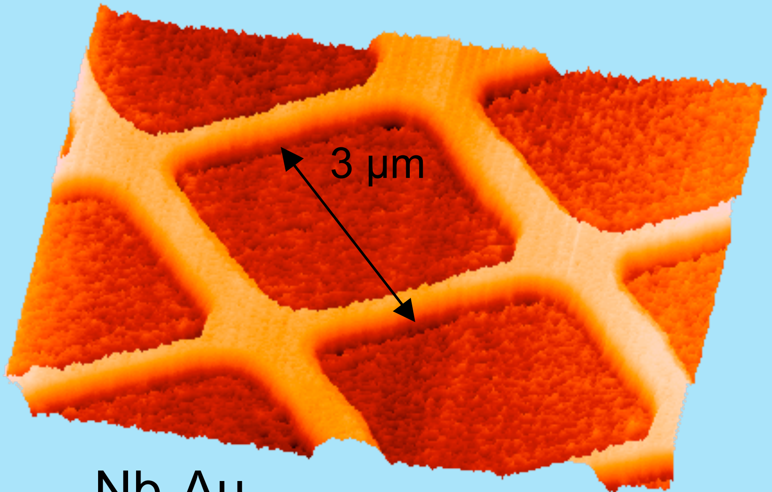
Very low temperature STM (60 mK)



N. Moussy, H. Courtois and B. Pannetier,
Rev. Sci. Instrum. 72, 128 (2001)



HOPG, 60 mK



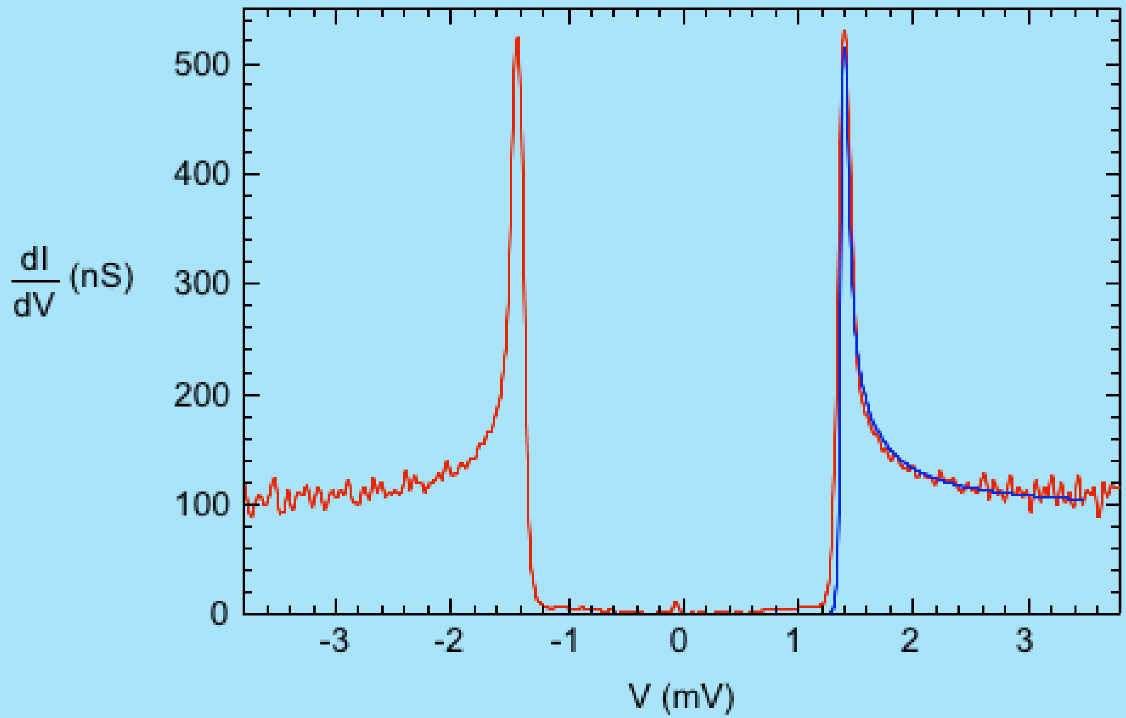
Nb-Au

High-resolution spectroscopy : the proof

Diff. conductance = LDOS smeared by temperature + noise

If temperature only :

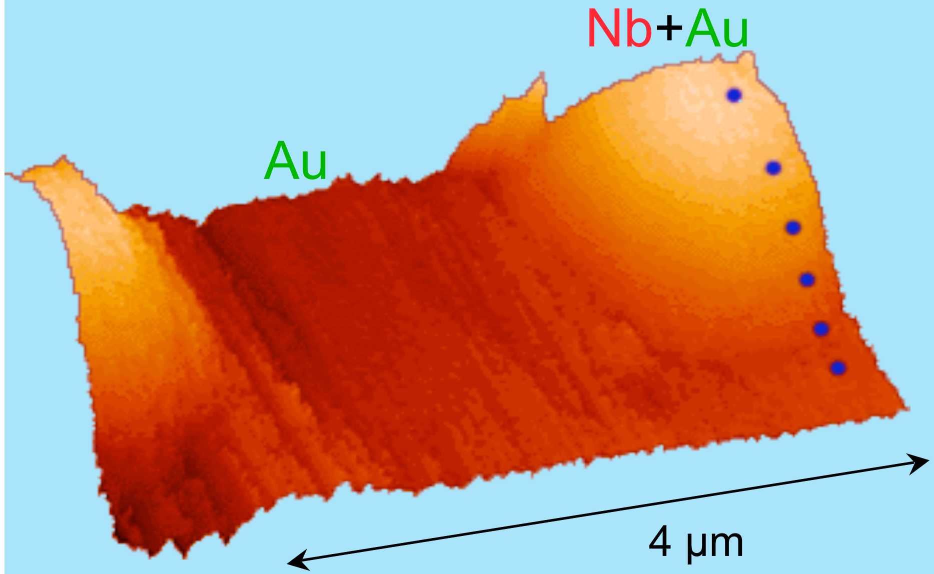
$$\frac{dI}{dV}(V) \propto \int_{+\infty}^{-\infty} \nu(\varepsilon) \cosh^{-2}\left(\frac{\varepsilon - eV}{2k_B T}\right) d\varepsilon$$

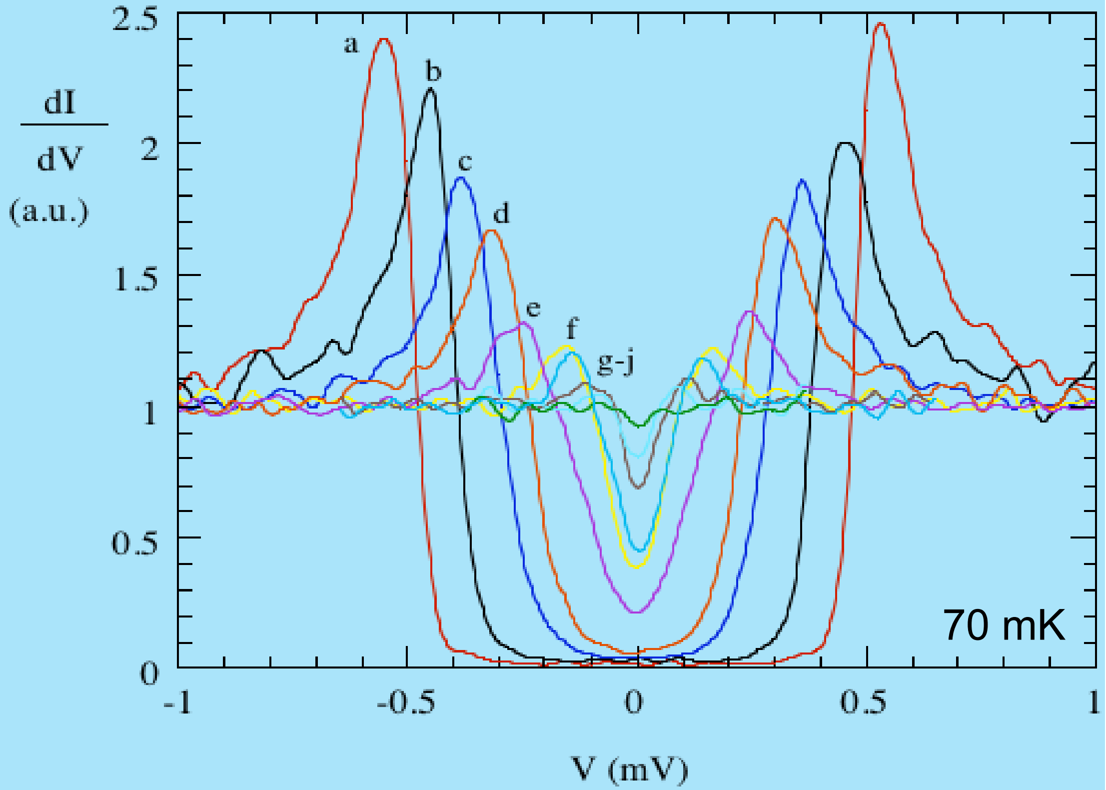


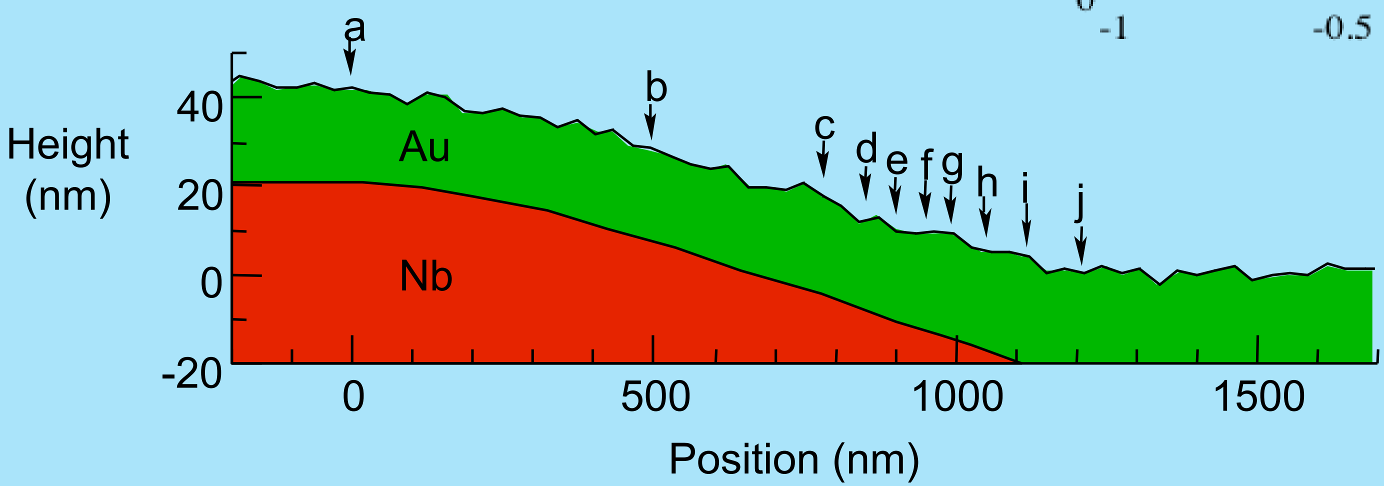
Test spectroscopy on a Nb film

Fit with $T_{eff.}$ = 170 mK, $\Gamma = 0$, Δ = 1.4 mV

Local spectroscopy of a N-S junction





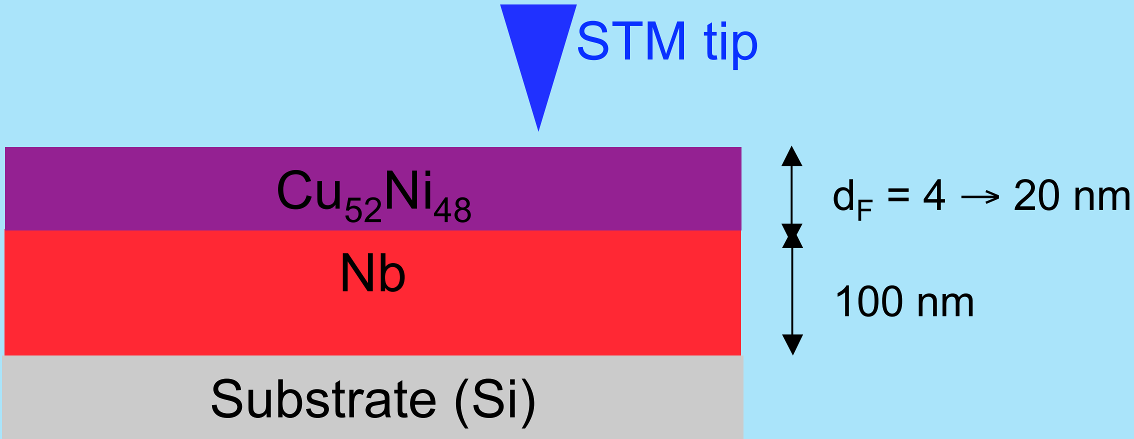


N. Moussy et al.,
EPL 55, 861 (2001)

Ferromagnet - Superconductor junctions

F-S bilayers

In collaboration with H. Sellier and F. Lefloch, SPSMS, CEA Grenoble



Same sputtering process than S-F-S junctions of H. Sellier et al., Phys. Rev. B 68, 054531 (2003)

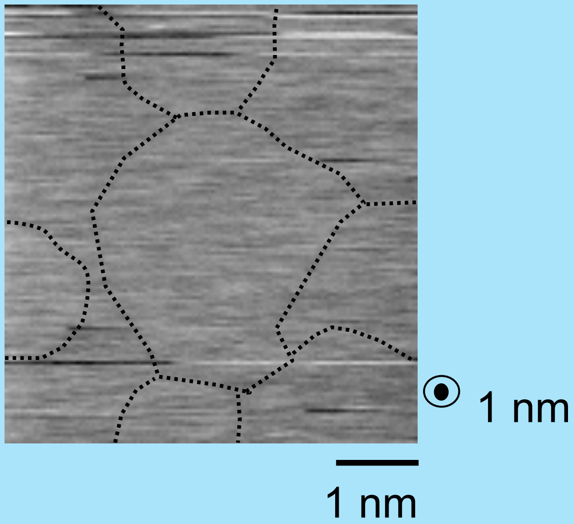
$\xi_{S,Nb} \approx 9$ nm $\qquad \xi_{F,CuNi} \approx 8$ nm

$T_{C,\,Nb} \approx 8{,}5$ K $\qquad E_{ex.} \approx 25$ K, $\qquad M_{sat} \approx 5.10^4$ A.m^{-2}

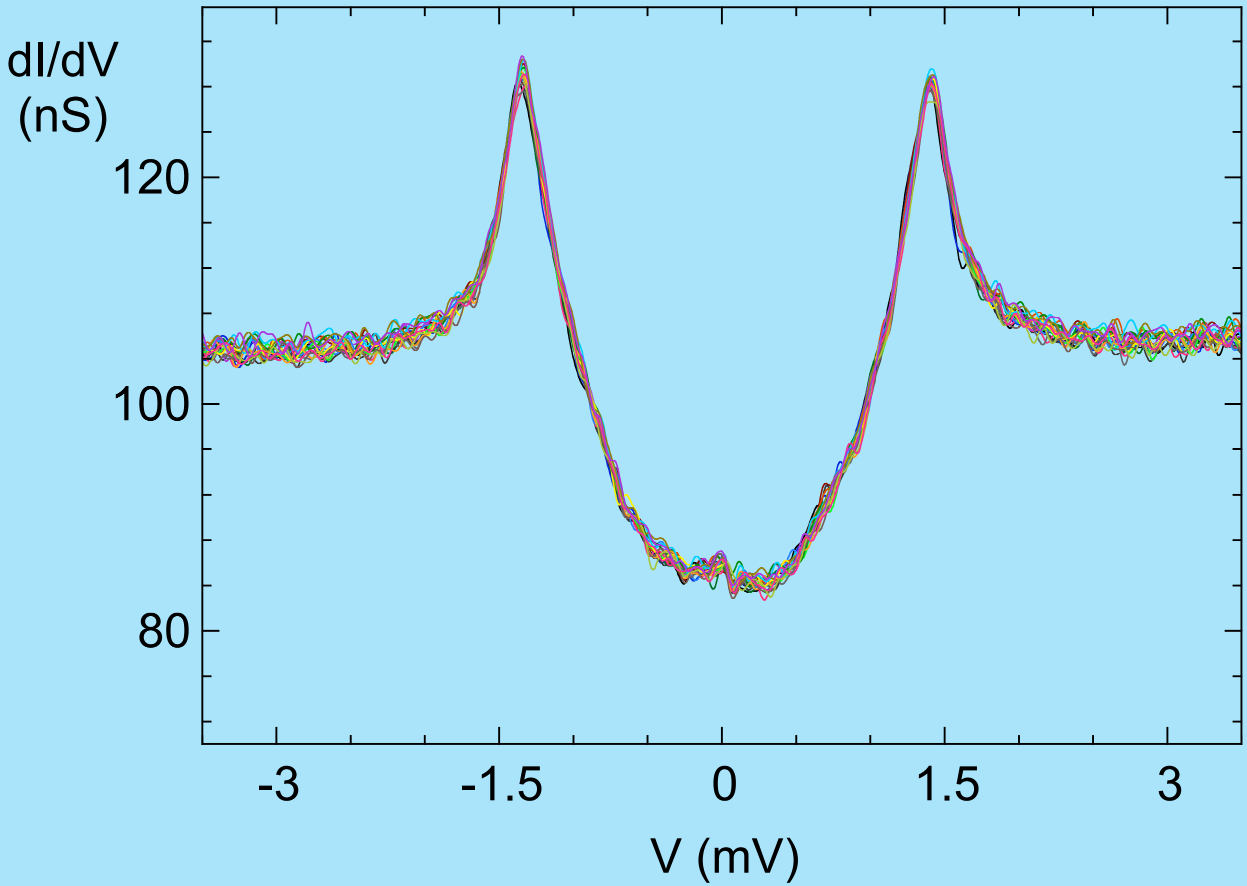
Aim : π-junction local observation, spatial resolution, check amplitude

Homogeneity

STM image at 100 mK



typical roughness ≤ 1 nm



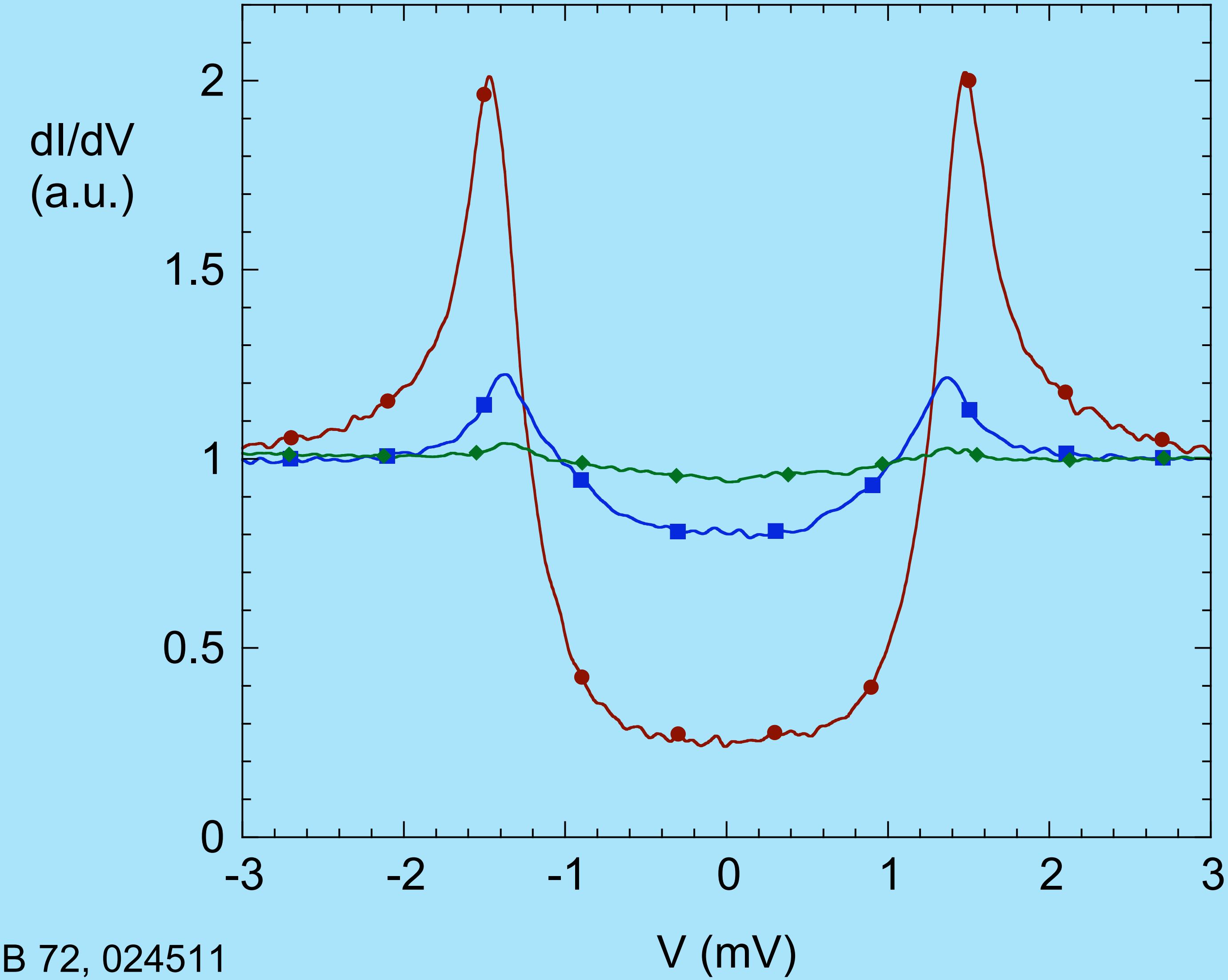
20 spectra measured along a line with a step of 11 nm : same result over 1 µm

Good homogeneity of the bilayer

Experimental results

Series of samples with a different CuNi thickness d_F.

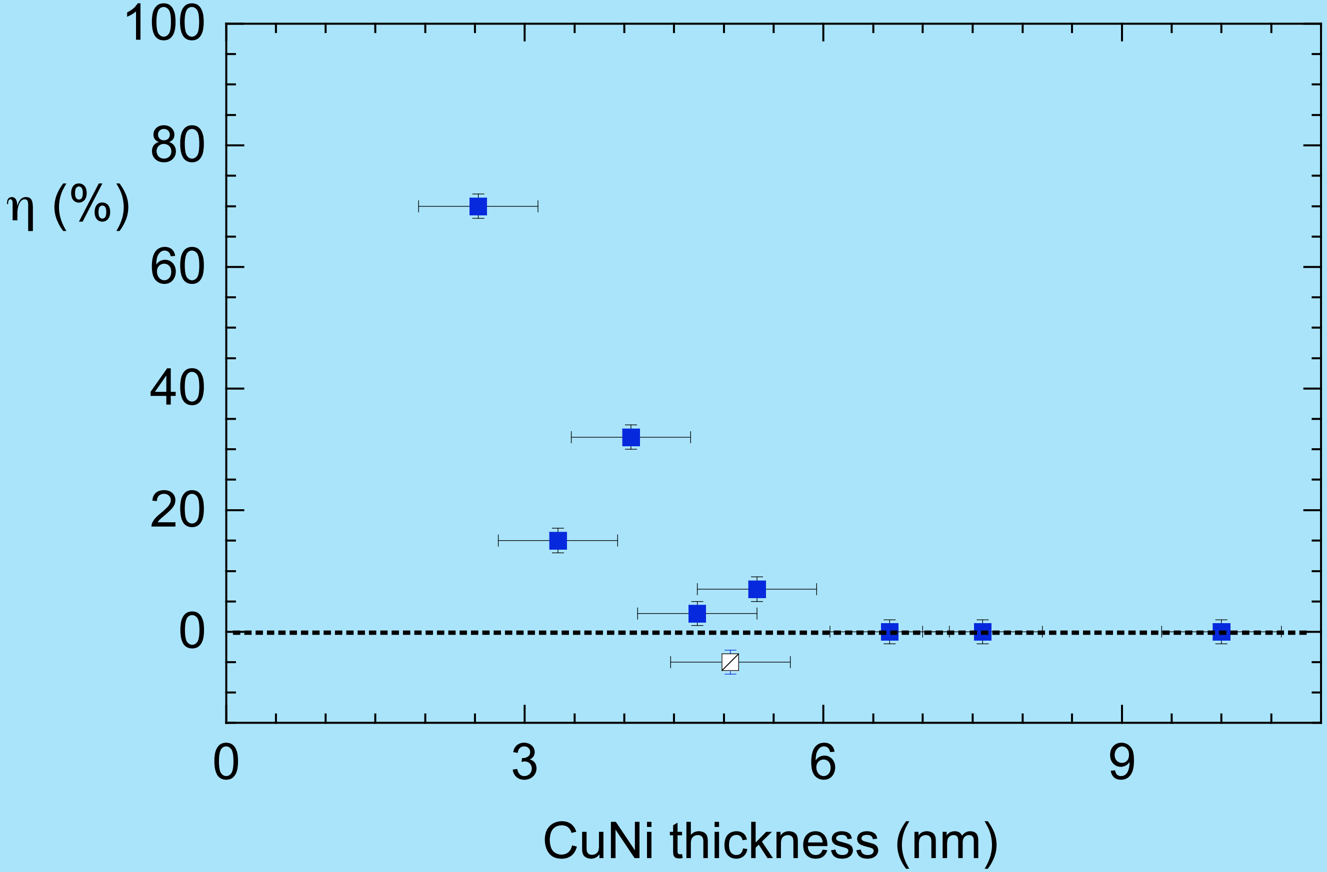
Tunnel resistance = 10 MΩ



L. Crétinon et al, Phys. Rev. B 72, 024511

Results summary

Significant scatter in the LDOS aperture at the Fermi level



The quasi-classical theory

The Usadel equation with the spin relaxation term :

$$-\frac{\hbar D_F}{2}\frac{\partial^2\theta}{\partial x^2}+\left(\omega+iE_{ex.}\right)\sin\theta+\frac{\hbar}{\tau_s}\sin\theta\cos\theta=0$$

The LDOS is : $N(\varepsilon)=N_0\Re e\left[\cos\theta\right]$

If small, the pairing angle at the F surface is :

$$\theta_{dF}=\frac{8}{\sqrt{1-k^2}}\exp\left(-\sqrt{2}\sqrt{iE_{ex}+\frac{\hbar}{\tau_s}+\omega}\,\frac{d}{\hbar D_F}\right)\sqrt{\frac{\sqrt{1-k^2\sin^2(\theta_0/2)}-\cos(\theta_0/2)}{\sqrt{1-k^2\sin^2(\theta_0/2)}+\cos(\theta_0/2)}}$$

where $k^2=\left(1+i\frac{\tau_s E_{ex}}{\hbar}\right)^{-1}$

M. Fauré, A. Buzdin, C.P.M.O.H. Bordeaux

Fitting procedure

— Exp. data

Calculation :

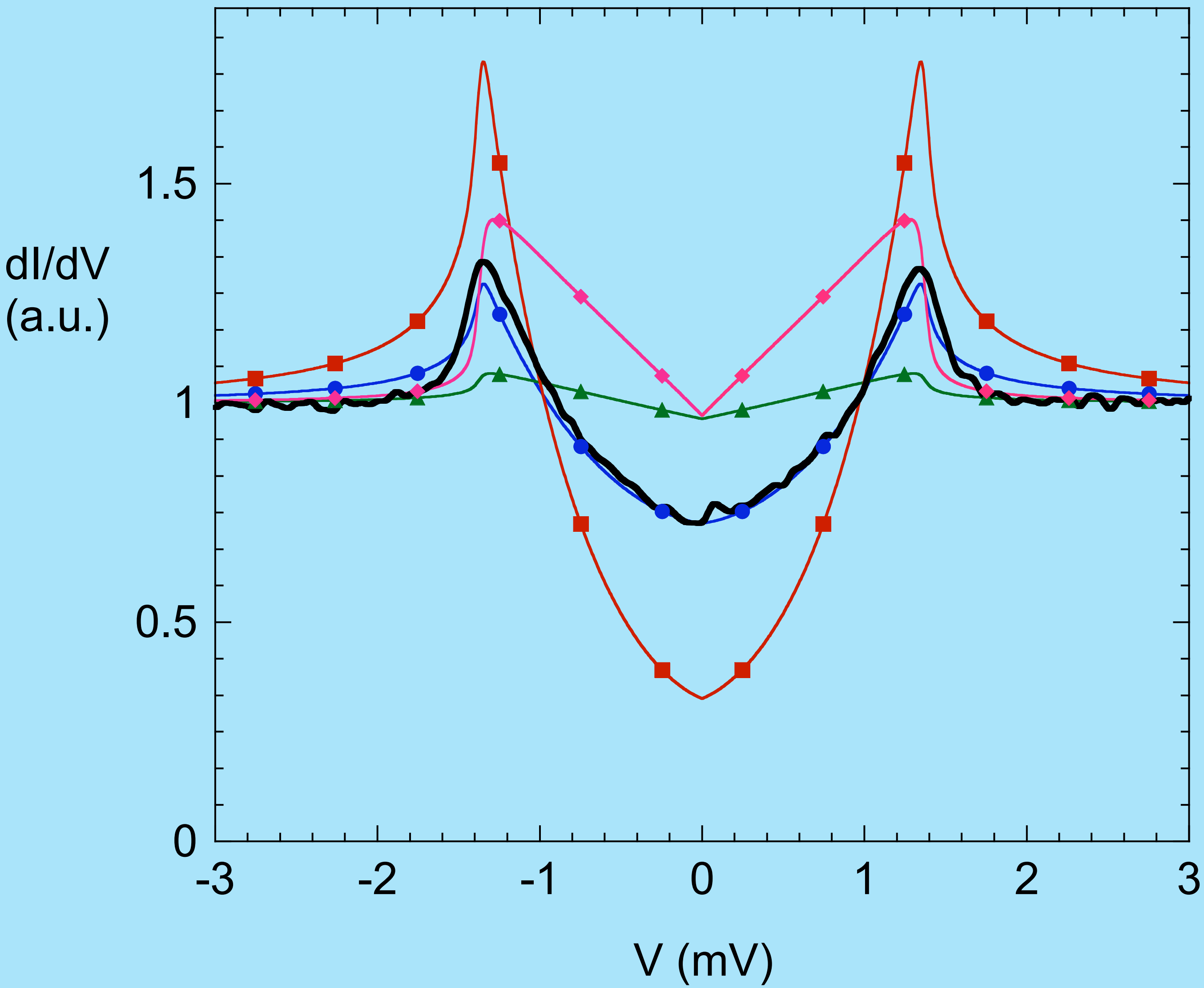
Δ = 1.37 meV, T = 170 mK

— : ξ_F = 4.1, L_s = 2.5 nm

— : ξ_F = 4.1, L_s = 4.5 nm

— : ξ_F = 15, L_s = 5 nm

— : ξ_F = 15, L_s = 3.5 nm



Very strong effect of the spin relaxation rate.

Increased ξ_F : signature of the weakened CuNi magnetism near the interface with Nb

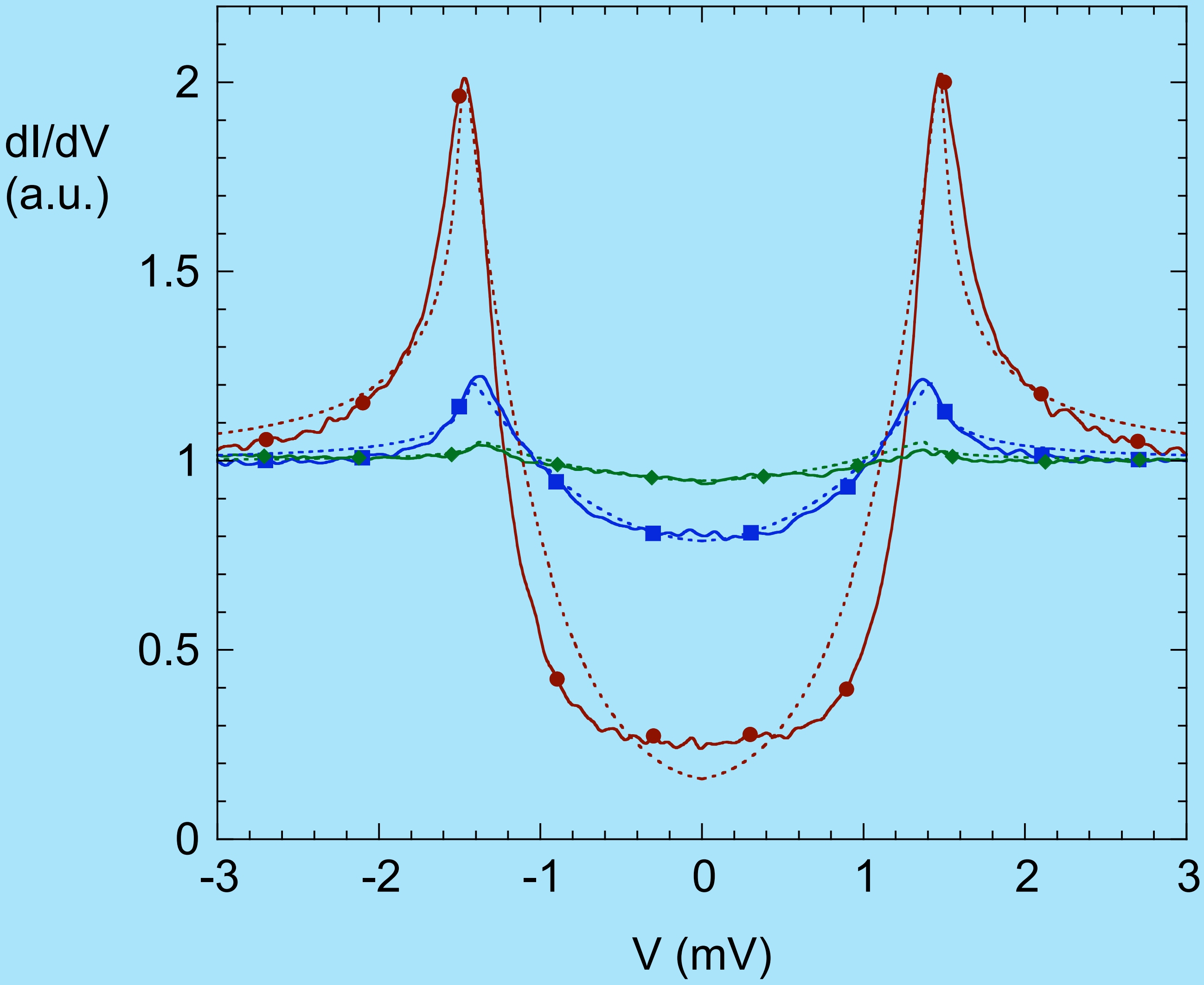
Experiment / theory comparison

Spin relaxation length fitted values varies by +/- 12 %

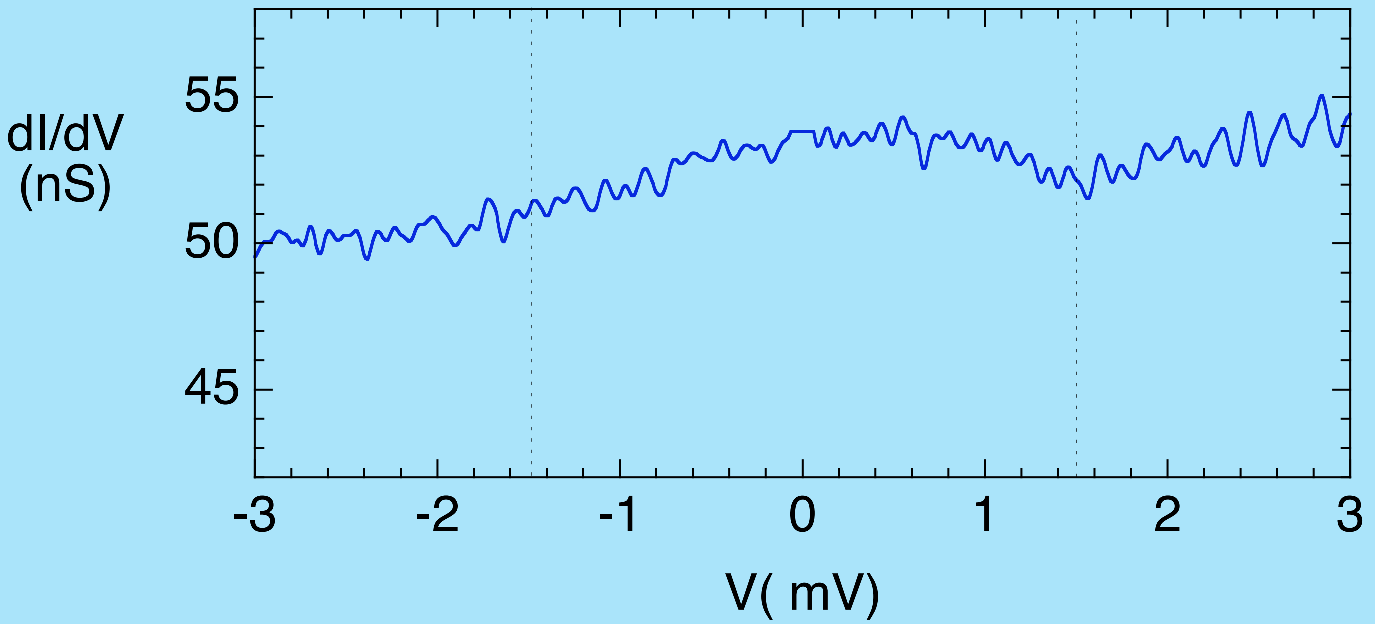
d_F (nm)	L_{sf} (nm)	Δ (meV)
2.5	3.4	1.5
3.3	2.6	1.45
4.1	3.5	1.37
5.3	3.0	1.4

ξ_F = 15 nm

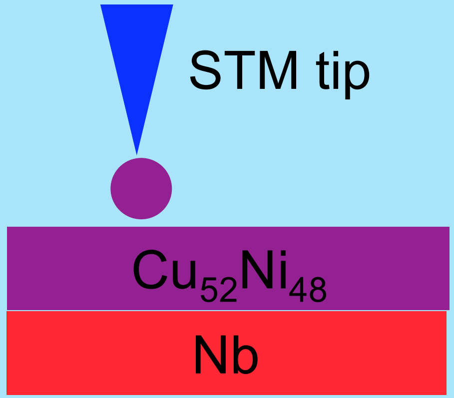
T = 170 mK

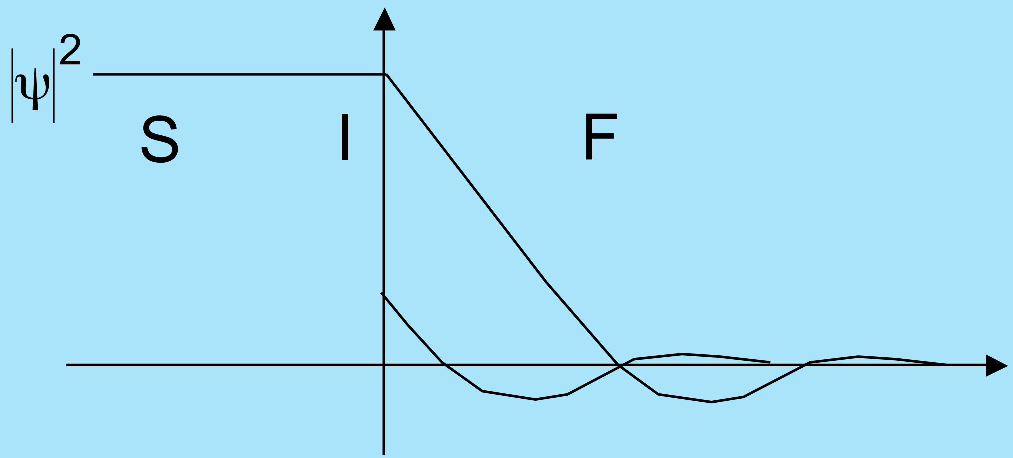


A π regime ?



Not a fully reproducible experiment :

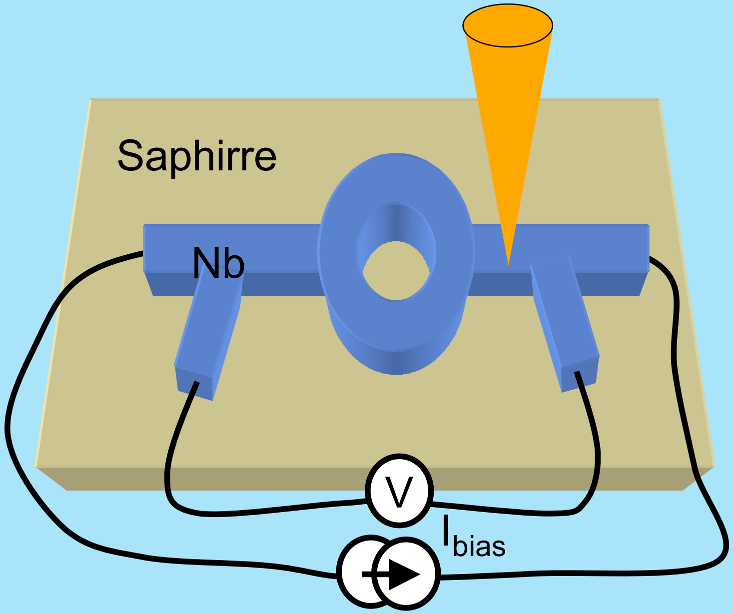


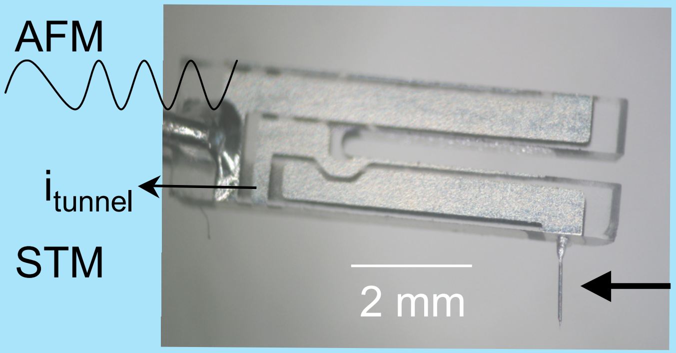


A barrier can be viewed as an extra F length (but without spin relaxation)
A. Buzdin (2004)

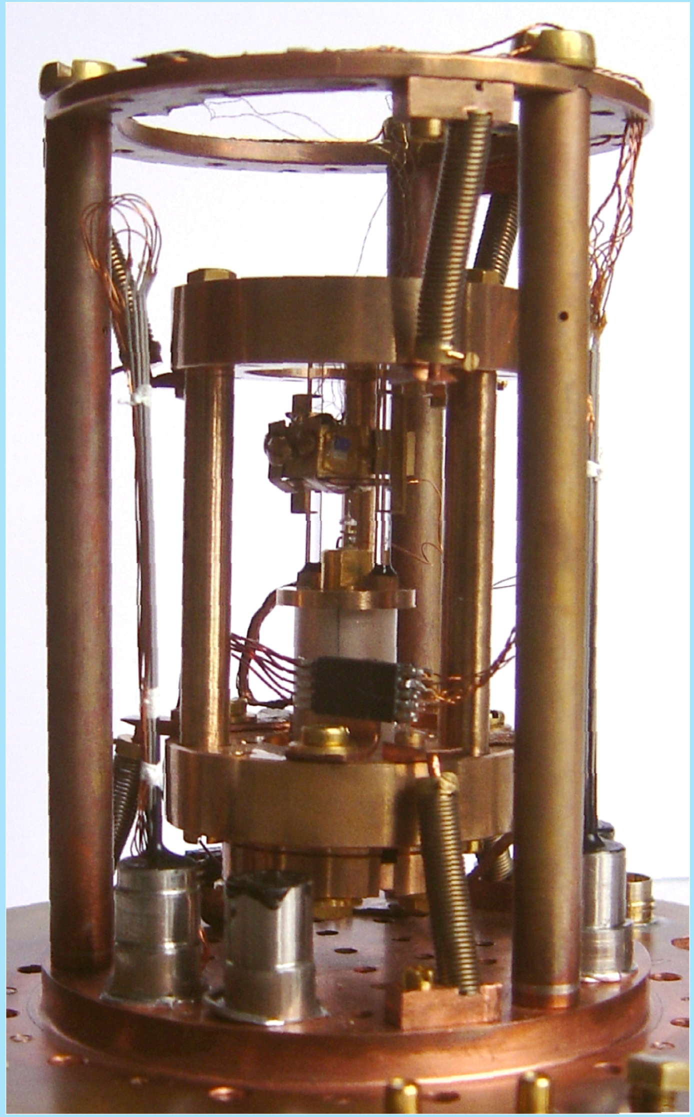
AFM-STM combined microscopy

Very low temperature AFM-STM





Tuning fork + tunnel tip (W)



Conclusion

- Local spectroscopy of superconducting nanostructures at 60 mK
- Proximity effect in a N or F layer in contact with S
- In the diluted alloy CuNi : strong contribution of spin relaxation, π regime not visible, weakened magnetism.
- AFM-STM at very low temperature: local spectroscopy of patterned conductors
- Perspectives: bias dependent LDOS, Phase-Slip Centers, …