中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

超导基础理论和实验技术讲座
National Lab for Superconductivity Lecture Series
【第100期】

Anomalous Magnetic Moments as Evidence of Chiral Superconductivity in Bi/Ni Bilayer

吕 力
中国科学院物理研究所

主办 中科院物理所超导国家重点实验室、学术服务部
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发展历程

2020年 08
牵头承担国家重点研发计划重大仪器专项无液氦低温强磁场综合物性测量仪
成功推出无液氦低温强磁场综合物性测量系统、低温真空泵

2018年 07
成功研制1.5K无液氦低温系统
开始研制稀释制冷机
国家级博士后工作站申报获批

2016年 06
GM低温制冷机实现MRI市场批量供货
GM低温制冷机首次完成海外市场批量供货

2015年 05
GM低温制冷机进军海外低温泵市场
氦回收纯化液化设备实现产业化，应用于各大科研院所

2014年 04
获批“高新技术企业”其中部分产品被认定为高新技术产品
系列化低温设备在大科学工程领域得到良好应用

2013年 03
加入中船重工，成立中船重工鹏力（南京）超低温技术有限公司

2011年 02
首批氦回收纯化液化设备研制成功
成功研制出4K/10K/77K系列低温设备，打破了国外垄断，保障了国内科研与军工领域的研究需求

2010年 01
1月，成立，注册资金：3000万
8月，成功研制出首套4.2K GM低温制冷机

公司定位

- 低温产品制造商
- 低温系统服务商

主要产品

公司始终专注于GM低温制冷机、稀有气体提纯和液化装备、低温恒温器的研制和生产，同时也是一家提供全方位低温应用及解决方案的服务商。可为客户提供指标优异、性能稳定的低温产品。

GM低温制冷机

氦回收纯化液化装置

无液氦低温强磁场综合物性测量仪

稀释制冷机

（超）低振动低温恒温器

低温泵

1.5K低温系统

氦循环制冷装置

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【第100期】

Anomalous Magnetic Moments as Evidence of Chiral Superconductivity in Bi/Ni Bilayer

吕力，中科院物理研究所研究员，主要从事低温凝聚态物理的实验研究，包括低维材料的电输运性质和热学性质研究、介观器件的制备和量子调控研究等。曾经担任物理所极端条件实验室、崔琦实验室、固态量子信息与计算实验室的主任，物理所副所长。目前是物理所怀柔研究部主任，同时也是中国物理学会出版工作委员会主任。2012年当选美国物理学会会士，2016年当选英国物理学会会士。

主办　中科院物理所超导国家重点实验室、学术服务部
协办　《物理学报》｜CPL｜CPB｜《物理》

超导基础理论和实验技术系列讲座（第100期）

Anomalous Magnetic Moments as Evidence of Chiral Superconductivity in Bi/Ni Epitaxial Bilayer

Junhua Wang, Guang Yang, Zhaozheng Lyu, Yuan Pang, Guangtong Liu, Zhongqing Ji, Jie Fan, Xiunian Jing, Changli Yang, Fanming Qu, **Li Lu**（吕力）

Institute of Physics, CAS, Beijing, China

Xinxin Gong and **Xiaofeng Jin**

Fudan University, Shanghai, China

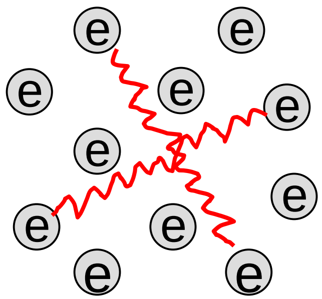
November4, 2020

Conventional vs. Unconventional Superconductivity

Conventional SC

***s*-wave pairing**
zero angular momentum

For extended electrons



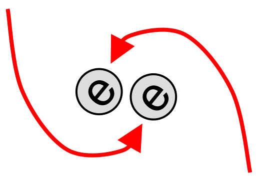
➢ Most known SCs

Unconventional SC

***p*-wave, *d*-wave, …**
high angular momentum

For electrons with more localized orbits

compromise between attractive & repulsive interactions



- Strongly correlated electron systems
- Hard-core atoms:
  - ➢ superfluid ^{3}He-A
  - ➢ cold atoms

Spinless, *p*-wave-like
… …

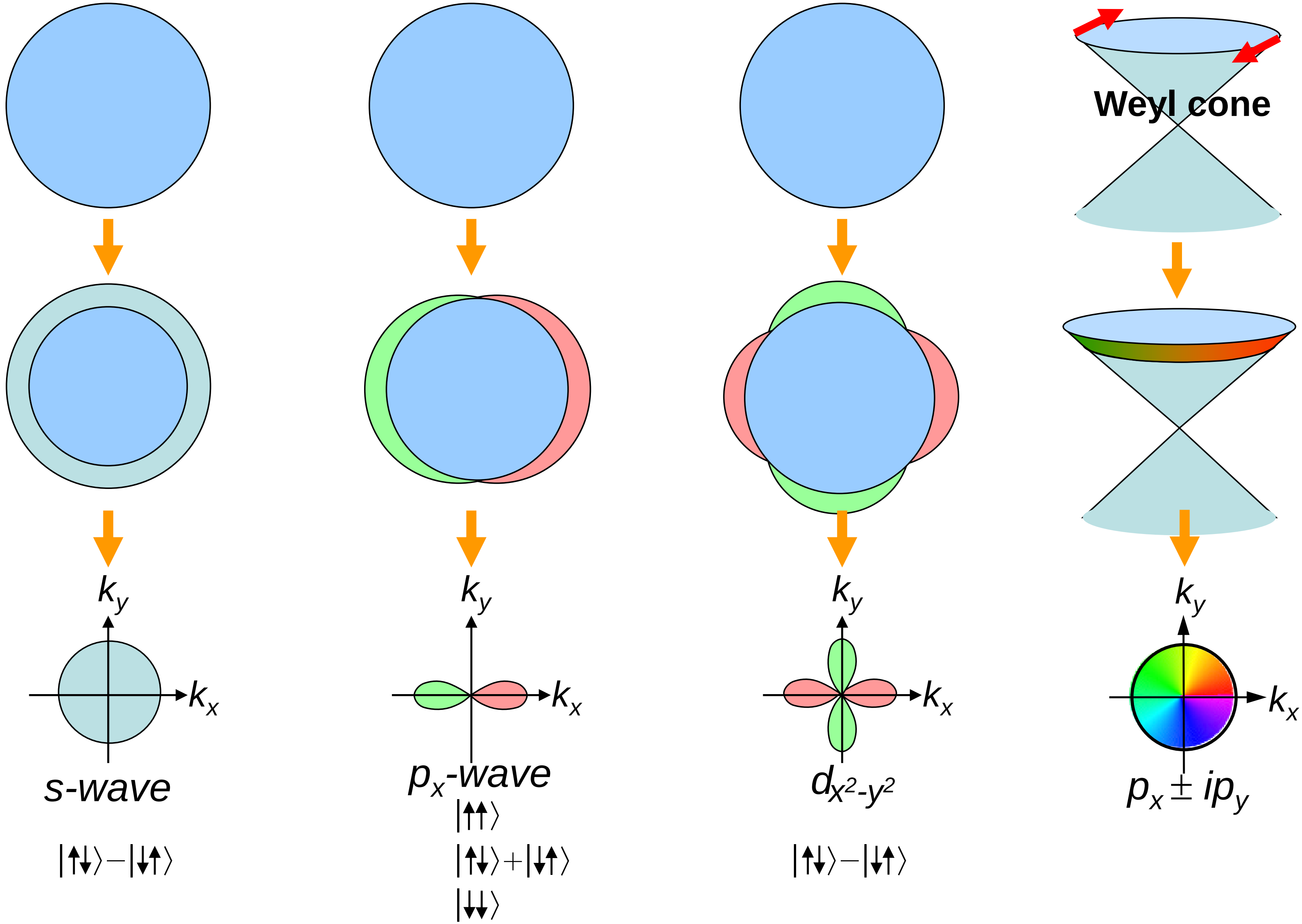
For electrons with strong SOC or spin-momentum locking

拓扑材料中的超导
顾开元 罗天创 葛军 王健
《物理学报》2020

Emerging topological superconductivity in new topological materials/hetrostruc.?

- ➢ Doped TIs, Weyl SM., Hybrid devices, …
- ➢ TMDC
- ➢ … …

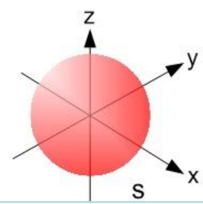
Pairing Symmetry, Even/Odd Parity



Pairing Symmetry, Even/Odd Parity

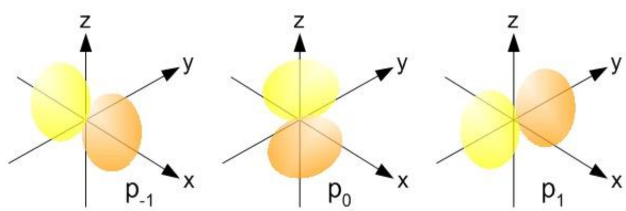
库珀对波函数： $\Psi = \Psi_{\text{质心}}\Psi_{\text{相对}}\Psi_{\text{自旋}}$

even



singlet: $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

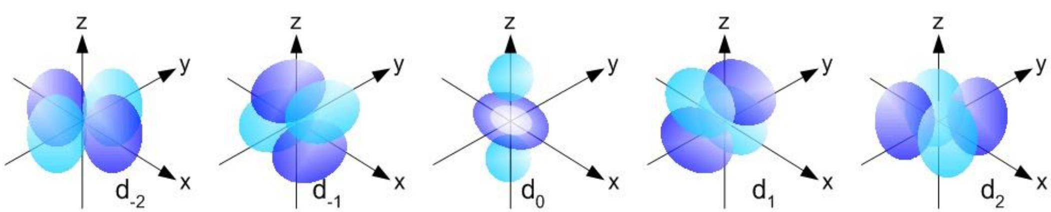
odd



p_x, p_y, p_z
$p_x + ip_x$

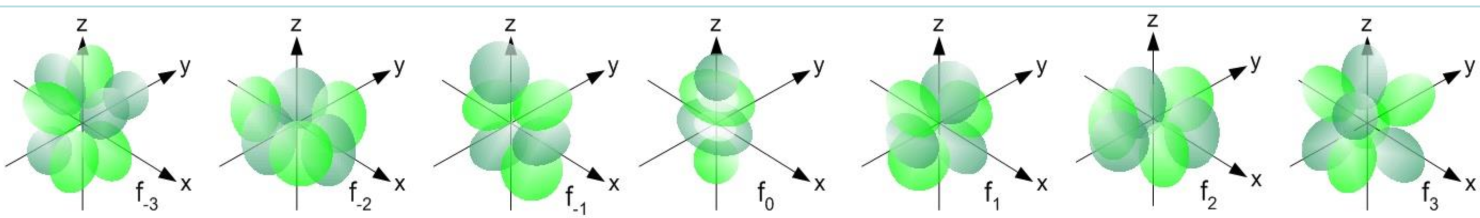
triplet: $|\uparrow\uparrow\rangle$, $|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$, $|\downarrow\downarrow\rangle$

even



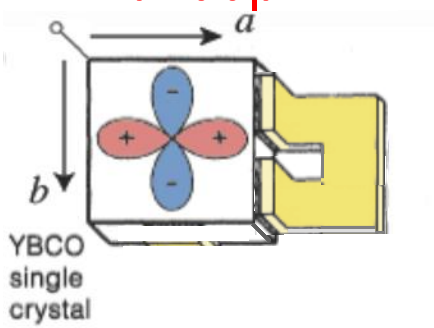
d_{xy}
$d_{x^2-y^2}$
$d_{xy} + id_{x^2-y^2}$

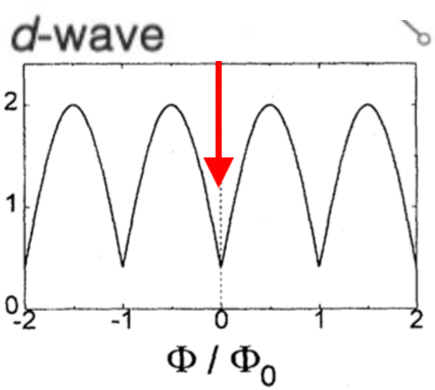
odd



d-wave superconductivity in cuprates confirmed by phase-sensitive experiments

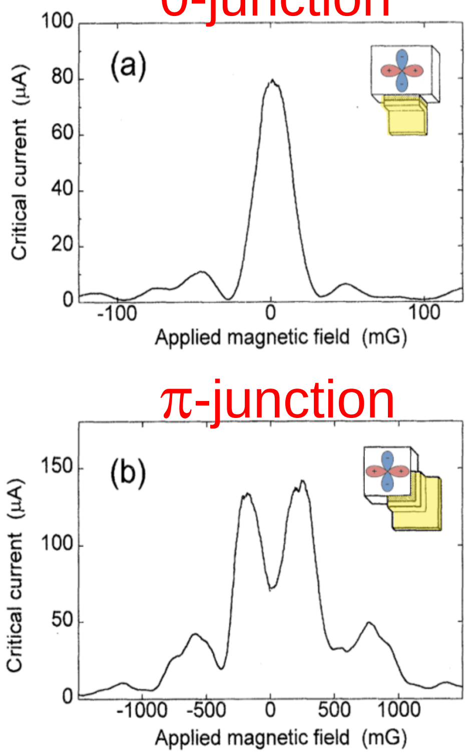
0-loop





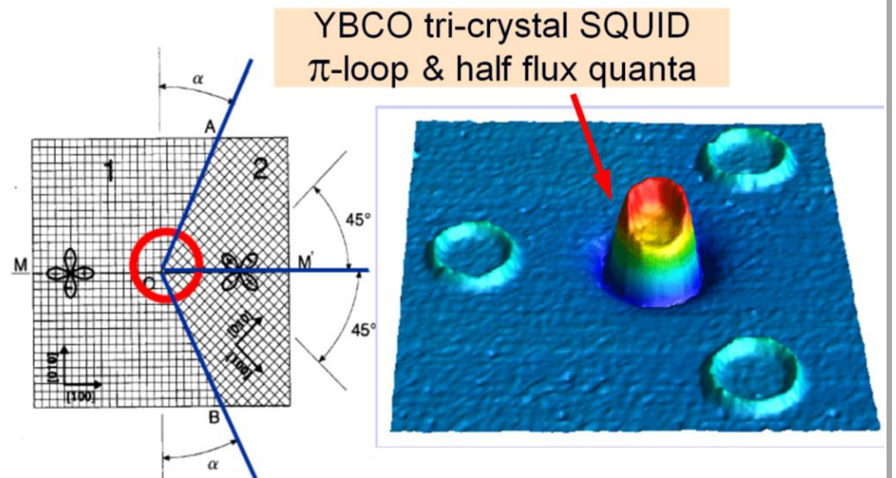
0-junction

π-junction



van Harlingen group

π-loop in a tri-crystal ring

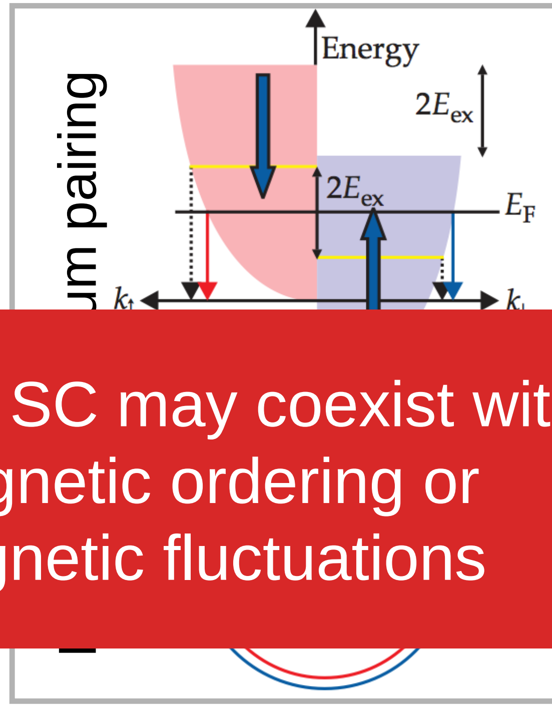


C. C. Tsuei group

Oliver E. Buckley Condensed Matter Physics Prize (1998)

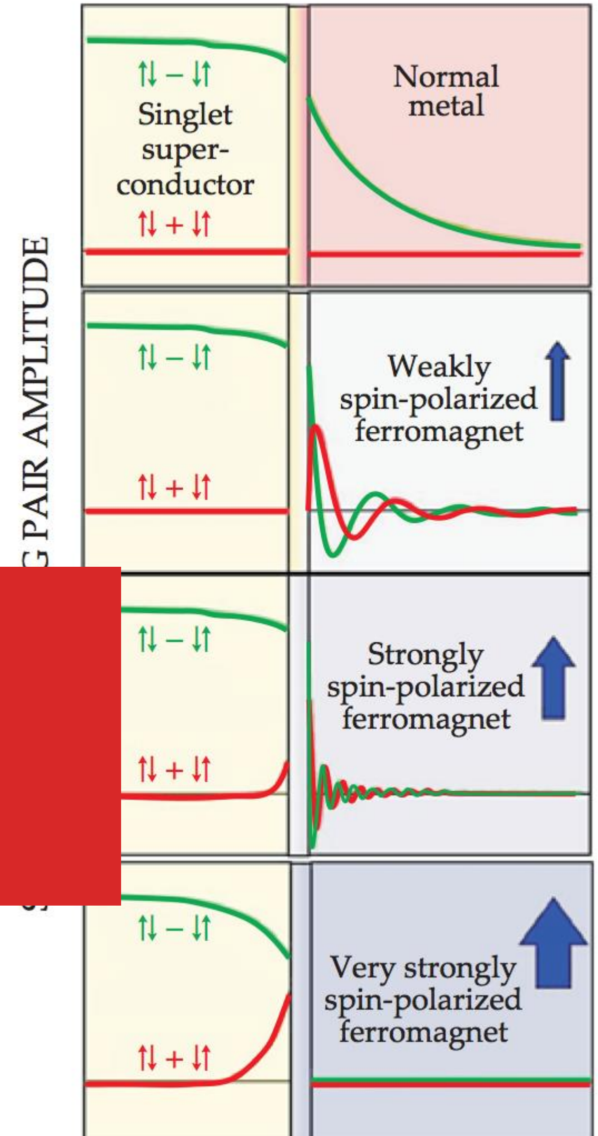
p-wave Superconductivity (Theory)

- Coexist. of SC and FM V. Ginzburg, 1956
- Triplet pairing near SC-FM interface
  FFLO mechanism
  Fulde, Ferrell, PR' 1964,
  Larkin, Ovchinnikov,
  Sov. Phys. JETP' 1965



p-wave SC may coexist with magnetic ordering or magnetic fluctuations

- Magnetic fluctuation-mediated triplet pairing
  Fay, Appel, PRB'1980



M. Eschrig, Phys. Today' 2011

p-wave Superconductivity (Experimental)

- ^{3}He-A D. M. Lee, D. D. Osheroff and R. C. Richardson, 1971 + A. J. Leggett

- Heavy fermion superconductors:

  $CeCu_2Si_2$, UGe_2, UPt_3, URhGe, UCoGe, … 30+

- … …

Table I. Selection of candidates of spin-triplet superconductors. HF: heavy fermion superconductors, NCS: Noncentrosymmetric superconductors, FM: ferromagnetic superconductors, ∗: superconductivity under pressure.

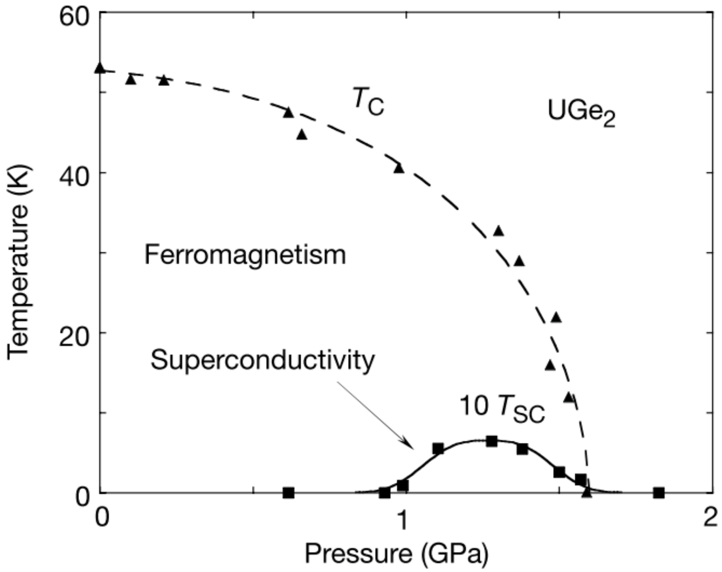
Materials	Classification	Spin evidence of triplet pairing	Properties
^{3}He	Superfluid	magnetization, NMR etc.[7]	*p*-wave, A phase is chiral
Sr_2RuO_4	Oxide	NMR, polarized neutron	2D analogue of ^{3}He-A Chiral *p*-wave
UPt_3	HF	NMR[18]	*f*-wave
UBe_{13}, URu_2Si_2, UNi_2Al_3	HF	NMR[13]	
UGe_2*, URhGe, UCoGe	FM, HF	Indirect	Anomalous H_{c2}[19–22]
UIr*	NCS, FM, HF	Indirect	
$CeIrSi_3$*	NCS, HF	NMR[23]	
Li_2Pt_3B	NCS	NMR[24]	
$CePt_3Si$	NCS, HF	Indirect	
$CeRhSi_3$*	NCS, HF	Indirect	Anomalous H_{c2}[25]
S/FM/S	Junctions	Indirect (I_c)[26–29]	Odd-freq., even-parity, *s*-wave

Y. MAENO, JPSJ 81, 011009 (2012)

p-wave Superconductivity (Experimental)

Anomalous properties in:

- ✓ heat capacity
- ✓ magnetic susceptibility
- ✓ penetration depth
- ✓ NMR
- ✓ … …

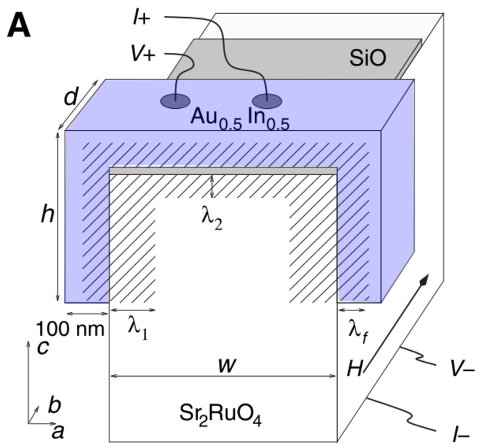


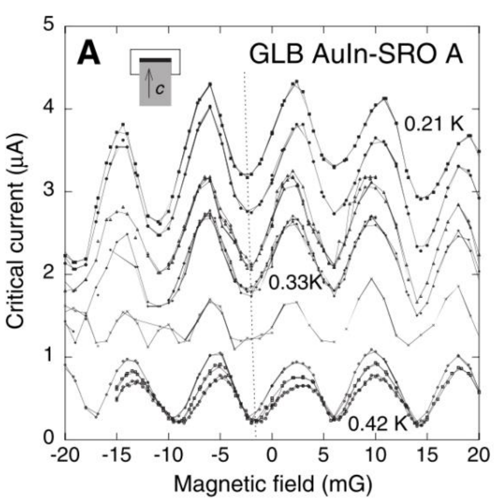
S. Saxena, et al., Nature' 2000.

Needs to rule out:

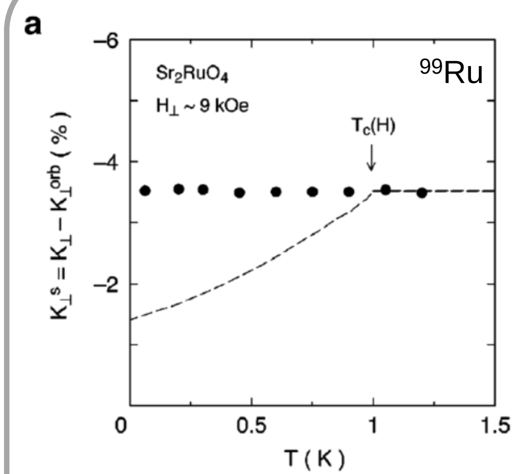
- local phase separation,
- inhomogeneity
- … …

Sr_2RuO_4: p_x+ip_y-wave SC candidate?

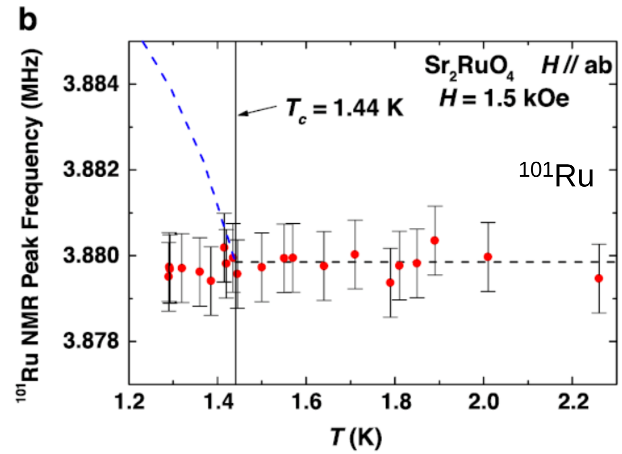




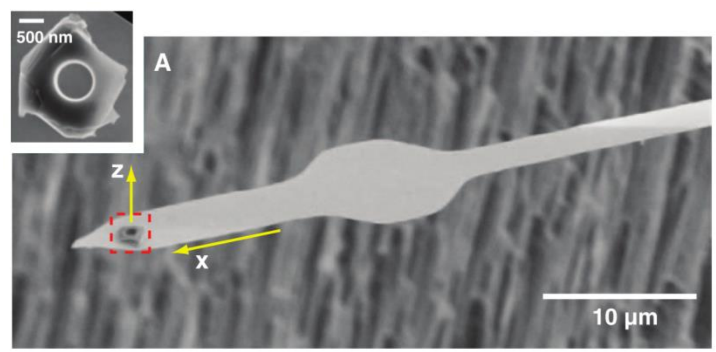
Y. Liu, Maeno, Science 2004

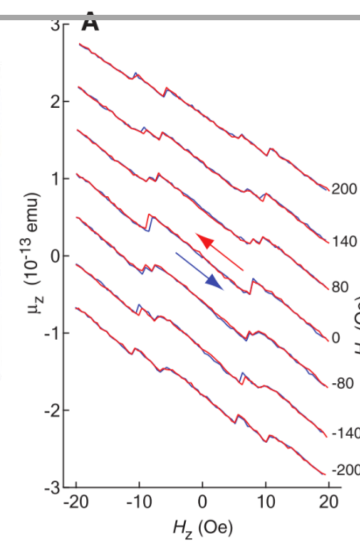


K. Ishida et al. PRB' 01



H. Murakawa et al. JPSJ' 07

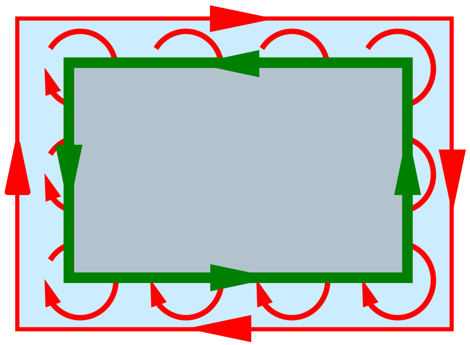




Budakian, Maeno, Science 2011

Chiral p_x+ip_y pairing, more features to expect

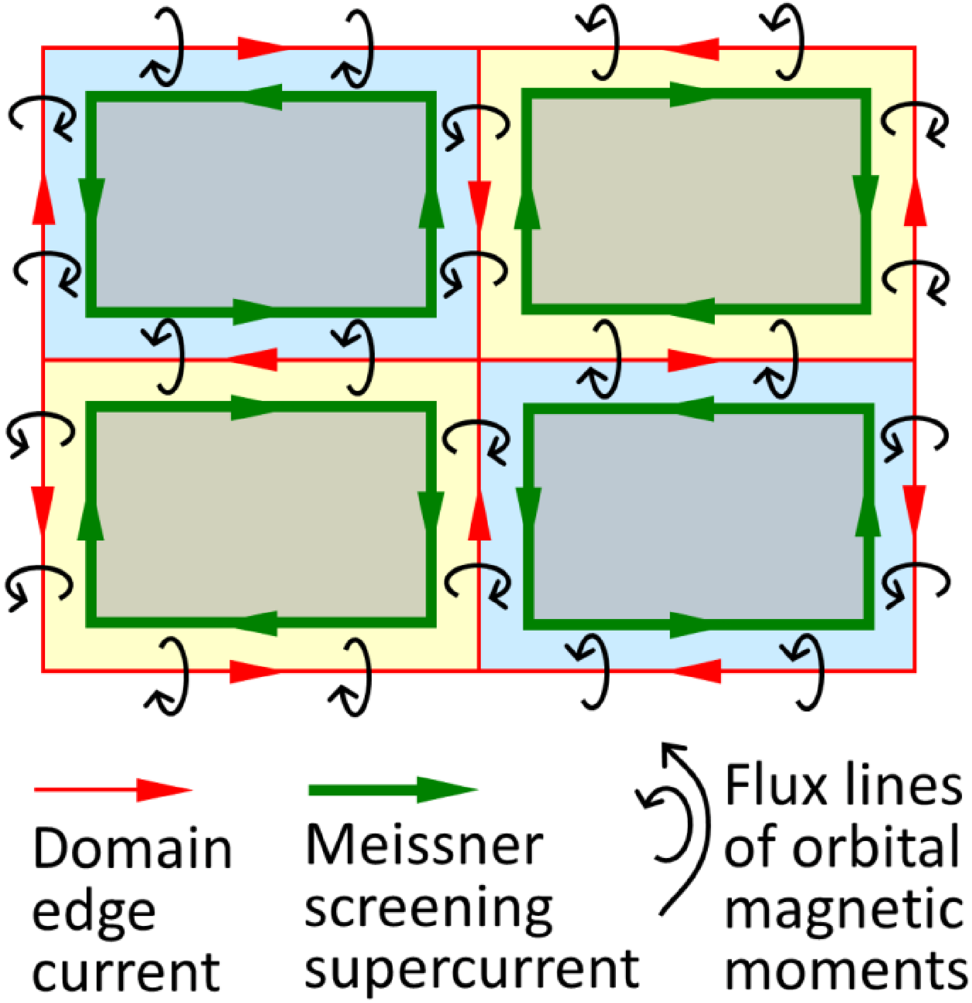
- Edge currents &
  Edge magnetization



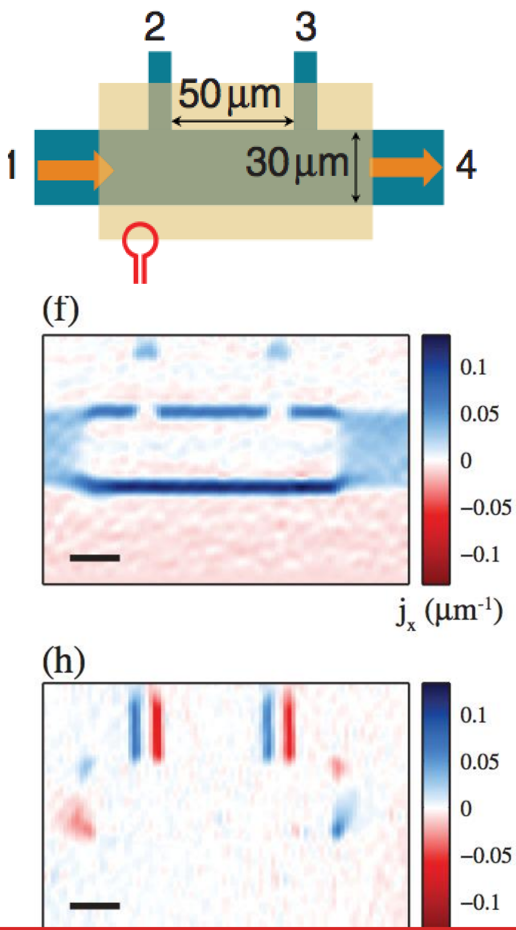
$\lambda > \xi$

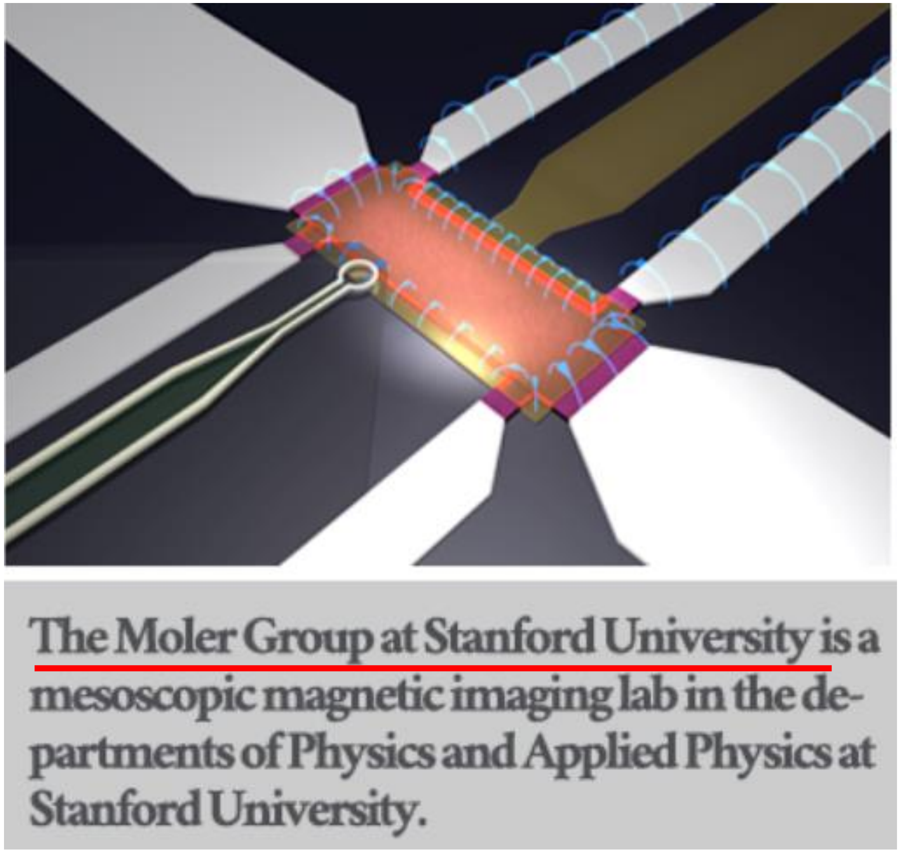
M. Sigrist, T. M. Rice, K. Ueda, PRL 63, 1727 (1989)

- Superconducting domains



Search for edge magnetization in Sr_2RuO_4

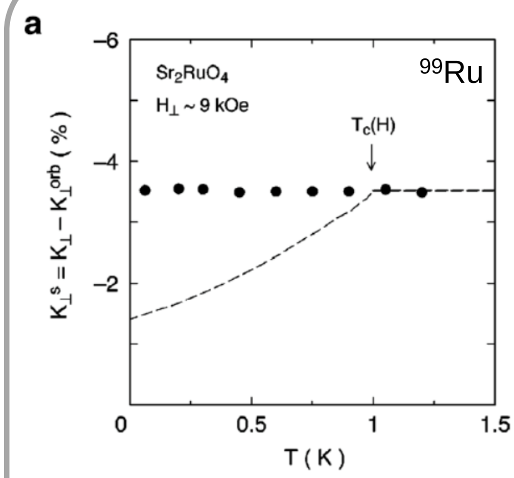




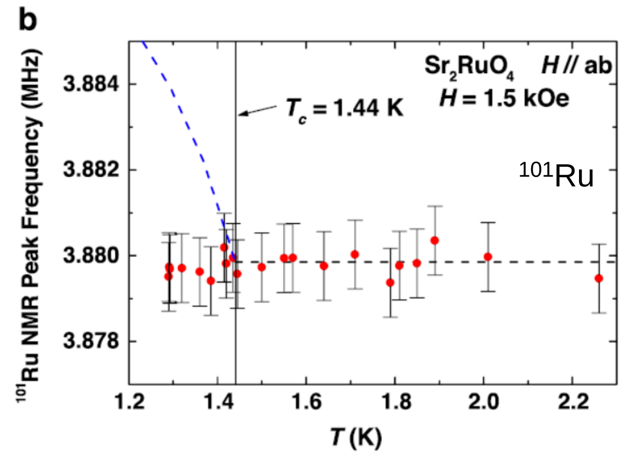
Fail to observe edge current and/or edge magnetization

Phys. Rev. B 72, 012504 (2005)
Phys. Rev. B 76, 014526 (2007)
Phys. Rev. B 81, 214501 (2010)

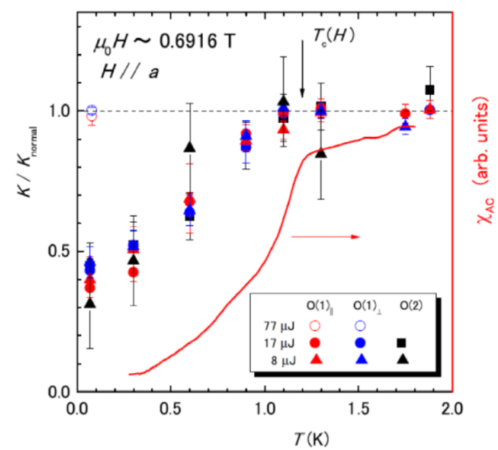
Sr_2RuO_4: p_x+ip_y-wave SC candidate?



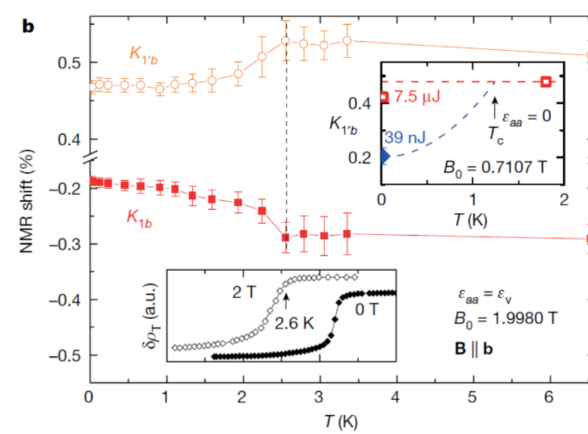
K. Ishida et al. PRB' 01



H. Murakawa et al. JPSJ' 07



K. Ishida et al., JPSJ' 2020



A. Pustogow et al., Nature' 2019

Sr_2RuO_4: p_x+ip_y-wave SC candidate?

npj | Quantum Materials

www.nature.com/npjquantmats

REVIEW ARTICLE OPEN

Even odder after twenty-three years: the superconducting order parameter puzzle of Sr_2RuO_4

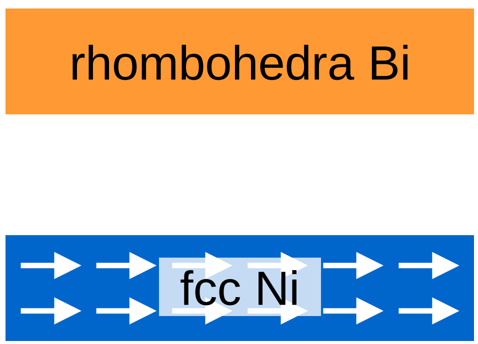
Andrew P. Mackenzie[1,2], Thomas Scaffidi[3], Clifford W. Hicks[1] and Yoshiteru Maeno[4]

In this short review, we aim to provide a topical update on the status of efforts to understand the superconductivity of Sr_2RuO_4. We concentrate on efforts to identify a superconducting order parameter symmetry that is compatible with all the major pieces of experimental knowledge of the material, and highlight some major discrepancies that have become even clearer in recent years. As the pun in the title suggests, we have tried to start the discussion from scratch, making no assumptions even about fundamental issues such as the parity of the superconducting state. We conclude that no consensus is currently achievable in Sr_2RuO_4, and that the reasons for this go to the heart of how well some of the key probes of unconventional superconductivity are really understood. This is, therefore, a puzzle that merits continued in-depth study.

npj Quantum Materials (2017)2:40 ; doi:10.1038/s41535-017-0045-4

Bi/Ni bilayer

- J. S. Moodera et al, PRB 42, 179 (1990).
- P. LeClair, J. S. Moodera, J. Philip, and D. Heiman, PRL 94 037006 (2005).

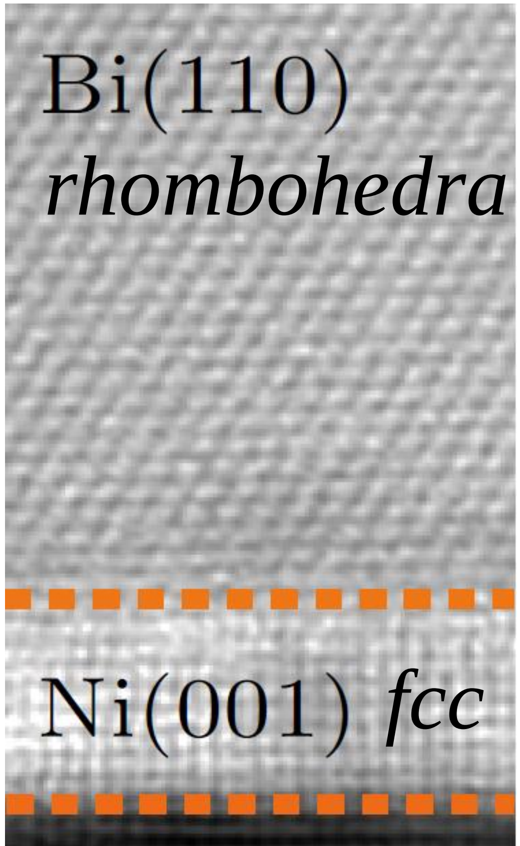


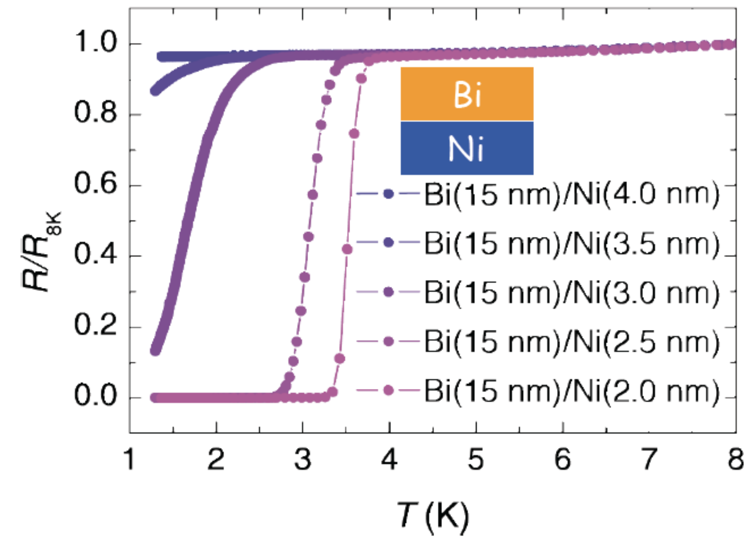
- Superconducting, $T_c \simeq 4.2$ K
- Coexistence of SC and FM

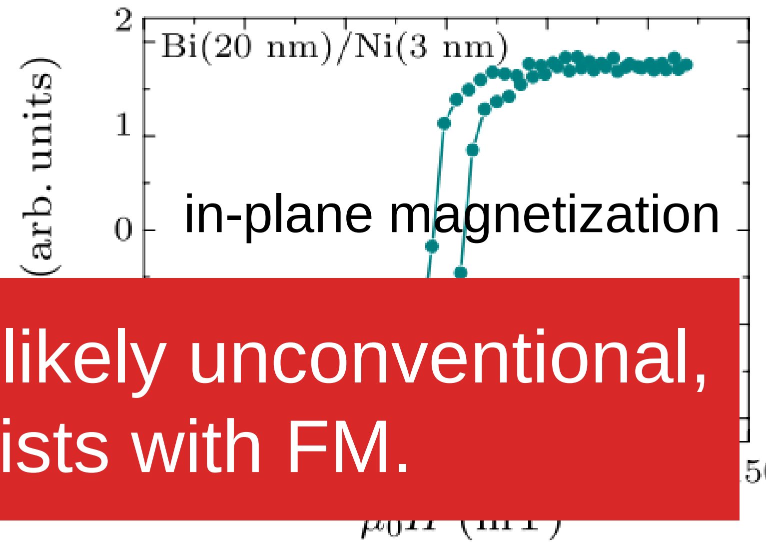
The SC was believed to arise from fcc-phase Bi induced by Ni.

Bi/Ni epitaxial bilayer from Fudan U

X.F. Jin group
at Fudan U







in-plane magnetization

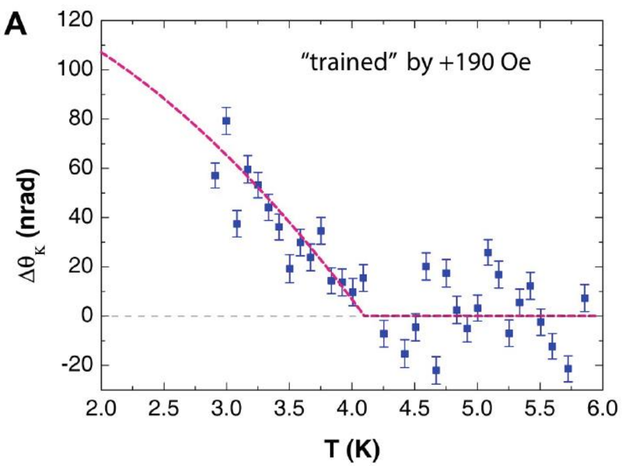
The superconductivity is likely unconventional, because it coexists with FM.

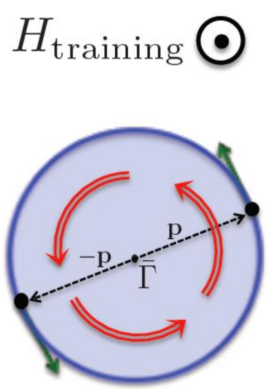
X. F. Jin group, Chin. Phys. Lett. 32, 067402 (2015)

Kerr Measurement based on Sagnac Interferometer

Time-Reversal-Symmetry-Breaking Superconductivity in Epitaxial Bismuth/Nickel Bilayers

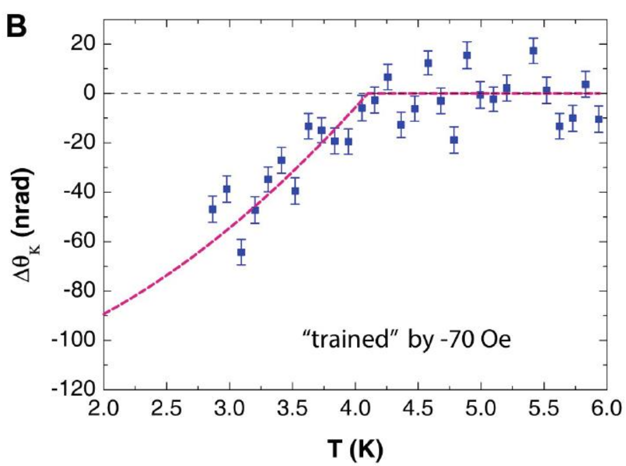
X.X. Gong et al., Sci. Adv. 3, e1602579 (2017)

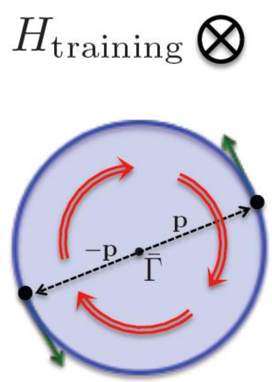




$J_z = 2$

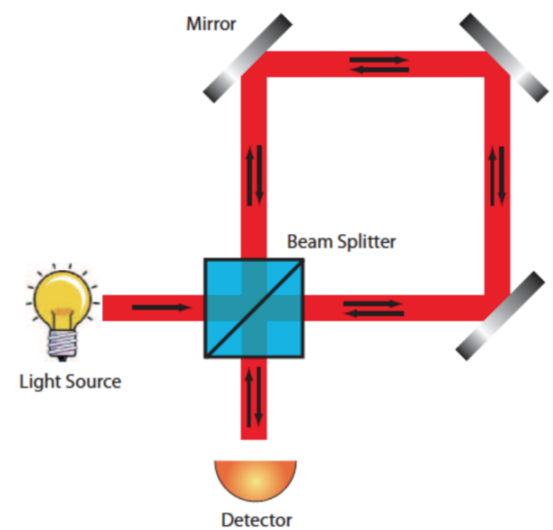
$d_{xy} + \mathrm{i}d_{x^2\text{-}y^2}$



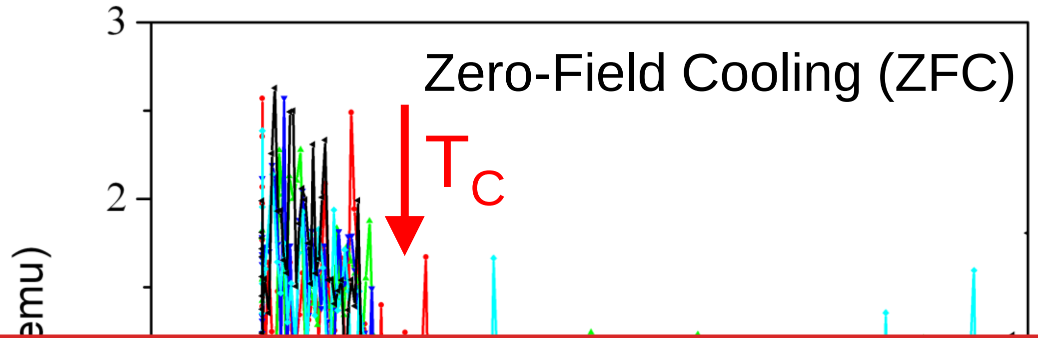


$J_z = -2$

$d_{xy} - \mathrm{i}d_{x^2\text{-}y^2}$



SQUID VSM measurement: Anomalous out-of-plane magnetic moment arises below Tc



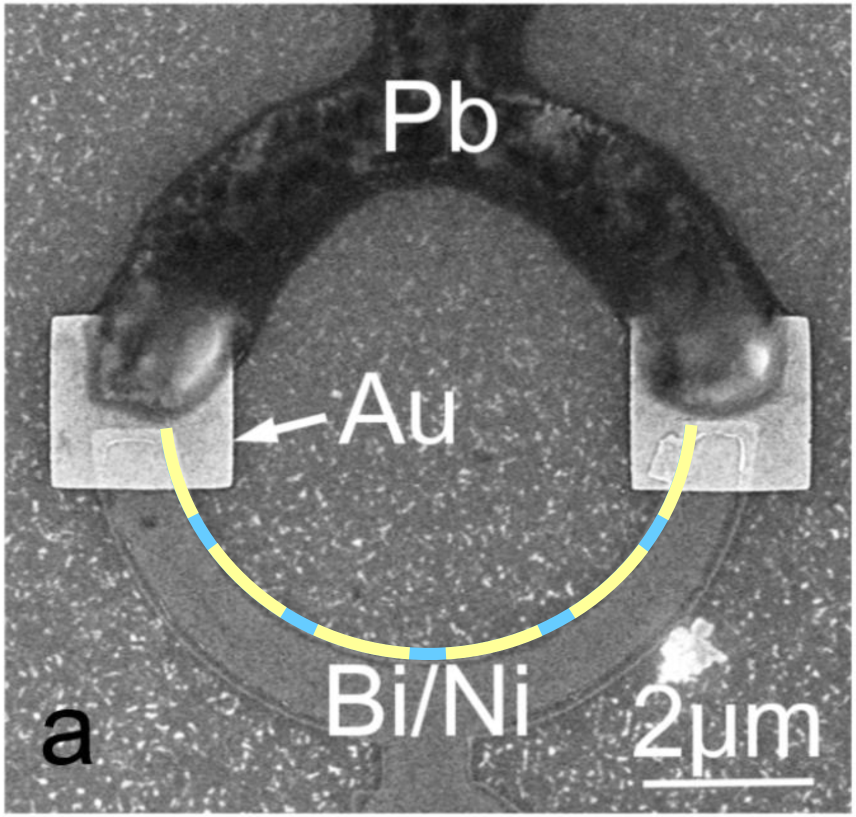
The motivation of this work:

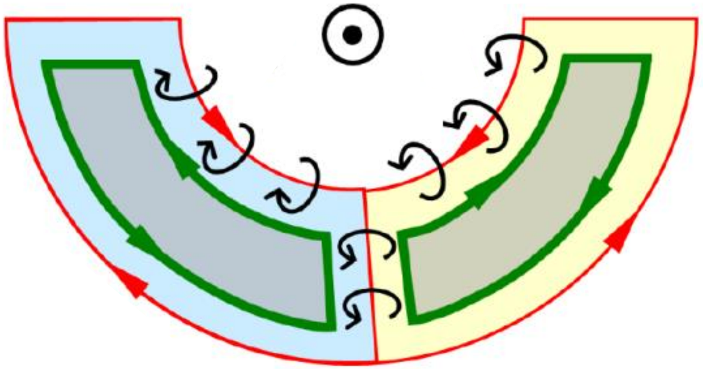
- What is the origin of this anomalous moment?
- Given the fact of SC and FM coexistence, could the moment arise from the orbital moments of Cooper pairs in a chiral superconductor?

Design of the experiment

Using Bi/Ni bilayer itself to form SQUIDs, to search for out-of-plane magnetic moments at the edges

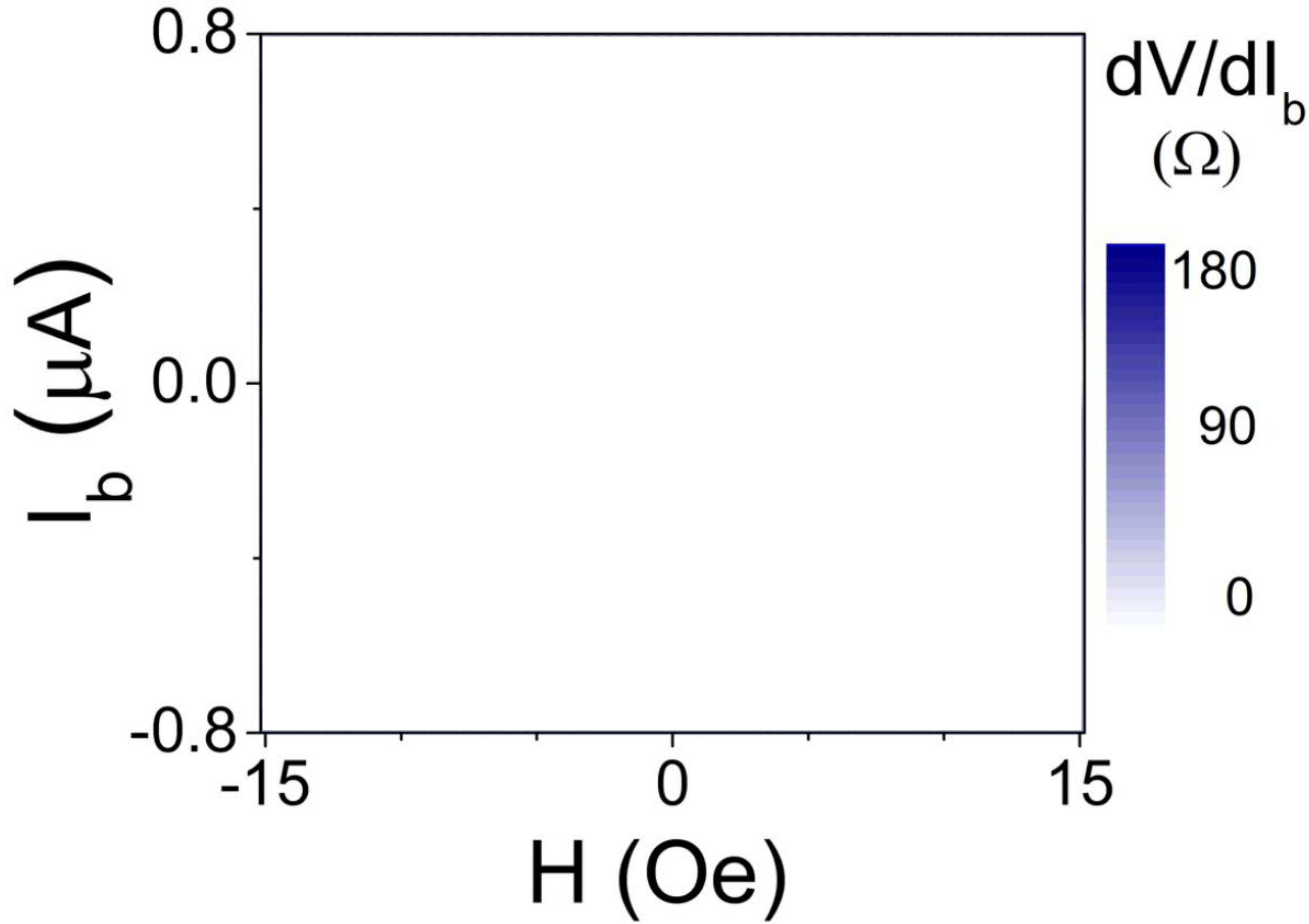
dc SQUID



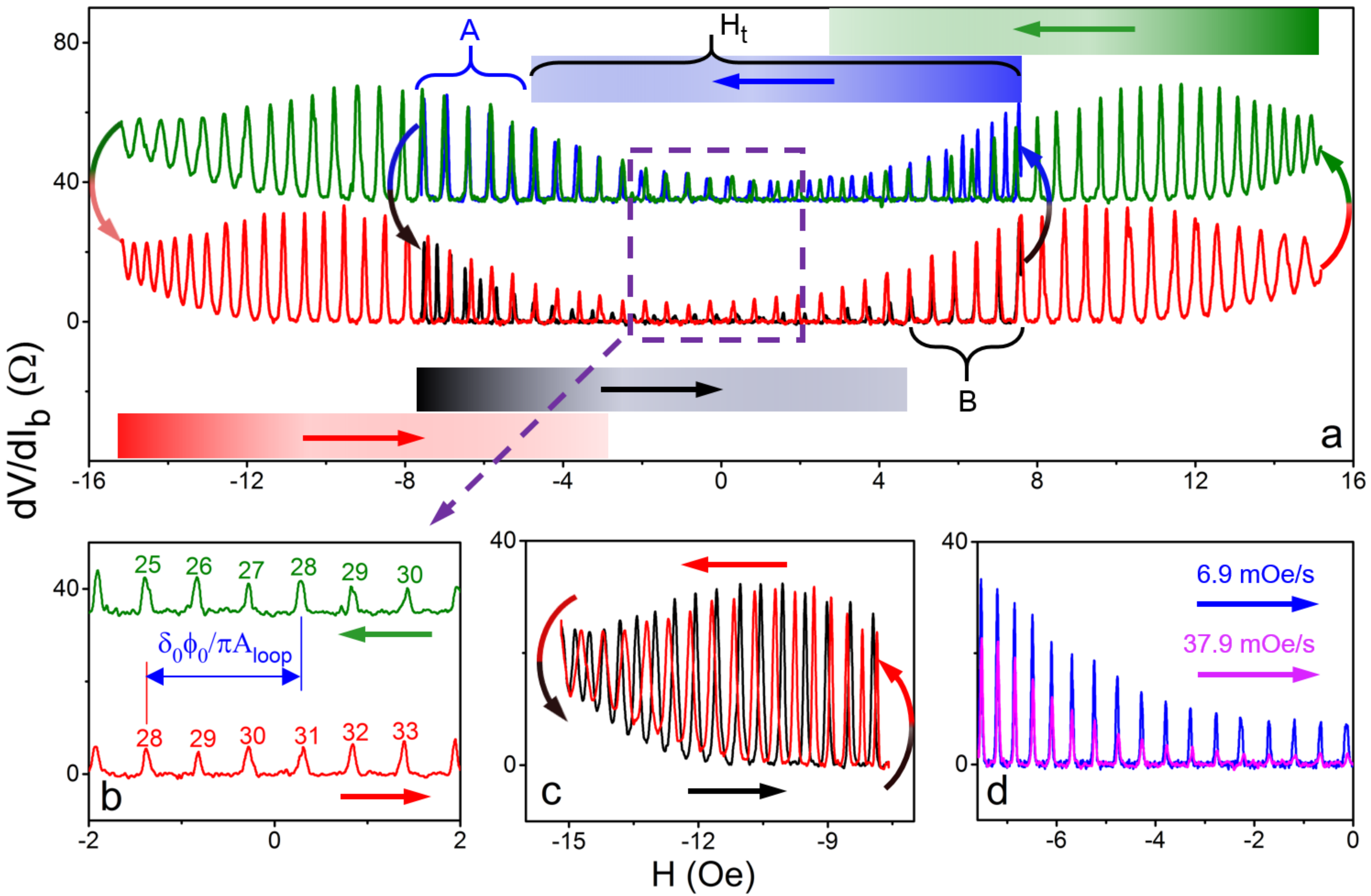


Top view

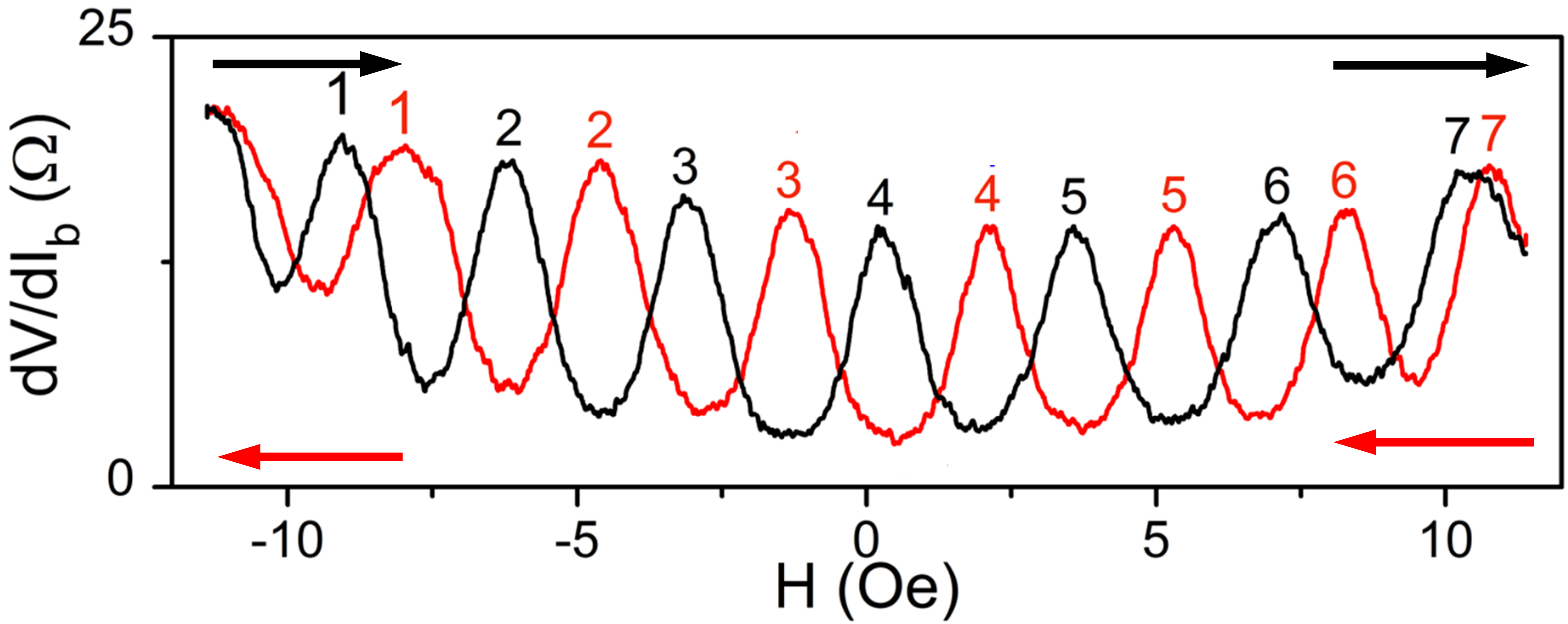
Superconducting quantum interference



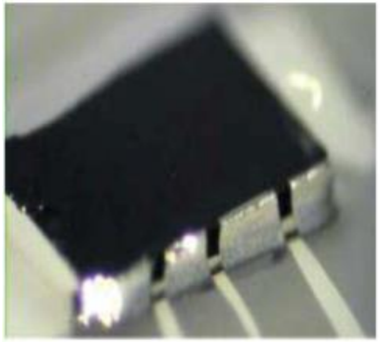
Anomalous “advanced” hysteresis

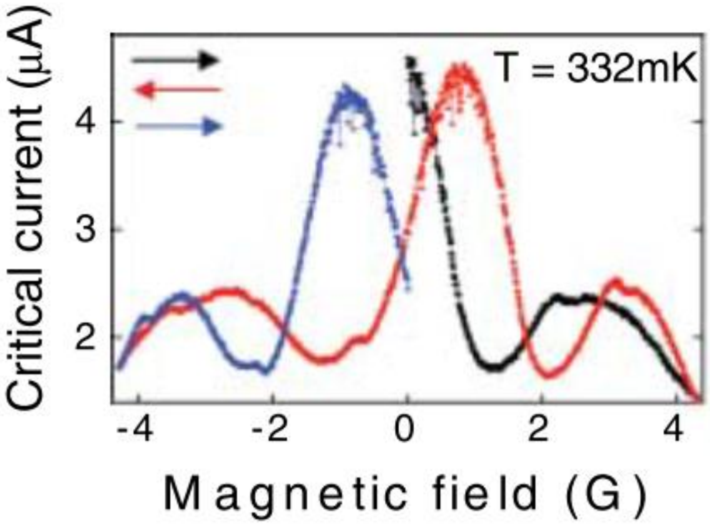


Anomalous "advanced" hysteresis

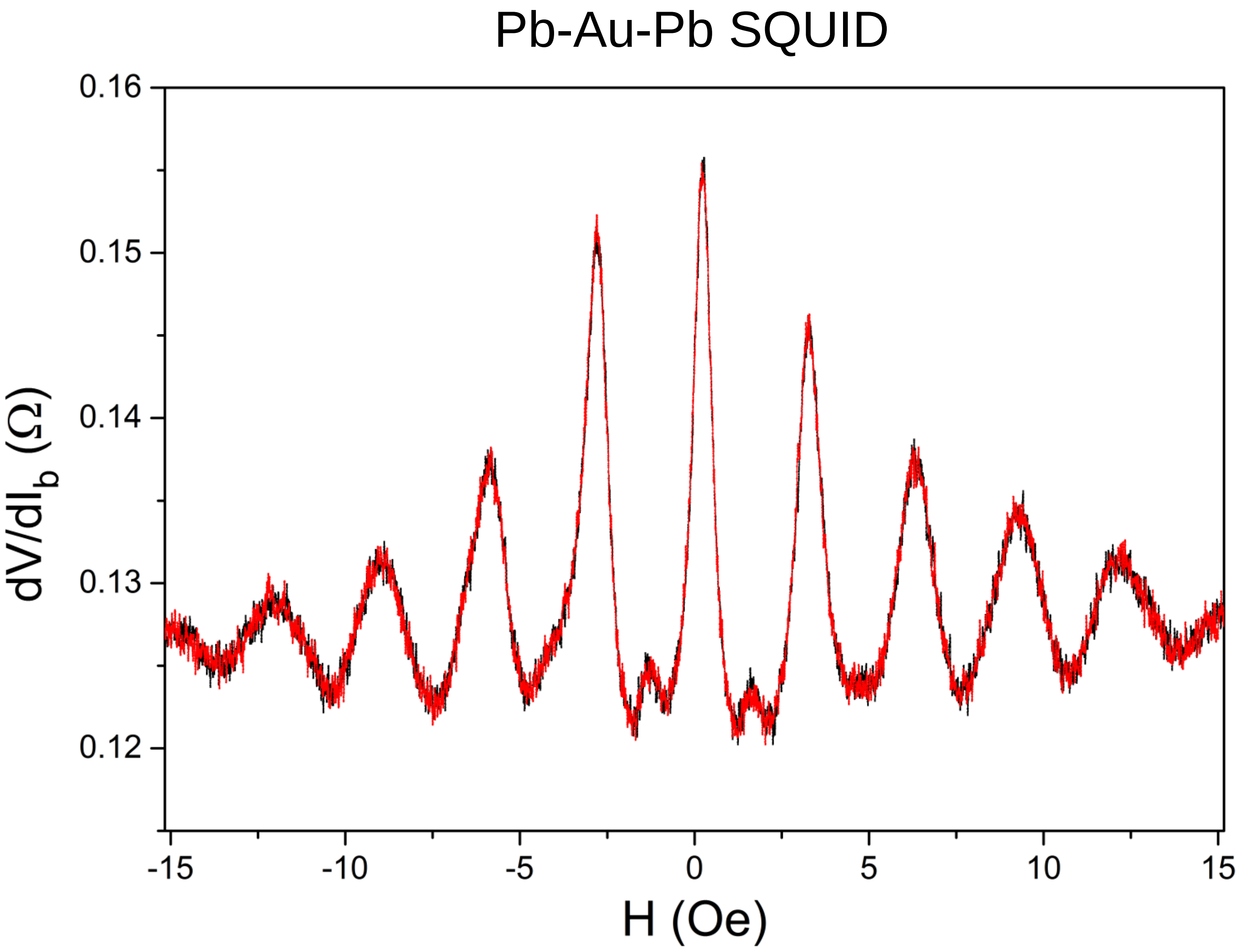


Sr_2RuO_4 - Pb
Josephson Junction
van Harlingen group
Science 2006

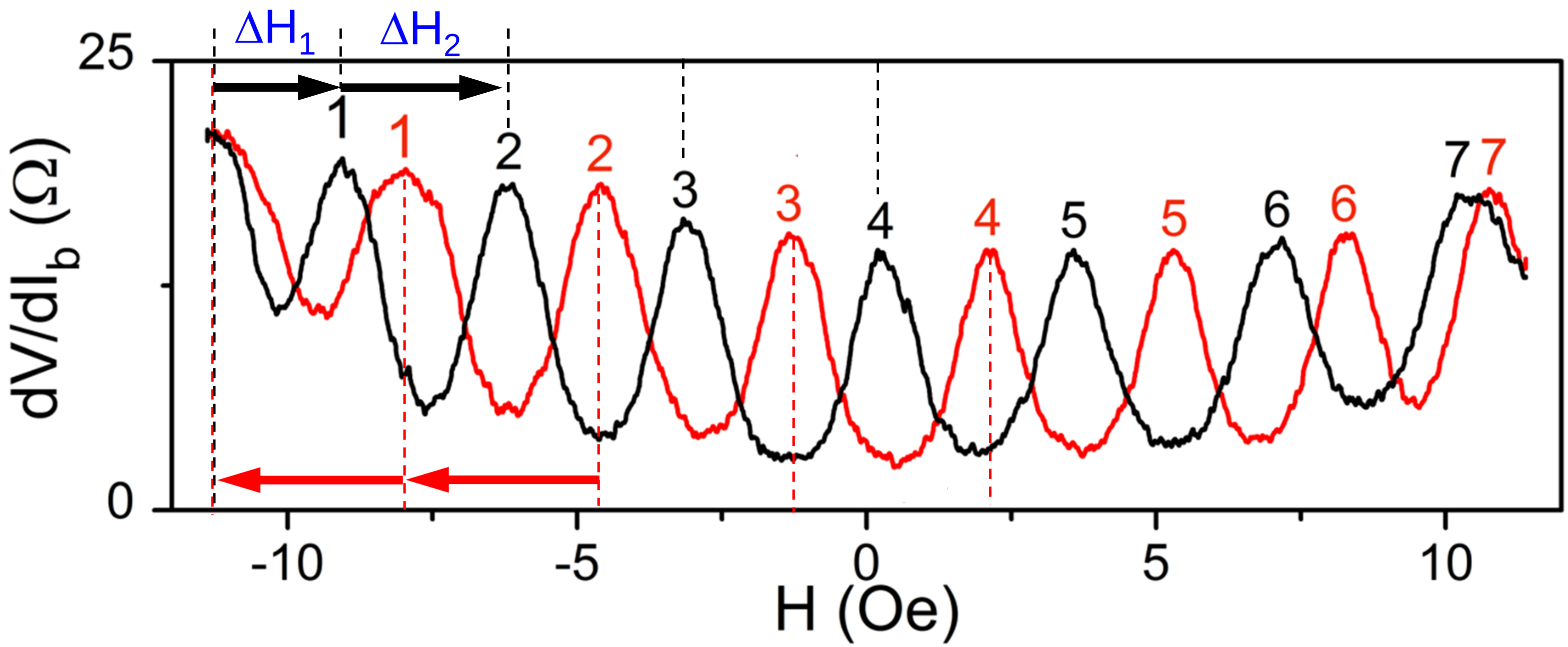




Control Experiment



Compressed periods due to anomalous phase shift



$$I_c \propto \cos[2\pi \frac{(H - H_0)A_{\rm loop}}{\phi_0} + \delta]$$

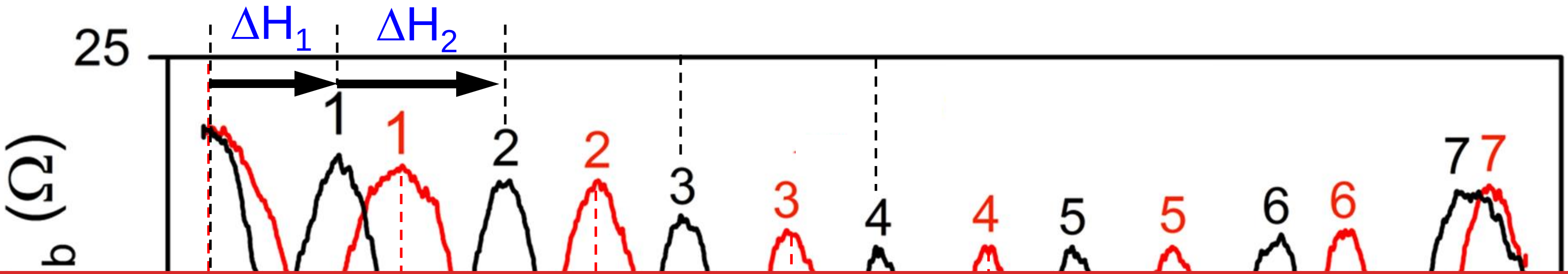
Accumulated anomalous phase shift

$$2\pi \frac{\Delta H_{\rm n} A_{\rm loop}}{\phi_0} + \Delta\delta_{\rm n} = 2\pi$$

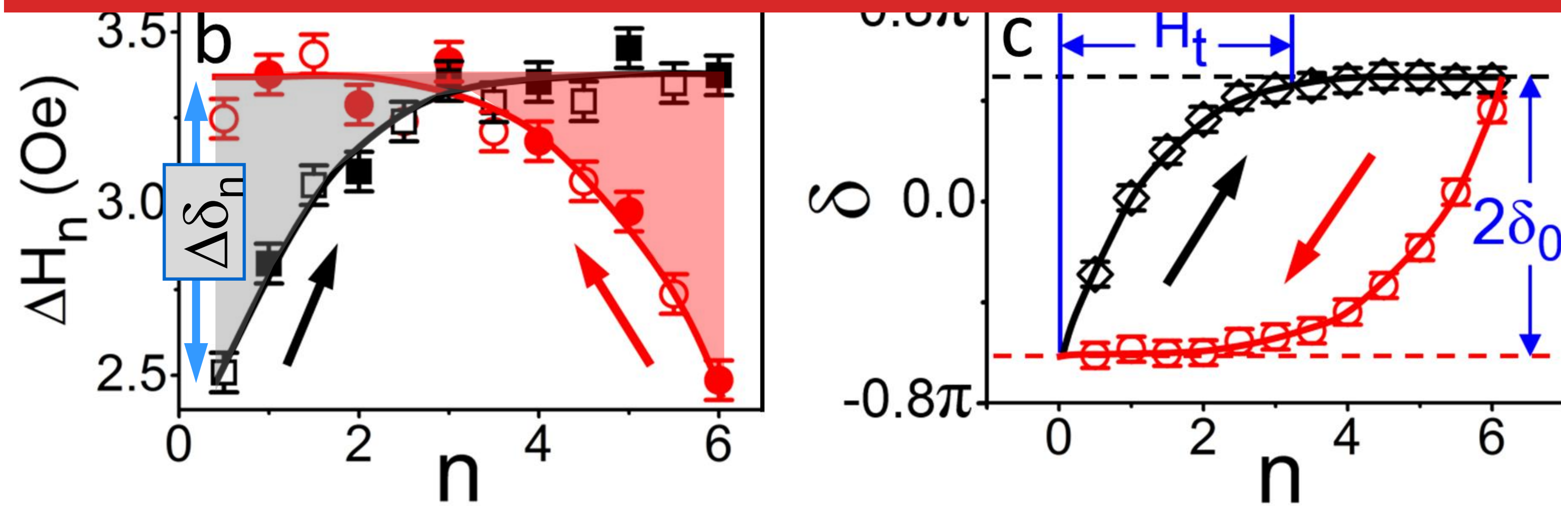
Compressed oscillation period

Anomalous phase shift in each period

Compressed periods due to anomalous phase shift



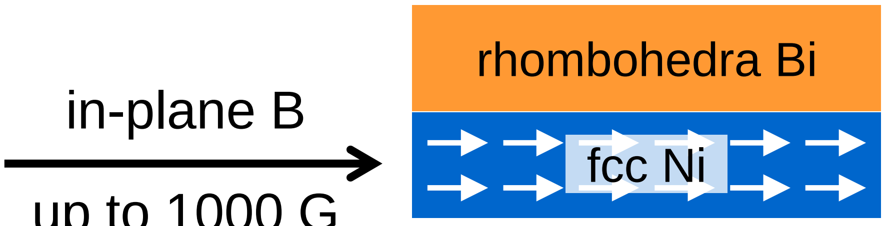
The hysteresis loop is clockwise,
which is “anomalous”, being qualitatively
different from the *ccw* ones for FM and flux pinning.



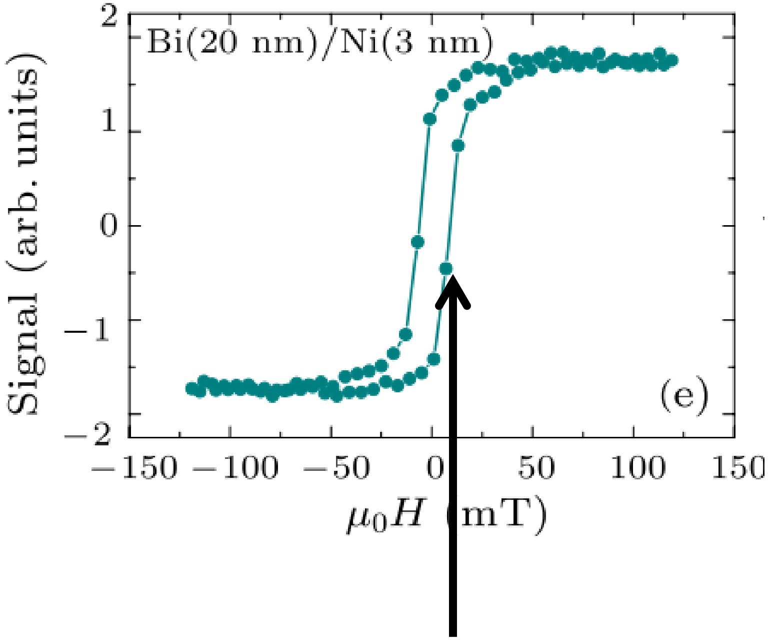
Is the anomalous hysteresis related to or influenced by the ferromagnetic moments of itinerant electrons?

in-plane B

up to 1000 G

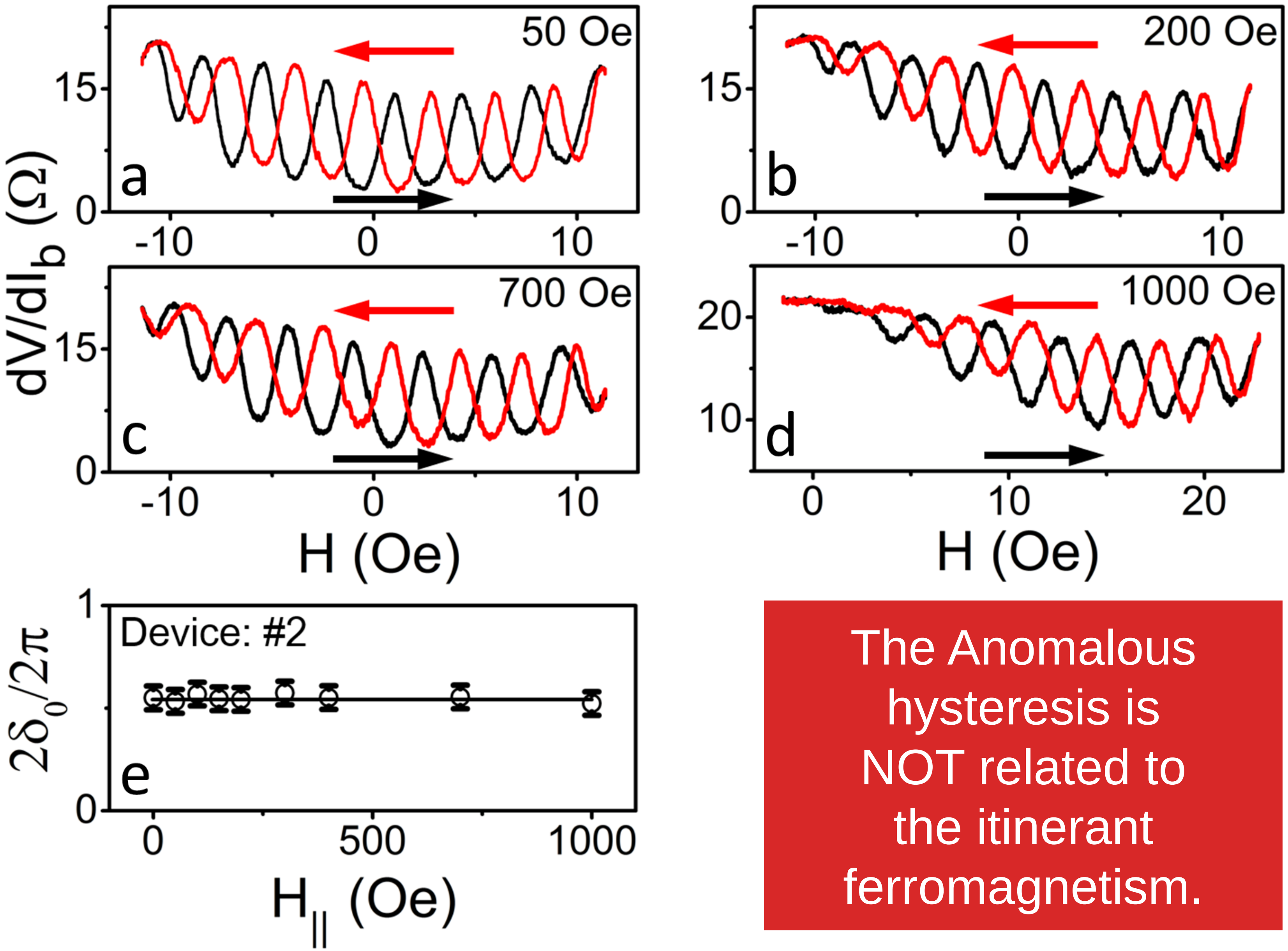


In-plane M-H curve



Coercive field
~ 100 G

In-plane field dependence of hysteresis



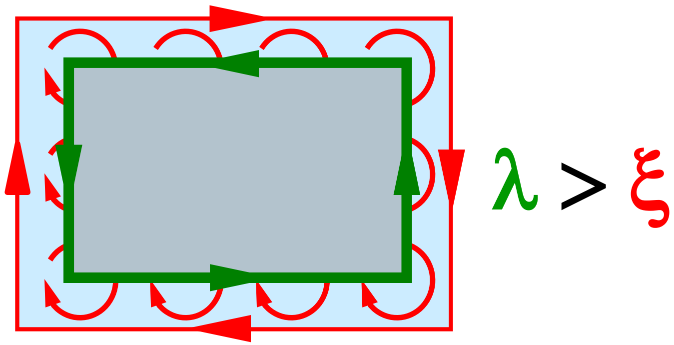
The Anomalous hysteresis is NOT related to the itinerant ferromagnetism.

The Picture

- Anomalous phase shift as reflected in interference → anomalous flux/moments
- The anomalous moments arise from the orbital moments of the Cooper pairs.
- While the orbital moments in the bulk of SC are screened by the Meissner screening current, the moments at the edge are not.

The Picture

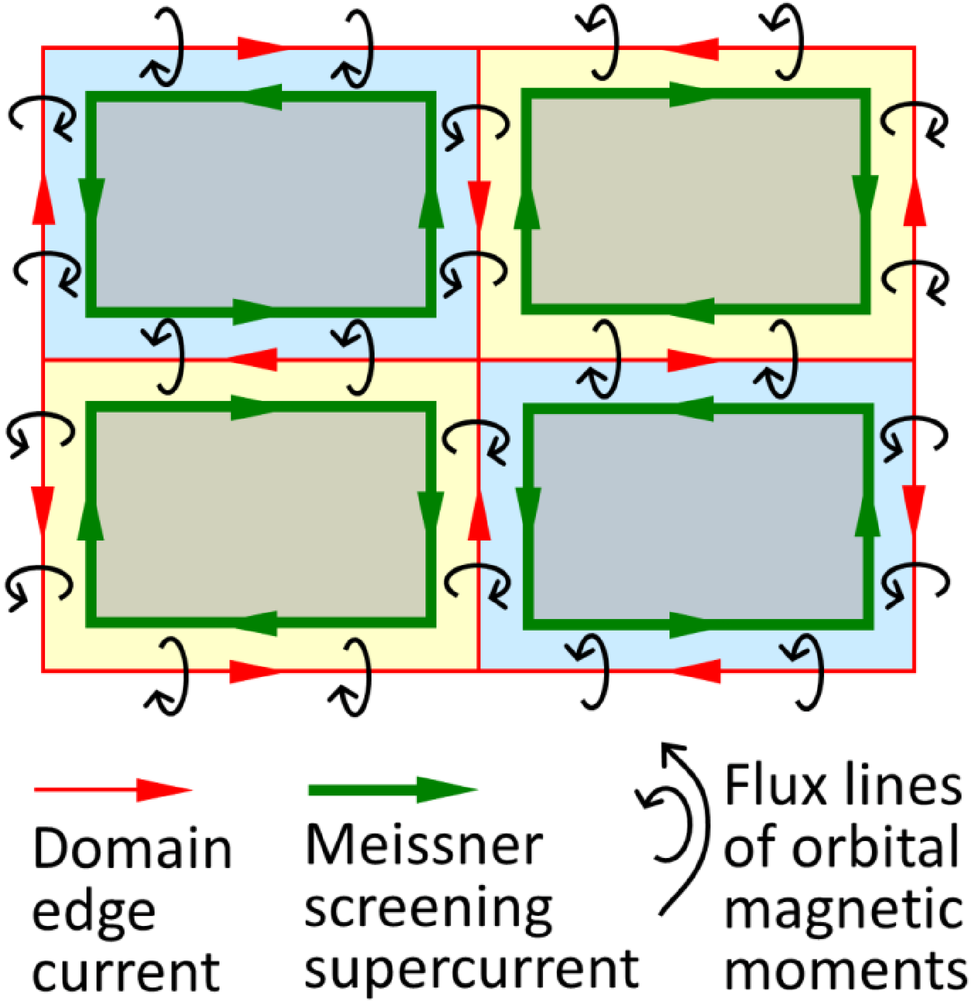
- Edge currents &
  Edge magnetization



M. Sigrist, T. M. Rice, K. Ueda,
PRL 63, 1727 (1989)

high angular
momentum pairing

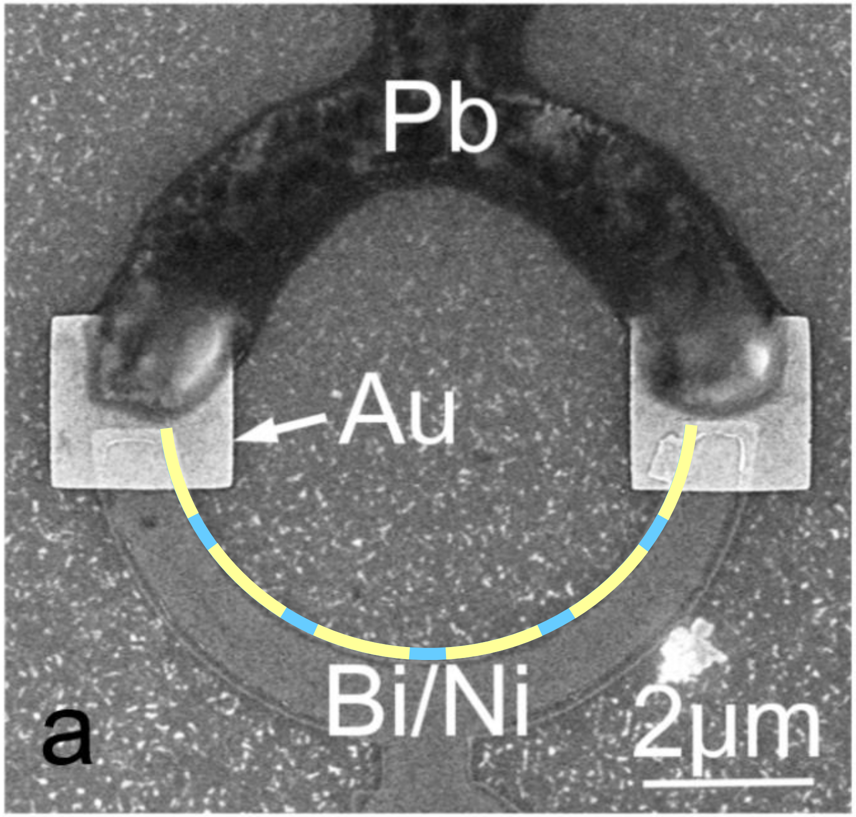
- Superconducting domains

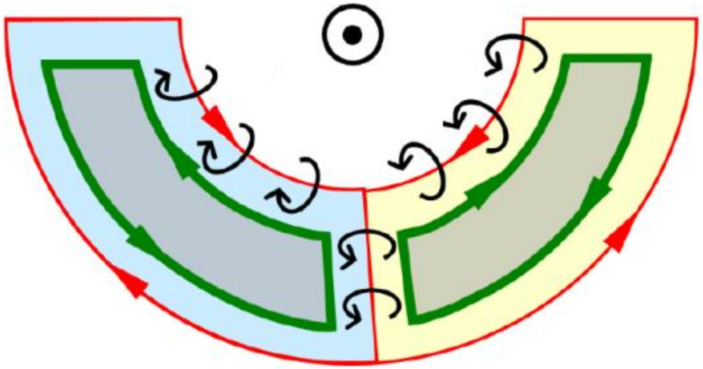


Design of the experiment

Using Bi/Ni bilayer itself to form SQUIDs, to search for out-of-plane magnetic moments at the edges

dc SQUID

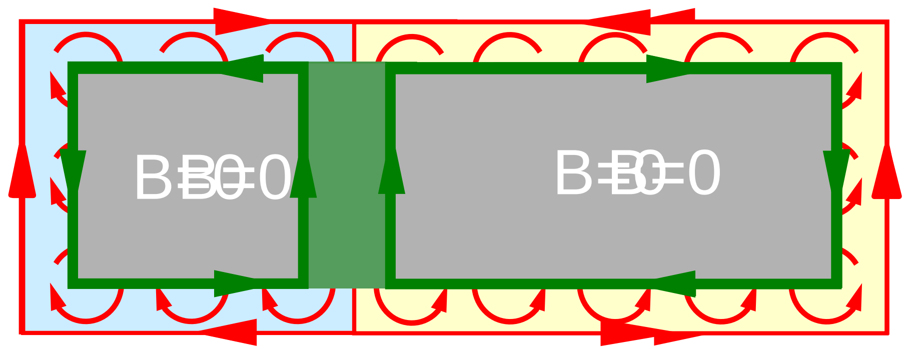




Top view

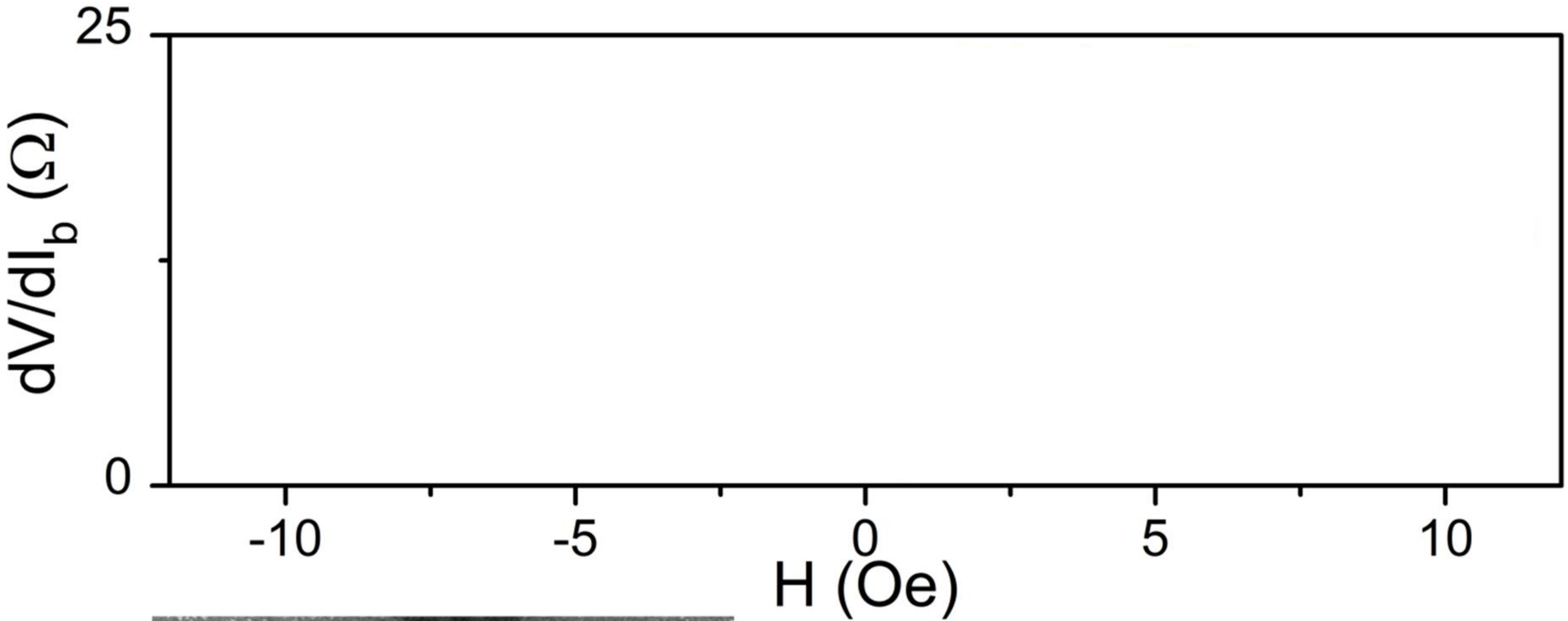
The Picture

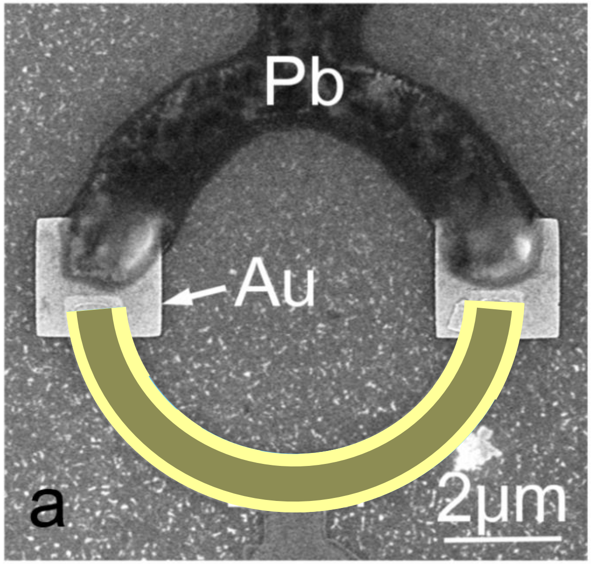
- The “advanced” hysteresis is related to the SC domain wall motion, triggered by ΔB instead of by B.

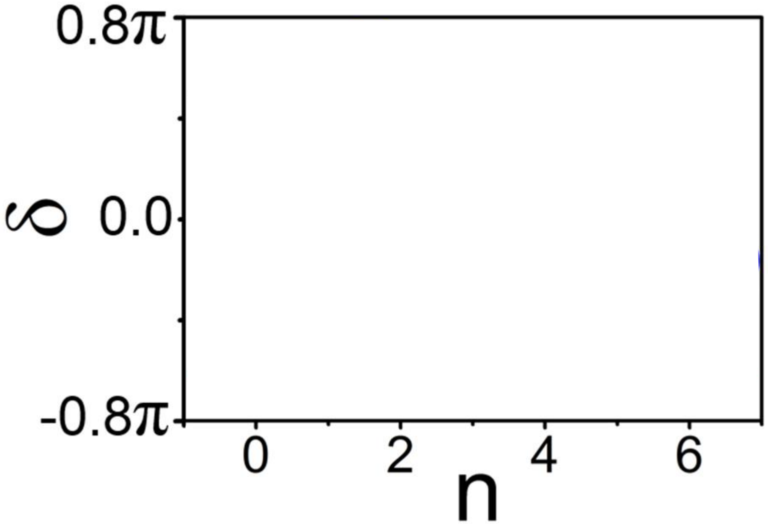


$$\tau_{Meissner} > \tau_{edge}$$

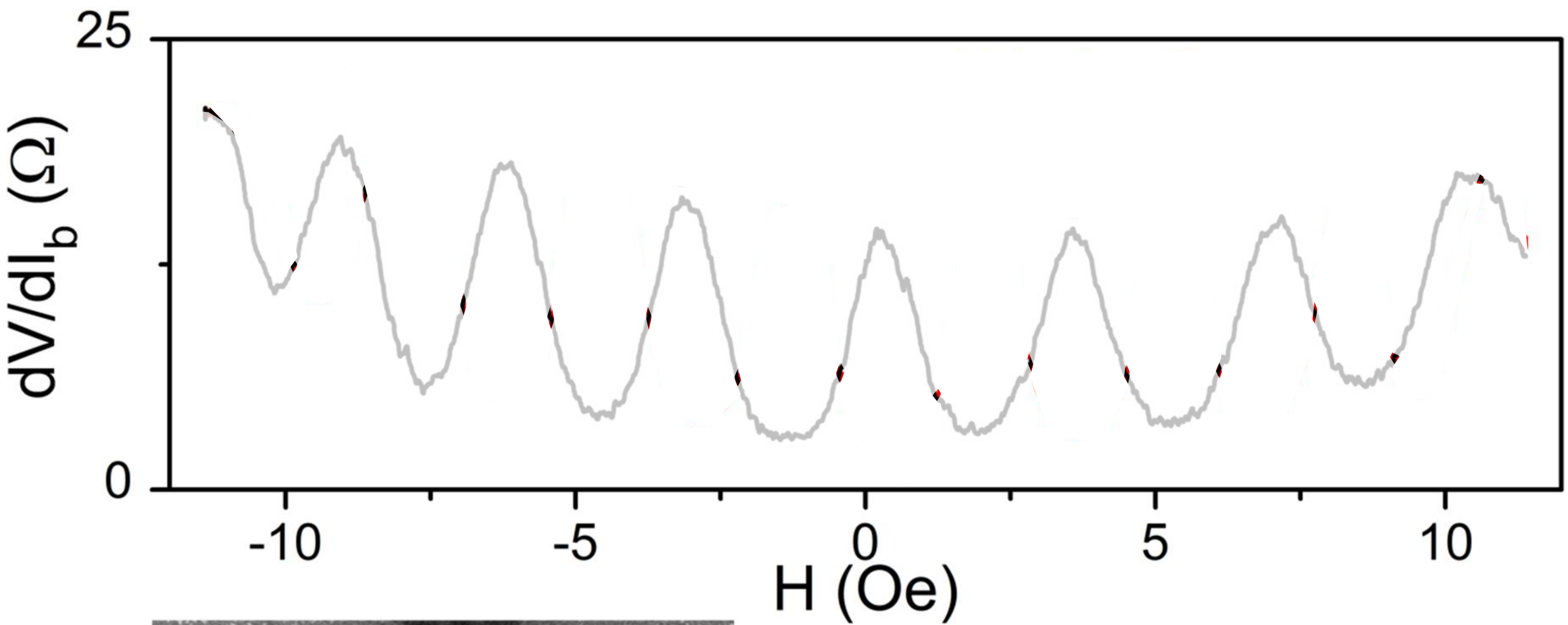
The Picture

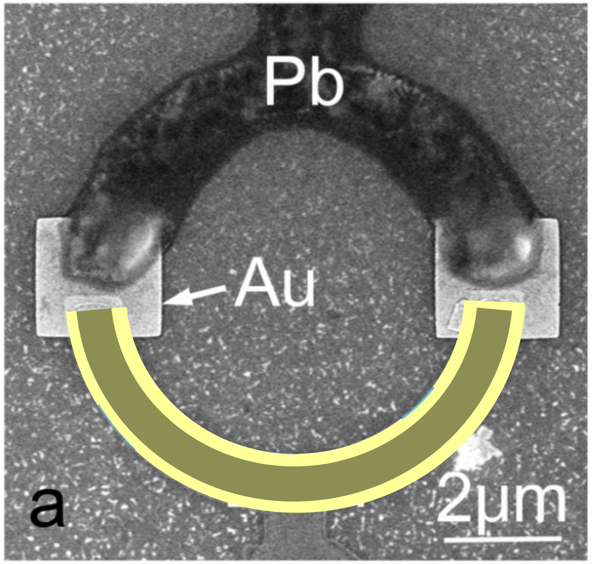


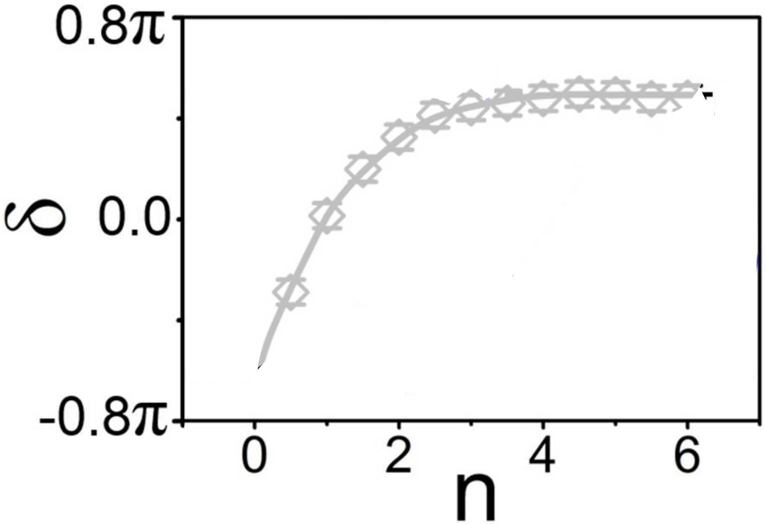




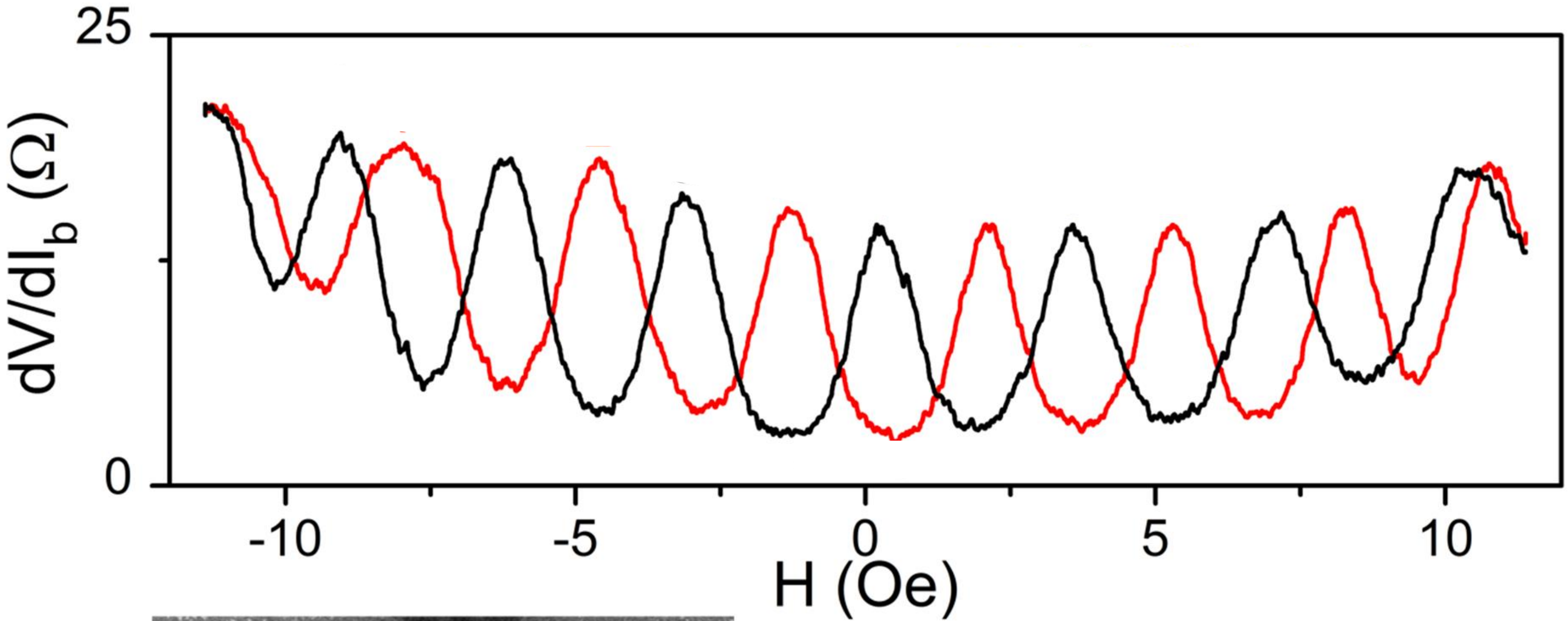
The Picture for “Advanced” Hysteresis

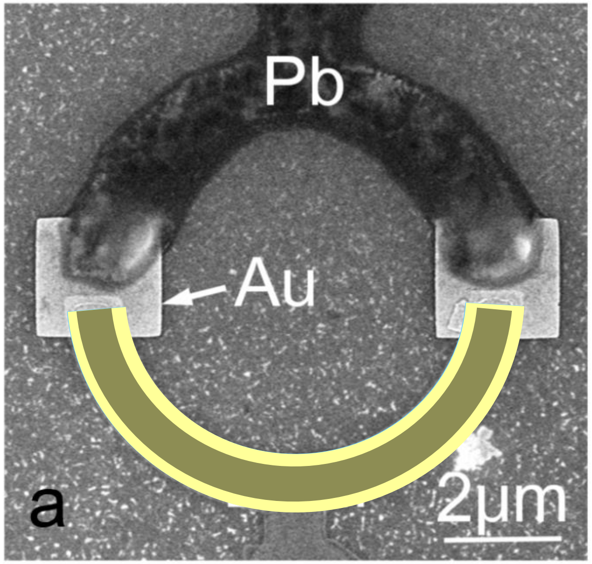


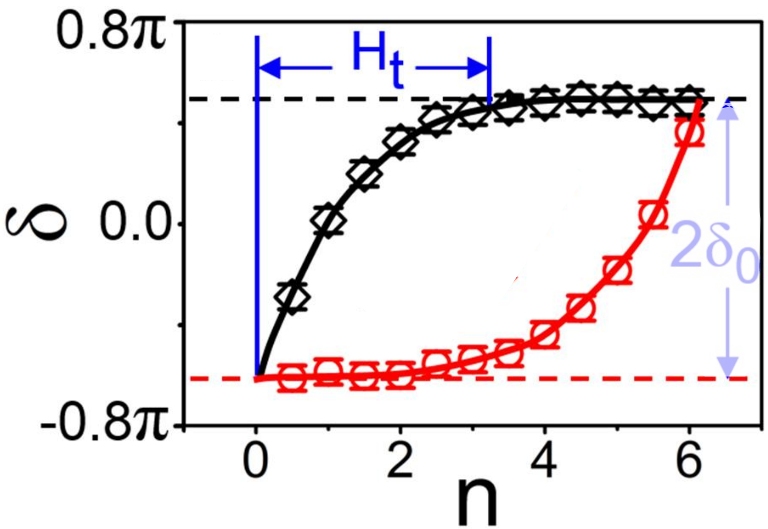




The Picture for “Advanced” Hysteresis



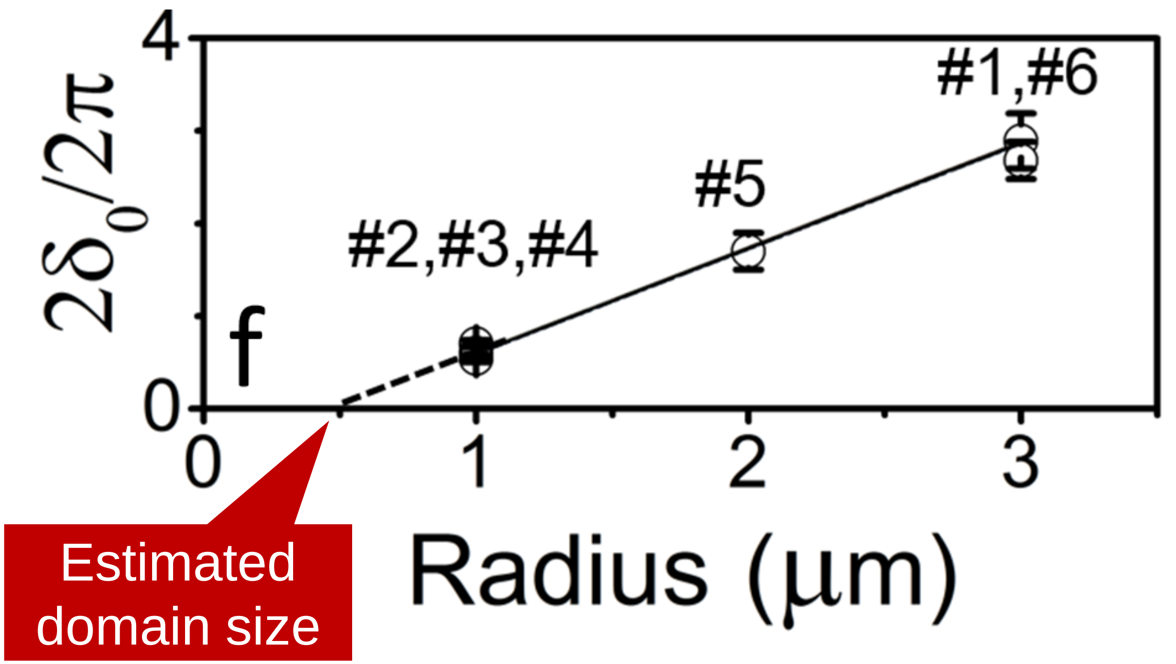




The anomalous phase shift is proportional to the perimeter of the Bi/Ni ring

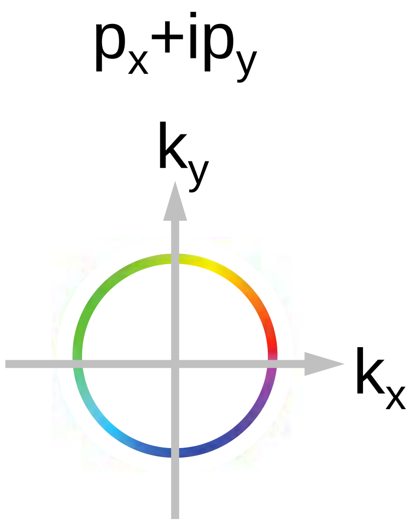
TABLE I: A list of the parameters of six devices investigated.

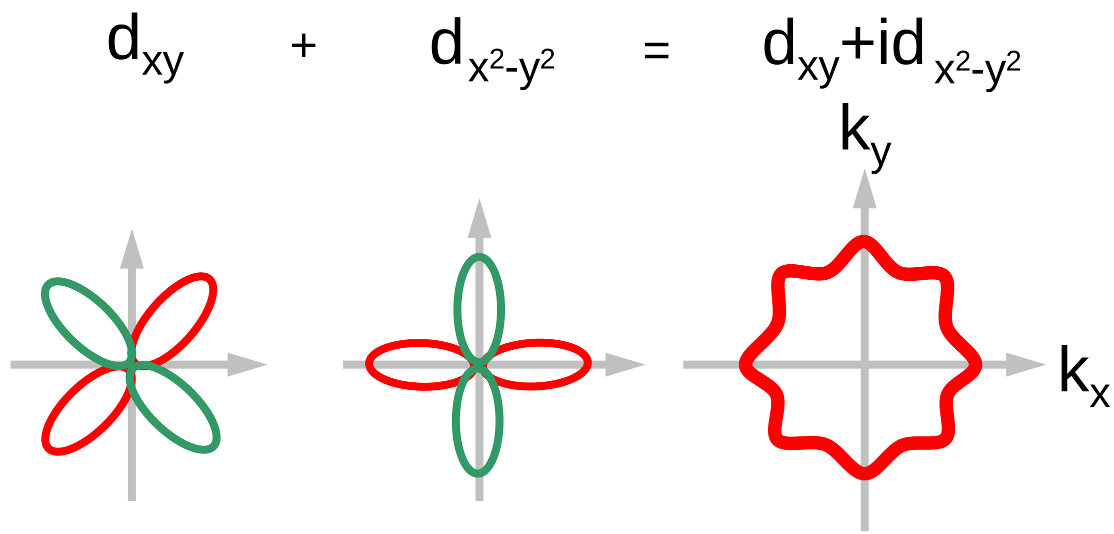
Device	Distance* (μm)	Inner Radius (μm)	Loop Area (μm^2)	Calculated Period (Oe)	Measured Period (Oe)	$2\delta_0/2\pi$
#1	0.4	3.0	39.3	0.53	0.55±0.03	2.89±0.01
#2	0.5	1.0	6.2	3.34	3.37±0.06	0.54±0.04
#3	0.2	1.0	6.1	3.39	3.13±0.08	0.70±0.04
#4	-0.4	1.0	5.6	3.69	3.5±0.2	0.60±0.07
#5	-0.4	2.0	17.6	1.18	1.12±0.09	1.7±0.2
#6	-0.4	3.0	35.9	0.59	0.58±0.03	2.7±0.2



Chiral-p or Chiral-d ?

SC domains, edge currents/magnetization → Chiral superconductivity





Chauhan et al., PRL 122, 017002 (2019)
(Armitage group, Johns Hopkins U)

Gong et al., Sci. Adv. 2017;3: e1602579
(Yakovenko group, U. Maryland)

Conclusion

- We have observed anomalous moments on Bi/Ni bilayer, showing “advanced” hysteresis.
- We attribute the moments to the orbital moments of Cooper pairs in chiral superconducting Bi/Ni, and attribute the hysteretic behavior to the motion of chiral superconducting domains.
- Further study is needed to identify whether the pairing symmetry is p_x+ip_y or $d_{xy}+id_{x^2-y^2}$

Thank You

J. H. Wang et al., PRB **96**, 054519 (2017)