Non-reciprocal transport in superconducting Nb channels

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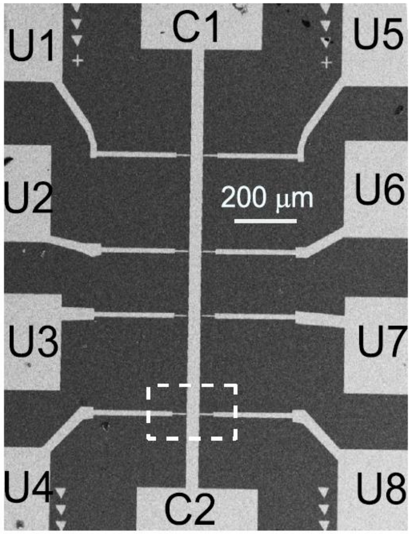


GDR MEETICC, Latresne-Bordeaux
31/05/2023

Non-reciprocal transport and rectification

Non-reciprocity in transport properties:
Unequal resistance for current flow in opposite directions resulting from a lack of inversion symmetry

For a conventional non-linear resistor: $R = R_0 + \alpha_2 I^2 + \alpha_4 I^4 + \dots\dots$ *(only even powers in current)*

Non-reciprocal transport: $R = R_0 + \boldsymbol{\alpha_1 I^1} + \alpha_2 I^2 + \boldsymbol{\alpha_3 I^3} + \alpha_4 I^4 + \dots\dots$

The simplest case :

$R = R_0 + \alpha I$

$V = R_0 I + \alpha I^2$

p-n junction diode

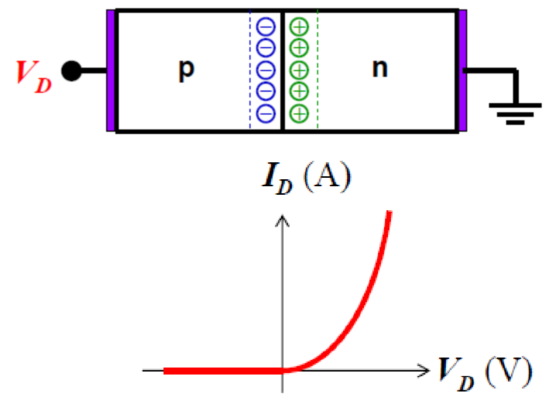


Image courtesy:
Lecture notes, Octavian Florescu
UC Berkeley (Summer 2005)

When an a.c. current is applied

$$I = I_{ac} \sin \omega t$$

The voltage has ***d.c.*** *and* ***second harmonic*** *components*

$$V = \frac{1}{2}\alpha I_{ac}{}^2 + R_0 I_{ac} \sin \omega t + \frac{1}{2}\alpha I_{ac}{}^2 \sin\left(2\omega t - \frac{\pi}{2}\right)$$

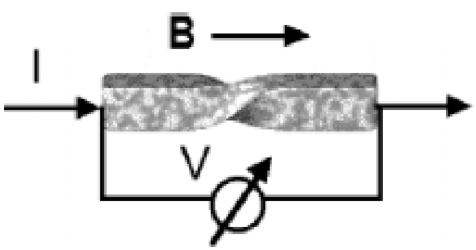
G. L. J. A. Rikken, J. Fölling, and P. Wyder
Phys. Rev. Lett. 87, 236602 (2001)

Two-terminal magnetoresistance is usually an even function of the magnetic field B.

$$\boldsymbol{R} = \boldsymbol{R_0}\,\{\,\boldsymbol{1} + \beta \boldsymbol{B^2}\}$$

A chiral conductor may have a term of the form ***k.B*** or ***k x B***.

$$R^{D/L}(\langle \mathbf{k} \rangle, \mathbf{B}) = R_o\{1 + \beta B^2 + \chi^{D/L}\mathbf{I} \cdot \mathbf{B}\}$$



A helix made from non-chiral material.

Axial magnetic field due to current applied:

$$B_a = \alpha^{D/L} I$$

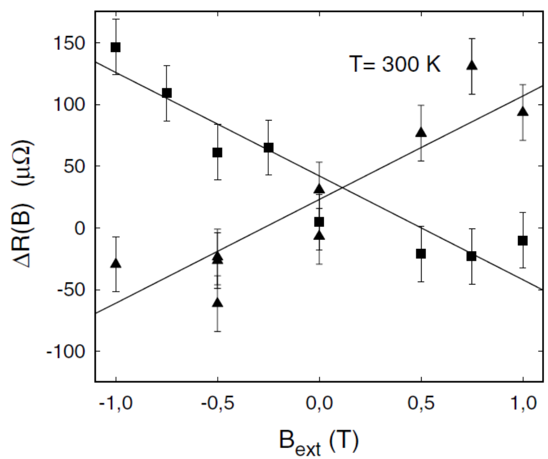
Field experienced by charge carriers:

$$B_{\rm ext} + B_a$$

Due to B^2 magnetoresistance:

$$R^{D/L}(I, B_{\rm ext}) = R_o\{1 + \beta B_{\rm ext}^2 + 2\alpha^{D/L}\beta I B_{\rm ext} + O(I^2)\}$$

$$\Delta R(I, B_{\rm ext}) \equiv R(I, B_{\rm ext}) - R(-I, B_{\rm ext})$$



Two-terminal magnetochiral resistance anisotropy of D (squares) and L (triangles) bismuth helices.

General features of non-reciprocal transport

The resistance has the form:

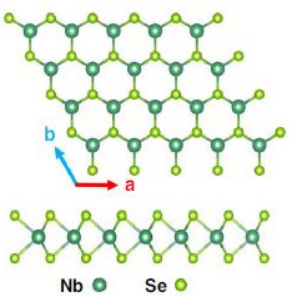
$$R = R_0 + \chi I B$$

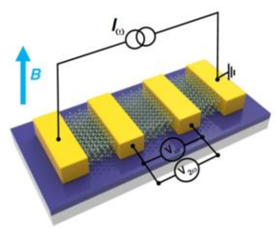
More generally:

$$R = R_0 + \chi . I . fodd\ (B)$$

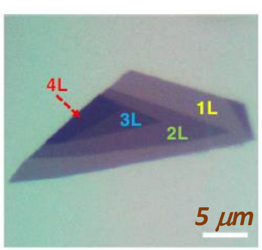
General characteristics:
- *There exists a* ***directional asymmetry*** *(χ) in the structure of the conductor*
- *The non-reciprocal signal is necessarily* ***anti-symmetric in the magnetic field***

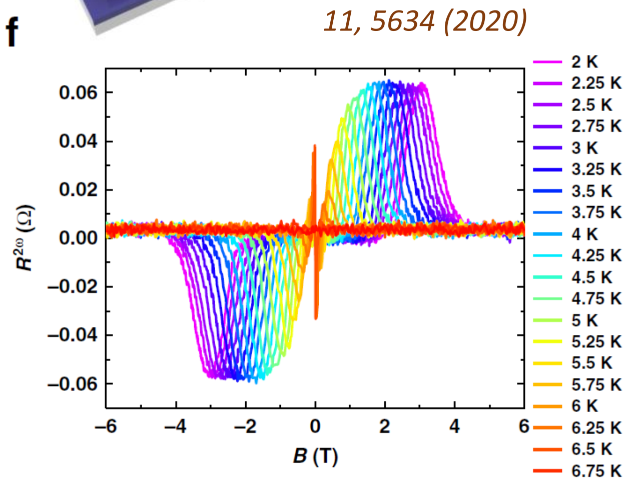
Non-centrosymmetric crystal



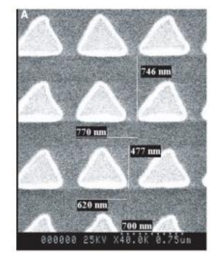


Zhang et al., Nature Commun. 11, 5634 (2020)

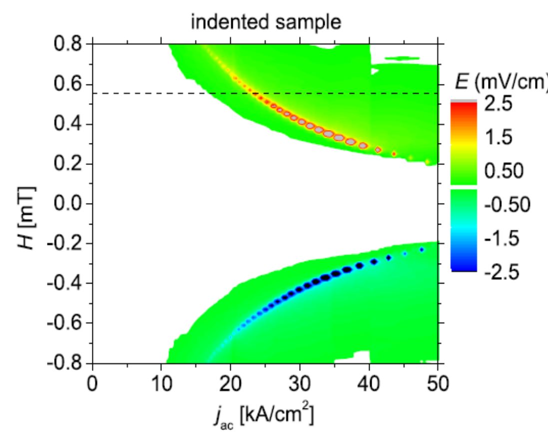




Vortex ratchets



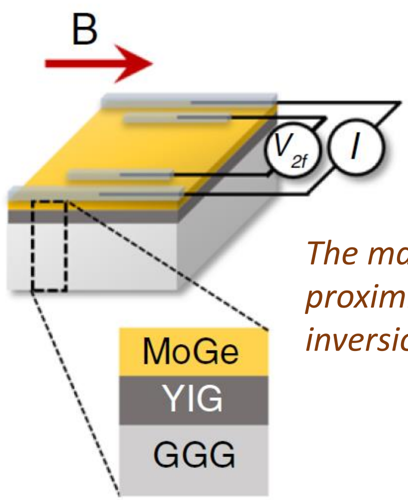
Villegas et al., Science 302, 1188 (2003)



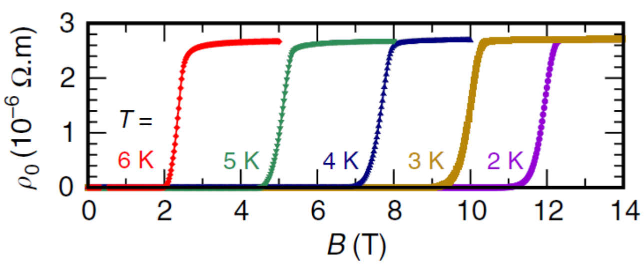
D. Cerbu et al., New. J. Phys. 15, 063022 (2013)

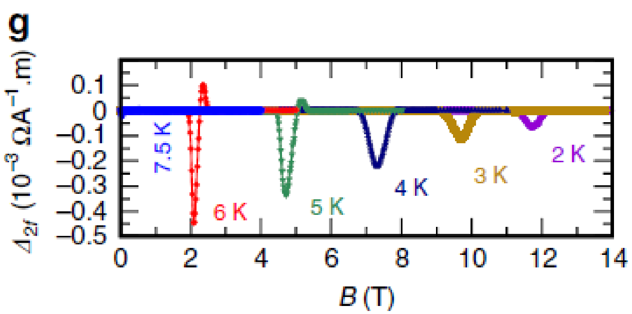
Superconductor on insulator magnet

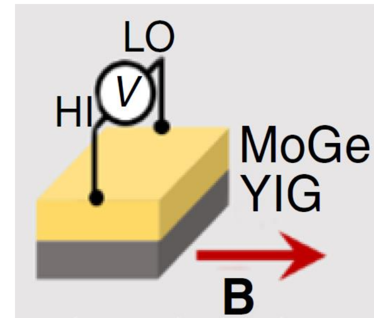
Lustikova et al.,
Nature Communications 9, 4922 (2018)



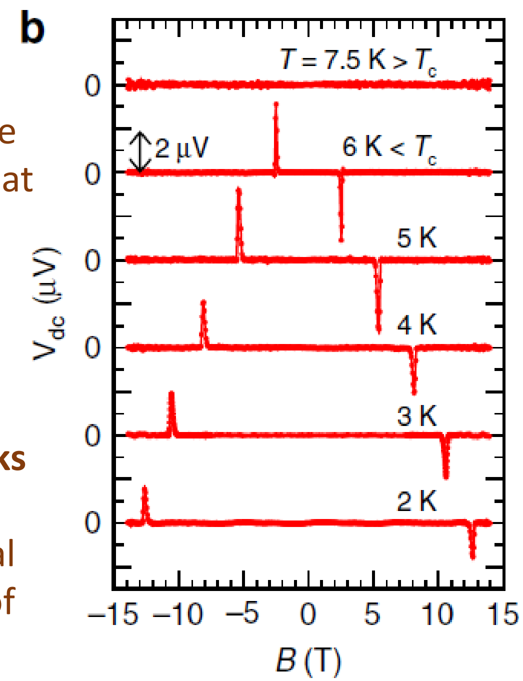
The magnetic moment in proximity breaks inversion symmetry.





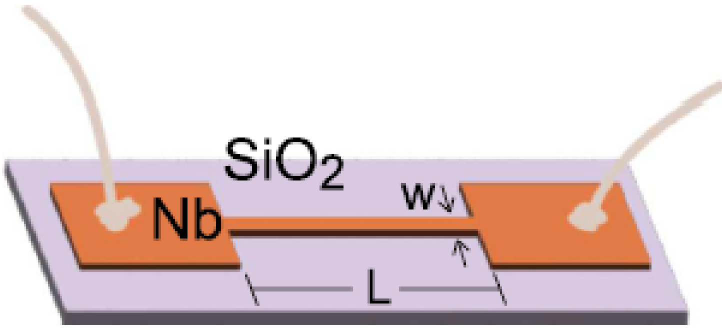


Spontaneous voltage peaks are observed at the critical field.

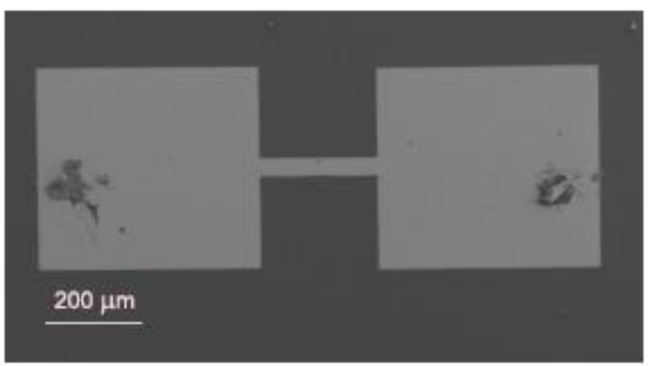


Antisymmetric peaks arise because the non-reciprocal signal is an **odd function** of applied magnetic field.

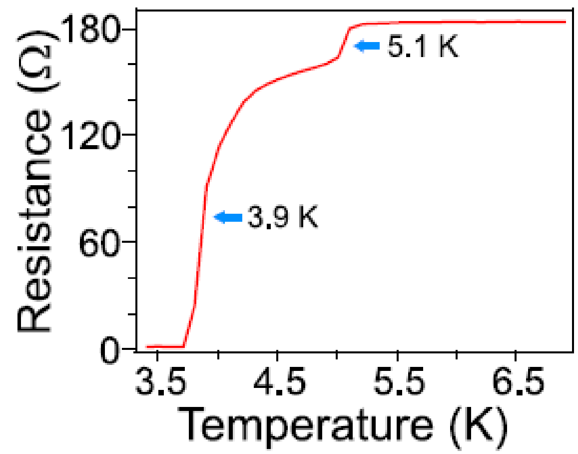
Niobium devices without structured asymmetry

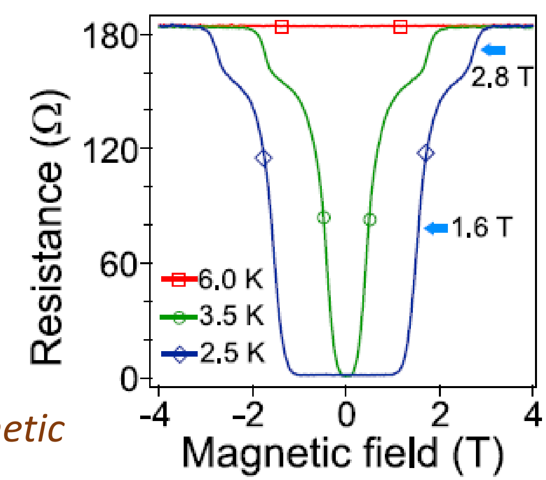


Evaporated films without crystalline order



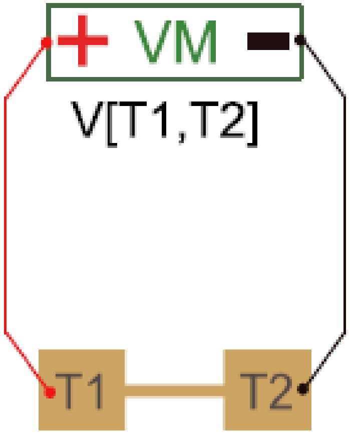
Superconducting transition at 3.9 K

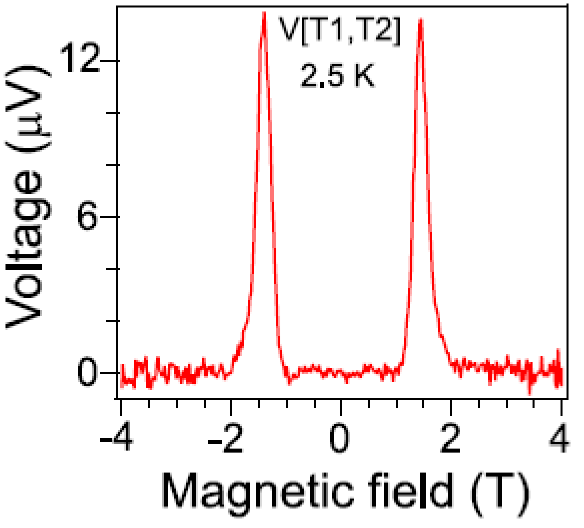




At 2.5 K, critical magnetic field is 1.6 T

Niobium devices without structured asymmetry





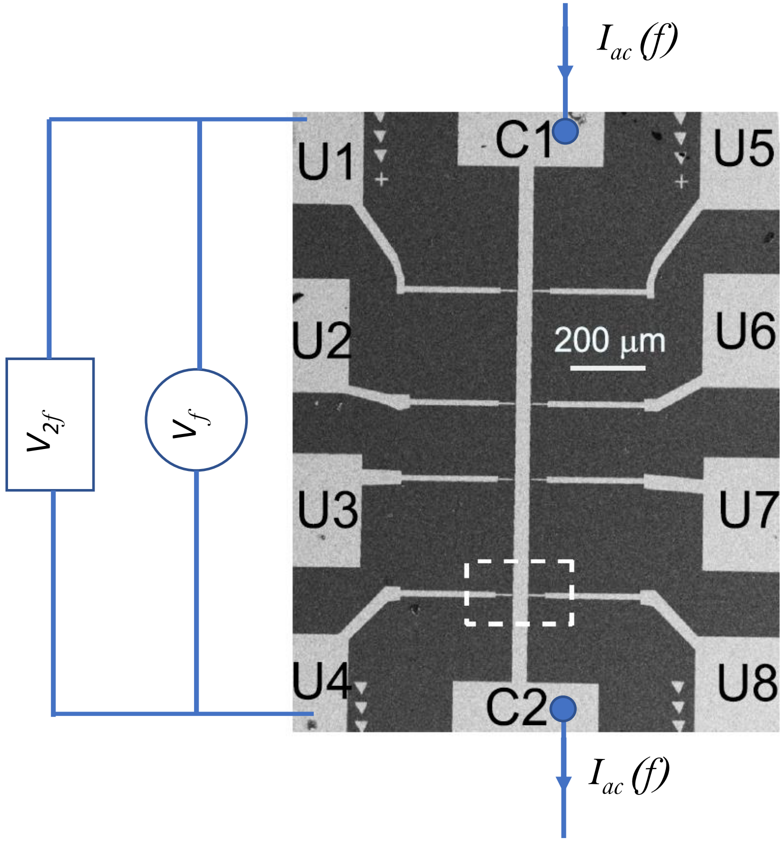
Spontaneous voltage peaks at the critical field

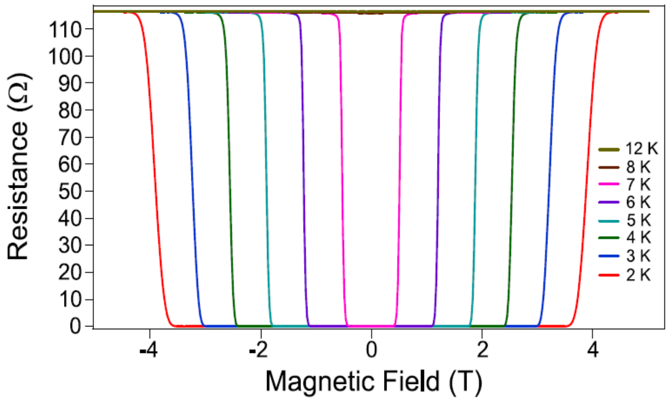
The peaks are **not** anti-symmetric in magnetic field!

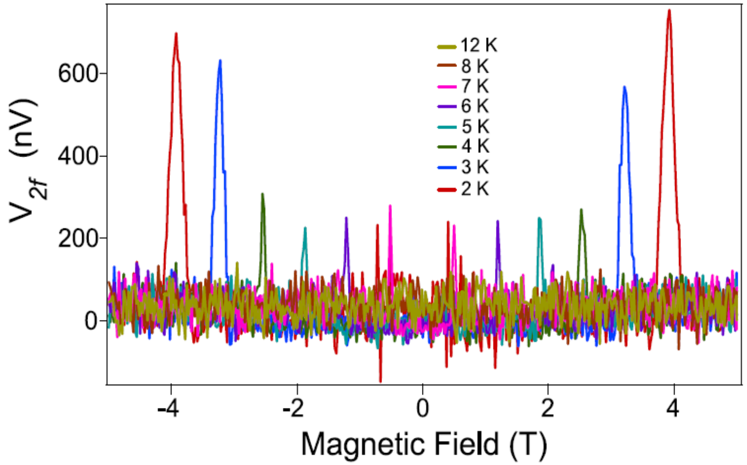
$$R = R_0 + \alpha I$$

Why is there a finite rectification signal at all in a symmetric film?

Second harmonic voltage







Second harmonic peaks confirm that indeed there is non-reciprocal transport.

Why does a film without structural asymmetry show these effects and why is the symmetry of peaks different from magnetochiral anisotropy?

Hypothesis:

1. *Inversion symmetry is **spontaneously broken***
2. *An **electric polarization** exists within the system*

Ferroelectricity in Free Niobium Clusters

*Moro et al., **Science** 300, 1265 (2003)*

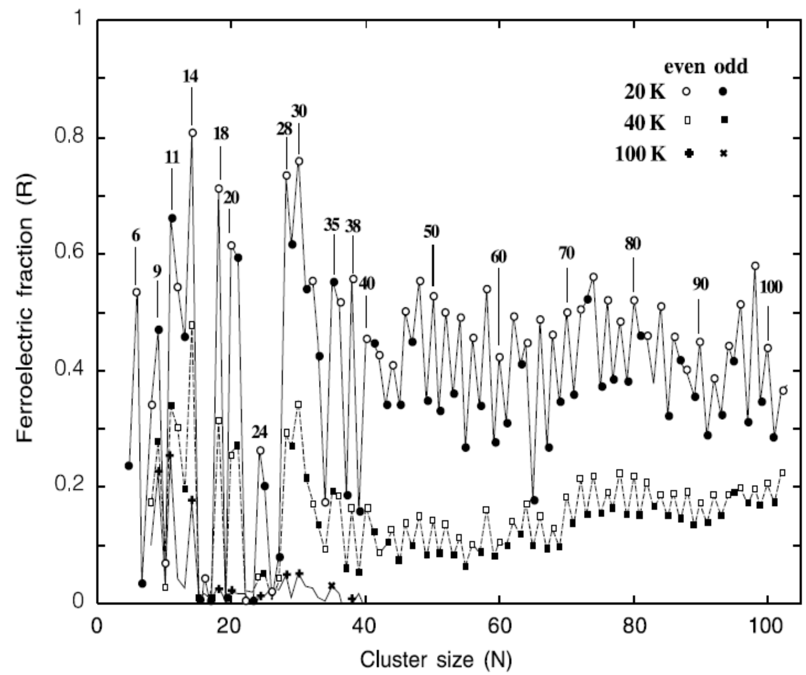
Electric deflections of gas-phase, cryogenically cooled, neutral niobium clusters [Nb_N; number of atoms (N) = 2 to 150, temperature (T) = 20 to 300 kelvin], measured in molecular beams, show that cold clusters may attain an anomalous component with very large electric dipole moments.

Clusters of Nb atoms have spontaneous-symmetry-broken ferroelectric moment.

The dipoles are not 'built into' the clusters.

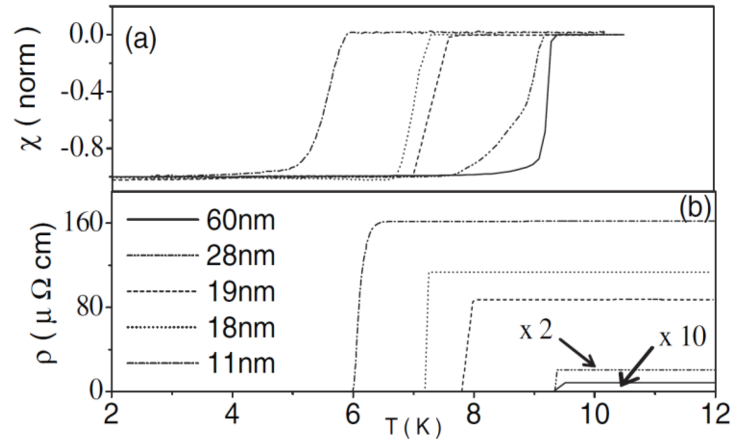
Xu et al., Phys. Rev. B 75, 085429 (2007)

Such dipole moments were observed in atomic clusters of elements which become superconducting as bulk crystals.

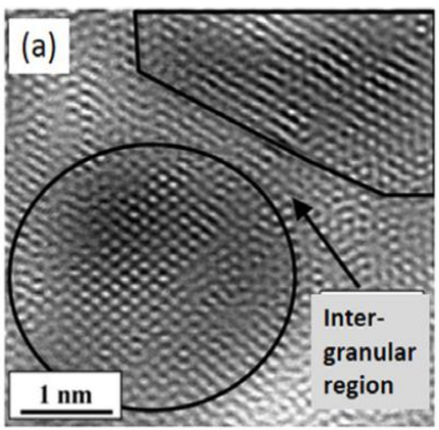


Grain-size dependence of superconductivity in Nb films

Mechanism of the Size Dependence of the Superconducting Transition of Nanostructured Nb
Bose et al., Phys. Rev. Lett. 95, 147003 (2005)

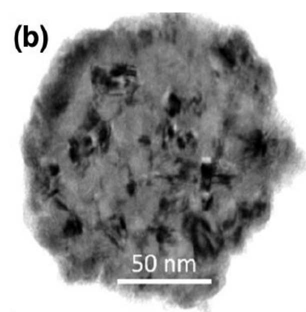


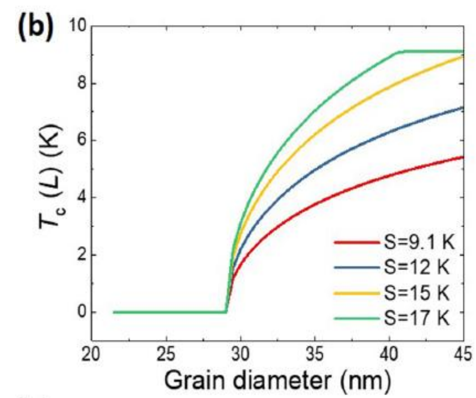
No superconductivity below an average grain size of 8 nm



Bose et al., Rep. Prog. Phys. 77, 116503 (2014)

Rare-region onset of superconductivity in niobium nanoislands
Durkin et al., Phys. Rev. B 101, 035409 (2020)





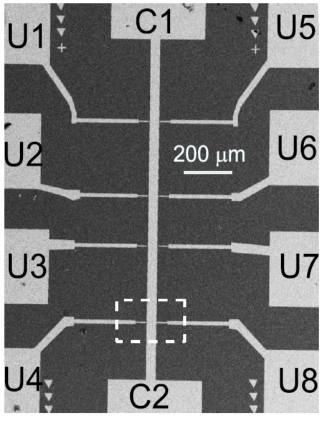
Superconductivity arises from large grains.
Much of the volume is occupied by smaller non-superconducting grains.

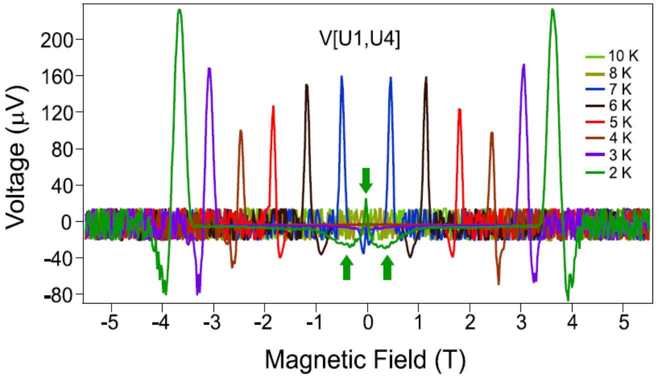
Stochastic nature of voltage peaks

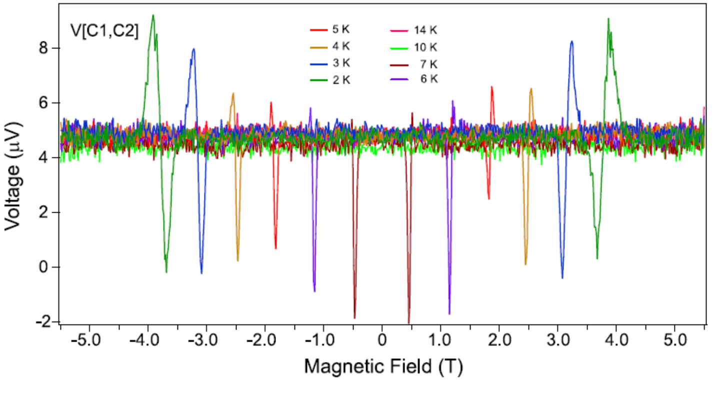
The observation of voltage peaks due to rectification effect in niobium films might be interpreted in terms of the presence of electric dipoles within nanoscale grains.

The signatures of non-reciprocal transport vary from one experimental run to another.

This further shows that the directional asymmetry leading to a rectification effect is not 'built into' the structure of the niobium film. This is a case of spontaneous symmetry breaking.







Conclusions

- We have observed a new type of non-reciprocal transport which is fundamentally different from the symmetry rules of magnetochiral anisotropy.
- Non-reciprocal effects arise without an asymmetry structured into the system, due to spontaneous breaking of inversion symmetry.
- The results suggest that nanoscale grains of niobium posses spontaneous-symmetry-broken electric dipole moments - a fact that was so far known only from experiments on atomic clusters.