Feb. 15, 2010, Kyoto Univ. GCOE Symposium

The Next Generation of Physics,
Spun from Universality and Emergence

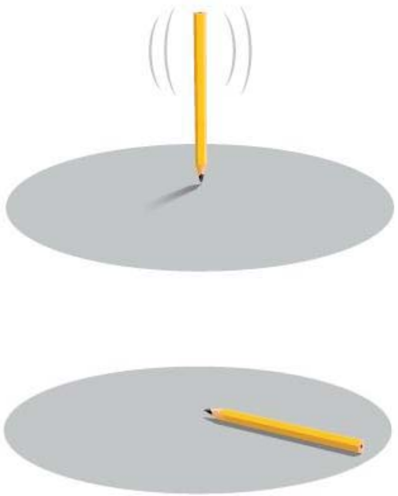
Symmetry Breaking and Topological Quantum Phenomena in Superconductors

"An attempt
by a condensed-matter experimentalist
to talk about profound concepts in physics."

Yoshiteru Maeno
Kyoto University

Spontaneous Symmetry Breaking

In 1960, spontaneous broken symmetry that described superconductivity was translated by Nambu into the world of elementary particles, where it became one of the corner stones of the most successful theory in particle physics – the Standard Model.



Superconductivity	**Elementary Particles**
electrons	fermions
phonon interaction	interaction
energy gap	mass
collective excitations	(mesons, bound states)
(Nambu-Goldstone modes)	

Superconducting Symmetries

Cooper-pair State vector $|\Psi(1,2)\rangle = -|\Psi(2,1)\rangle$: Anti-Sym. （Fermions）

State Vector	Spin State	Orbital Wave function
$\|\psi\rangle = \varphi \|\chi\rangle$	$\|\chi(\sigma_1, \sigma_2)\rangle$	$\varphi(r_1, r_2)$

Spin singlet （一重項） $S = 0$	$S_z = 0$	$\frac{1}{\sqrt{2}}(\|\uparrow\downarrow\rangle - \|\downarrow\uparrow\rangle)$ **Anti-Sym.**	$\ell = 0,\ 2, \ldots$ *s*-wave, *d*-wave Sym. (EVEN PARITY)

Spin triplet （三重項）	$S_z = +1$	$\|\uparrow\uparrow\rangle$	
$S = 1$	$S_z = 0$	$\frac{1}{\sqrt{2}}(\|\uparrow\downarrow\rangle + \|\downarrow\uparrow\rangle)$	$\ell = 1,\ 3, \ldots$ *p*-wave, *f*-wave
	$S_z = -1$	$\|\downarrow\downarrow\rangle$ **Sym.**	Anti-Sym. (ODD PARITY)

Symmetry Breaking in Superconductivity

1957 → 2010 : a lot of progress

Unconventional Superconductivity （異方的超伝導）

One or more symmetries in addition to $U(1)$

are broken at T_c. (超伝導転移温度）

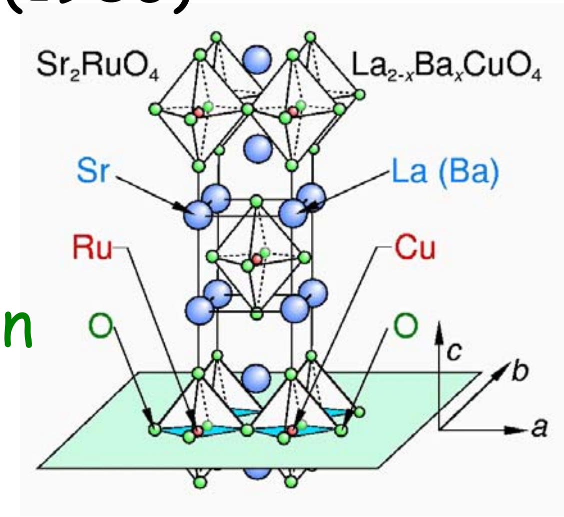
Full symmetry group G

$$G = U(1) \otimes G_c \otimes SU(2) \otimes T$$

$U(1)$	Gauge	Superconducting “Phase”
G_c	Crystal Structure	Orbital rotation
$SU(2)$	Spin Rotation	Singlet / Triplet
T	Time Reversal	Magnetism

Unconventional Superconductors

100 Years since the discovery by Onnes (1911),
50+ Years Since the BCS Theory (1957),
20+ Years Since High- T_c Copper Oxides (1986)



1. Superconductors with Anisotropic wave function (d-wave, p-wave)

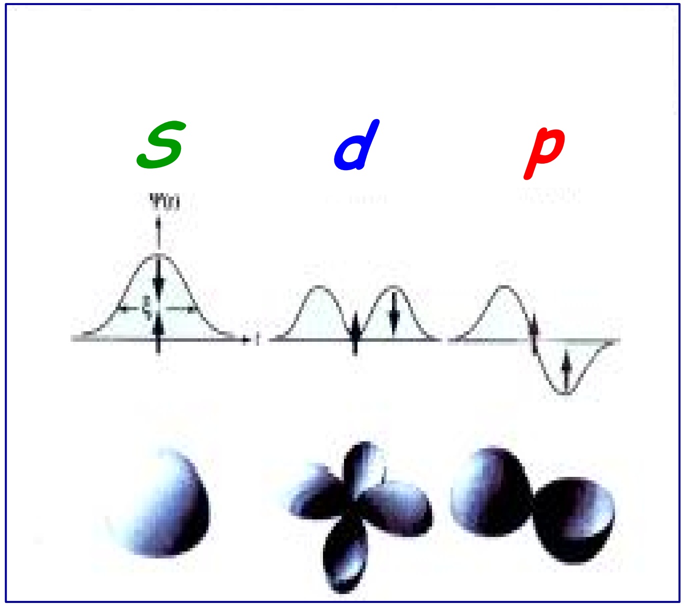
2. Superconductors with Spatial Modulation
   Translational symmetry is broken

3. Superconductors without Inversion Symmetry

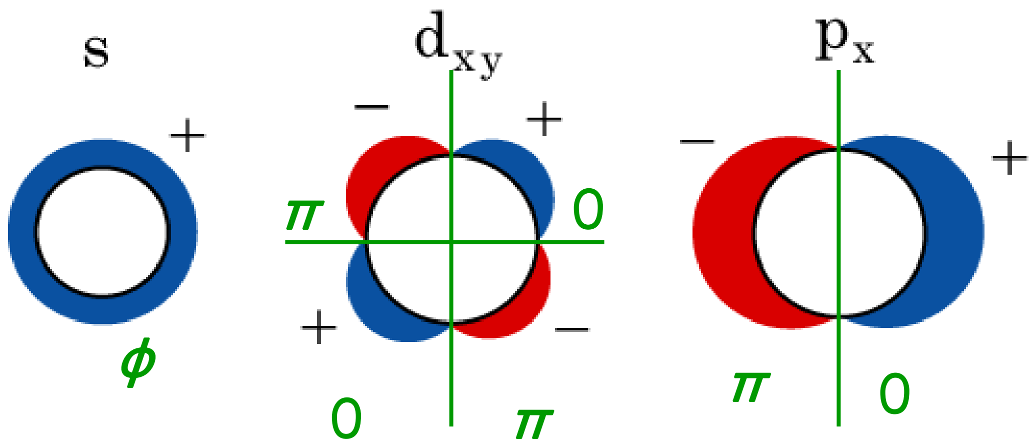
4. Spin Triplet Superconductors
   with Broken Time-Reversal Symmetry

Origin of Unconventional Superconductivity

Systems for which Coulomb <u>repulsion</u> among the electrons are important (strongly-correlated electron systems) : s-wave state having a large probability at zero-distance is unfavorable.



$\Delta(k)$: Phase and magnitude of superconducting gap



phase ϕ

Instead of electron-phonon interaction,
Coulomb **repulsion** leads to electron pairing.

Broken
Translational Symmetry

並進対称性の破れ

FFLO (Fulde-Ferrell-Larkin-Ovchinnikov) State

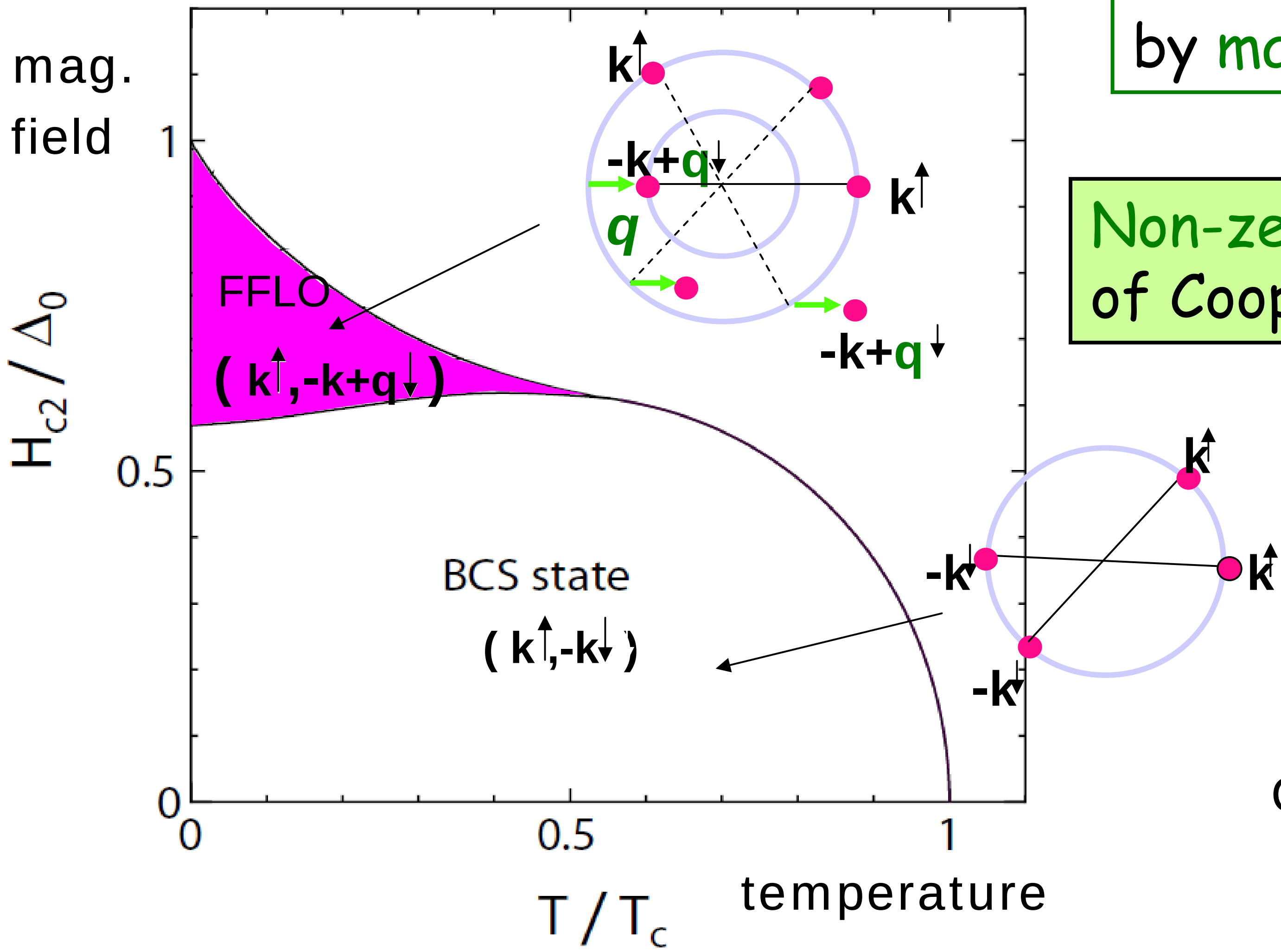
Broken Translational Symmetry

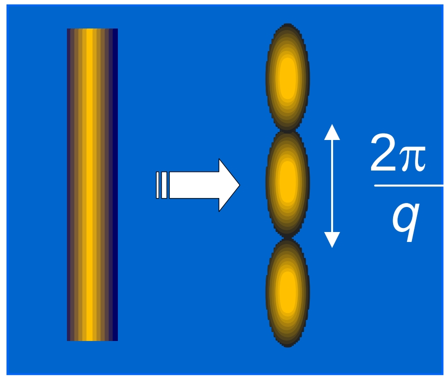
Spatial modulation of the gap

Splitting of spin up and down Fermi surfaces by magnetic field

⇓

Non-zero momentum of Cooper pairs *q*



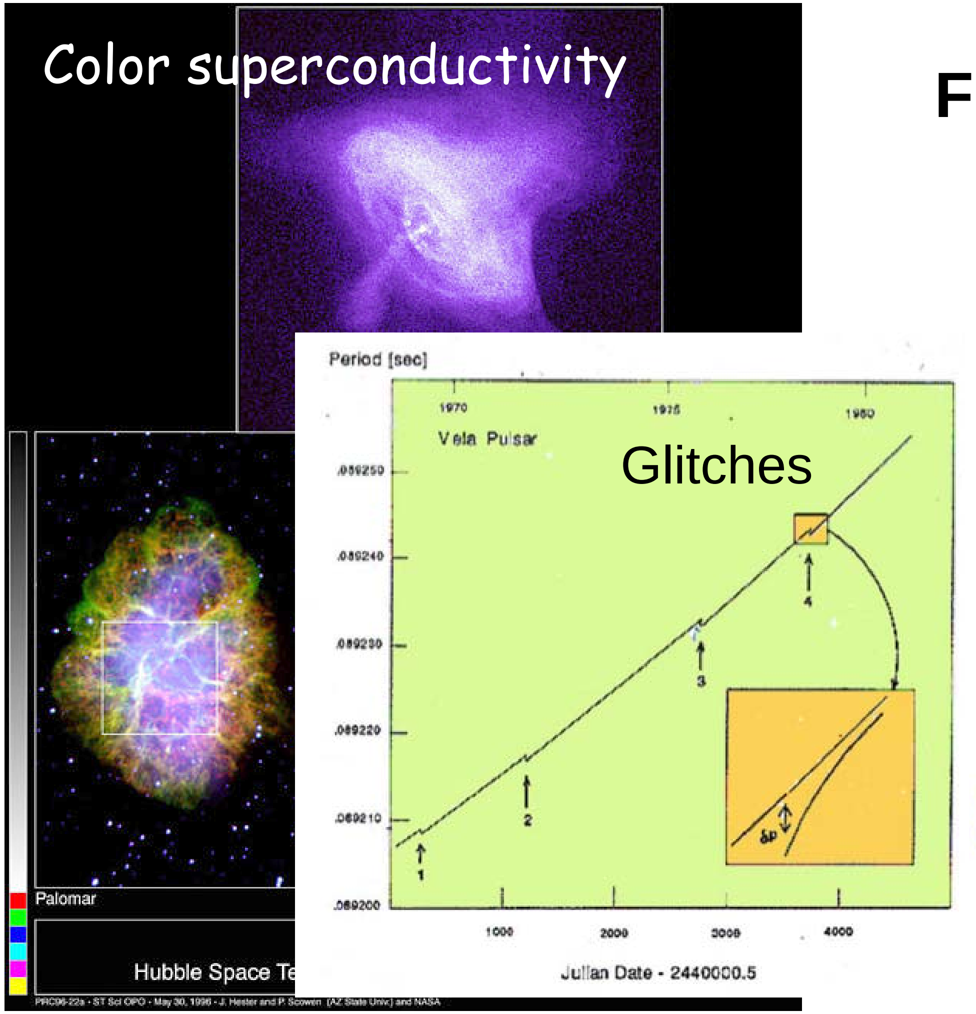


Quantized vortex

by Yuji Matsuda

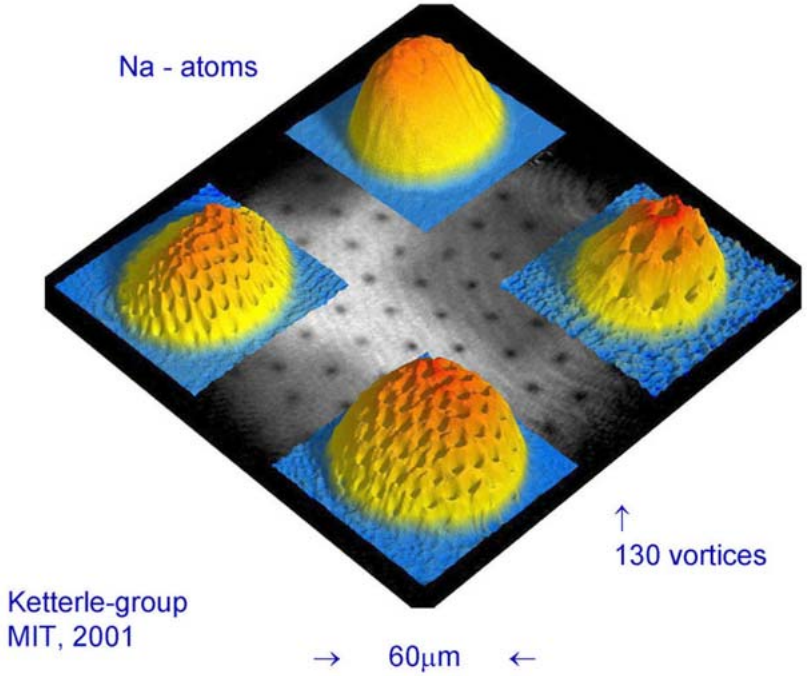
FFLO State in Other Physical Systems

FFLO State in Neutron Star



R.Casalbuoni and G.Nardulli
Rev. Mod. Phys. (2004).

FFLO State in Rotating BEC



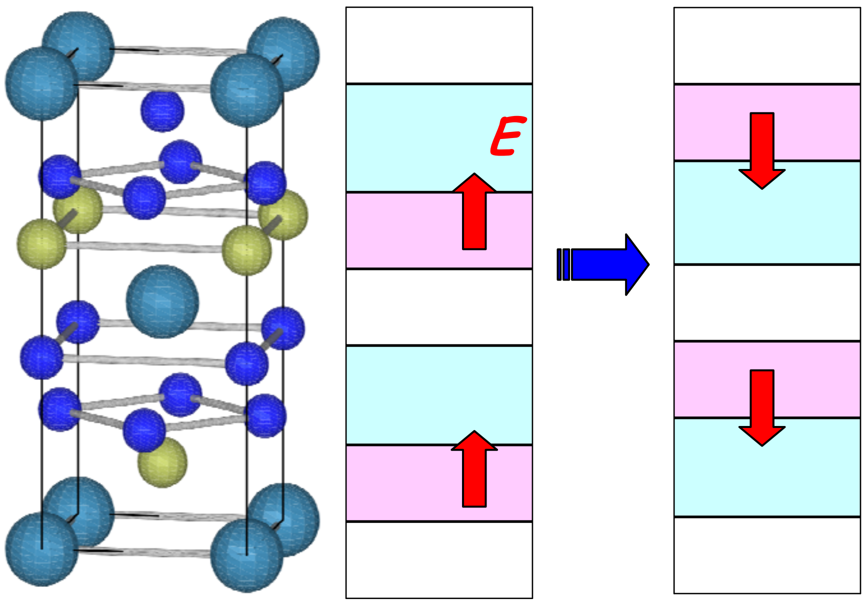
by Yuji Matsuda

Broken
Inversion Symmetry

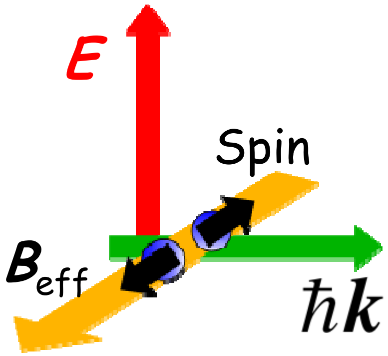
空間反転対称性の破れ

NCS (Non-Centrosymmetric Supercpnductivity)

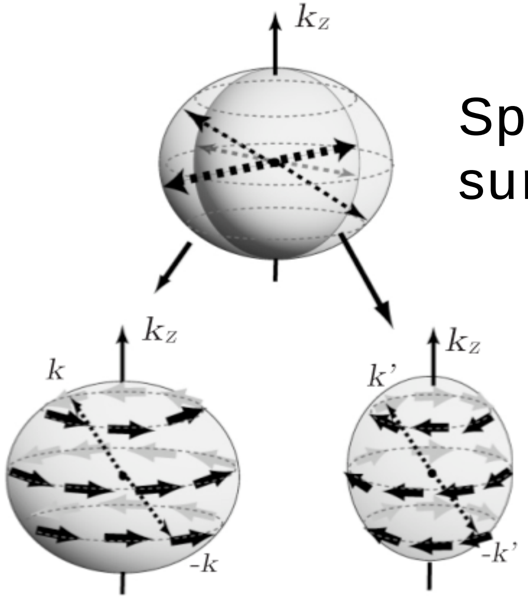
Broken Inversion Symmetry
of crystal structure
(x,y,z) -> (-x,-y,-z)



A moving electron in *E* field
feels an effective *B*



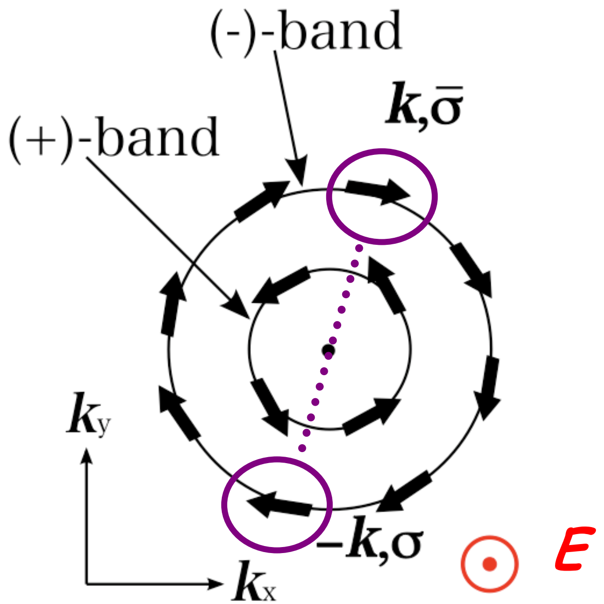
$$\boldsymbol{B}_{\text{eff}} \propto \hbar \boldsymbol{k} \times \boldsymbol{E}$$

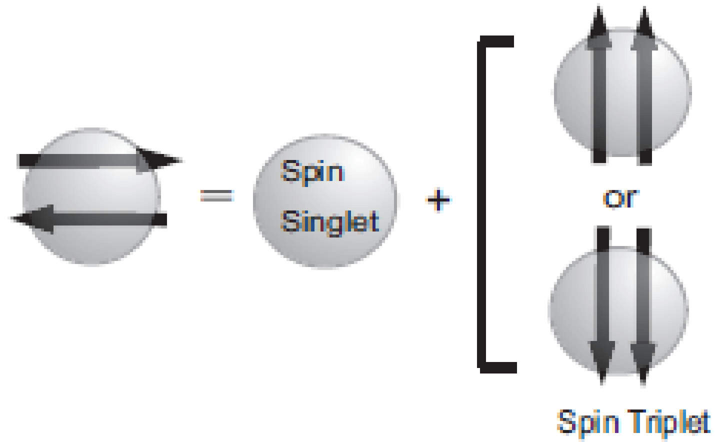


Split Fermi
surfaces

S. Fujimoto,
J. Phys. Soc. Jpn.
76, 051008 (2007).

NCS (Non-Centrosymmetric Supercpnductivity)





$$|\boldsymbol{k},\sigma\rangle|-\boldsymbol{k},\overline{\sigma}\rangle = \frac{1}{2}(|\boldsymbol{k},\sigma\rangle|-\boldsymbol{k},\overline{\sigma}\rangle - |\boldsymbol{k},\overline{\sigma}\rangle|-\boldsymbol{k},\sigma\rangle) + \frac{1}{2}(|\boldsymbol{k},\sigma\rangle|-\boldsymbol{k},\overline{\sigma}\rangle + |\boldsymbol{k},\overline{\sigma}\rangle|-\boldsymbol{k},\sigma\rangle)$$

Spin singlet (S = 0) Spin triplet (S = 1, S_z = 0)

Singlet-triplet mixing superconductivity !

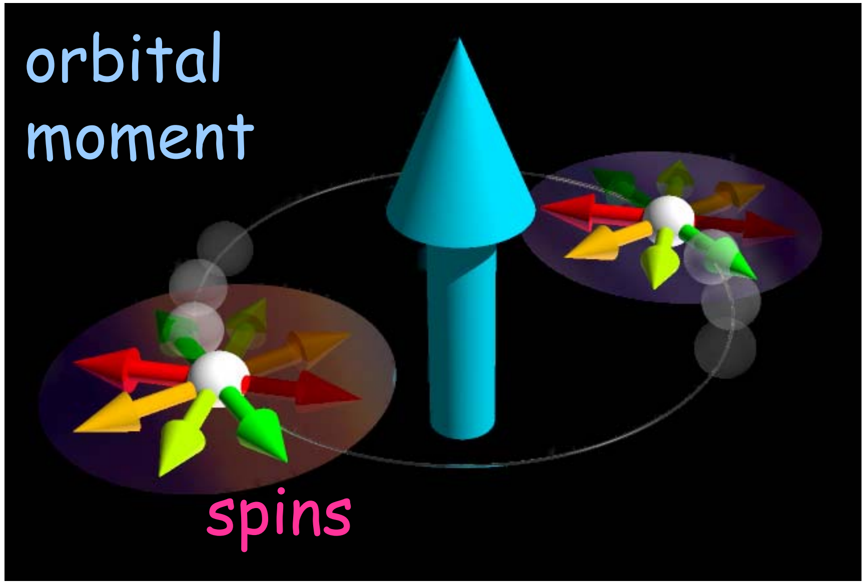
People realized this only in 2004

triggered by the discovery of a new superconductor. *"Emergence"*

Broken
Spin-Rotation Symmetry
スピン三重項超伝導

Broken
Time-Reversal Symmetry
時間反転対称性の破れ

Cooper-Pair State of Sr_2RuO_4



Spins: $S = 1$, $S_z = 0$
orbital moment: $L = 1$, $L_z = 1$

A.P. Mackenzie and Y. Maeno,
Rev. Mod. Phys. **75**, 657 (2003).

Spin **Broken SU(2)**

- NMR Knight shifts
- Polarized neutrons

➜ **Spin Triplet Pairng**

Orbital **Broken *T***

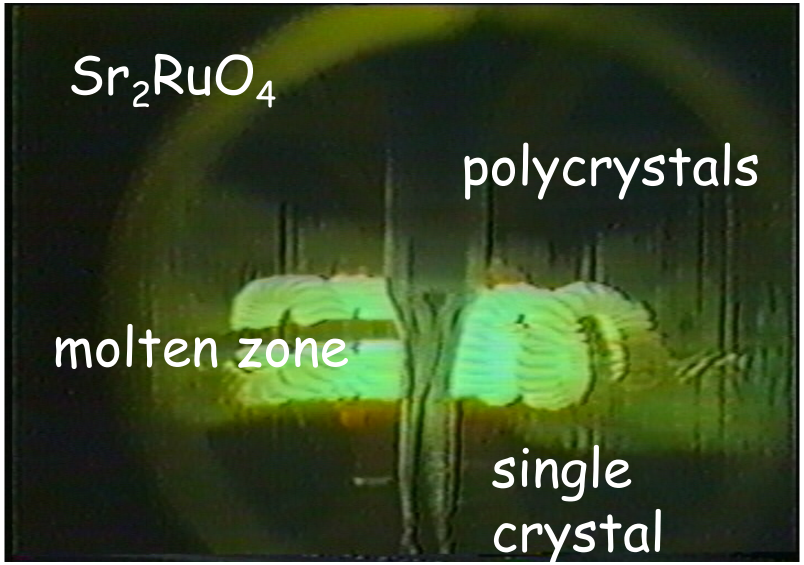
- μ SR
- Vortex lattice
- Kerr effect

➜ **Broken Time Reversal Symmetry**

- **Josephson effect**

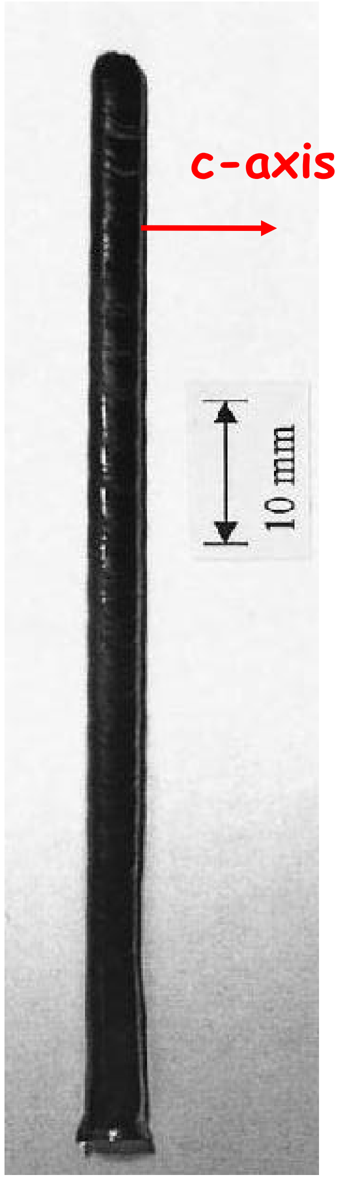
➜ **Odd Parity (*p*-wave)**

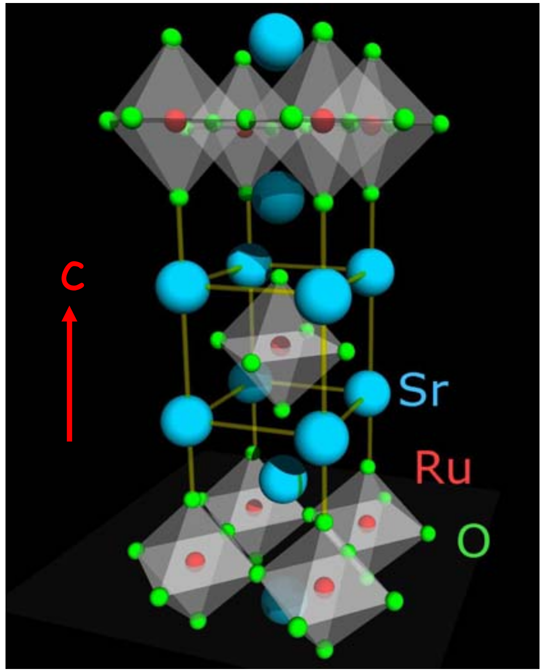
Large, high-quality single crystals



Crystal growth by a
floating-zone method
at 2100°C

Z.Q. Mao *et al.*,
Mater. Res. Bull. **35**, 1813 (2000).





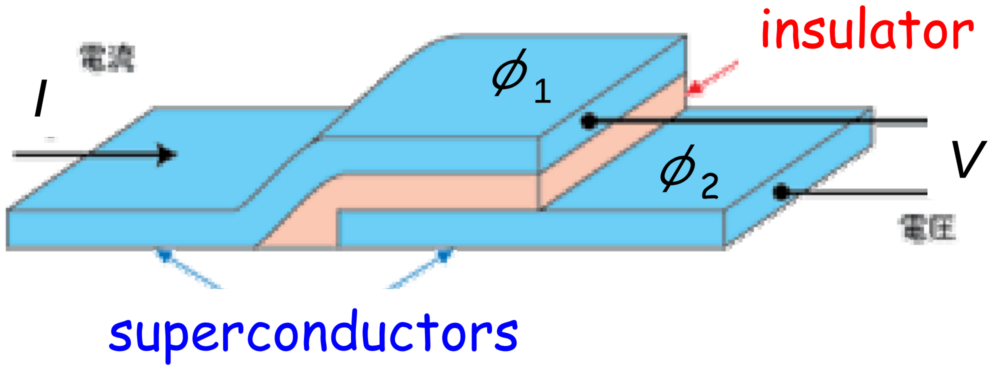
K_2NiF_4 structure
without distortion

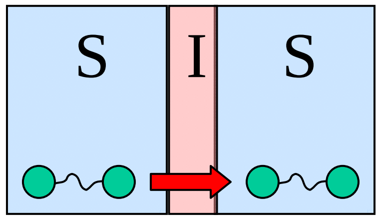
T_c = 1.5 K

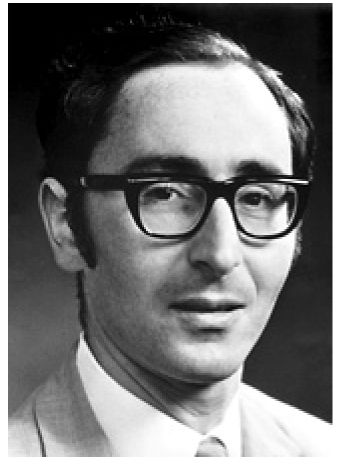
ρ_0 < 100 nΩcm

Josephson effect (Cooper-pair tunneling)

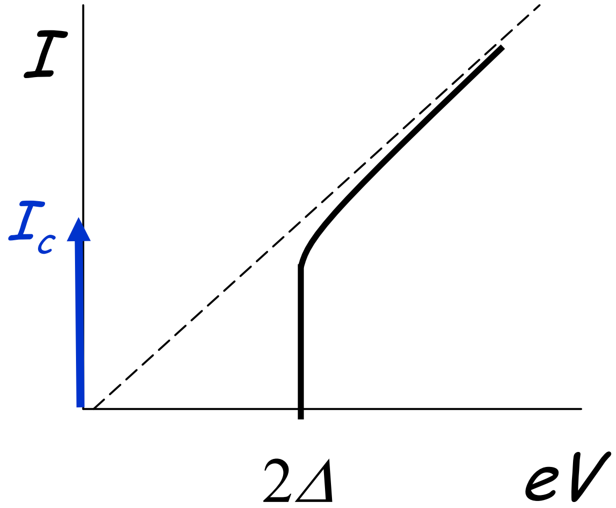
Manipulation of the **superconducting phases**







B.D. Josephson
(1973 Nobel prize)

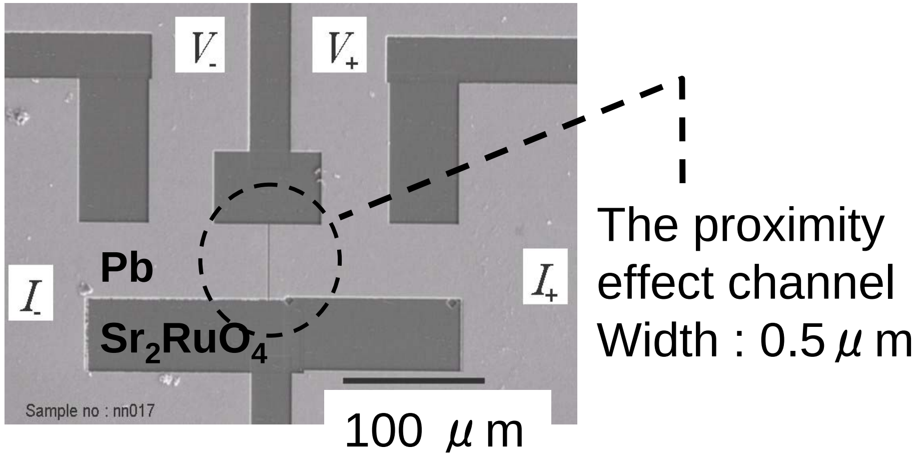


$$\Delta\varphi = \varphi_1 - \varphi_2$$

$$I = I_c \sin \Delta\varphi$$

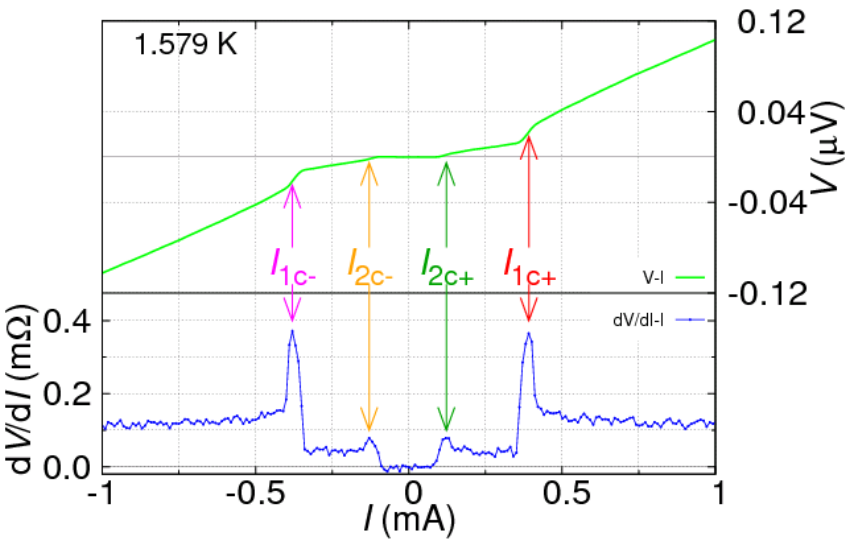
The superconducting phase can be controlled by an external current.

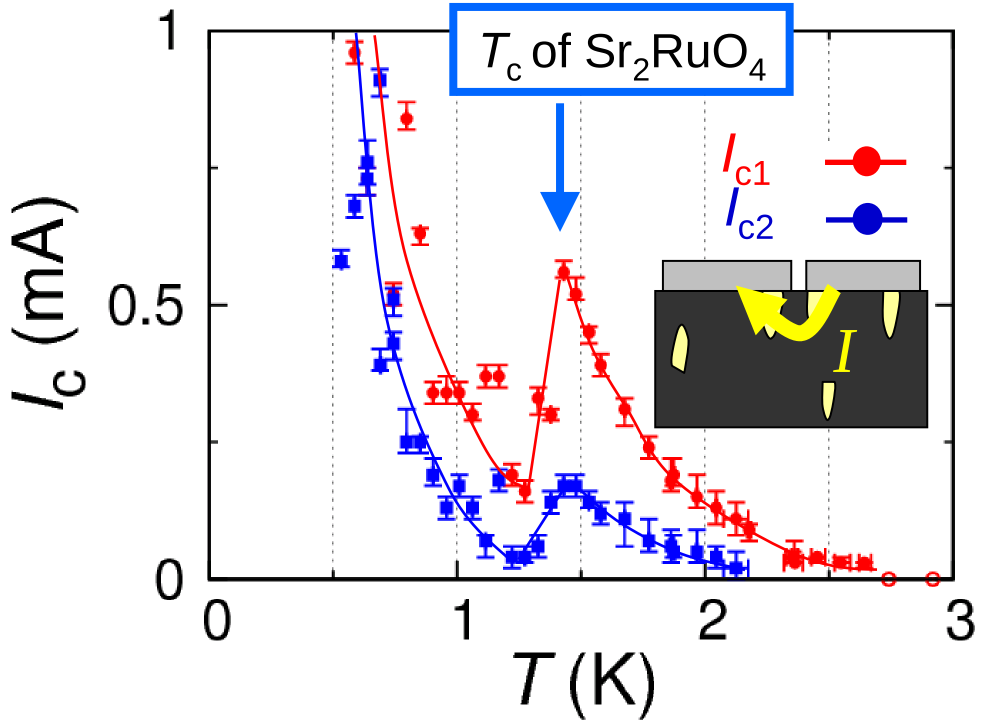
Interference as evidence for odd parity superconductivity of Sr_2RuO_4



The critical current between Pb and Sr_2RuO_4 exhibits an unusual temperature dependence.

Nakamura, Nakagawa *et al.*





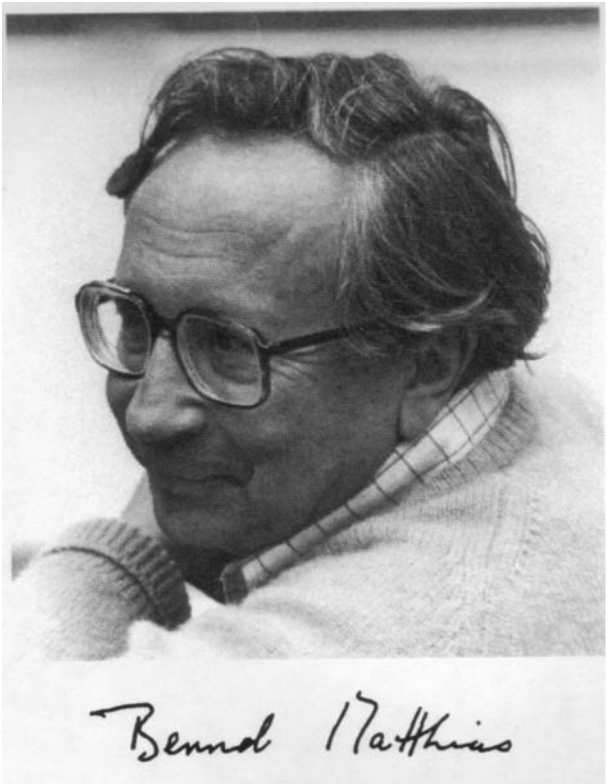
Matthias Prize for Sr_2RuO_4 (2009)

Once every three years:

Matthias Prize: Superconducting Materials → Hosono, Maeno

Onnes Prize: Superconducting Phenomena

Bardeen Prize: Theory of Superconductivity → D. Pines

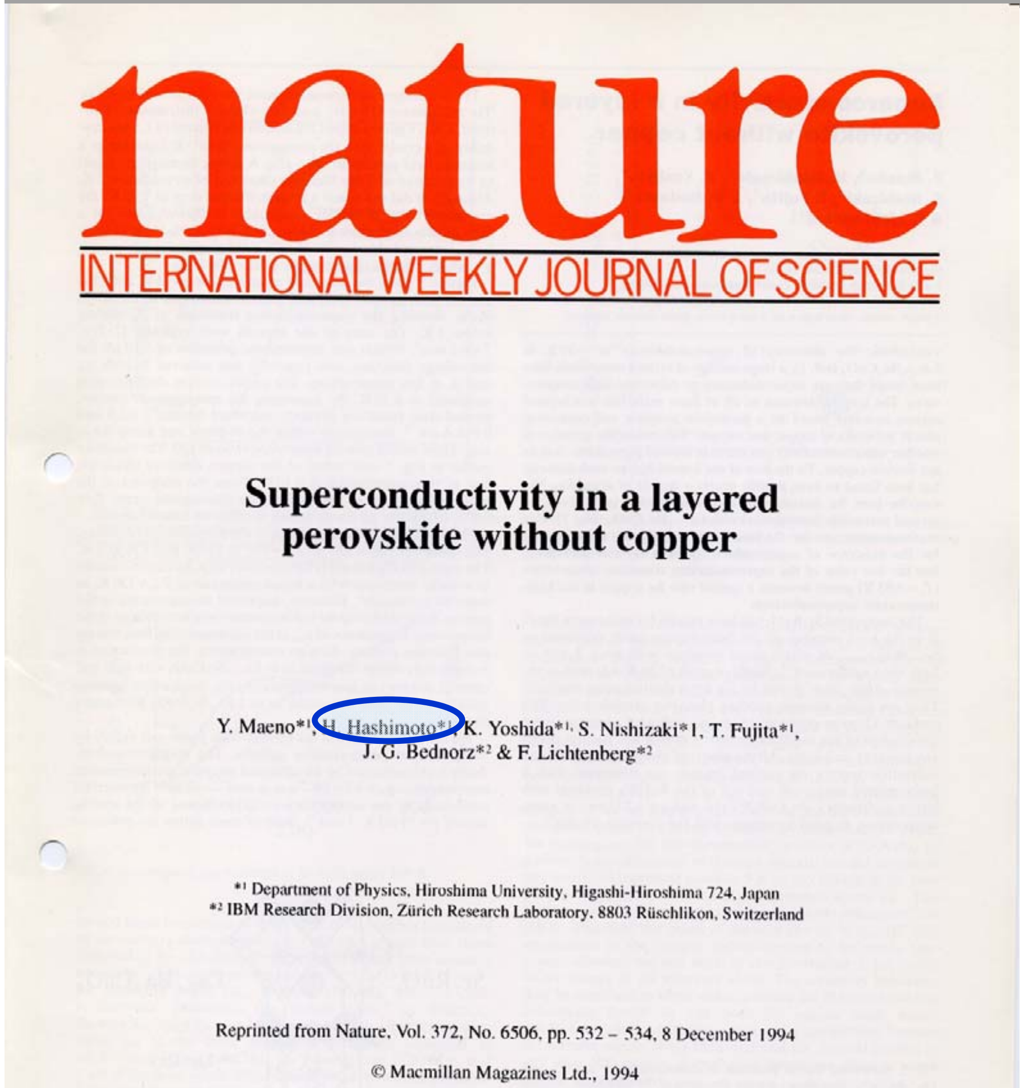


(1918-1980)

Bernd T. Matthias Prize
for superconductivity materials

"For his 1994 discovery and subsequent purification of ***Sr_2RuO_4*** *that creates a unique platform for revealing decisively some unusual features of superconductivity."*

Hiroaki Hashimoto



nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Superconductivity in a layered perovskite without copper

Y. Maeno*[1], H. Hashimoto*[1], K. Yoshida*[1], S. Nishizaki*[1], T. Fujita*[1], J. G. Bednorz*[2] & F. Lichtenberg*[2]

*[1] Department of Physics, Hiroshima University, Higashi-Hiroshima 724, Japan
*[2] IBM Research Division, Zürich Research Laboratory, 8803 Rüschlikon, Switzerland

Reprinted from Nature, Vol. 372, No. 6506, pp. 532 – 534, 8 December 1994

cited 1130 times (Sep. 2009)

Elected to the House of Representatives

in the national election on Aug. 30, 2009. (Age: 39)

衆議院選挙　当選！

Topological Quantum Phenomena in Superconductivity

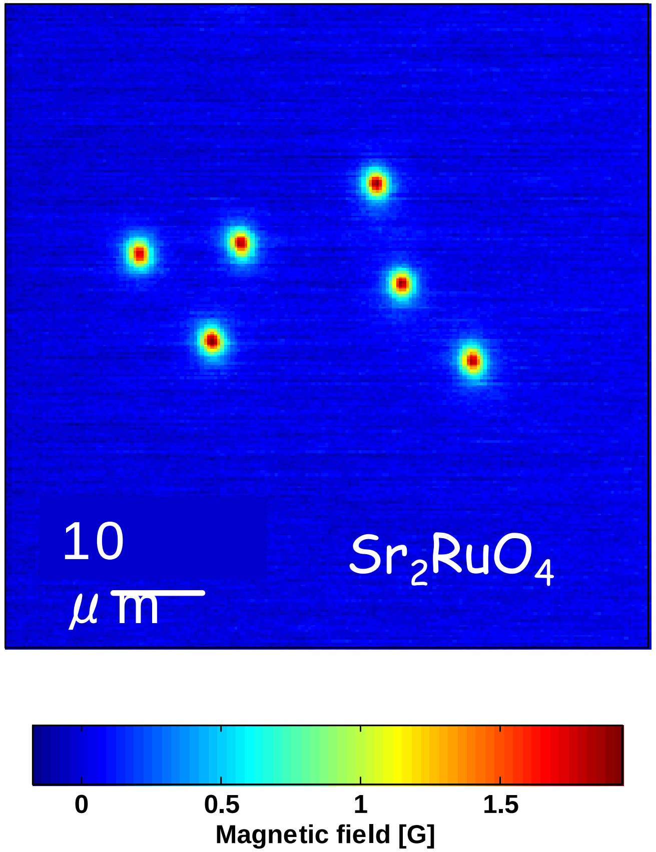
Fluxoid quantization

Single-valuedness
around a singularity
requires magnetic-flux quantization.

$$\Psi = |\Psi| \exp(i\phi)$$

$$\oint \nabla\phi \bullet ds = 2\pi n$$

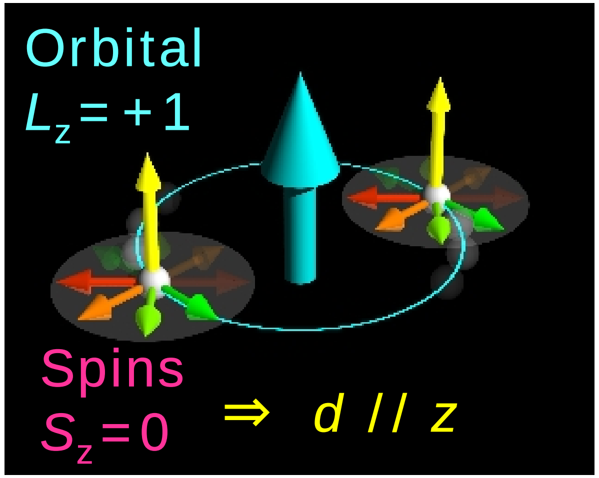
Flux quantum
$\Phi_0 = h/2e = 20.7\ G\ (\mu m)^2$

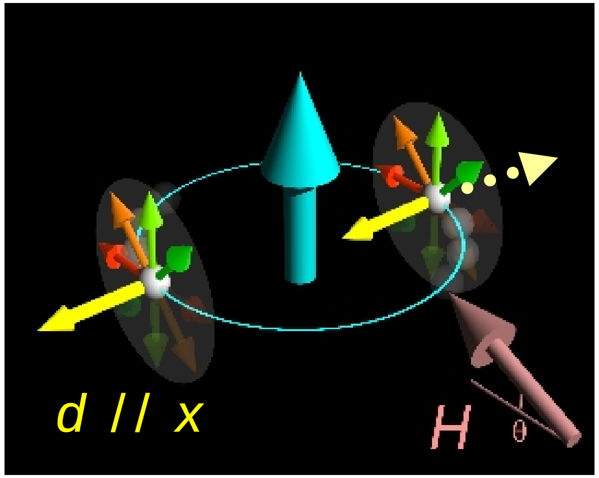


Quantized vortices

Moler *et al.*

Spin Orientation (*d*-vector) in Sr_2RuO_4





Both spin states are compatible with experiments.

Murakawa, Ishida *et al.*

For *d* //ab (rotating),
half-quantum vortex (HQV) is possible.

The rotation of the *d*-vector by π,
with the orbital phase winding of π.

HQV

Chung, Bluhm, Kim,
PRL **99**, 197002 (2007).

Search for Half-Quantm Vortex (HQV)

Proposals for HQV
in superfluid ^3He-A and Sr_2RuO_4

For spin-triplet superfluids
with Broken Time-Reversal
Symmetry (L_z = 1)

Volovik and Mineev (1976).

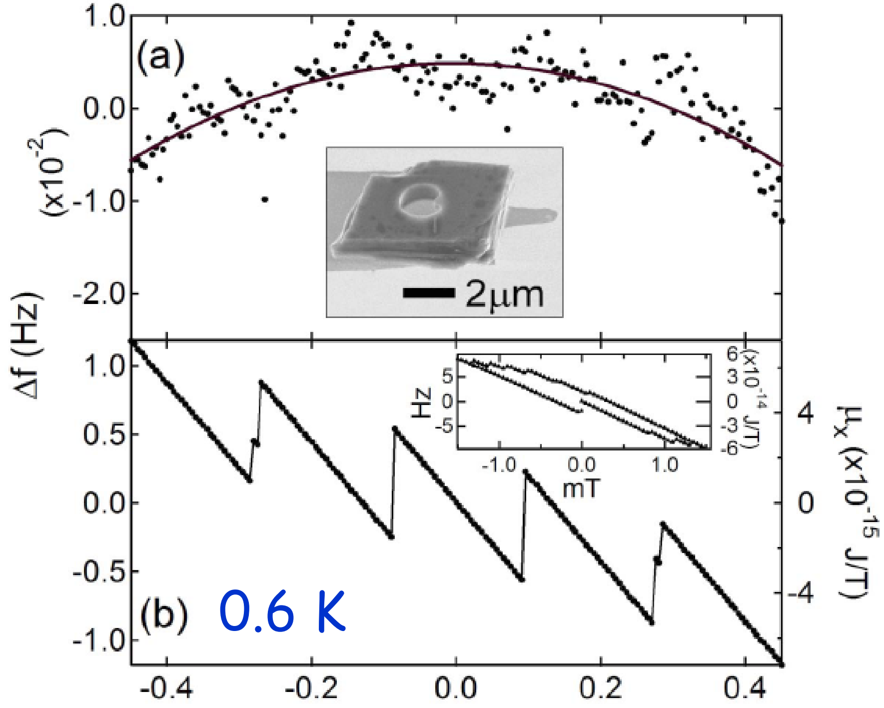
Salomaa and Volovik, PRL (1985).

Chung, Bluhm, Kim, PRL (2007).

Vakaryuk and Leggett,
PRL **103**, 057003 (2009).

Not observed yet.

Micron-size Sr_2RuO_4 crystal



J. Jang, R. Budakian, Y. Maeno,
arXiv: 0908.2673.
Univ. Illinois at Urbana-Champaign

Concluding Message:
Will Nambu's analogy revive with "unconventional" superconductivity?

Emergent Superconductors

with Unusual Symmetry Breaking

1. Non-s-wave pairing by repulsive Coulomb interaction
2. Broken Translational Symmetry: FFLO
3. Without Inversion Symmetry: spin singlet-triplet mixing
4. Spin triplet pairing

   with Broken Time-Reversal Symmetry

Topological Quantum Phenomena

Interference, Half-quantum vortex (HQV), Edge currents, Majorana Fermions, etc.

END