Absence of zero-energy surface bound states in $Cu_xBi_2Se_3$ via a study of Andreev reflection spectroscopy

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Main Motivation:

Search of a realization of Topological Superconductor

Topological Superconductor (TSC) :
Superconducting state with a full bulk gap protected by particle-hole symmetry, but with stable gapless (Majorana) surface bound states.
(candidates: ^{3}He-B phase; interface topological insulator/s-wave SC; *p*-wave SC)

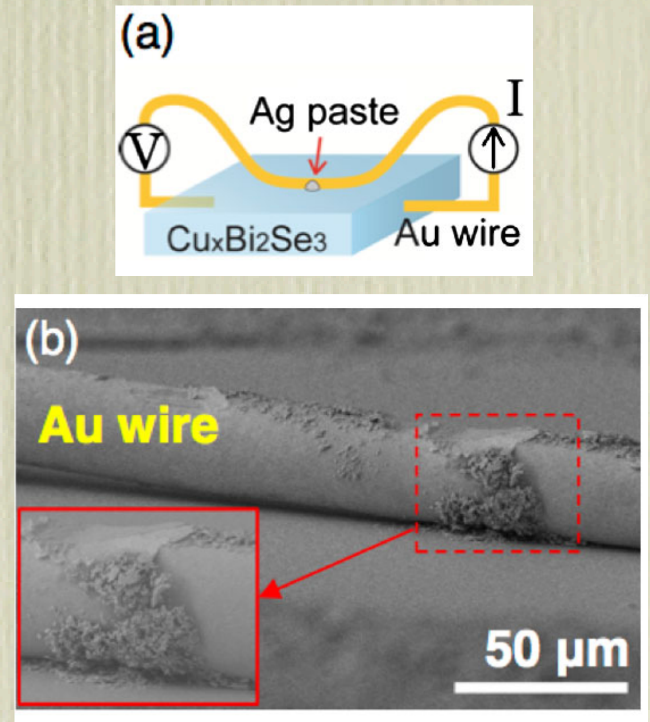
analog to:

Topological Insulator (TI) :
Insulating state with a bulk gap protected by time-reversal symmetry, but with gapless surface states with an odd number of Dirac points.
(example: Bi_2Se_3)

-[2010]: superconductivity below T_c = 3.8 K was observed in an electron-doped topological insulator $Cu_xBi_2Se_3$ [Y. S. Hor et al., Phys. Rev. Lett. **104**, 057001]

-[2010]: Theory Proposed $Cu_xBi_2Se_3$ as candidate of TSC using a phenomenological model, predicting the existence of an odd-parity full SC gap with TRS and a resultant zero-energy surface Andreev bound states (Majorana fermions) [L. A. Fu, and E. Berg, Phys. Rev. Lett. **105**, 097001 (2010)]

-[2011]: This appears to be confirmed by the successful detection of a zero-bias-conductance-peak (ZBCP), as evidence for the existence of zero-energy Majorana fermions, by means of a "soft" point-contact technique.
[S. Sasaki, M. Kriener, K. Segawa, K. Yada, Y. Tanaka, M. Sato, and Y. Ando, Phys. Rev. Lett. **107**, 217001 (2011)]



In view of the significance of the observation and the complexity involved in point-contact devices, further **stringent** experimental test on the existence of zero-energy Majorana fermions is needed.

A newly developed nanoscale Andreev reflection (AR) spectroscopy method employed to elucidate the superconducting gap structures of $Cu_xBi_2Se_3$ as a function of temperature and magnetic field.

The results show that **the ZBCP can be tuned in or out** from $Cu_xBi_2Se_3$ samples **depending on the** normal metal/superconductor (N-S) **barrier strength *Z***.

“While the appearance of ZBCP may be traced to different origins, its **absence under finite barrier strength entails the absence of zero-energy Majorana fermions**”
(the ZBCP should be persistently present in all N-S junctions with different barrier strength Z ranging from the transparent limit to the tunneling limit).

“The present observations thus call for a reexamination of the nature of the superconducting state in $Cu_xBi_2Se_3$”.

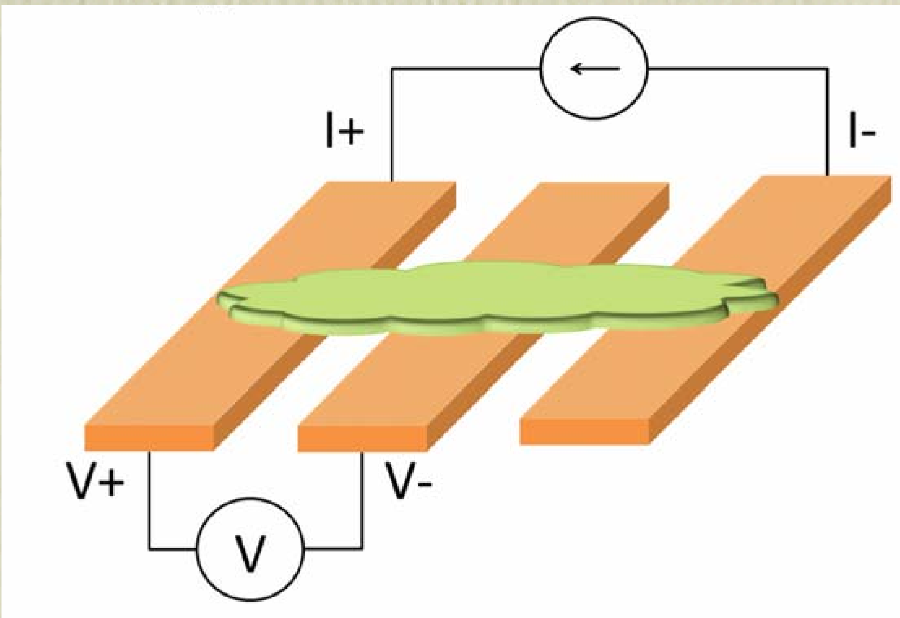
Single crystals of $Cu_xBi_2Se_3$, with $x \simeq 0.15$, up to cm size with *c*-axis preferred. Measured an onset bulk $T_c \simeq 3.4$ K and a superconducting volume fraction up to ≃20 % at 2 K (close to results previously reported).

Newly developed technique to construct nanoscale N-S devices and perform Andreev reflection spectroscopy:

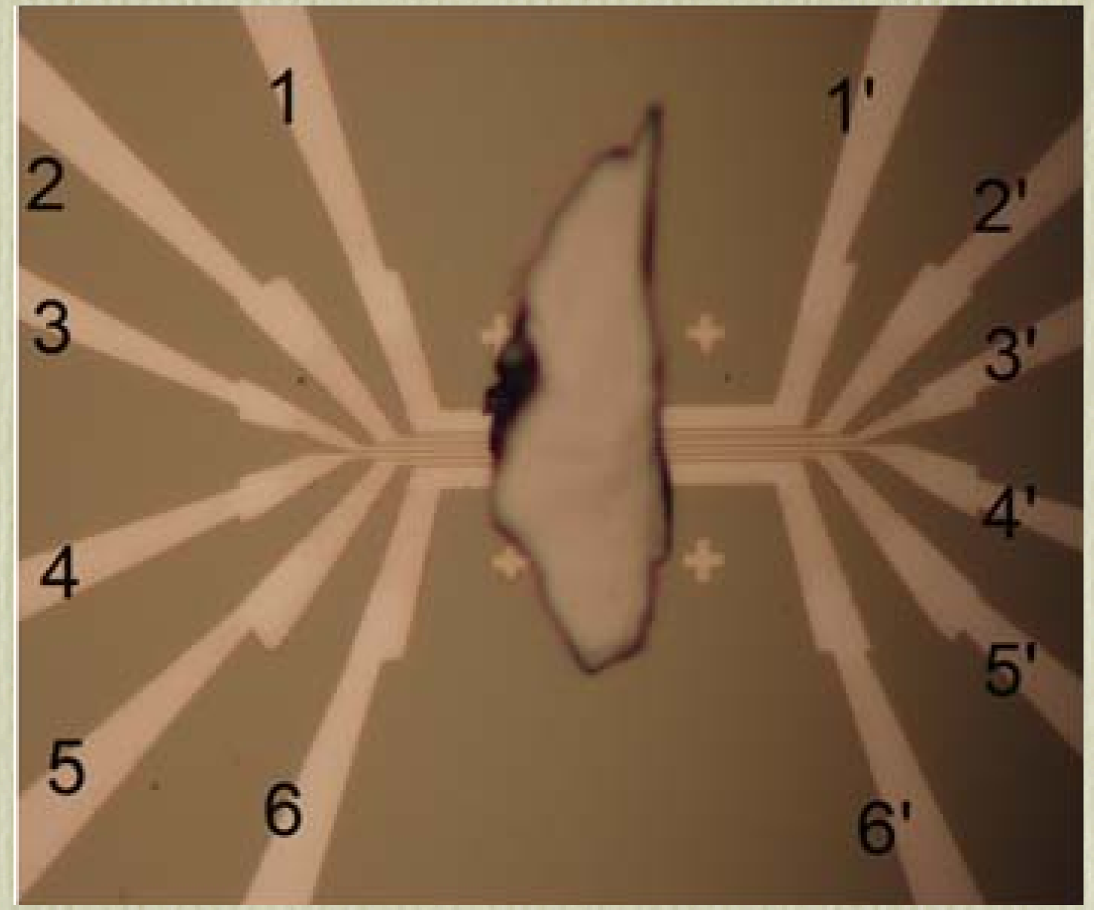
- The bulk sample of $Cu_xBi_2Se_3$ is mechanically cleaved into micro-scale crystals;

- Immediately transferred into a vacuum chamber;

- A sharp probe tip attached on a micro-manipulator is used to place a piece of microcrystal on top of multiple parallel metal electrodes spaced ≃500 nm apart (as designed via electron-beam lithography)

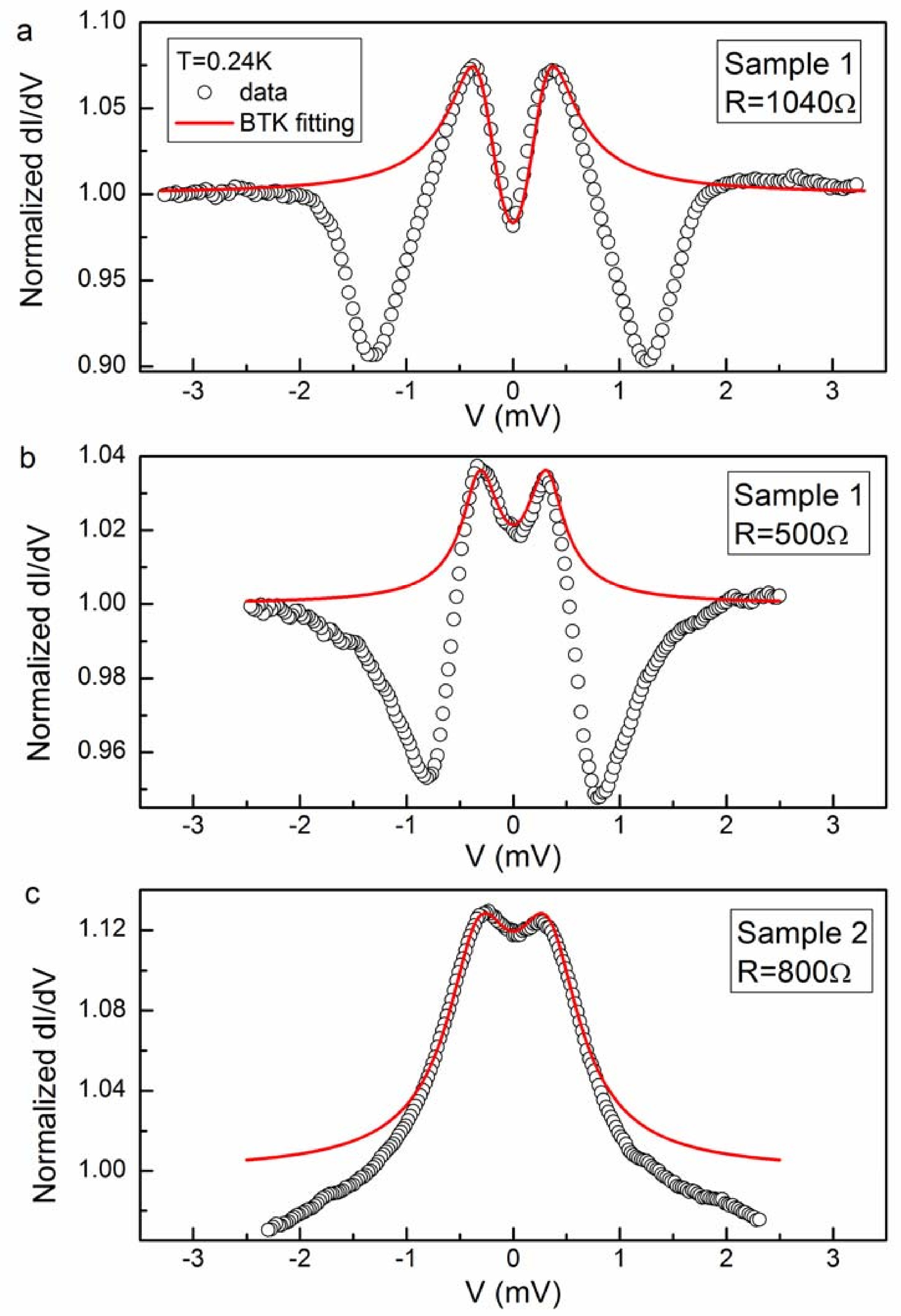


- To obtain AR spectra for a target N-S junction, a special circuit is used, where a small AC current superimposed to a DC bias current is applied between the I_+ and I_- terminals, while both the DC and the AC voltages across the N-S junction are measured between the V_+ and V_- terminals.



The four central electrodes (labeled as 2-5) are designed to be 1 μm wide while the two external electrodes (labeled as 1 and 6) are 4 μm wide.

The flexibility in selecting the configuration for the measurement terminals enables one to study various N-S junctions between different metal electrodes and the same superconductor crystal with **different *Z* parameters** in a single device.



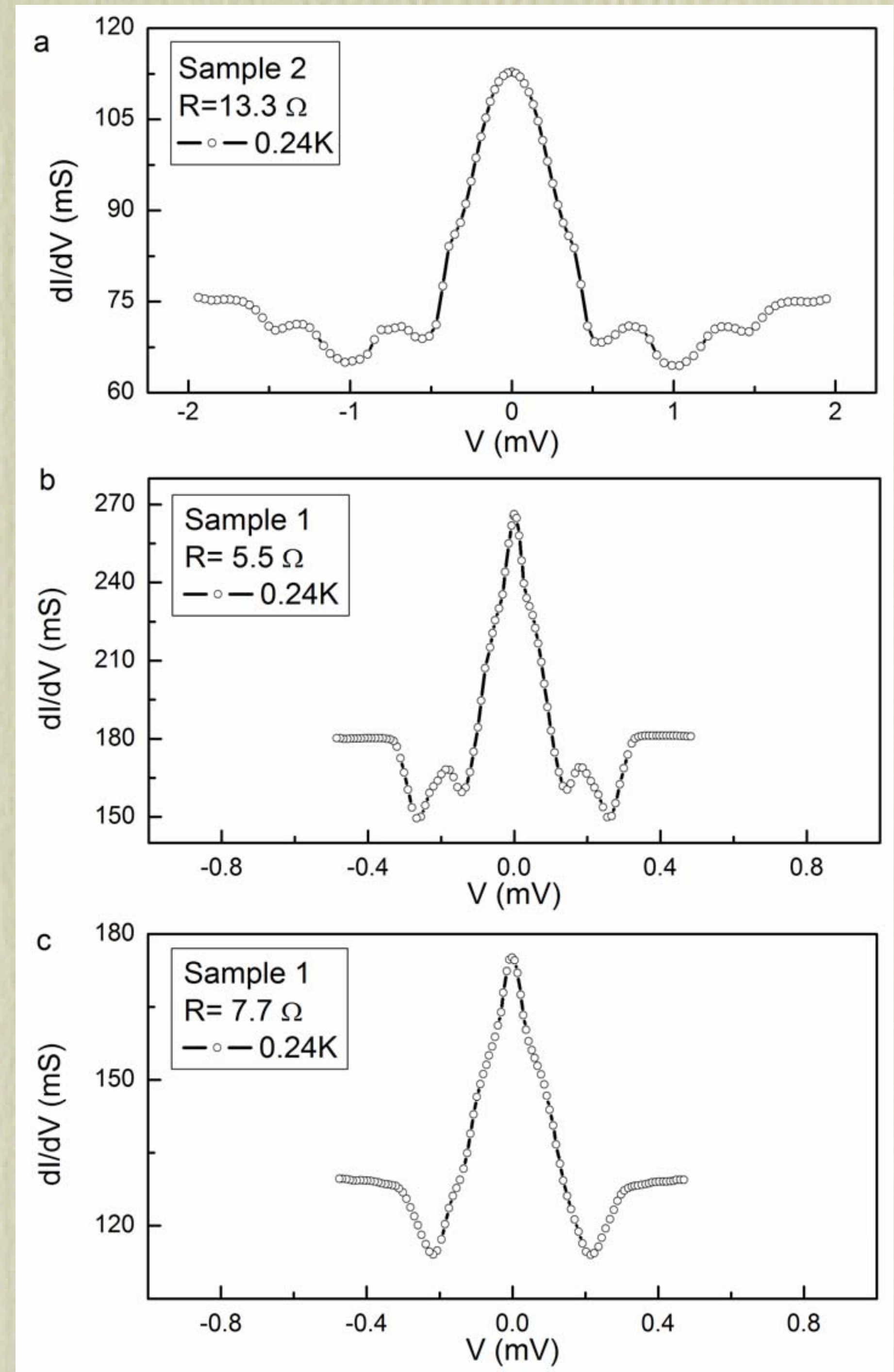
- Three different N-S junctions;
- T = 240 mK;
- *dI/dV* dip at zero bias;
- Two shoulders at V≃±0.4 mV;
- Typical for N-S interface with finite barrier strength *Z* according to the BTK theory;
- Solid lines represents a fitting of the experimental *dI/dV* data (normalized to the normal state data) by the generalized BTK theory, including broadening;
- Considering the coexistence of SC and non-SC phases in bulk $Cu_xBi_2Se_3$, one can express the total normalized conductance as: $\sigma = w\sigma_s + (1-w)$
- From the fitting one gets the gap energy:

$$\Delta = 0.35 \pm 0.04 \text{ meV};$$

$$\Gamma = 0.13 - 0.27 \text{ meV}$$

Note 1: The three junctions have different values of w (from 13% to 80%), different values of Z, but they all notable yield the same value for the gap Δ.

Note 2: These three "spectroscopic" junctions have rather large normal state resistance $R_N \gg 100\ \Omega$, whereas for junctions with small R_N ($\lesssim 10\ \Omega$) the behavior is different:



- *dI/dV* zero-bias peak;
- followed by a dip at the peak edge;
- typical for nearly transparent N-S interface with weak barrier strength;

Large-R_N junctions (≫100 Ω)	Low-R_N junctions (≲10 Ω)
No ZBCP	ZBCP
Lateral Peaks (shoulders)	Lateral Dips
Good indication of the gap Δ	No information on the gap Δ

Observations consistent with the commonly adopted empirical formula for determining ballistic transport regime ($a \ll \ell$):

$$R_{\mathrm{N}} \gg 4\rho/3\pi\ell$$

(with ρ bulk material resistivity and ℓ mean free path in the junction).

Meaning: $R_{\mathrm{N}} = (4\rho\ell)/(3\pi a^2)$
the point contact size has to be less than the mean free path to ensure ballistic transport across the N-S interface, which is sufficient for providing correct spectroscopic, energy-resolved information of the superconducting gap.

In this system ($\rho \simeq 140\ \mu\Omega\text{cm}$, $\ell \simeq 45$ nm) the rule gives a critical $R_N \simeq 13\ \Omega$.

compatible with phenomenology

The zero bias peak for the transparent junctions can be explained as the Andreev reflection plateau within the bulk superconducting gap, with a cut-off of plateau width corresponding to reaching the critical current at relatively low bias $V < \Delta/e$ because of the low junction resistance.

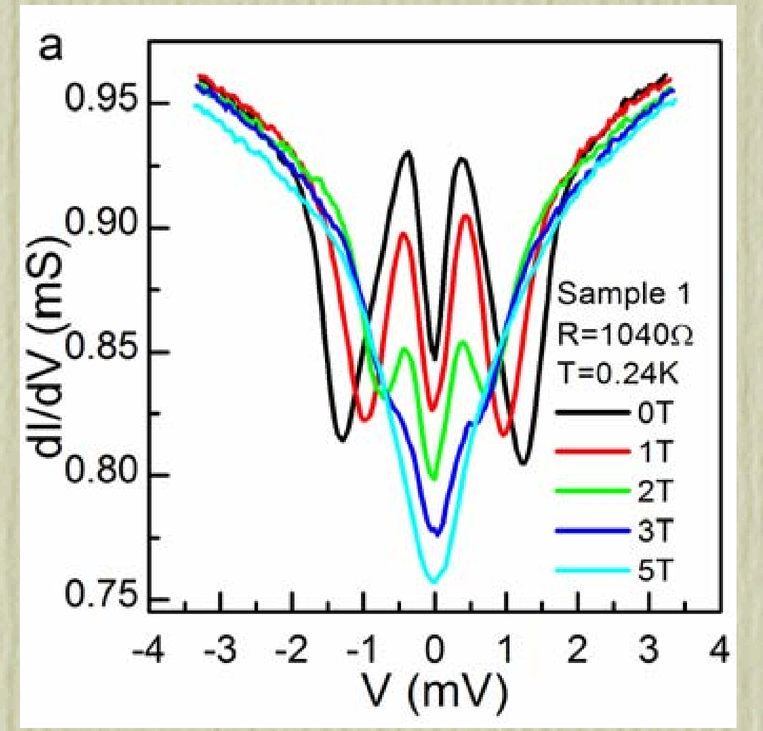
The width of the ZBP does not reflect the gap energy correctly, because the normal state resistance R_N is less than the threshold R_N value for ballisticity ($\simeq 13\ \Omega$), and thus these junctions are scattering electrons: the estimated point contact size is larger than the electron mean free path.

(Threshold case of $R_N \simeq 13\ \Omega$ has a ZBP width compatible with the energy gap.)

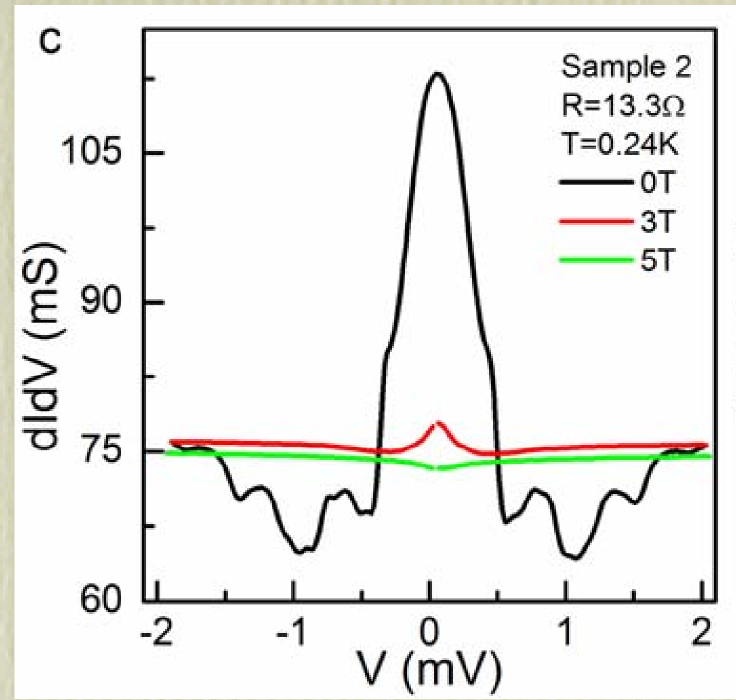
Additional check: same low-resistance junctions measured again after 6 months, exhibit larger $R_N \simeq 100\ \Omega$ and compatible extracted gap values.

Magnetic field evolution:

Large-R_N junctions (≫100 Ω)



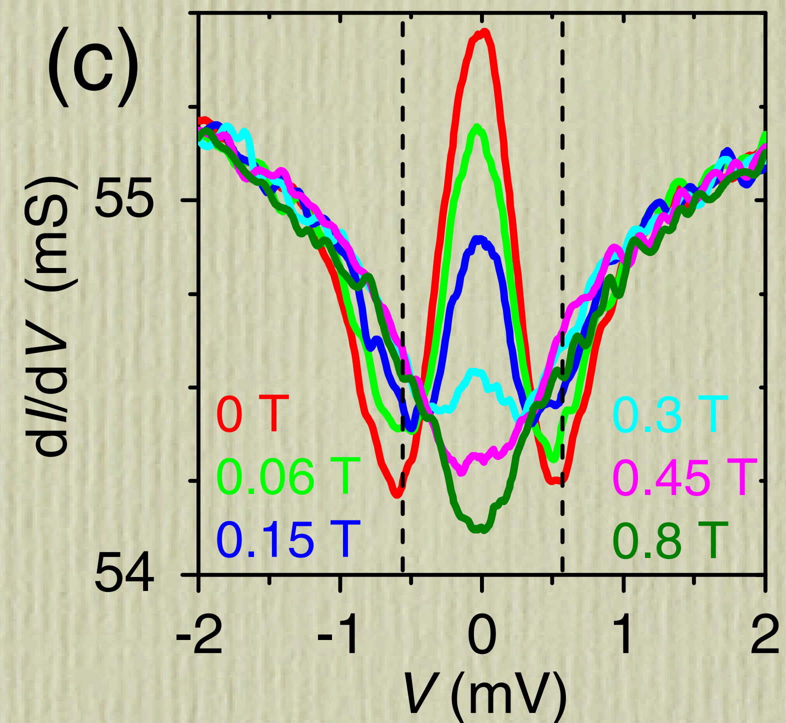
Low-R_N junctions (≲10 Ω)

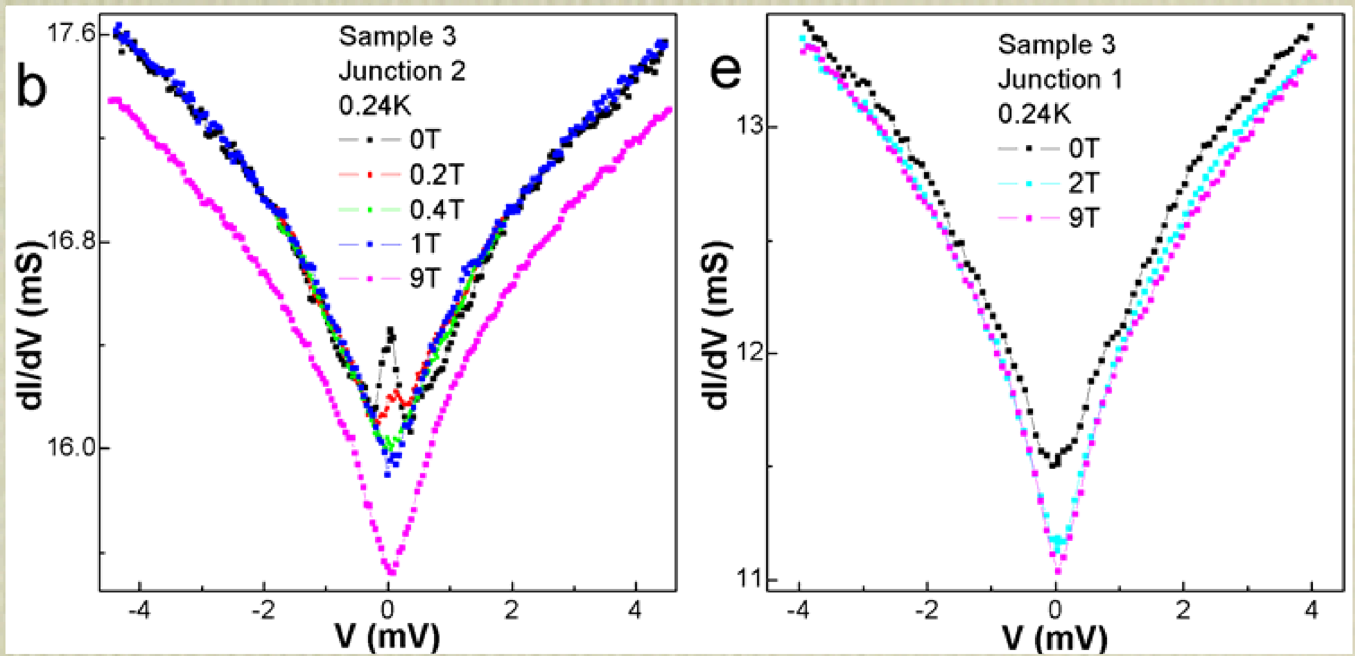


- The double peaks move to lower bias and decrease in amplitude;
- Double-peak feature disappears completely at B≃5 T, close to the nominal upper B_{c2};
- Double dips at high bias move towards the center in a much faster pace;

- The zero-bias conductance peak is already greatly suppressed at B = 3 T;
- The zero-bias conductance peak disappears at B = 5 T;
- dI/dV oscillations supra-gap but before the reach of the normal state;

Comparison with previous experiment:

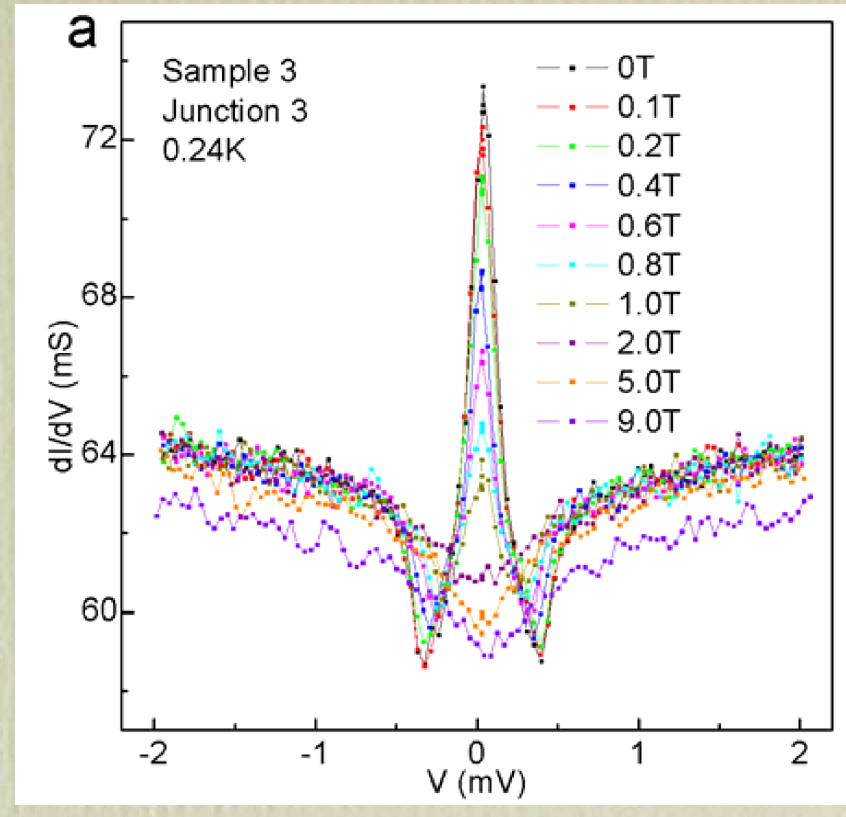




- The ZBCP is on top of a strong non-saturating V-shape *dI/dV* background;
- Observed ZBCP disappears completely in a magnetic field ≃0.45 T (an order of magnitude smaller than B_{c2});
- Reproduced similar behaviors by placing the SC microcrystals onto the electrodes while still electrically disconnected;
- Electrical connection established via annealing (short voltage pulse);
- Left: similar features, ZBP destroyed at B ≃0.4 T, indicating a thick degraded SC surface layer dominating the N-S transport
- Right: pure strong V-shape spectrum, no hint for AR signature, can be explained by a thick non-superconducting surface layer.

Cross check:

For two additional junctions in the same device, which were electrically connected initially without the need of voltage annealing, the AR spectra are dominated by a pronounced ZBCP but with much smaller V-shape background (likely due to much less contribution from a non-SC surface layer), and the ZBCP is suppressed at higher B field ≃2 T (indicating better-quality SC layers at the junctions).



Conclusion:

"Therefore, our control experiments suggest that a ZBCP disappearing at a magnetic field much lower than the bulk critical field and showing a strong non-saturating V-shape background reflects the existence of a **degraded** superconducting surface layer in **non-ideal** N-S junctions, and thus **cannot be used as the signature for zero-energy Majorana fermions**".