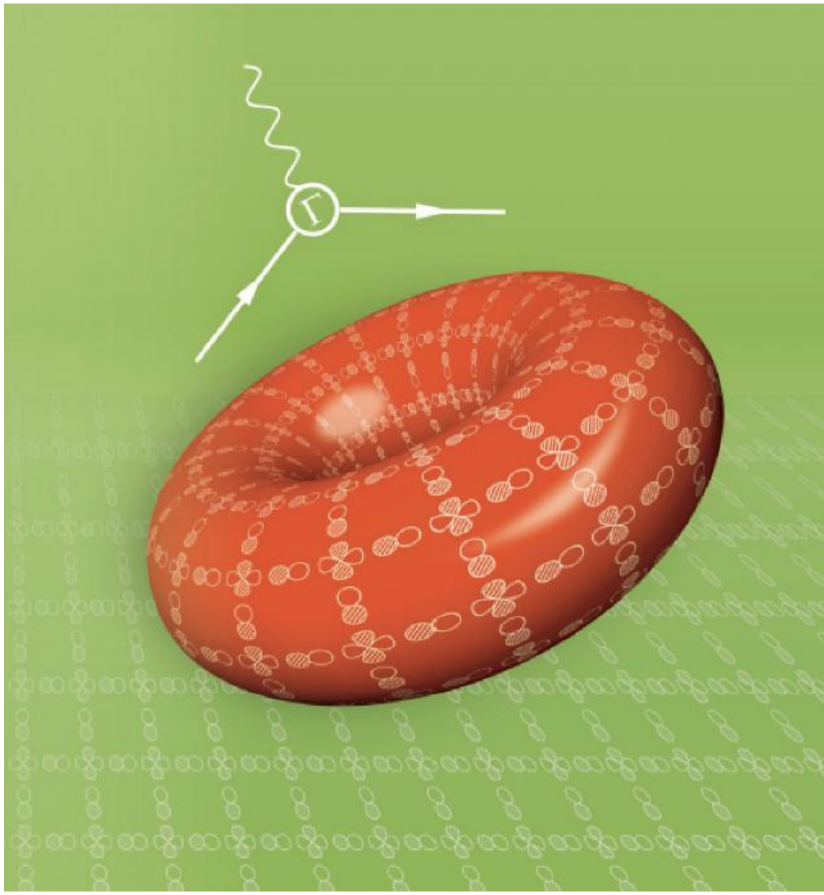
Correlations and Phase Transitions

Eva Pavarini and Erik Koch (Eds.)

Lecture Notes of the Autumn School on Correlated Electrons 2024



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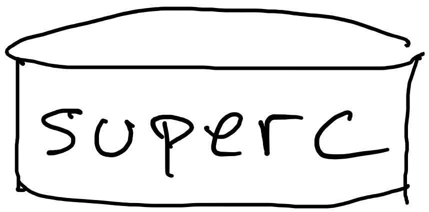
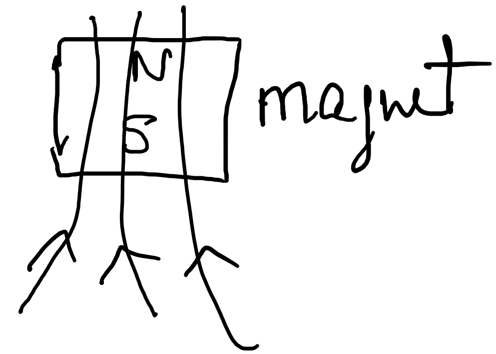
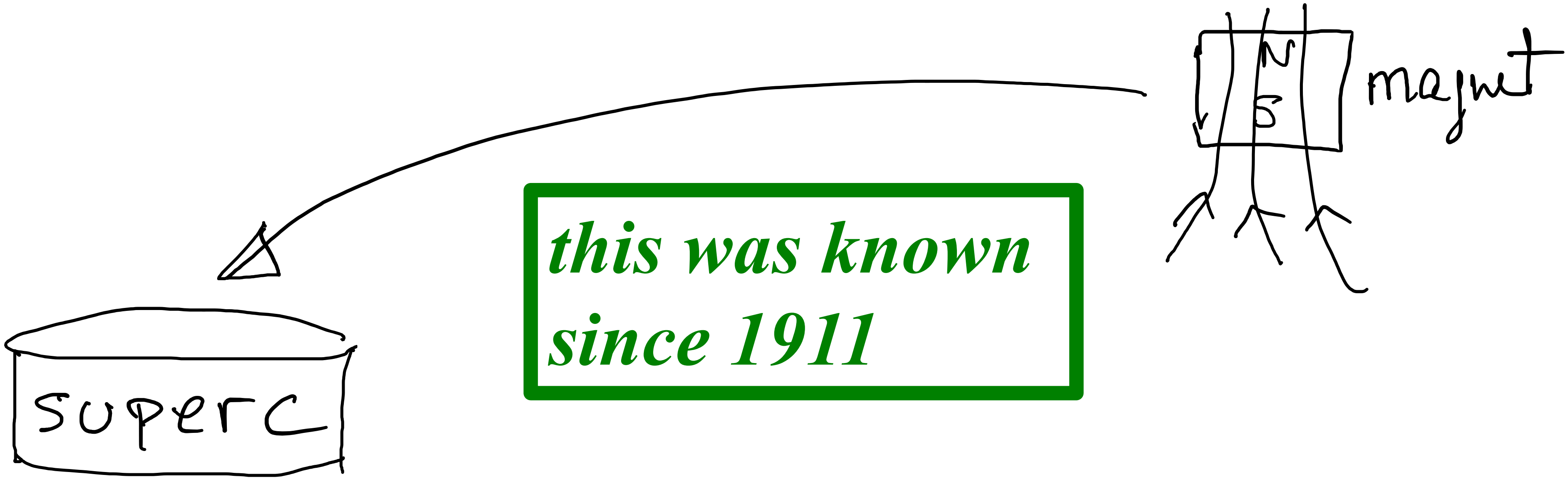
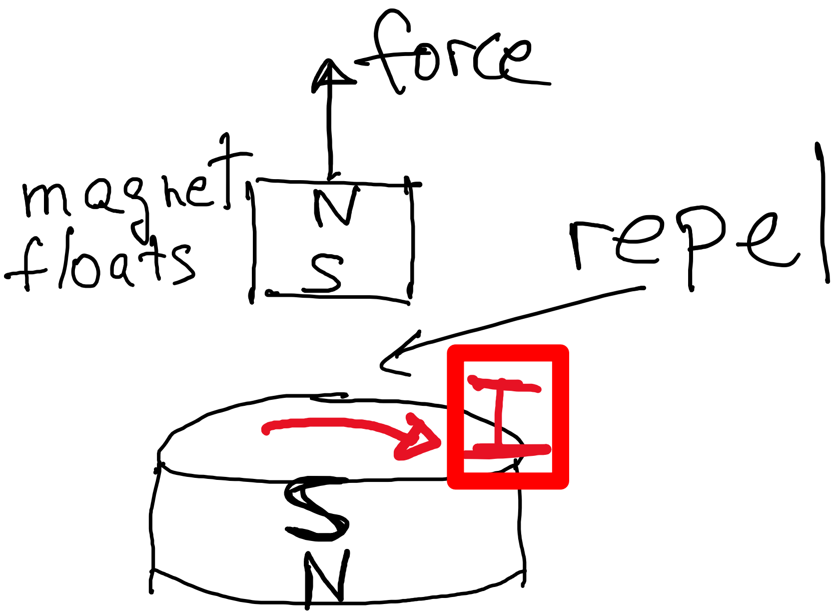

superc

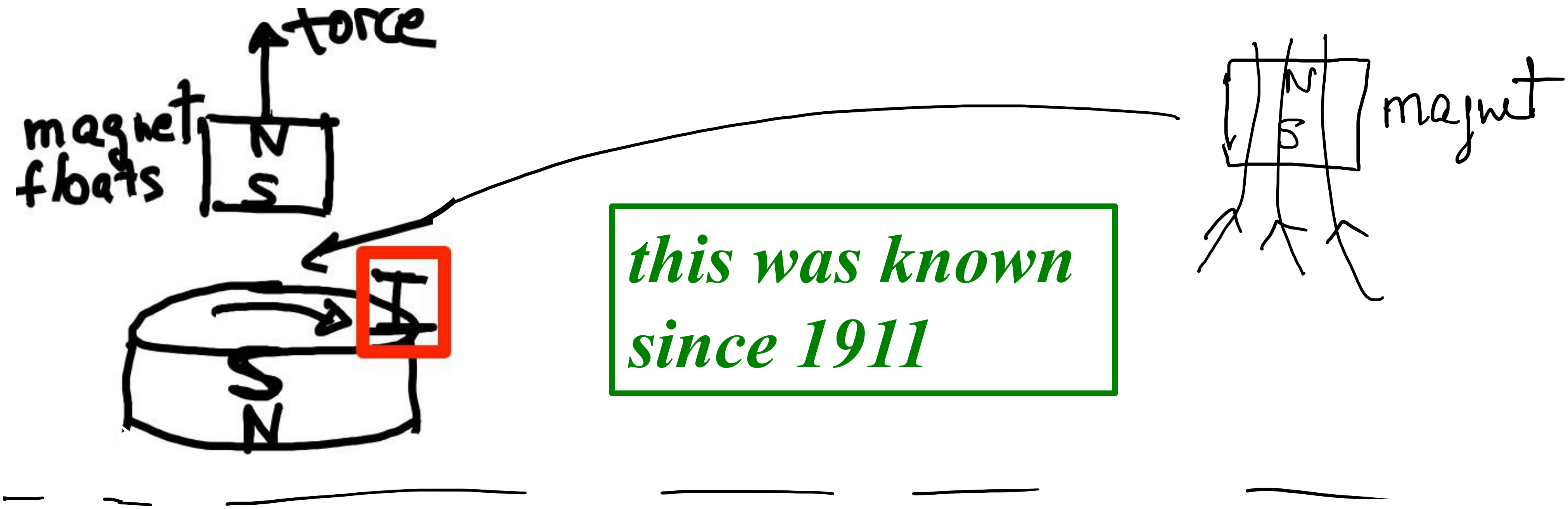

N
S
magnet



this was known since 1911

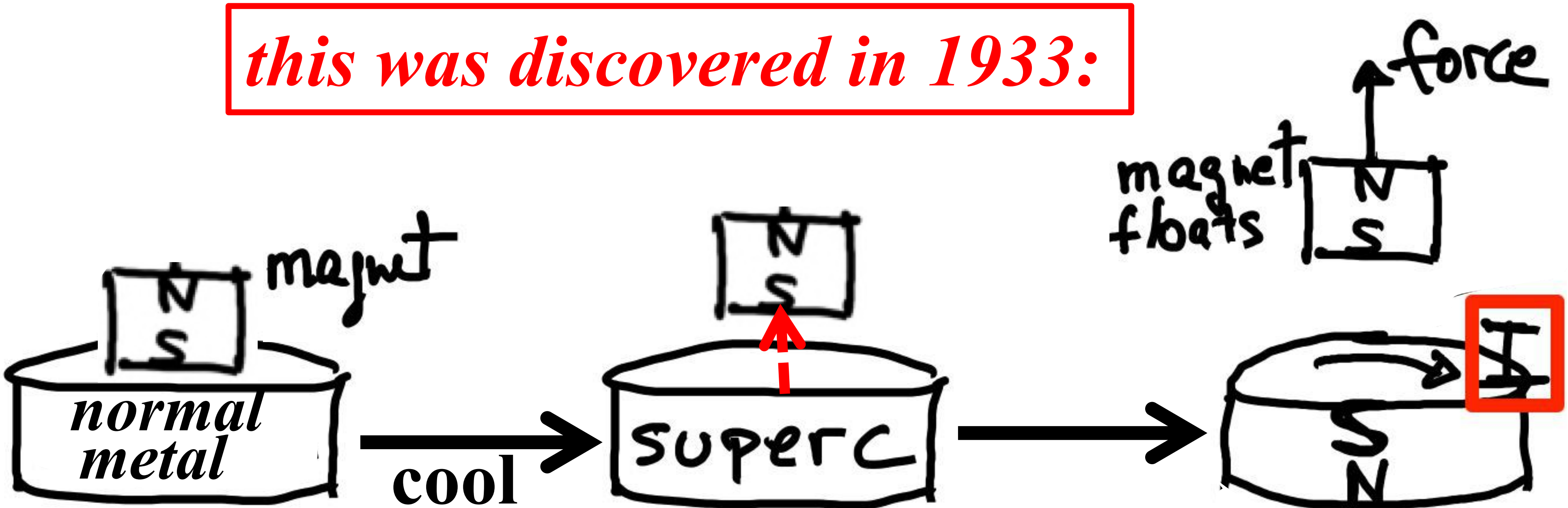


This is NOT the Meissner effect



this was known since 1911

this was discovered in 1933:



this is the Meissner effect

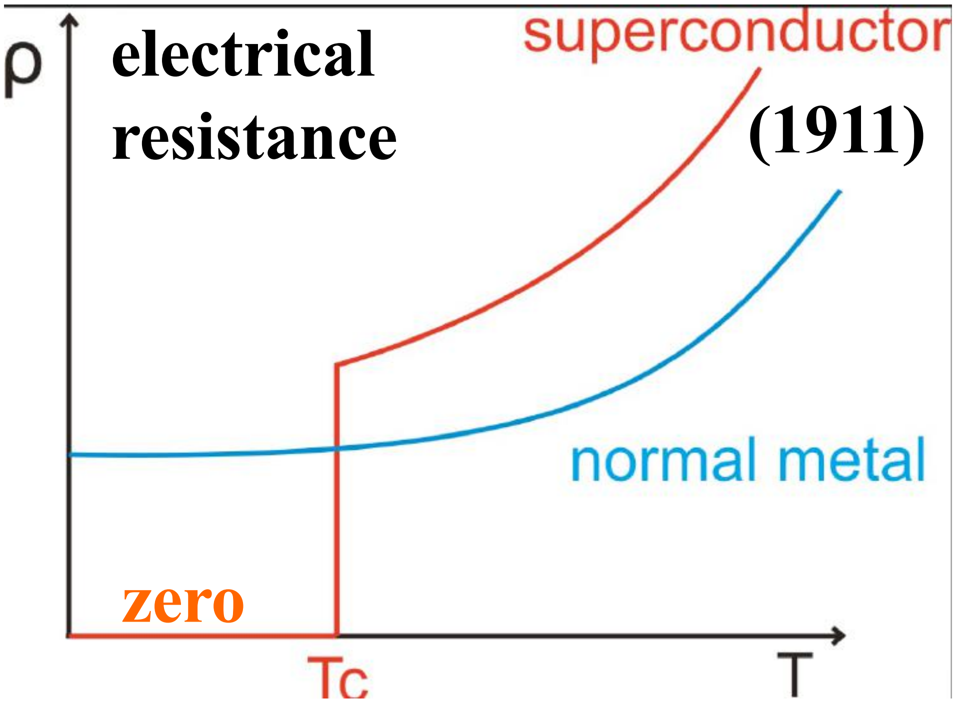
same final state
VERY different process

1933

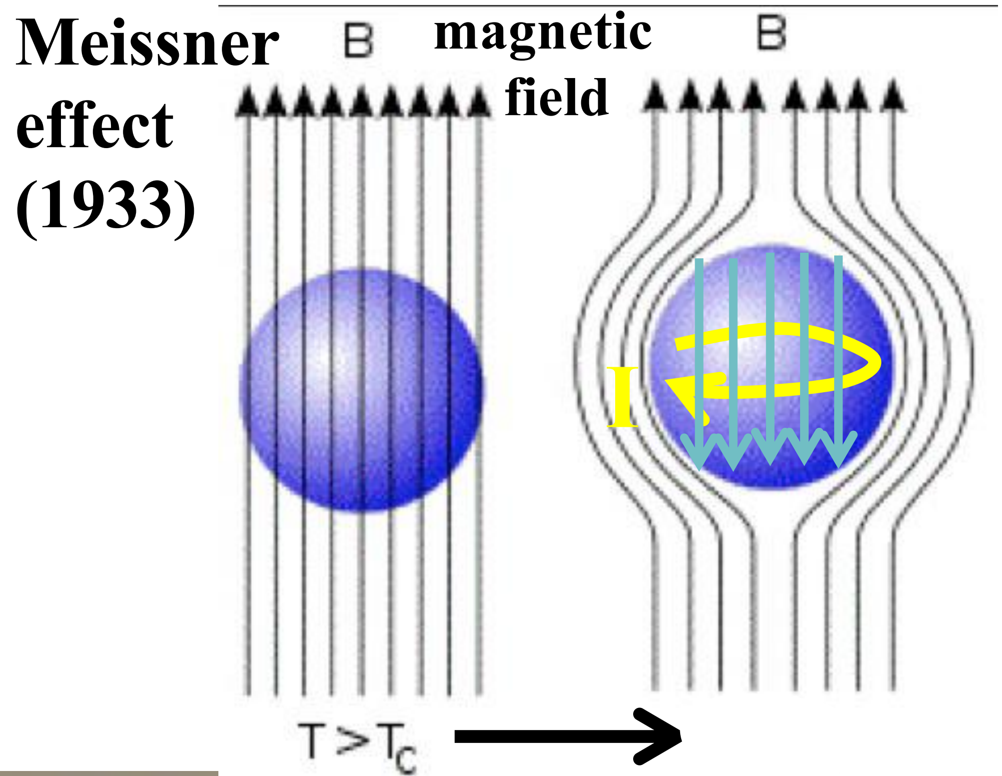
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit.

Bringt … zylindrischen Supraleiter, z. B. Blei oder Zinn, … eines Sprungpunktes in ein senkrecht zu seiner A… tetes homogenes Magnetfeld, so gehen die Kraftli… der sehr geringen Suszeptibilität de Supraleite… schwach paramagnetisch, Blei diamagnetisch) fast ungehindert durch sie hindurch. Nach den bisherigen Anschauungen war zu erwarten, daß die Kraftlinienverteilung unverändert bleibt, wenn man die Temperatur, ohne an dem äußeren Magnetfeld etwas zu ändern, bis unter den Sprungpunkt erniedrigt. Unsere Versuche an Zinn und Blei haben im Gegensatz hierzu folgendes ergeben:

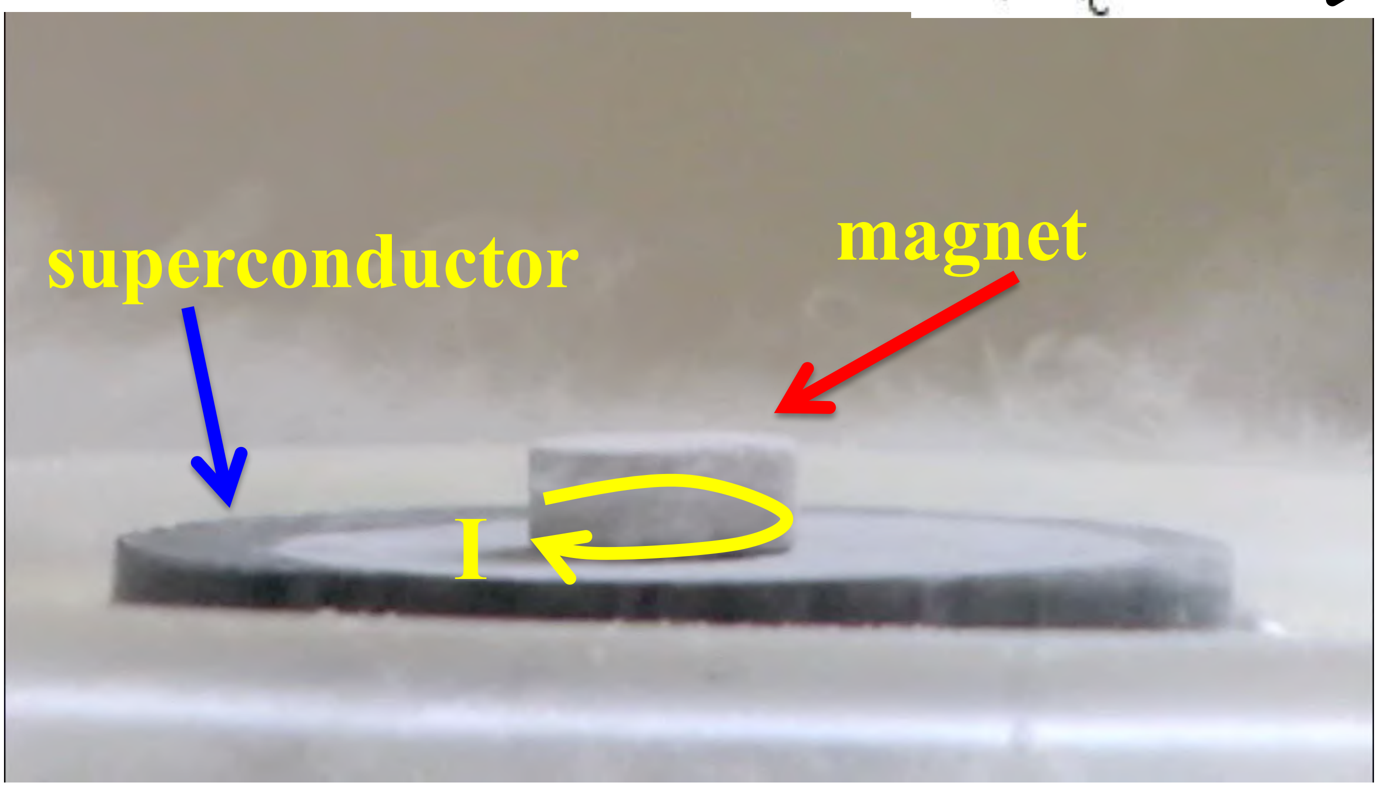
1. Beim Unterschreiten des Sprungpunktes ändert sich die Kraftlinienverteilung in der äußeren Umgebung der Supraleiter und wird nahezu so, wie es bei der Permeabilität 0, also der diamagnetischen Suszeptibilität $-\frac{1}{4\pi}$, des Supraleiters zu erwarten wäre.



ρ
electrical
resistance
superconductor
(1911)
normal metal
zero
Tc
T



Meissner
effect
(1933)
B
magnetic
field
B
I
T > Tc



superconductor
magnet
I

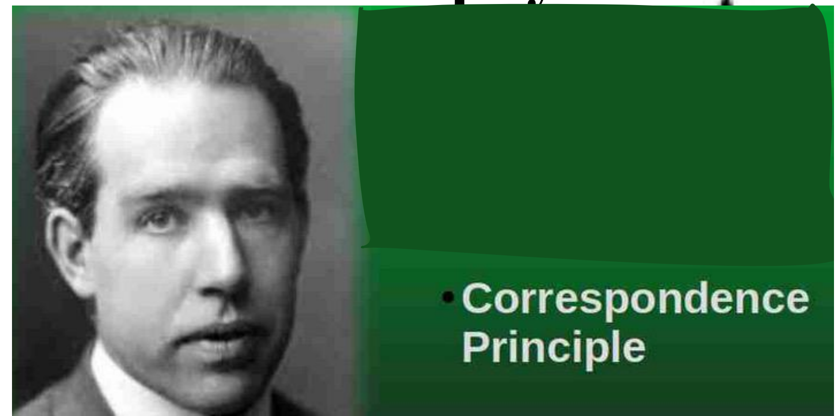
The Meissner effect seems to violate the laws of classical physics

(1) Law of inertia

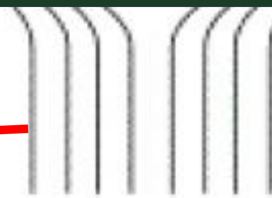
(2) Faraday's law

(3) Law of momentum conservation

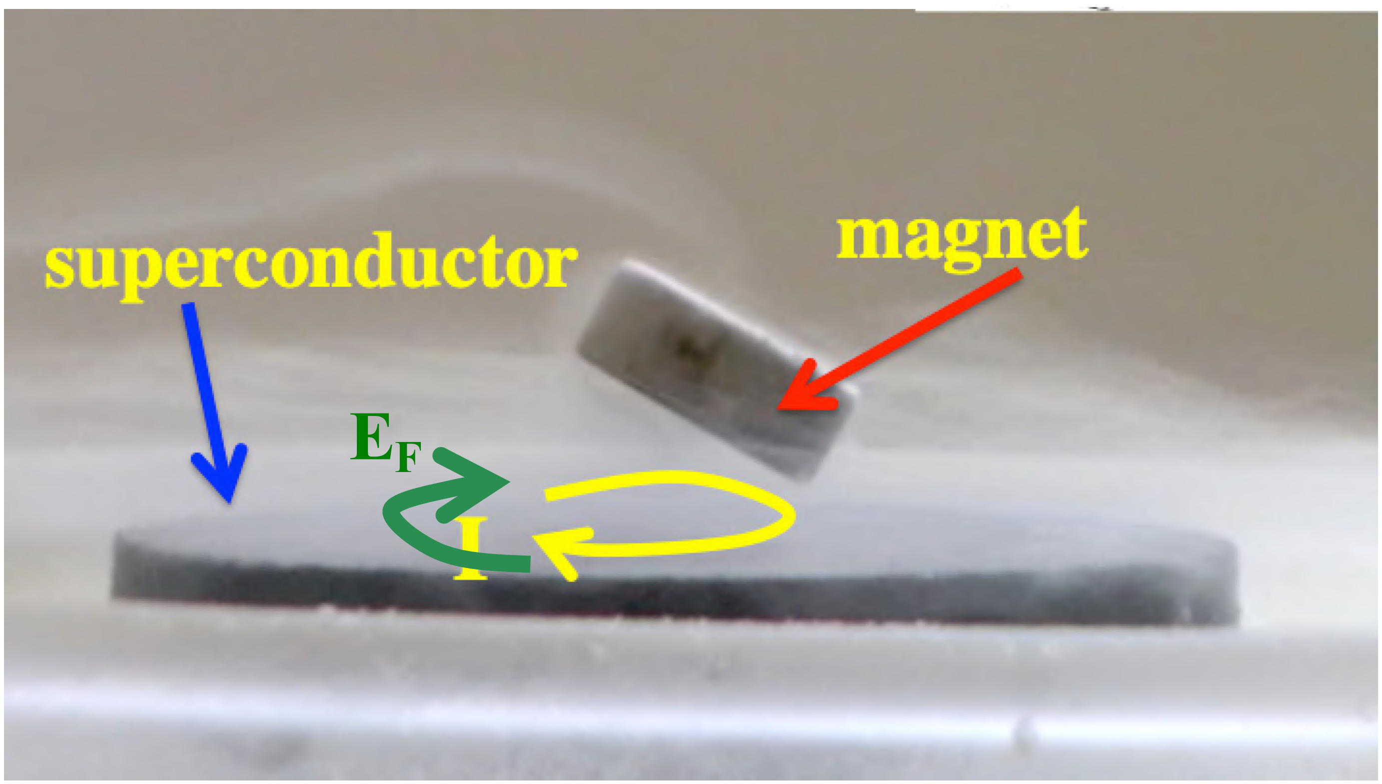
(4) Laws of thermodynamics



How do superconductors manage to do this???



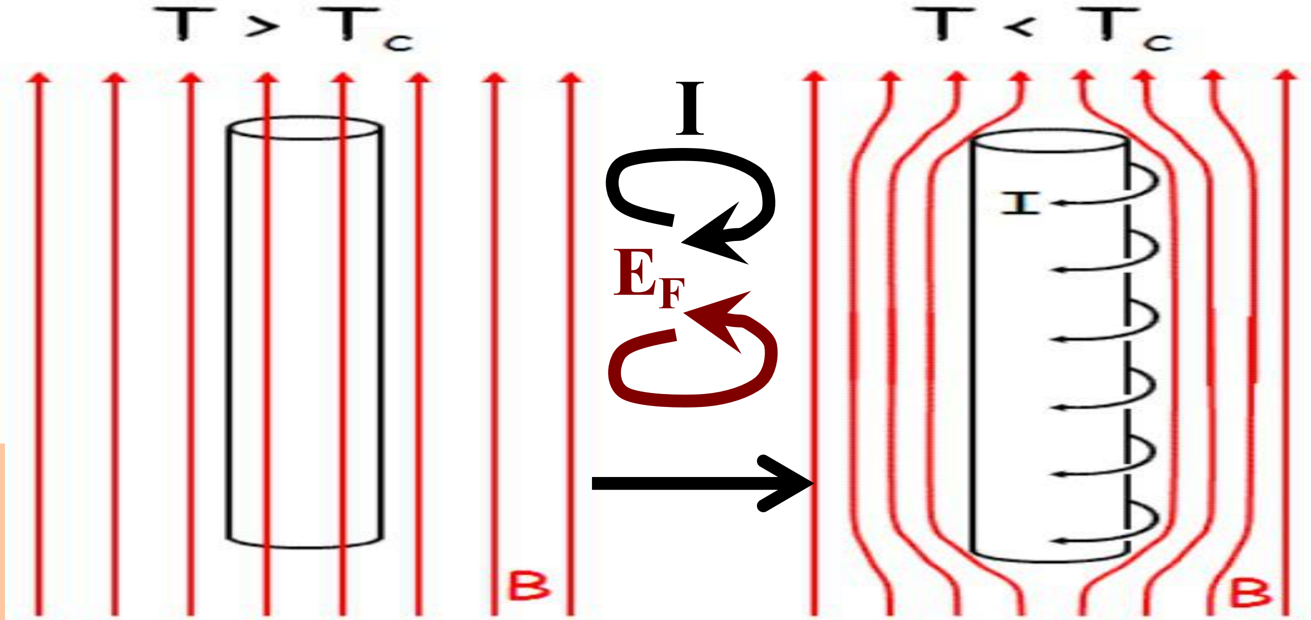
~~Easy, it's quantum mechanics at play~~



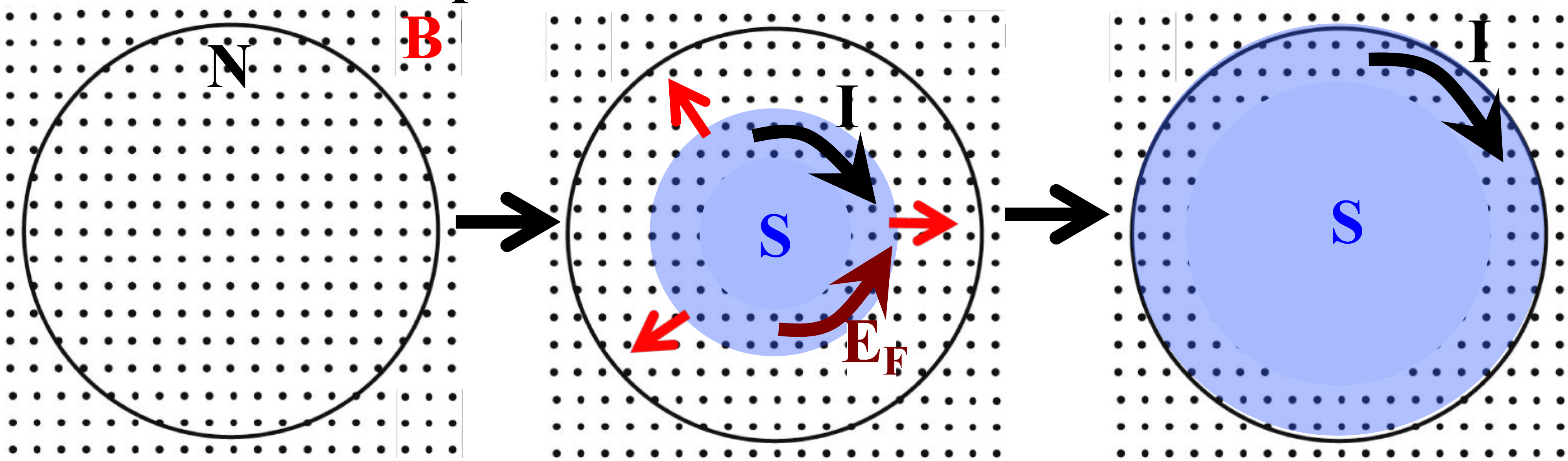
Meissner effect puzzle

How does the current overcome the Faraday field E_F (counter-emf) that wants to stop it?

$$\varepsilon = \oint \vec{E}_F \cdot \vec{d}\ell = -\frac{\partial}{\partial t}\int \vec{B}\cdot\vec{d}S$$



View from the top

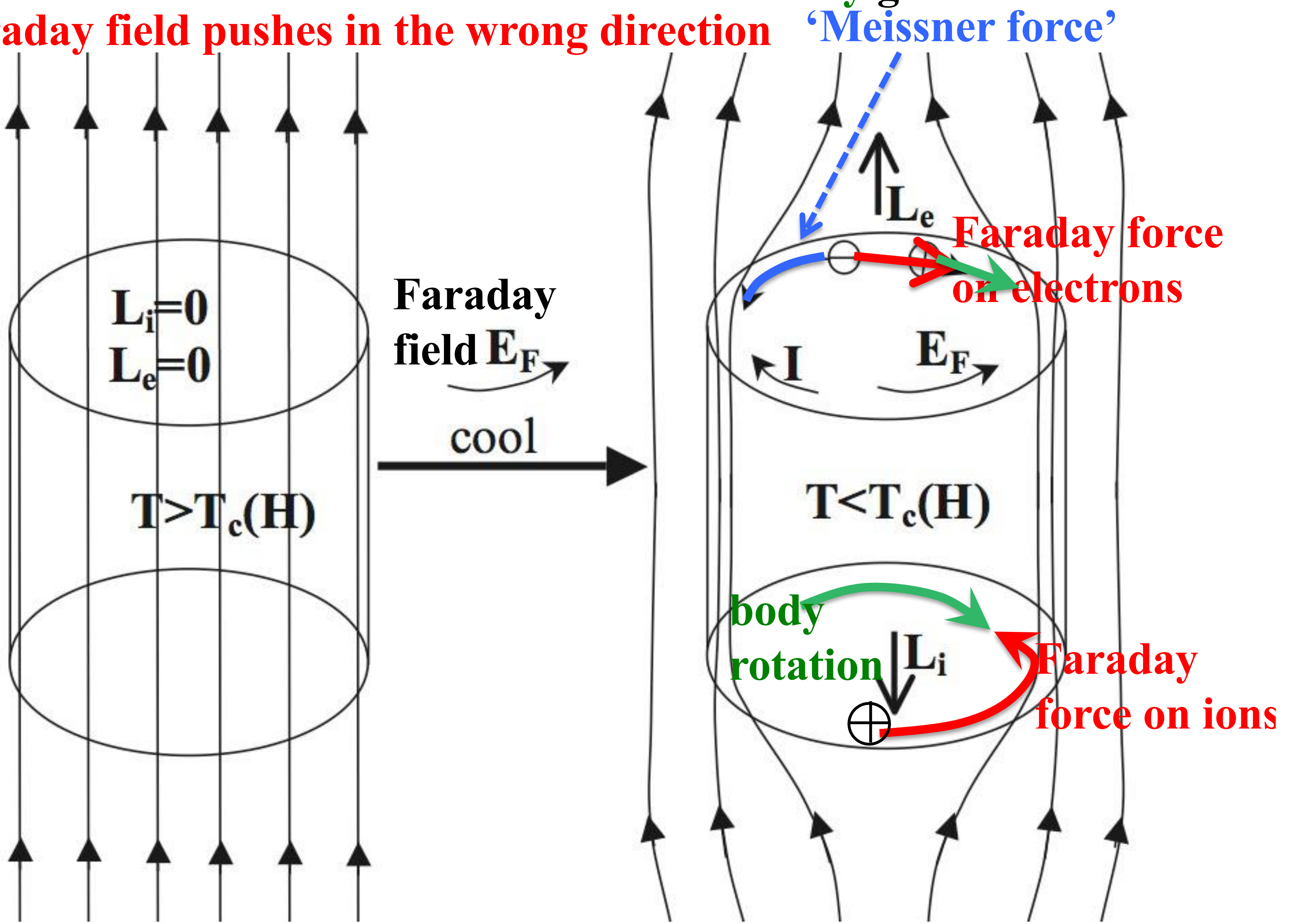


How is the momentum of the supercurrent compensated?

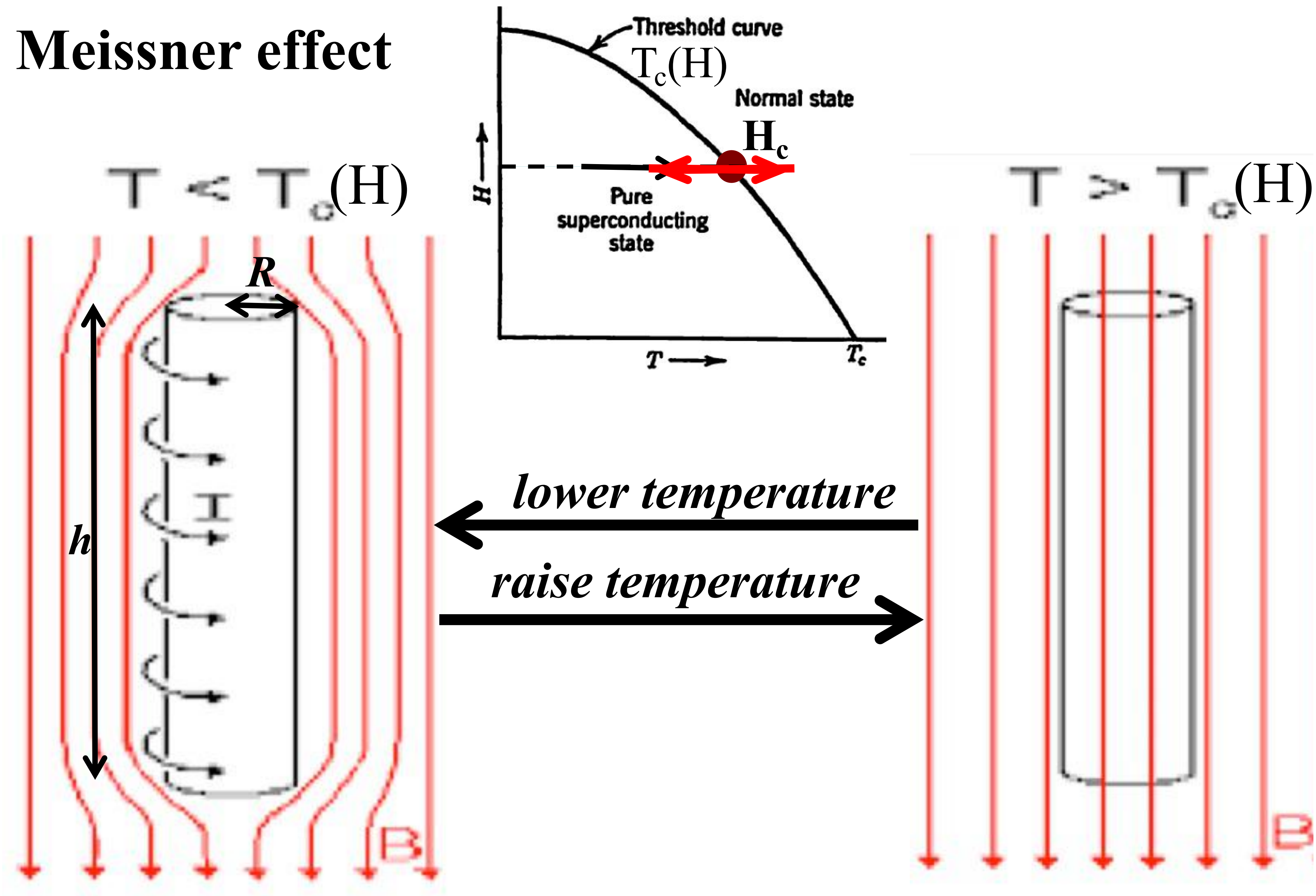
<u>Meissner effect puzzle: momentum conservation</u>

How is the momentum of the electrons and body generated?

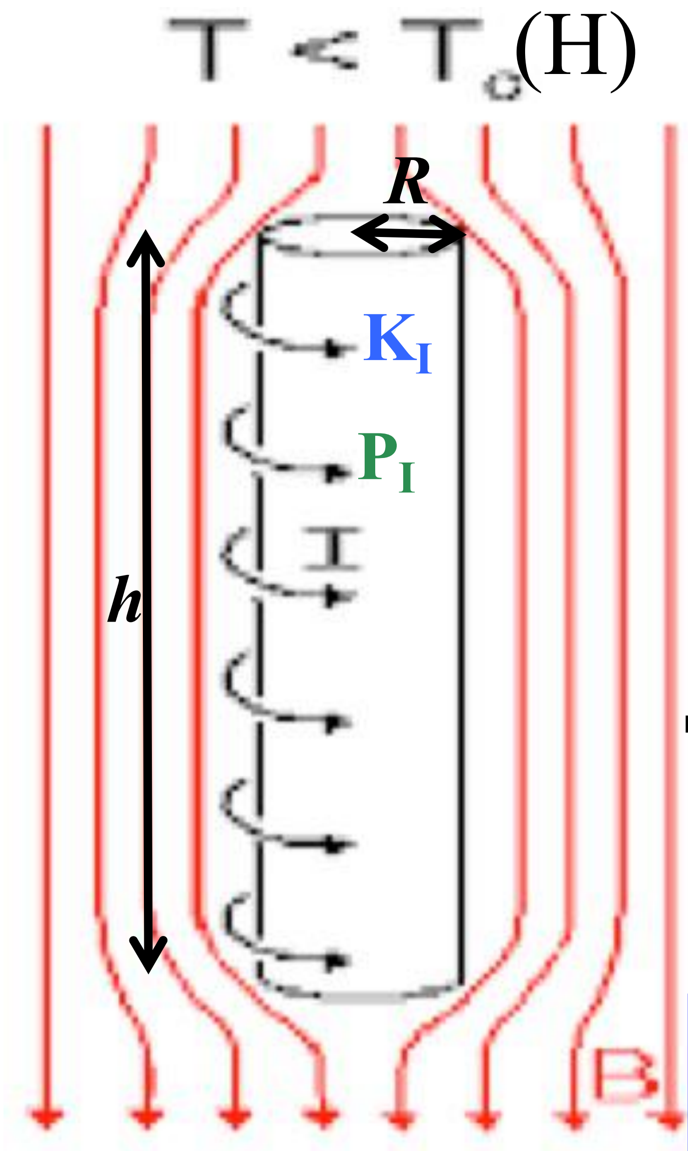
Faraday field pushes in the wrong direction

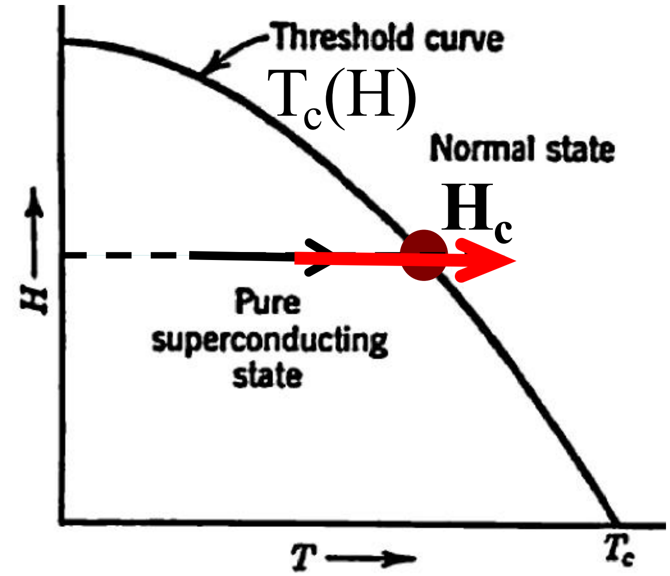


Meissner effect



Question:





K_I=kinetic energy of I

$$= n_s (m_e v_s^2 / 2) \times (2\pi R \lambda_L h)$$

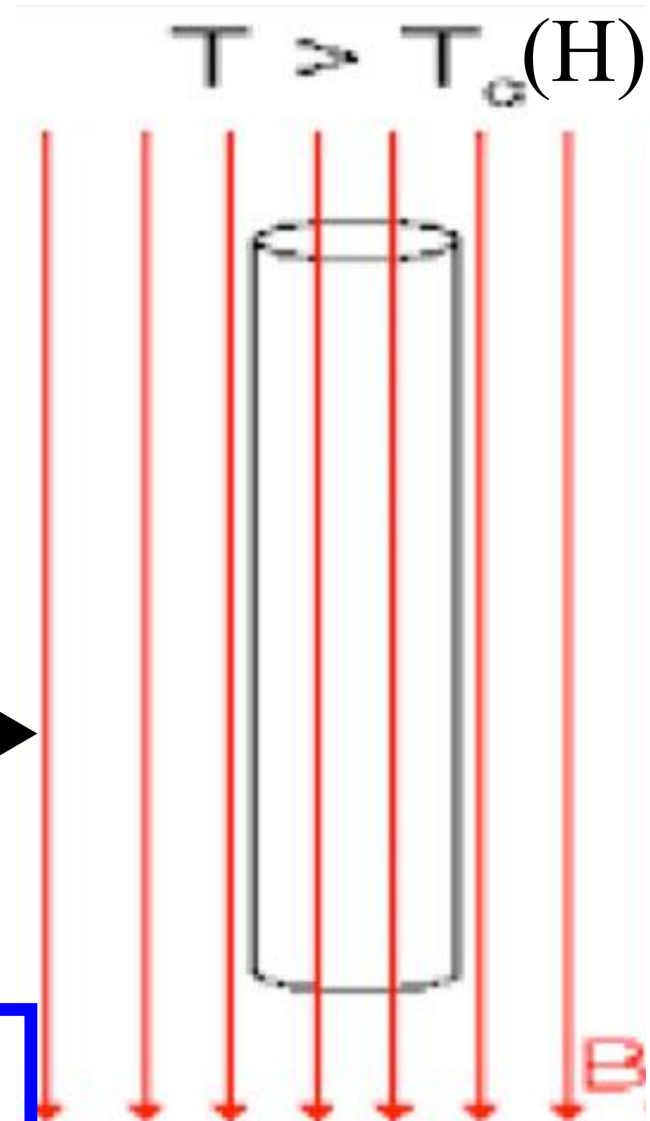
$$= (H^2 / 8\pi) \times (2\pi R \lambda_L h)$$

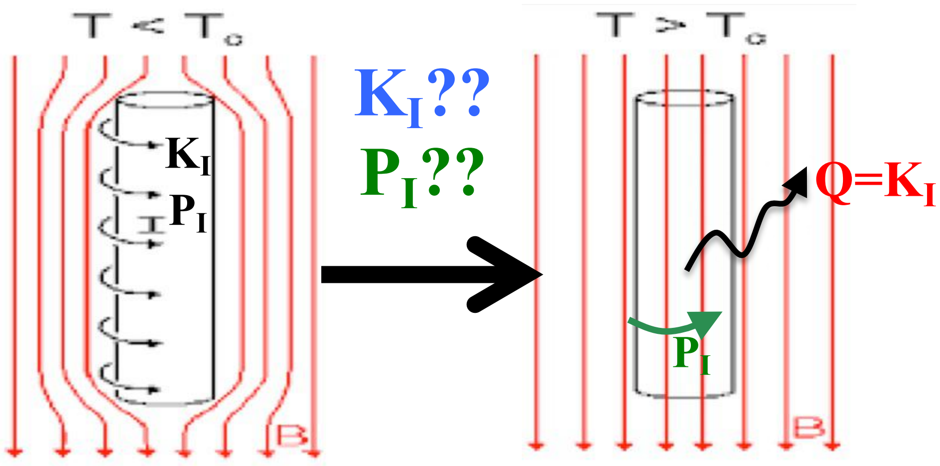
raise temperature

P_I=momentum of I

$$= \sum_k m_e v_k = \frac{m_e c}{2e}(hR)H$$

where are K_I and P_I in the final state ?





For a cylinder of R=1cm, h=5cm, H~500 G, λ_L=500A:

I~ 2,000 Amps

P_I ~ 1 mg moving at 1 mm/s

K_I ~ 2.7 erg

A simple answer (1911 to 1933):

As the system becomes normal, resistivity becomes non-zero. I decays by collision processes with phonons and/or impurities, its kinetic energy (K_I) is dissipated as Joule heat Q, its momentum (P_I) is transmitted in the collisions to the body as a whole, body starts to rotate.

Simple answer is WRONG.

Discovery of the Meissner effect (1933) suggested Joule heat is zero

Joule heat was measured to high accuracy, it is zero

Keesom (1934-1938)

closed. We call $r/T + \sigma$ the increase in entropy which occurs in passing the magnetic threshold curve at (H, T), σ being due to some possible irreversible process going on at that event.

There is NO Joule heat!

TABLE III.

Test of reversibility of [illegible] magnetic threshold value curve.

T	Δ [illegible] U cal/mol	T [illegible] S cal/mol	Δ [illegible] F cal/mol	$A \cdot \frac{H^2}{8\pi d}$ cal/mol	$T\sigma$ cal/mol
[illegible]	0.000 311	0.000 295	0.0000 16	0.0000 18	0.0000 02
1.91	446	396	50	58	08

Considering the numbers of the last column we conclude that a definite indication of irreversibility is not present. Comparing those numbers with the values of r (the differences do not reach 2%) seems to entitle us to admit that the process mentioned may be considered as reversible as far as thermodynamical consequences go, viz. that

Keesom (1934)

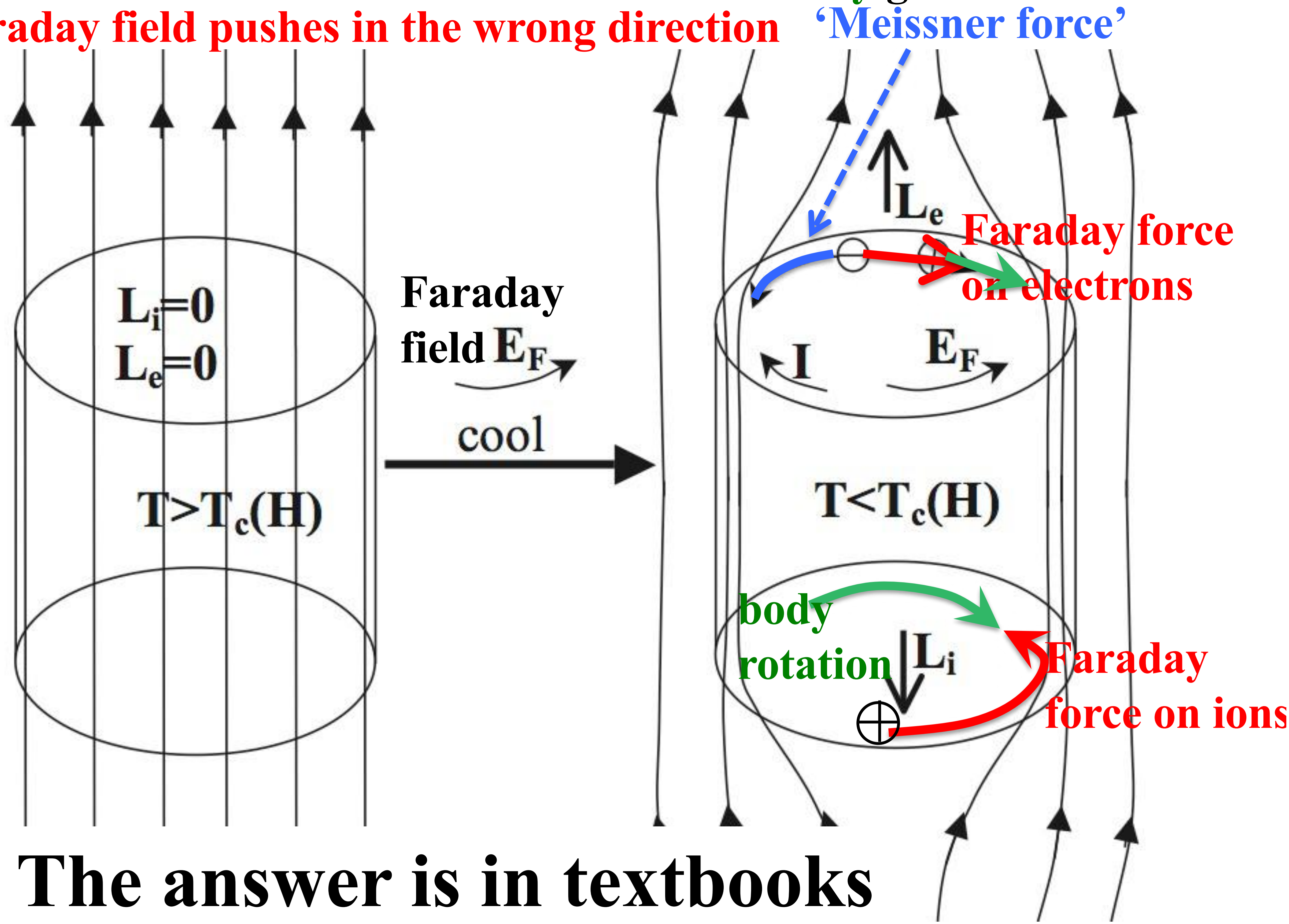
Till now we imagined that the surplus work served to deliver the J o u l e-heat developed by the persistent currents the metal getting resistance while passing to the non-supraconductive condition. As, however, the conception of J o u l e-heat can rather difficultly be reconciled with reversibility we think now that there must be going on another process that absorbs energy. So we admit that in passing the threshold value curve, what happens first is the penetrating of the magnetic field into the supraconductive material. By this process which is to be considered as reversible, the persistent currents are annihilated by induction. At this process an amount of energy is absorbed equal to twice the energy of the magnetic field that comes into existence. It is not clear for what purpose the surplus of absorbed energy serves. It is to be supposed that some reversible process is involved which probably is connected with the transition to the non-supraconductive state. In this picture of what happens it is essential that the persistent currents have been annihilated before the material gets resistance, so that no J o u l e-heat is developed.

how does the supercurrent get 'annihilated' without Joule heat?

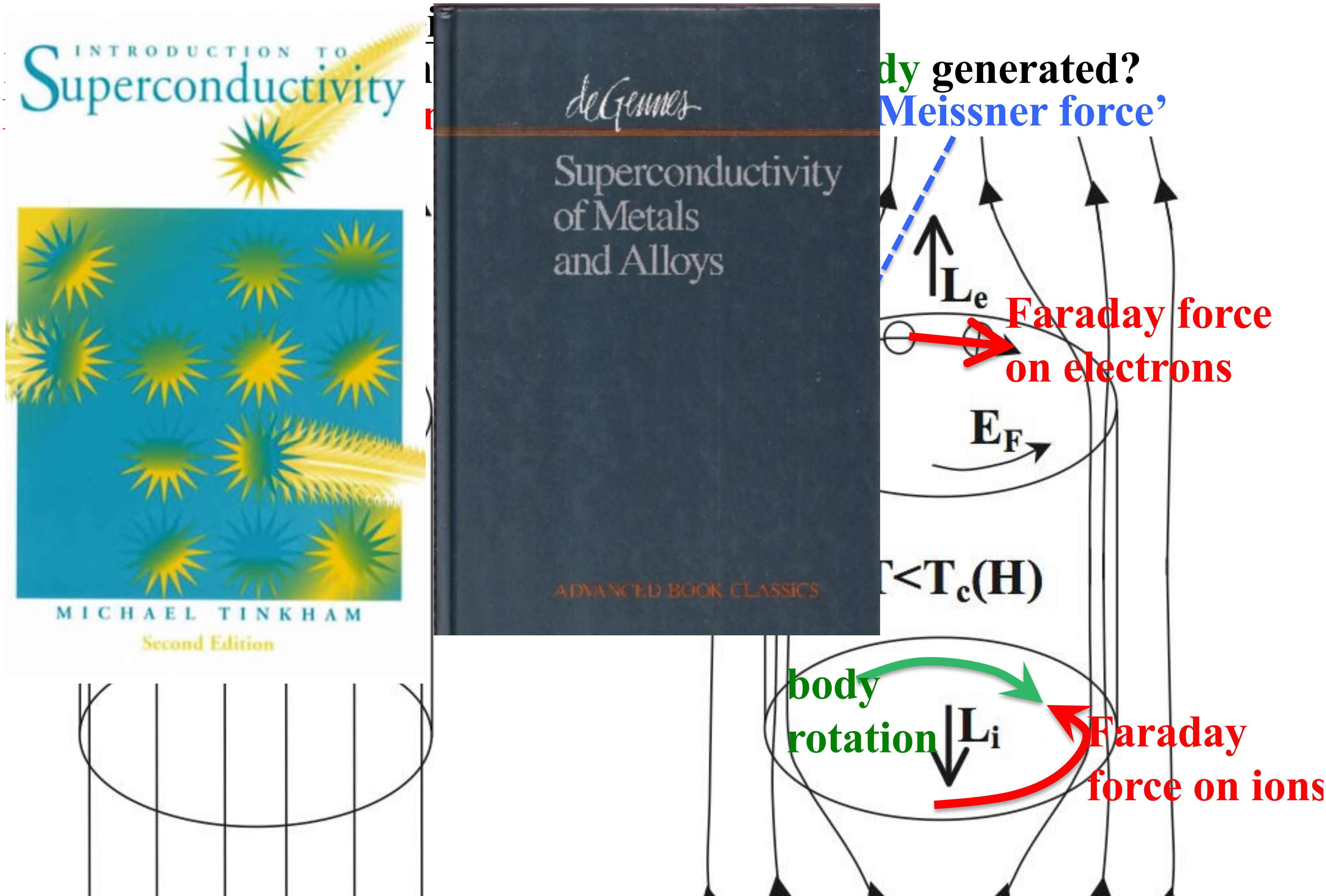
Meissner effect puzzle: momentum conservation

How is the momentum of the electrons and body generated?

Faraday field pushes in the wrong direction



The answer is in textbooks

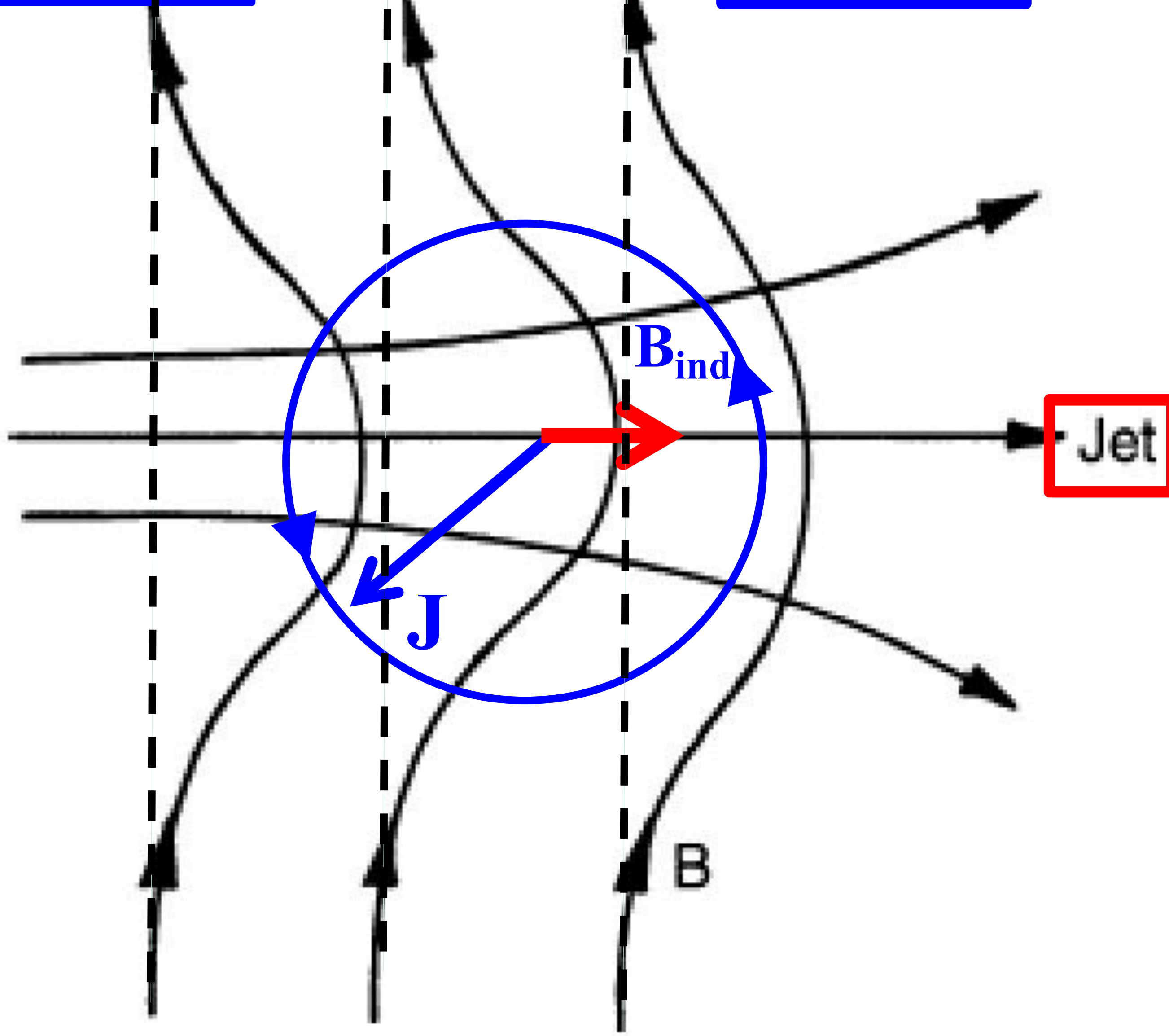


The answer is in textbooks

The answer is in textbooks

$$F_L = q\frac{\vec{v}}{c}\times\vec{B}$$

$$\vec{\nabla}\times\vec{B} = \frac{4\pi}{c}\vec{J}$$



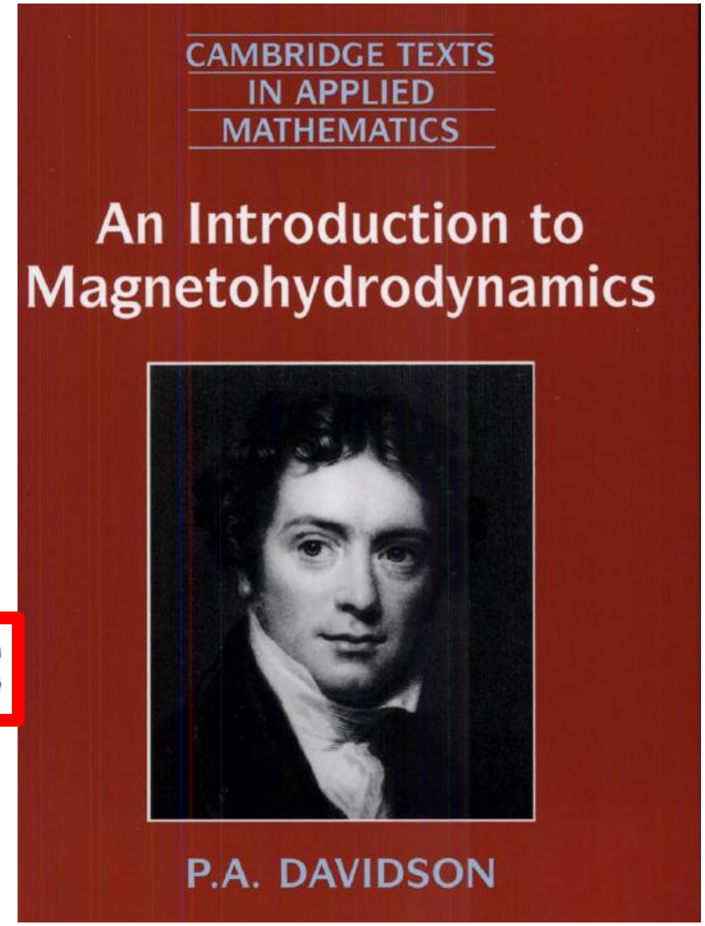
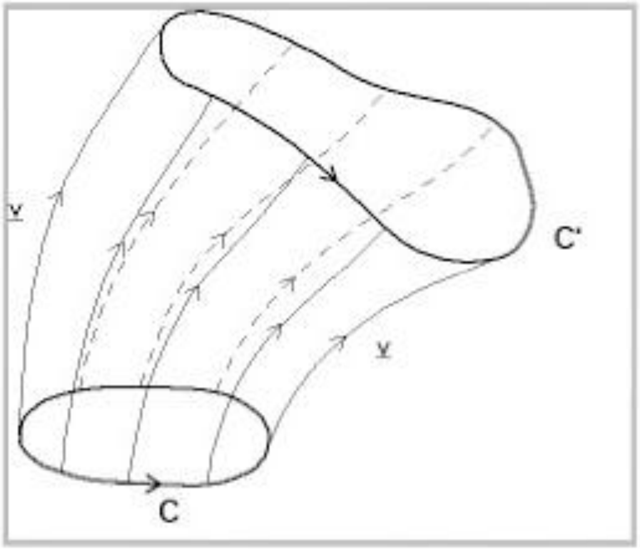


Figure 2.8 An example of Alfvén's theorem. Flow through a magnetic field causes the field lines to bow out. P. A. Davidson. Introduction to Magnetohydrodynamics

Outflows & Jets: Theory & Observations

MHD theory

3) MHD equations, flux freezing



Alfven's theorem (1943): " In a perfectly conducting fluid, magnetic field lines move with the fluid: field lines are "frozen" into the plasma."

--> A motion along magnetic field lines does not change the field, motions transverse to the field carry the field with them.

Integrate induction equation $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$. with Gauss' theorem $\int_V \nabla \cdot \mathbf{A} dV = \int_S \mathbf{A} \cdot d\mathbf{S}$,

(**S** is a closed surface enclosing volume **V**) and with Stokes' theorem $\int_S \nabla \times \mathbf{A} \cdot d\mathbf{S} = \int_C \mathbf{A} \cdot d\mathbf{l}$,

(**C** is a closed curve around the open surface **S**; $d\mathbf{S} = \hat{\mathbf{n}} dS$ with the outward unit normal $\hat{\mathbf{n}}$)

(i) Since for all time $\nabla \cdot \mathbf{B} = 0$ ==> $0 = \int_V \nabla \cdot \mathbf{B} dV = \int_S \mathbf{B} \cdot d\mathbf{S}$, $\forall t$, (closed surface **S**)

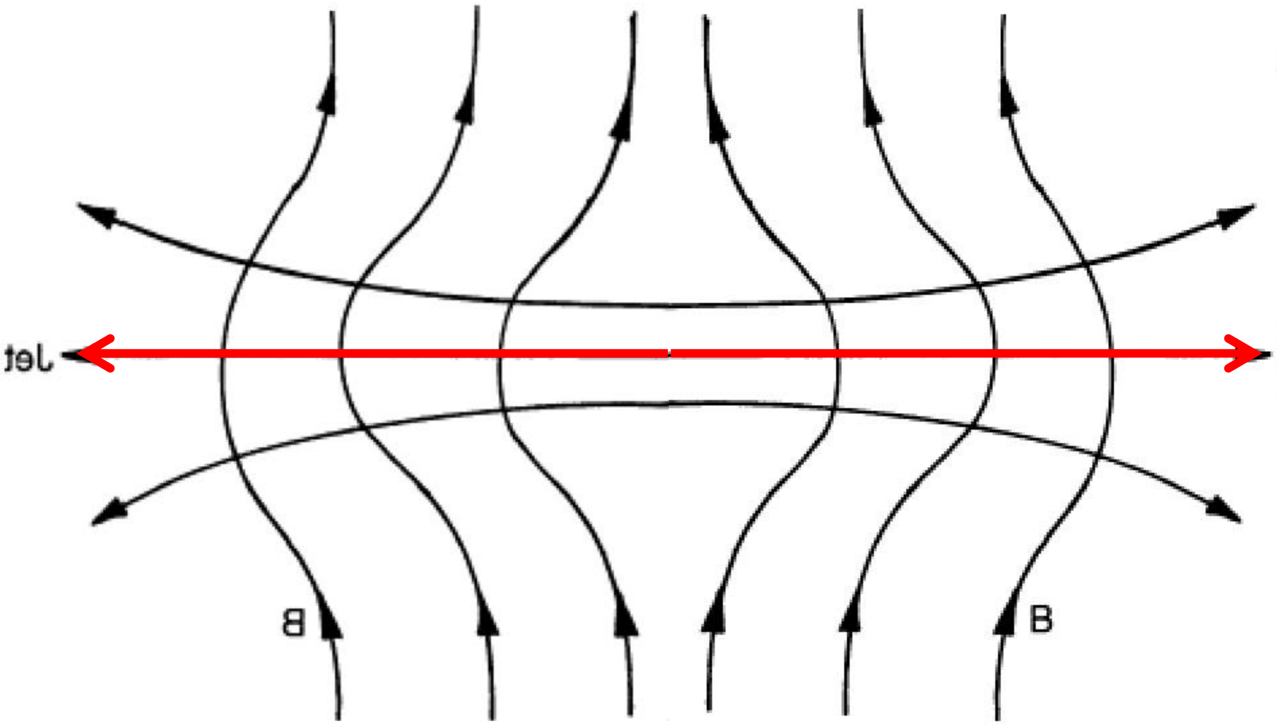
(ii) Time behaviour of the magnetic flux Φ through closed curve **C**, around an open surface **S**1:

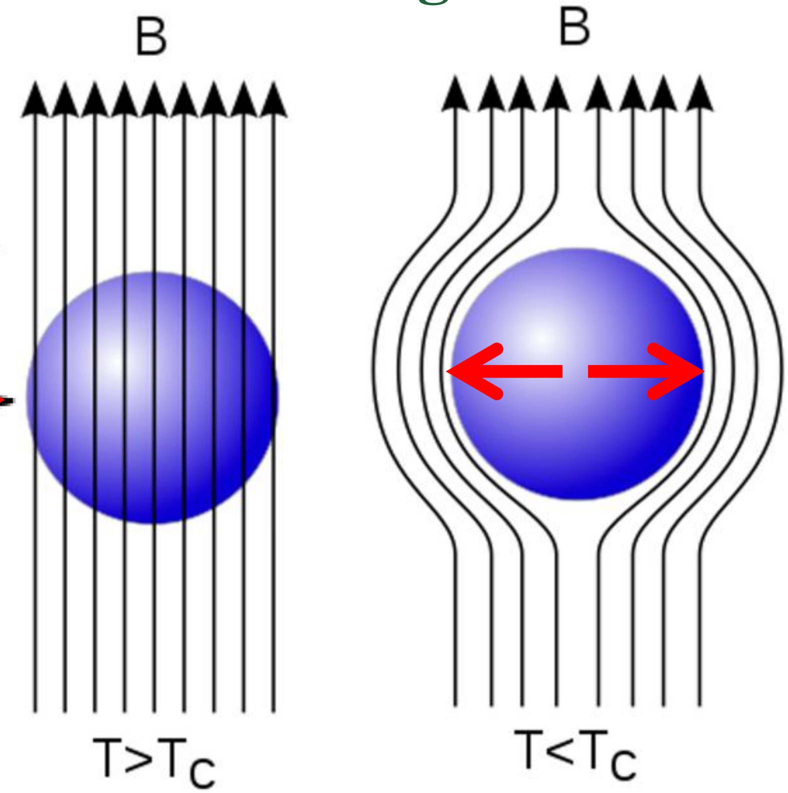
$$\Phi = \int_{S_1} \mathbf{B}(\mathbf{r}, t) \cdot d\mathbf{S}.$$

Now Φ changes in time since **B = B(t)** and since curve **C** changes in response to plasma motions.

www.mpia-hd.mpg.de/homes/fendt/Lehre/Lecture_OUT/lect_jets4.pdf

<u>Alfven's theorem:</u> **in a perfectly conducting fluid, the magnetic field is frozen into the fluid and moves along with it**





$$\boxed{\frac{d\vec{v}}{dt} = \frac{e}{m_e}\vec{E} + \frac{e}{m_e c}\vec{v}\times\vec{H} - \frac{\vec{\nabla}P}{\rho}}$$

equation of motion for perfectly conducting fluid

$$\boxed{\vec{\nabla}\times\vec{E} = -(1/c)\partial\vec{H}/\partial t}$$

Faraday's law

$$\frac{d\vec{v}}{dt} = \frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{v} = \boxed{\frac{\partial\vec{v}}{\partial t} + \vec{\nabla}\left(\frac{v^2}{2}\right) - \vec{v}\times(\vec{\nabla}\times\vec{v}) = \frac{e}{m_e}\vec{E} + \frac{e}{m_e c}\vec{v}\times\vec{H} - \frac{\vec{\nabla}P}{\rho}}$$

Taking the curl on both sides, and defining generalized vorticity:

$$\boxed{\vec{w}(\vec{r},t) = \vec{\nabla}\times\vec{v} + \frac{e}{m_e c}\vec{H}}$$

$$\boxed{\frac{\partial\vec{w}}{\partial t} = \vec{\nabla}\times(\vec{w}\times\vec{v})}$$

eq. of motion for w

$$\boxed{\vec{w} = 0 \implies \vec{\nabla}\times\vec{v} = -\frac{e}{m_e c}\vec{H} \quad \text{is London equation}}$$

Initially $\boxed{\vec{w}(\vec{r},t=0) = \frac{e}{m_e c}\vec{H}(\vec{r},t=0) = \vec{w}_0 \neq 0}$

$\vec{w}$ **has to evolve from $\vec{w}_0$ to 0**

In cylindrical coordinates $\vec{w}(\vec{r},t) = w(r,t)\hat{z}$

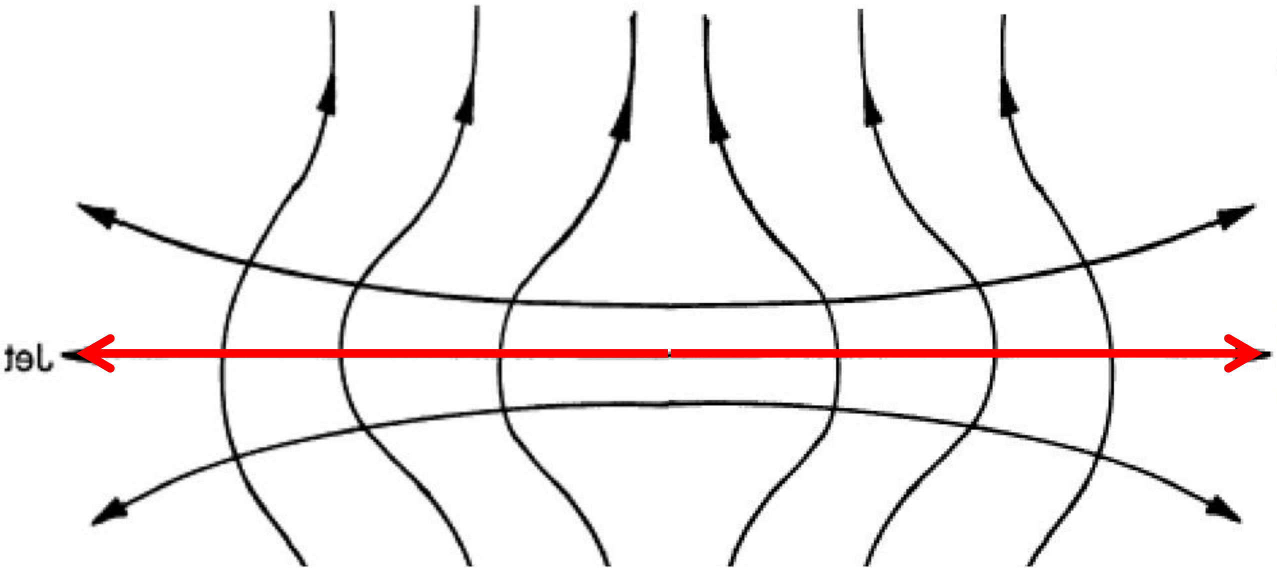
$$\boxed{\frac{\partial w}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rwv_r)}$$

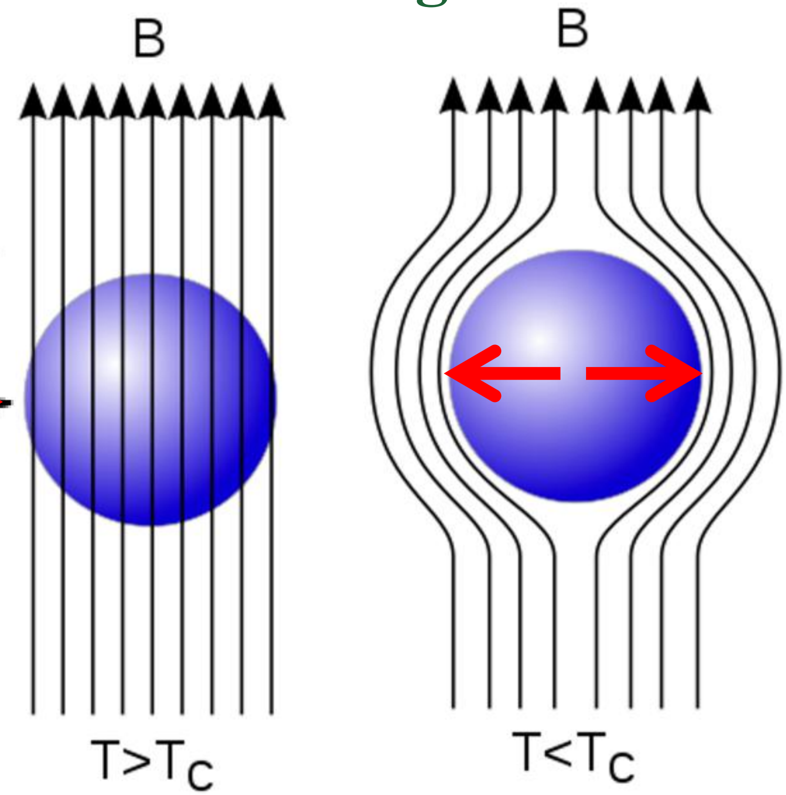
==> need <u>radial velocity</u> v_r for w to change with time

$$\boxed{\frac{\partial\vec{w}}{\partial t} = -\vec{\nabla}\cdot(w\vec{v}) \quad \text{continuity equation for generalized vorticity}}$$

***w* has to flow out radially**

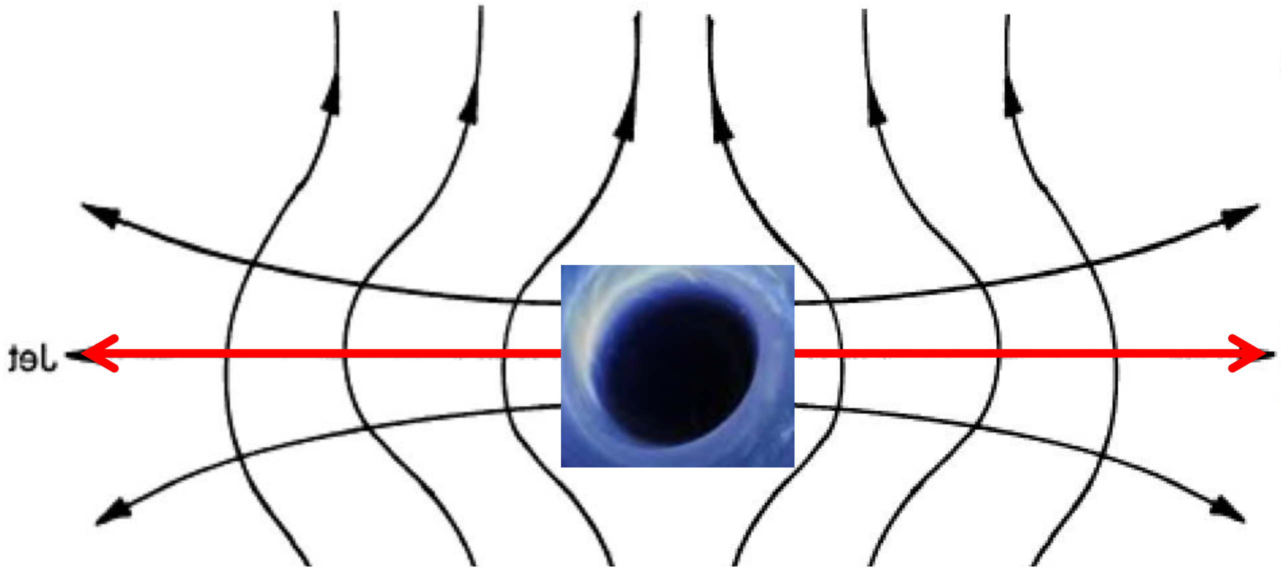
<u>Alfven's theorem:</u> **in a perfectly conducting fluid, the magnetic field is frozen into the fluid and moves along with it**

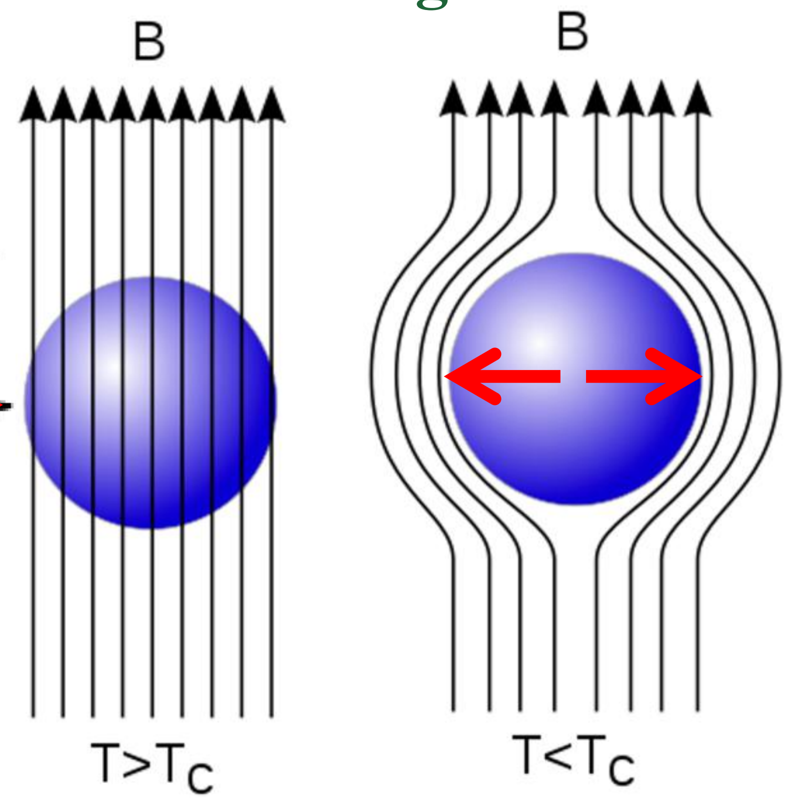




Why haven't plasma physicists explained the Meissner effect to solid state physicists long ago?

Alfven's theorem: in a perfectly conducting fluid, the magnetic field is frozen into the fluid and moves along with it





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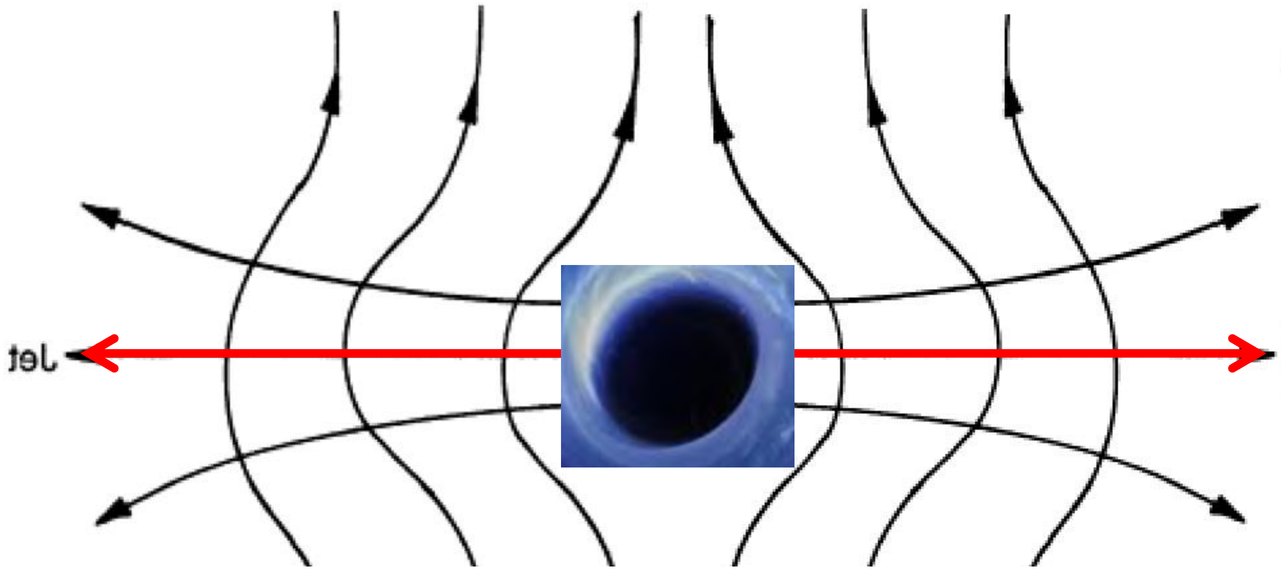
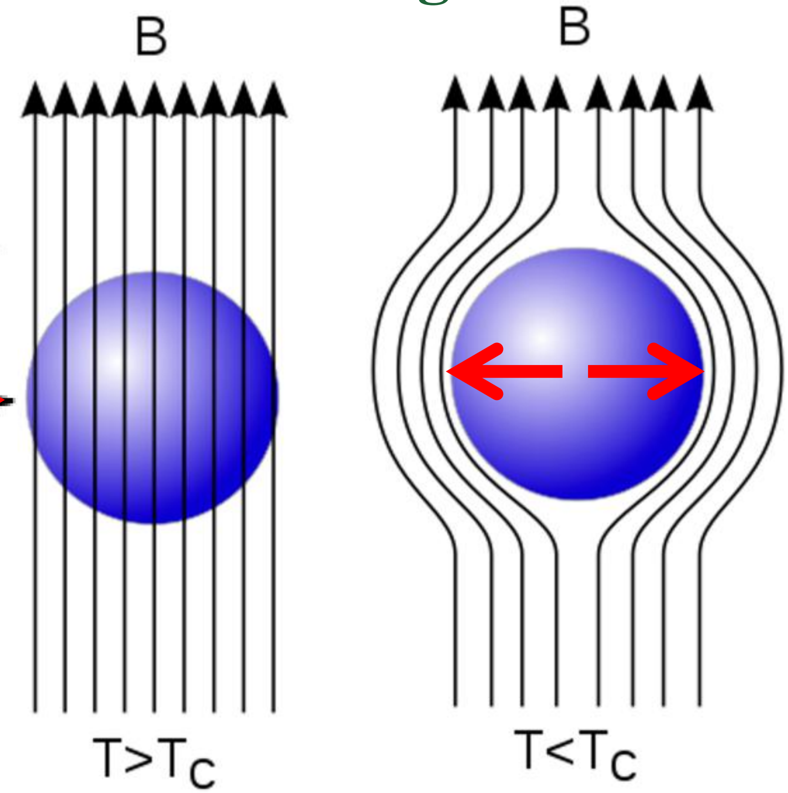




Why haven't plasma physicists explained the Meissner effect to solid state physicists long ago?

The 'fluid' flowing out has to carry zero charge and zero mass

The 'fluid' flowing out is electrons + holes

Holes flowing out = mass flowing IN

Theory of hole superconductivity

1988

For ALL superconductors

2024

References: http://physics.ucsd.edu/~jorge/hole.html

Collaborators: Frank Marsiglio; S. Tang, X. Q. Hong, H.Q. Lin

* Key to the cuprates is $O^{=}$
* Key to Fe-As compounds is As^{3-}
* Key to MgB_2 is B^-

Negatively charged anions

Hole conduction necessary

* Superconductivity is driven by lowering of kinetic energy

Models:
* Dynamic Hubbard models
* Correlated hopping model

Experimental support:
* T_c versus hole concentration
* Tunneling asymmetry (theory 1989, exp. 1995-2012)
* Optical sum rule violation (theory 1992, exp. 1999-2012)

* Explains dynamics of the Meissner effect- BCS can't

Fig. 5.1 The hole is denoted by the dotted circle. It moves from the second to the third place in the row, i.e. to the right. Equivalently, an electron moved to the left, from third to second place.

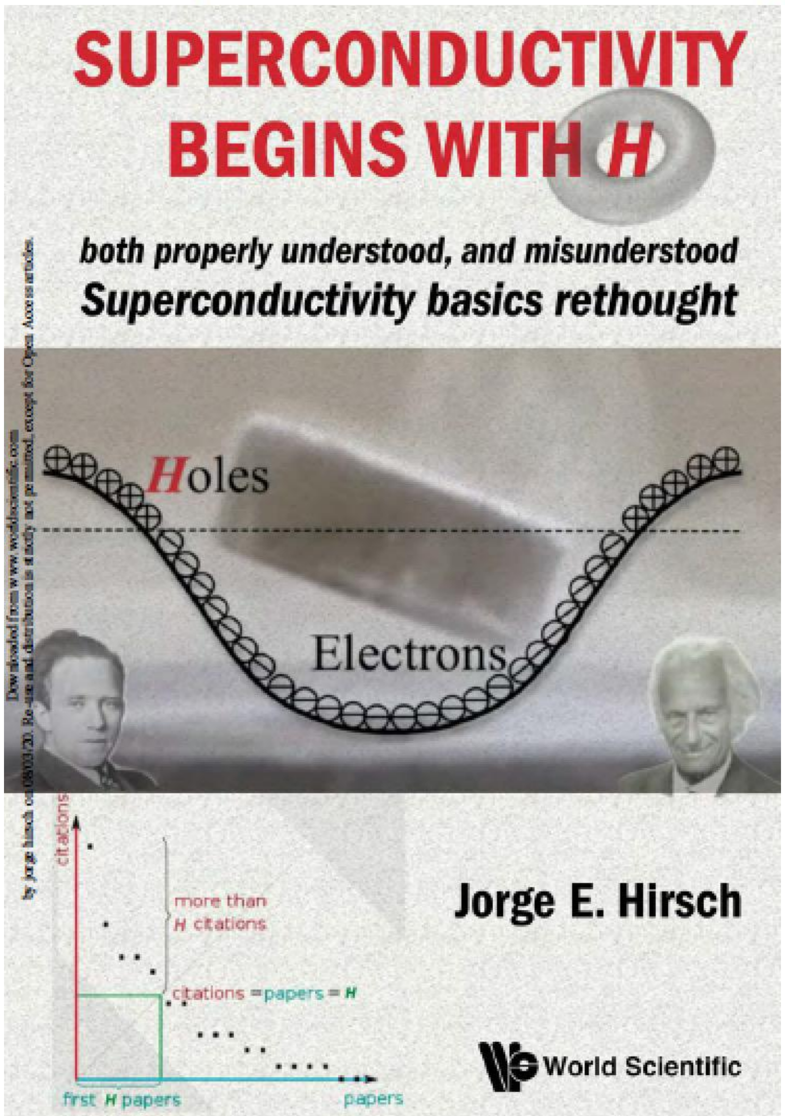


Fig. 5.1 The hole is denoted by the dotted circle. It moves from the second to the third place in the row, i.e. to the right. Equivalently, an electron moved to the left, from third to second place.

Electrons and Holes in Semiconductors

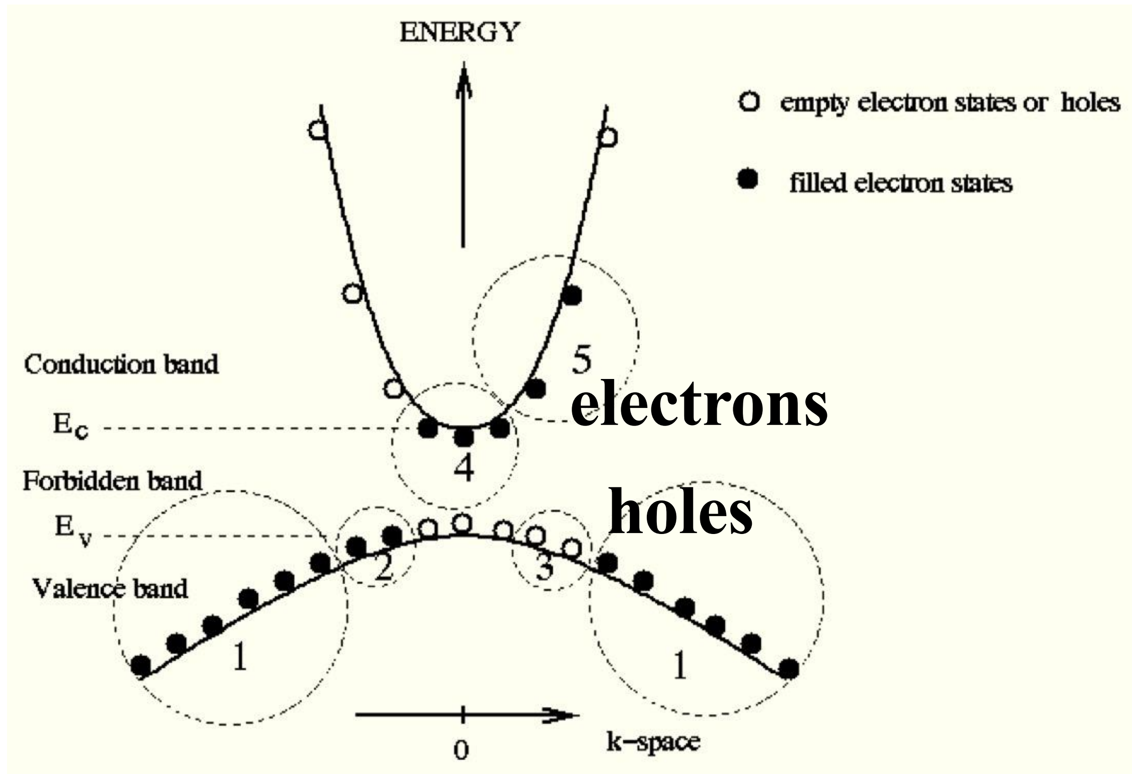
WITH APPLICATIONS TO TRANSISTOR ELECTRONICS

By

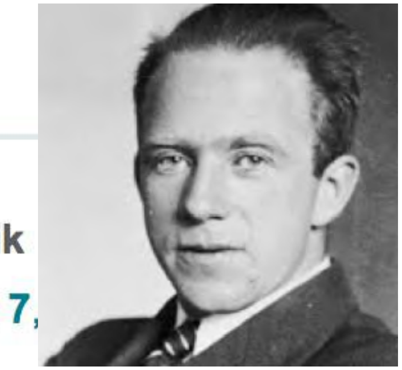
WILLIAM SHOCKLEY

Member of the Technical Staff

BELL TELEPHONE LABORATORIES, INC.



Zum Paulischen Ausschließungsprinzip **1931**



W. Heisenberg

Issue

Annalen der Physik
Volume 402, Issue 7,
888–904, 1931

DOI: 10.1002/andp.19314020710

The conductivity in metals with a small number of holes can then in every respect be described as the conductivity in metals with a small number of positive conduction electrons. From this follows directly the anomalous Hall effect for such metals.

Elektronentheorie der Metalle.

Von R. PEIERLS, Zürich. **(1932)**

A band that has only a few electrons behaves, in every respect, like a band where there is only room left for a few electrons, with the difference, that the empty places have to be assigned an opposite – i.e. positive – charge. Since the conductivity is independent of the sign of the charge, the difference will not be apparent in the conductivity.

Electron-hole symmetry in solids

(Ashcroft and Mermin book)

R_H=Hall coefficient

Holes

One of the most impressive achievements of the semiclassical model is its explanation for phenomena that free electron theory can account for only if the carriers have a positive charge. The most notable of these is the anomalous sign of the Hall coefficient in some metals (see page 58). There are three important points to grasp in understanding how the electrons in a band can contribute to currents in a manner suggestive of positively charged carriers:

1. Since electrons in a volume element $d\mathbf{k}$ about $\mathbf{k}$ contribute $-e\mathbf{v}(\mathbf{k})d\mathbf{k}/4\pi^3$ to the current density, the contribution of all the electrons in a given band to the current density will be

$$\mathbf{j} = (-e)\int_{\text{occupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}), \tag{12.19}$$

where the integral is over all occupied levels in the band.[23] By exploiting the fact that a completely filled band carries no current,

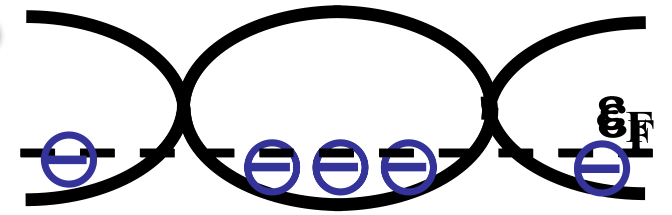
$$0 = \int_{\text{zone}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}) = \int_{\text{occupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}) + \int_{\text{unoccupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}), \tag{12.20}$$

we can equally well write (12.19) in the form:

$$\mathbf{j} = (+e)\int_{\text{unoccupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}). \tag{12.21}$$

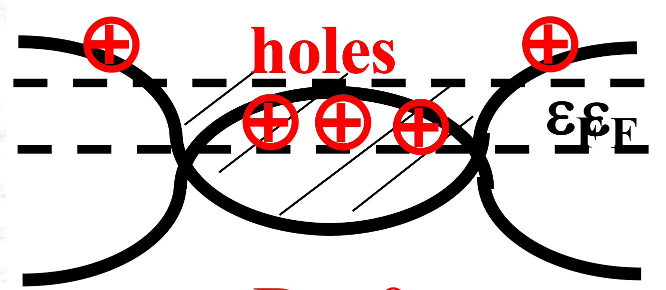
Thus *the current produced by occupying with electrons a specified set of levels is precisely the same as the current that would be produced if* (a) *the specified levels were unoccupied and* (b) *all other levels in the band were occupied but with particles of charge* $+e$ *(opposite to the electronic charge).*

Thus, even though the only charge carriers are electrons, we may, whenever it is convenient, consider the current to be carried entirely by fictitious particles of positive charge that fill all those levels in the band that are unoccupied by electrons.[24] The fictitious particles are called *holes*.



electrons

$R_H<0$



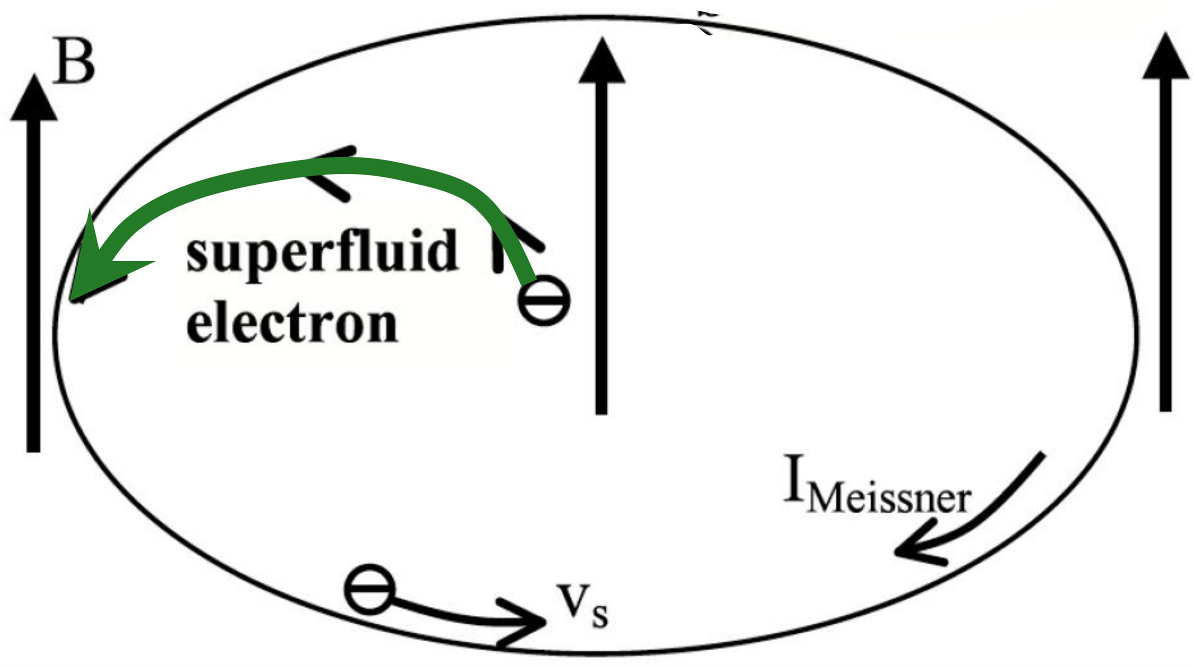
$R_H>0$

The simple physics that explains the Meissner effect:

1) **Electrons flow radially outward** (generate Meissner current)

$$\vec{F}_B = \frac{e}{c}\vec{v} \times \vec{B}$$

Lorentz force



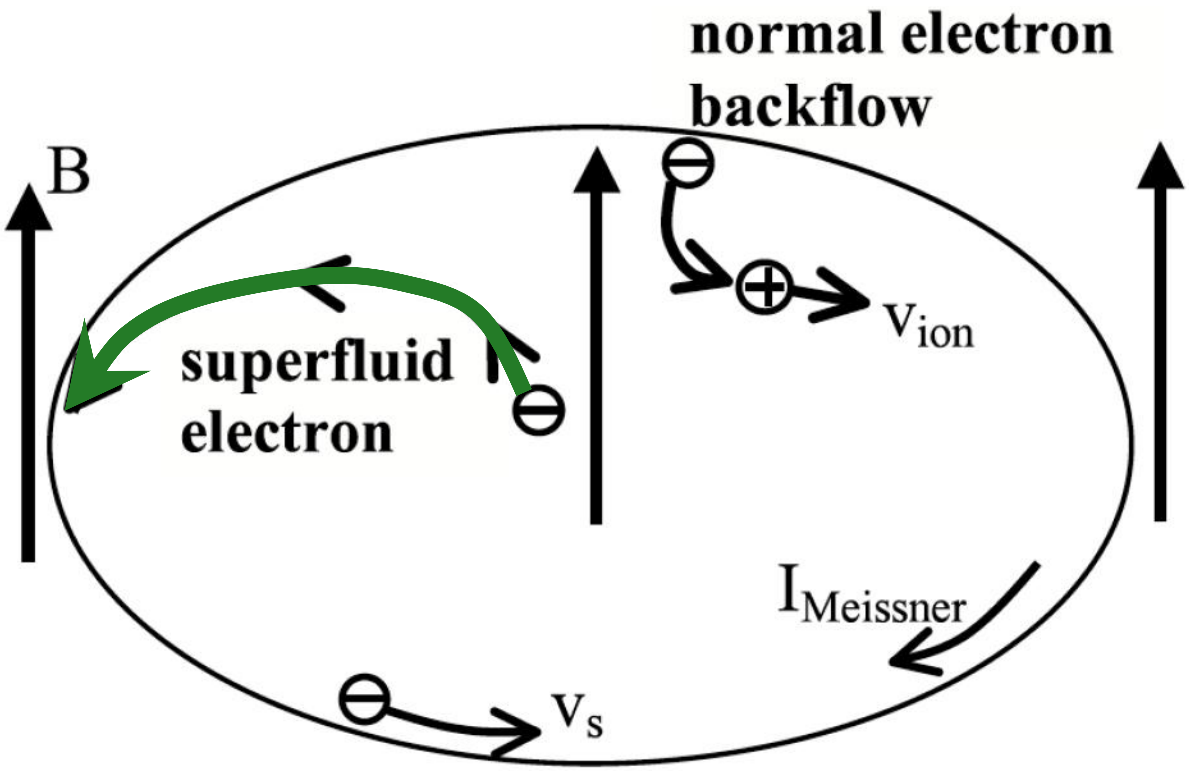
The simple physics that explains the Meissner effect:

1) Electrons flow radially outward (generate Meissner current)

$$\vec{F}_B = \frac{e}{c}\vec{v} \times \vec{B}$$

Lorentz force

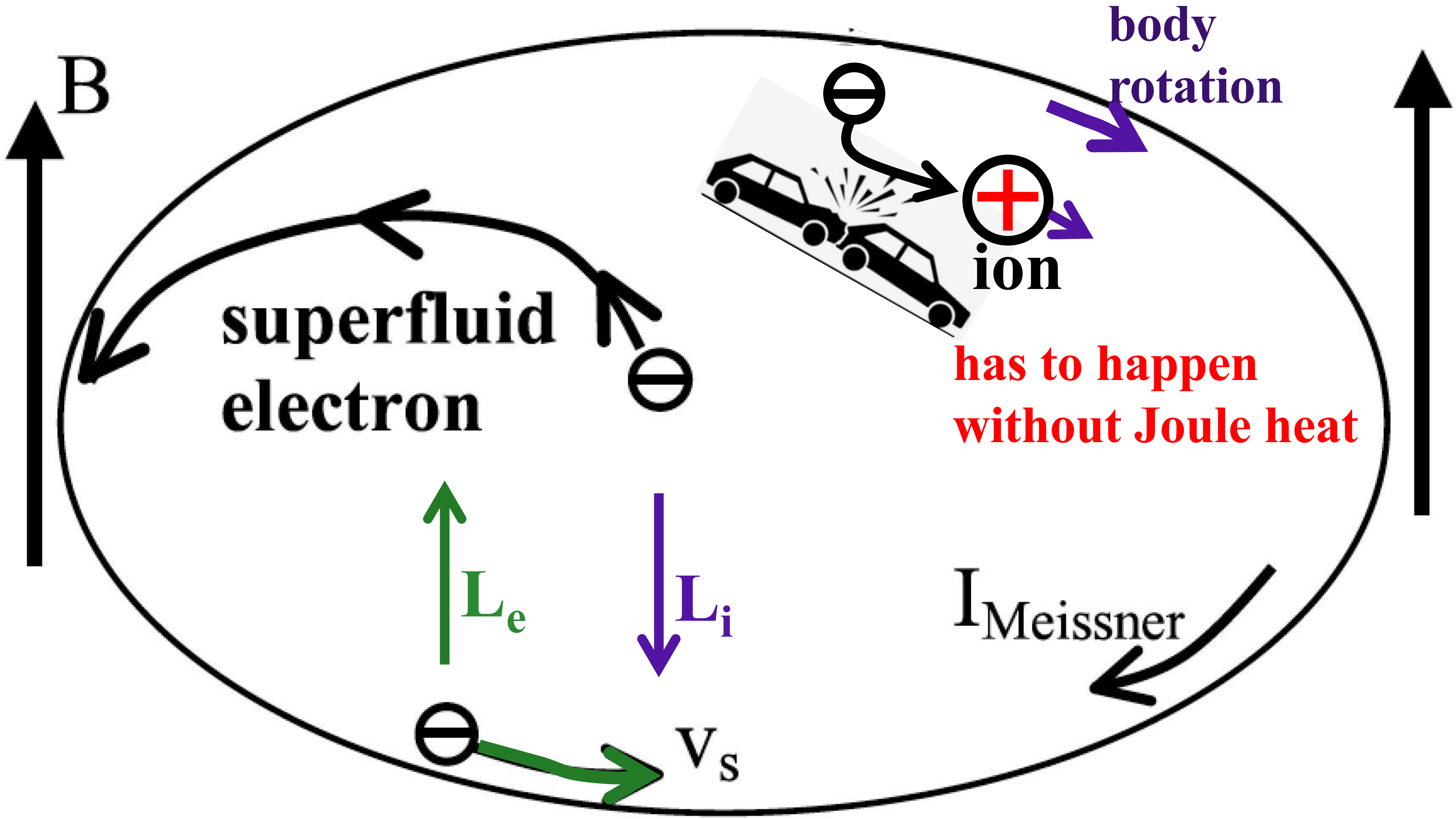
2) Backflow of normal electrons transfers momentum to the body



The transition is reversible

$$F_L = q\frac{\vec{v}}{c}\times\vec{B}$$

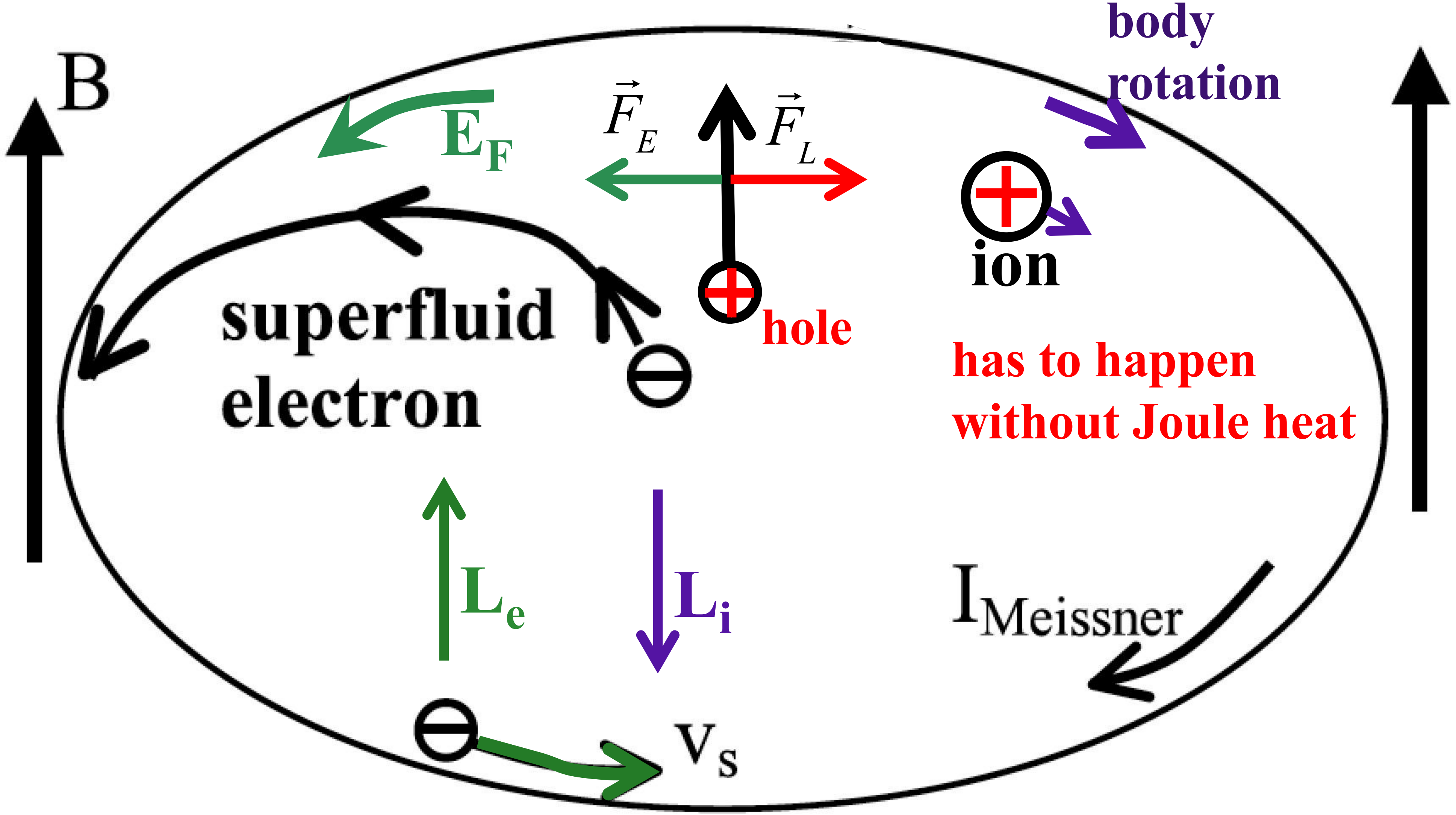
Normal electron backflow
get deflected by Lorentz force
transfer azimuthal momentum to ions
angular momentum is conserved
Meissner current is not cancelled



Explanation

$$\boxed{F_L = q\frac{\vec{v}}{c}\times\vec{B}}$$

Normal hole outflow
Lorentz force canceled by Faraday force
holes move radially out
transfer azimuthal momentum to ions
without collisions!

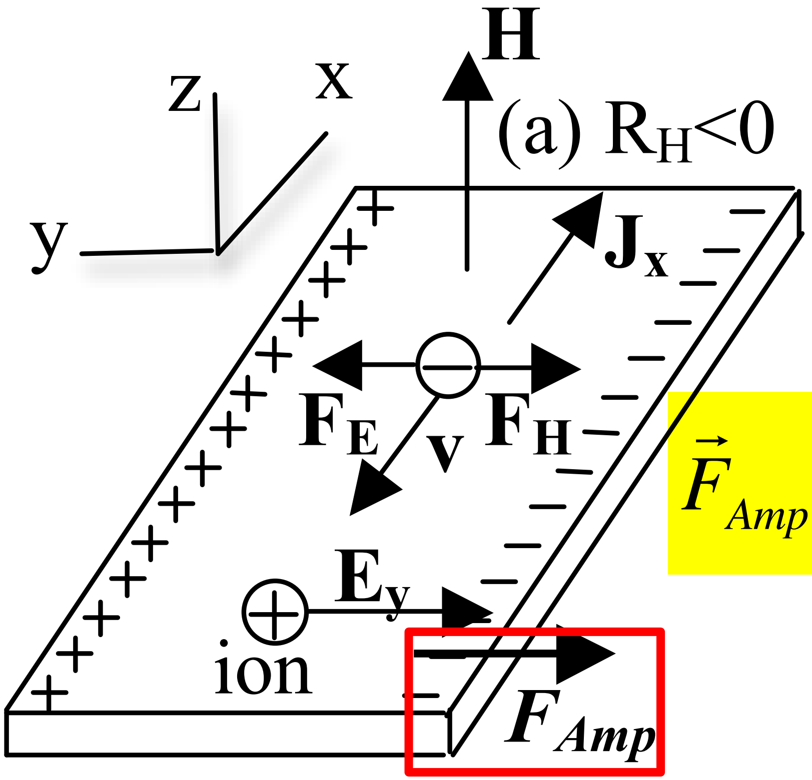


What is the difference between electrons and holes?

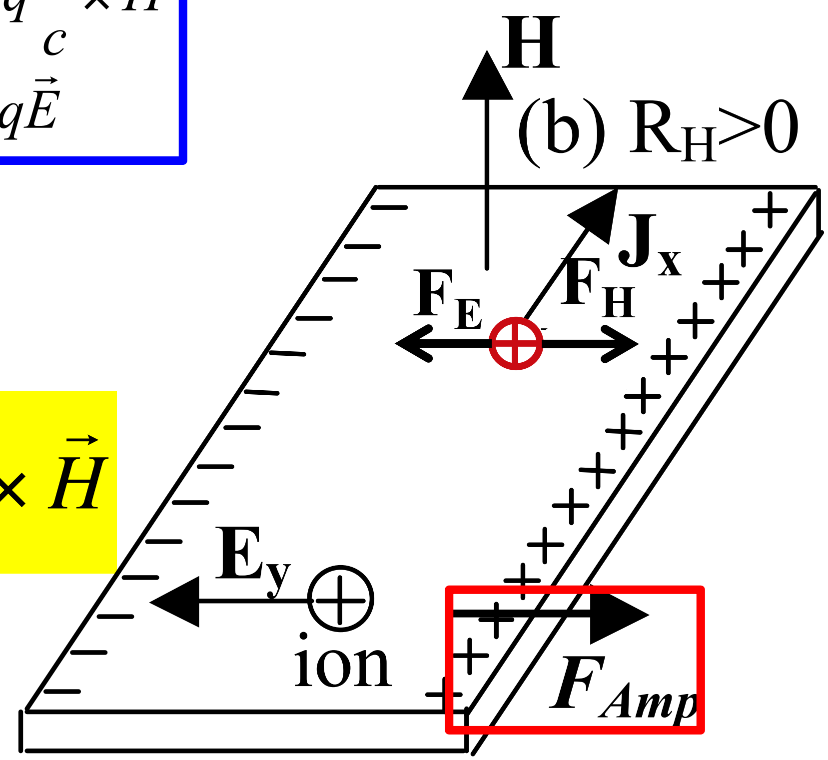
Hall effect

$$\vec{F}_H = q\frac{\vec{v}}{c} \times \vec{H}$$

$$\vec{F}_E = q\vec{E}$$



$$\vec{F}_{Amp} = \frac{I}{c}\vec{L} \times \vec{H}$$



F_{Amp} = ⊕ $\xrightarrow{\;}$ E_y

no net transverse force on electrons

no other force on ions

$F_{Amp} \neq$ ⊕ $\xleftarrow{\;}$ E_y

no net transverse force on holes

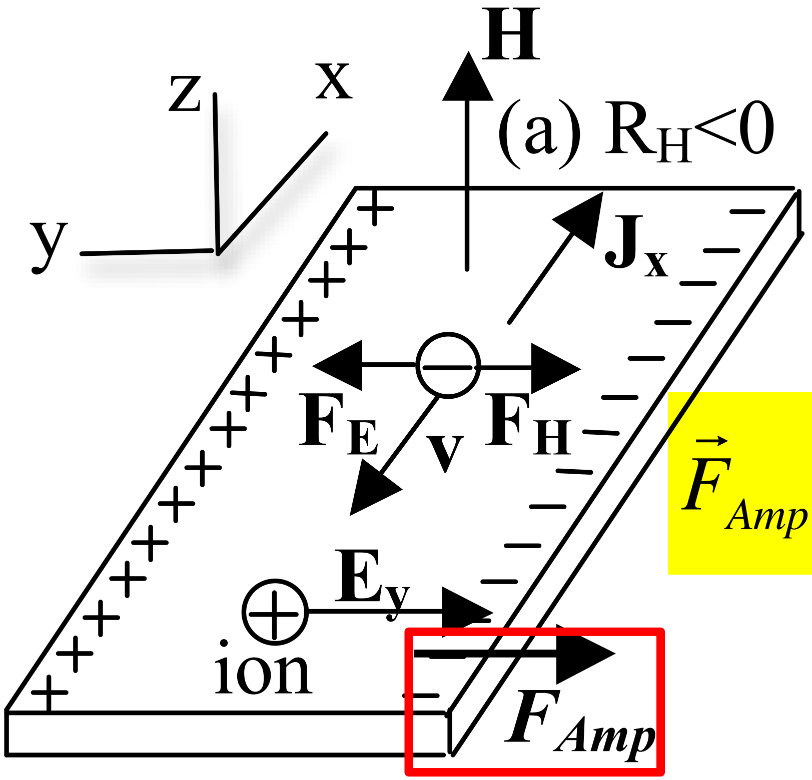
there is another force on ions

What is the difference between electrons and holes?

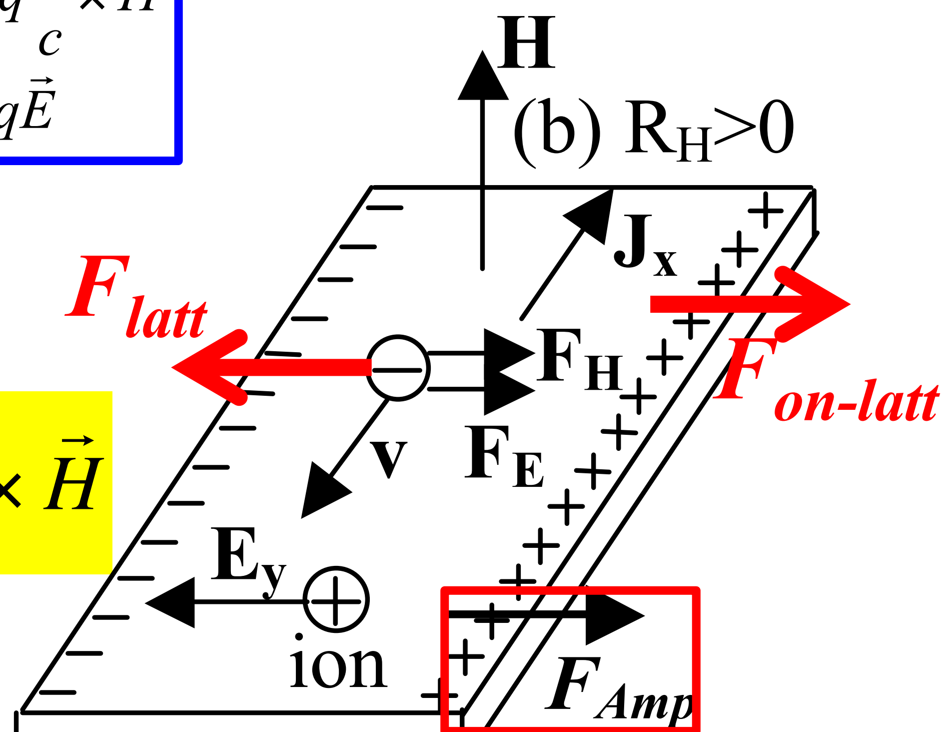
Hall effect

$$\vec{F}_H = q\frac{\vec{v}}{c}\times\vec{H}$$

$$\vec{F}_E = q\vec{E}$$



$$\vec{F}_{Amp} = \frac{I}{c}\vec{L}\times\vec{H}$$



electrons transfer momentum to the body without dissipation!

$$F_{Amp} = \oplus \xrightarrow{\quad E_y \quad}$$

no net transverse force on electrons

no other force on ions

$$F_{Amp} \neq \oplus \xleftarrow{\quad E_y \quad}$$

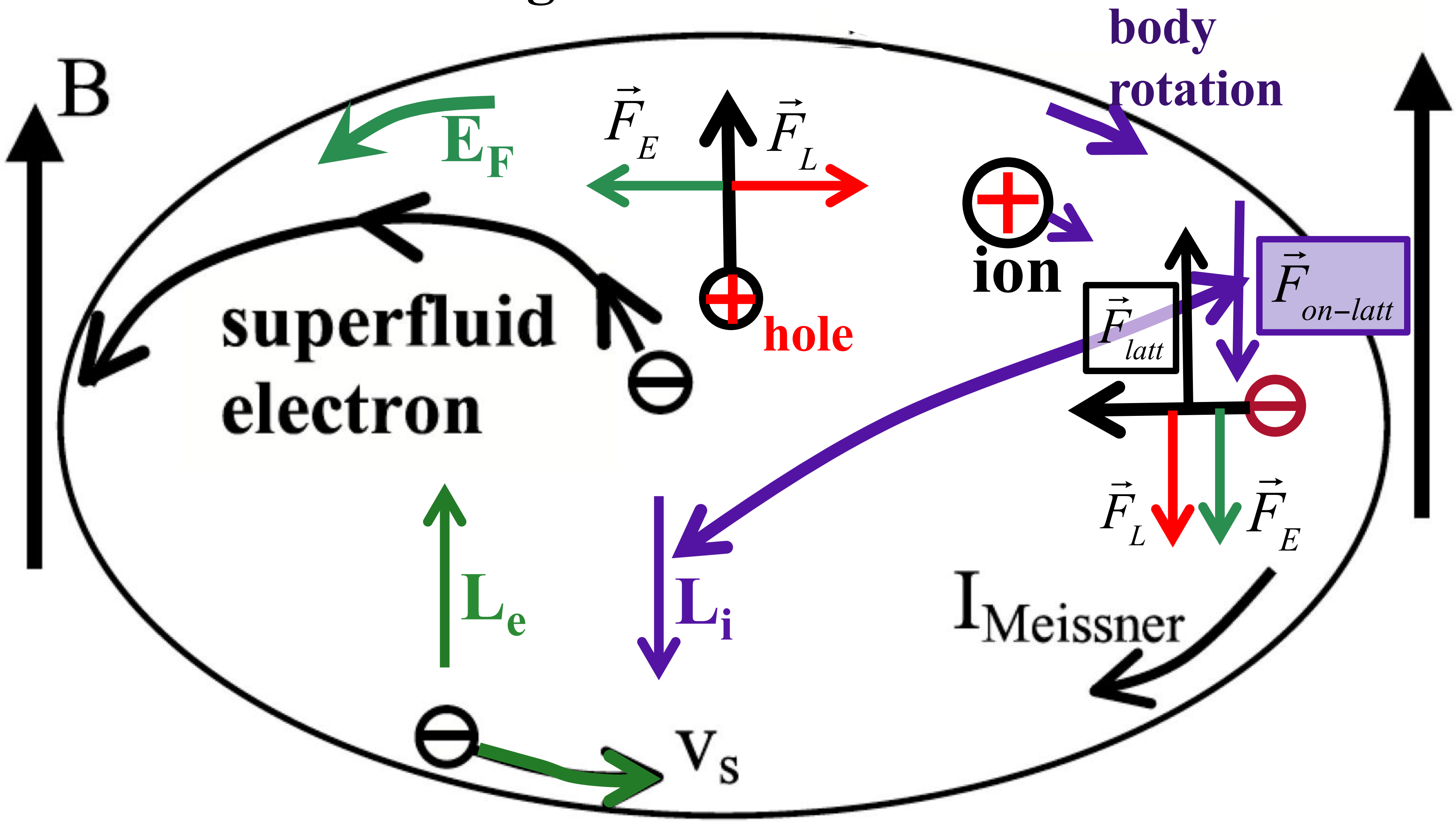
no net transverse force on electrons?

there is another force on ions

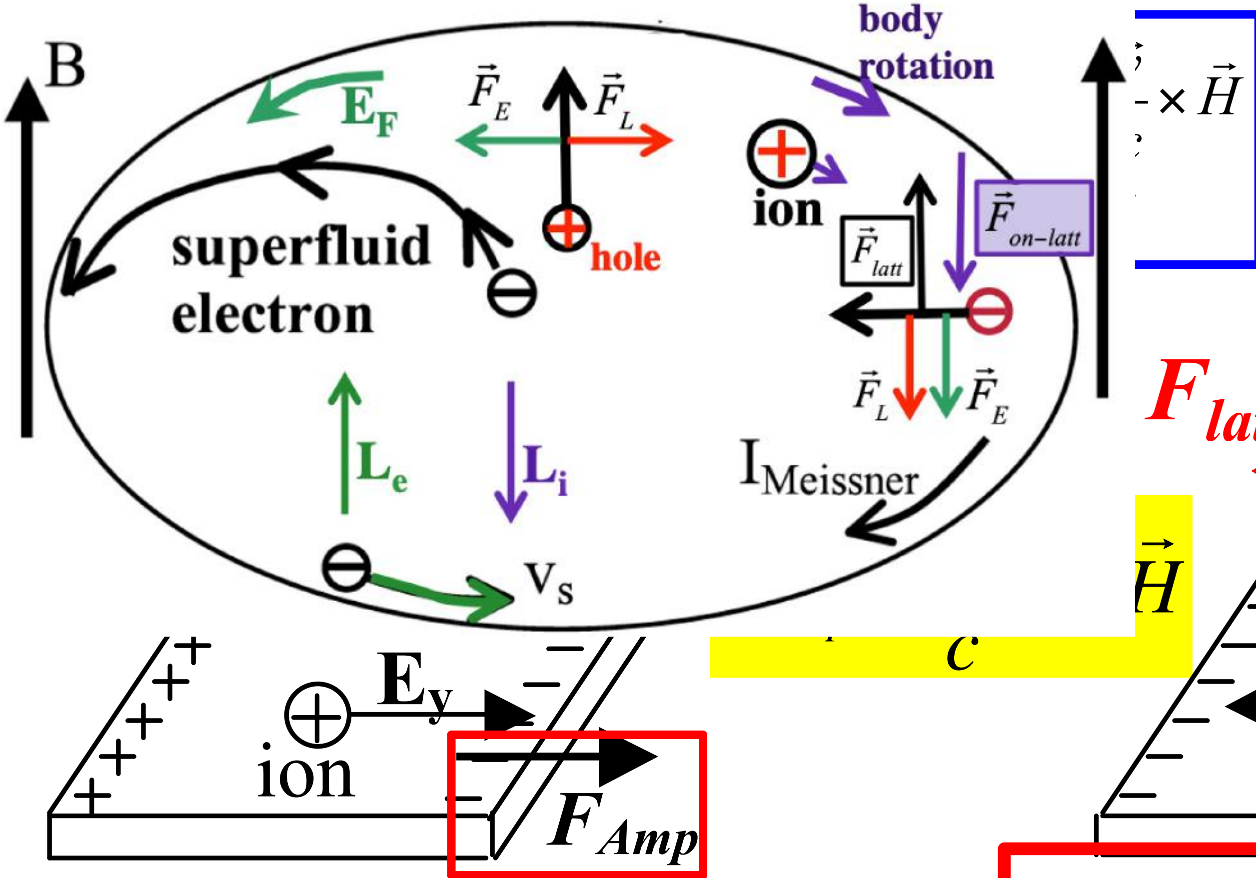
Explanation

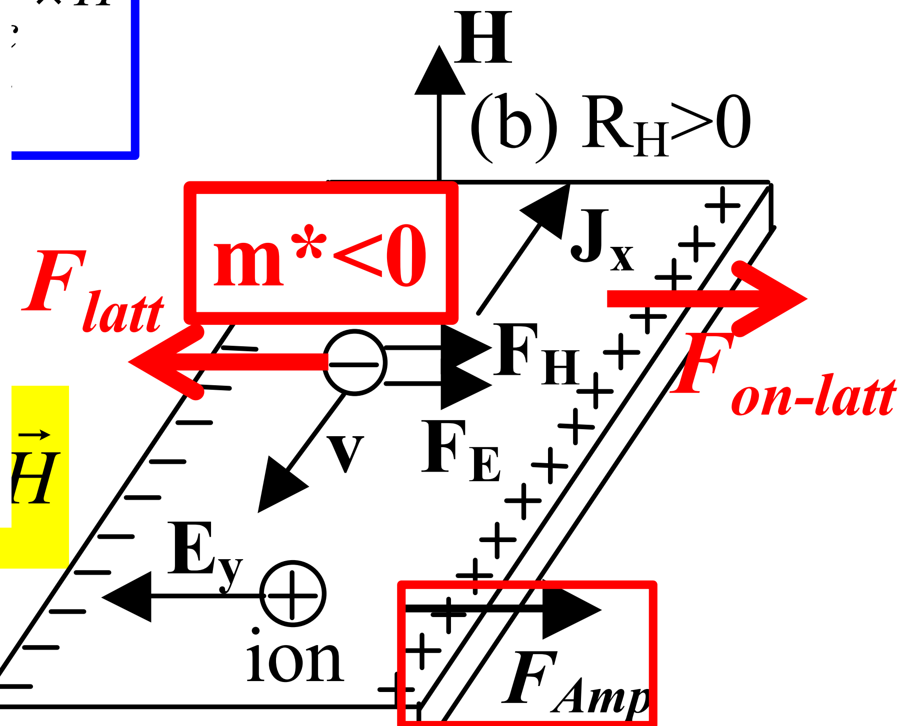
$$F_L = q\frac{\vec{v}}{c}\times\vec{B}$$

Normal antibonding electron backflow move radially in transfer azimuthal momentum to ions without collisions! angular momentum is conserved



What is the difference between electrons and holes?





electrons transfer momentum to the body without dissipation!

$F_{Amp} = \oplus \xrightarrow{E_y}$

no net transverse force on electrons

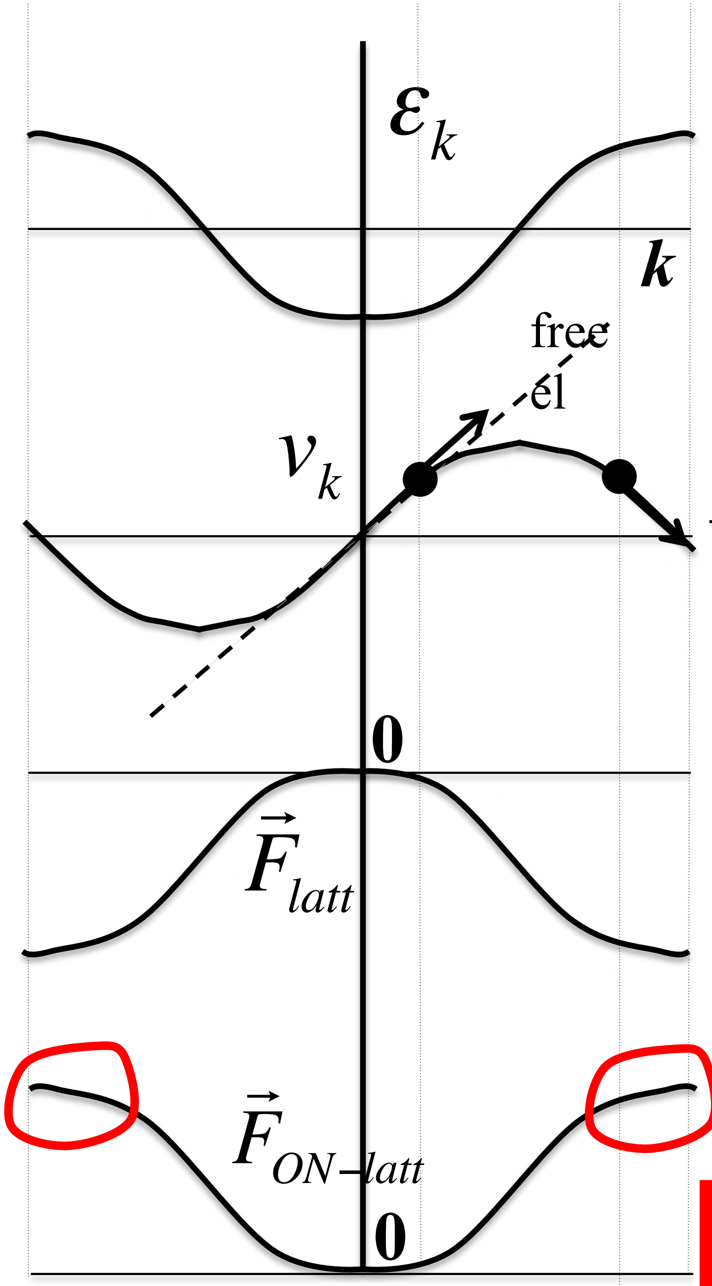
no other force on ions

$F_{Amp} \neq \oplus \xleftarrow{E_y}$

no net transverse force on electrons?

there is another force on ions

Semiclassical dynamics



$$\frac{d}{dt}(\hbar\vec{k}) = \vec{F}_{ext} = e\vec{E} + \frac{e}{c}\vec{v}\times\vec{H}$$

$$\boxed{v_k = \frac{1}{\hbar}\frac{\partial\varepsilon_k}{\partial k}}$$

$$\frac{d}{dt}(m_e\vec{v}_k) = \vec{F}_{ext} + \vec{F}_{latt}$$

$\vec{F}_{latt}$ = **force exerted by lattice on electron**

$$\frac{d}{dt}(m_e\vec{v}_k) = \frac{d}{d(\hbar k)}(m_e\vec{v}_k)\times\frac{d(\hbar k)}{dt} = \frac{d}{d(\hbar k)}(m_e\vec{v}_k)\times\vec{F}_{ext}$$

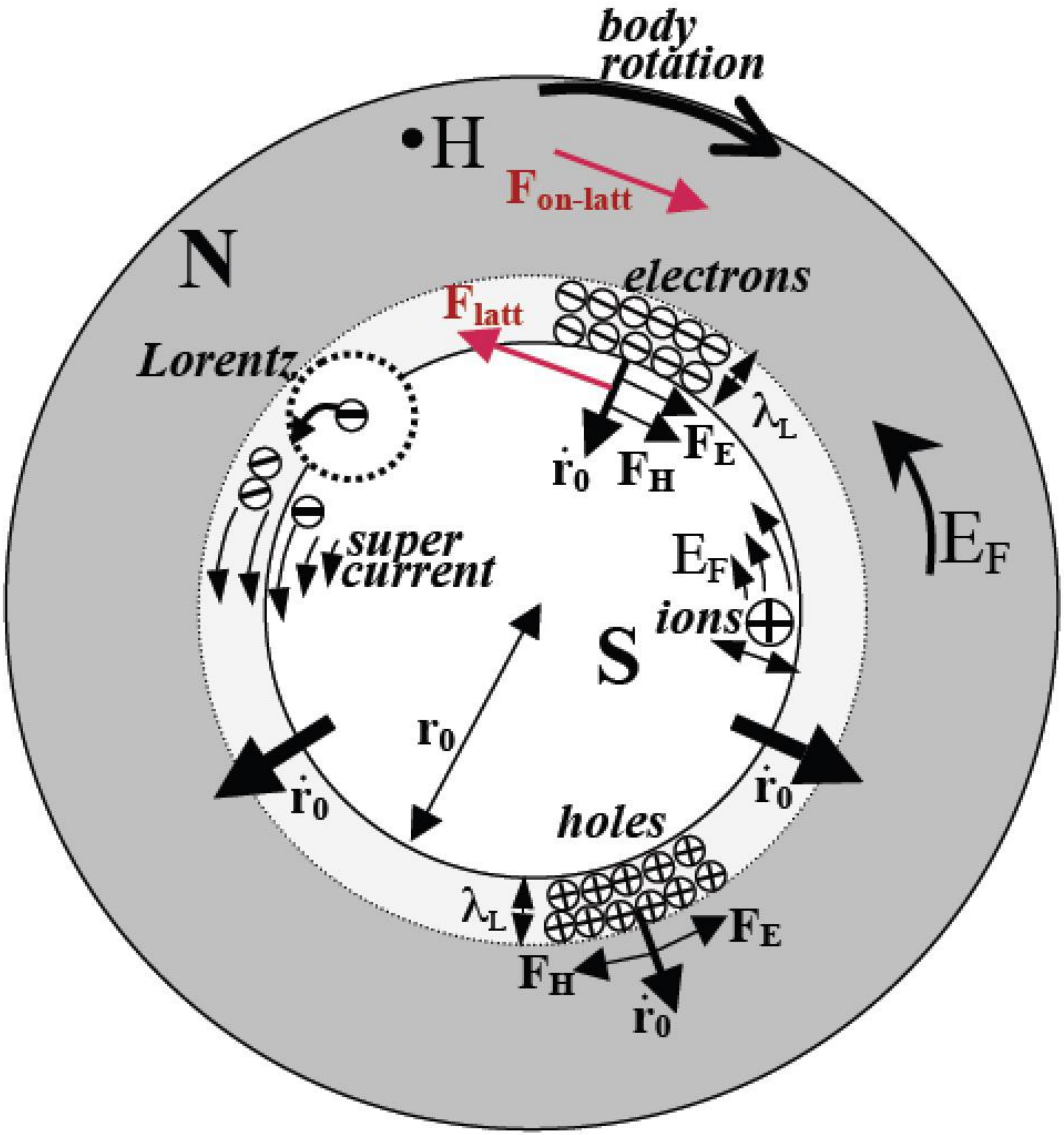
$$\boxed{\frac{d}{d(\hbar k)}(m_e\vec{v}_k) = m_e\frac{1}{\hbar^2}\frac{\partial^2\varepsilon_k}{\partial k\partial k}}$$

$$m_e\frac{1}{\hbar^2}\frac{\partial^2\varepsilon_k}{\partial k\partial k}\times\vec{F}_{ext} = \vec{F}_{ext} + \vec{F}_{latt}$$

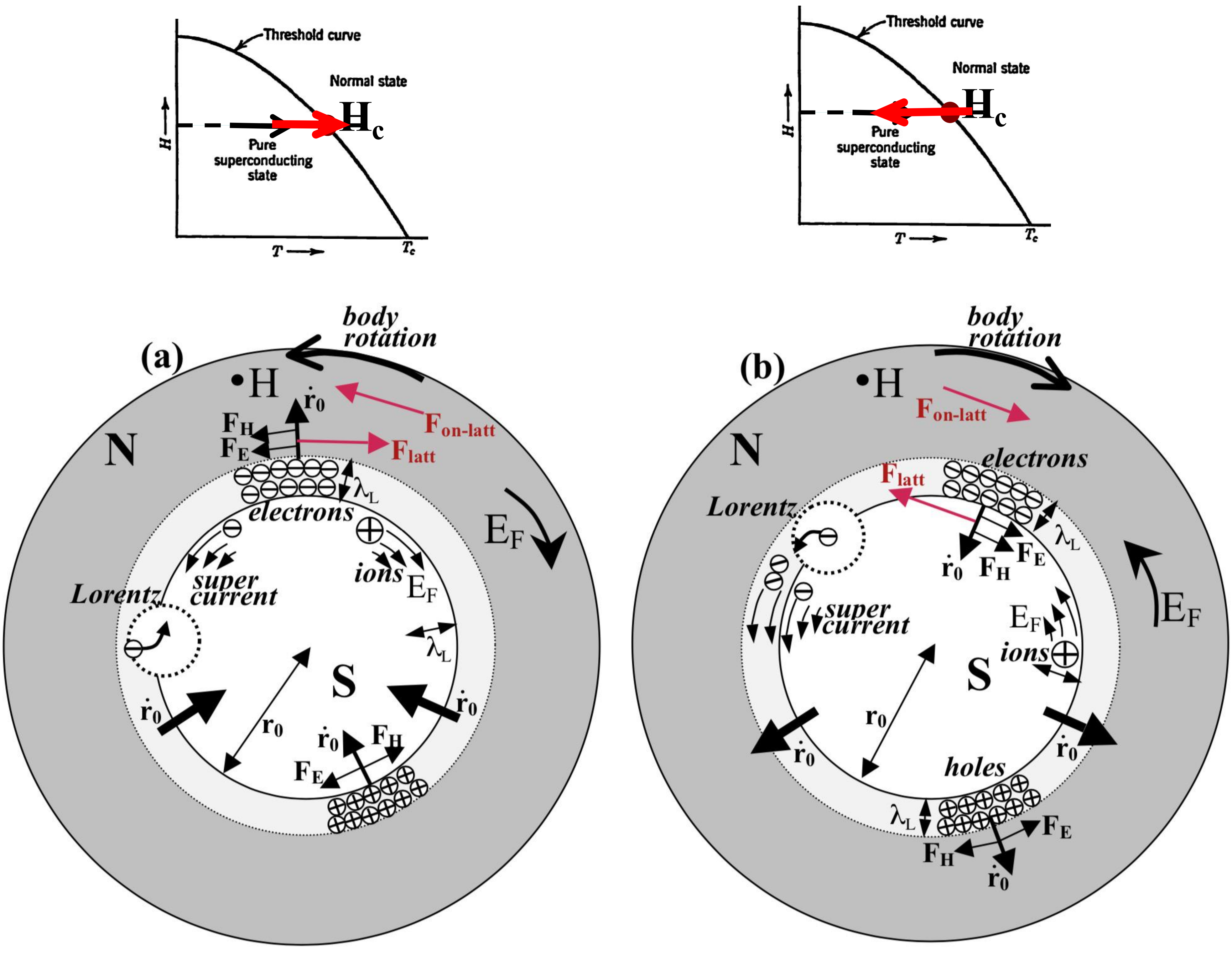
$$\vec{F}_{latt} = (m_e\frac{1}{\hbar^2}\frac{\partial^2\varepsilon_k}{\partial k\partial k} - 1)\times\vec{F}_{ext}$$

$$\boxed{\vec{F}_{ON-latt} = -\vec{F}_{latt} = (1 - m_e\frac{1}{\hbar^2}\frac{\partial^2\varepsilon_k}{\partial k\partial k})\times\vec{F}_{ext}}$$

==> electrons near the top of the band exert a large force ON the lattice ==> transfer momentum to the lattice



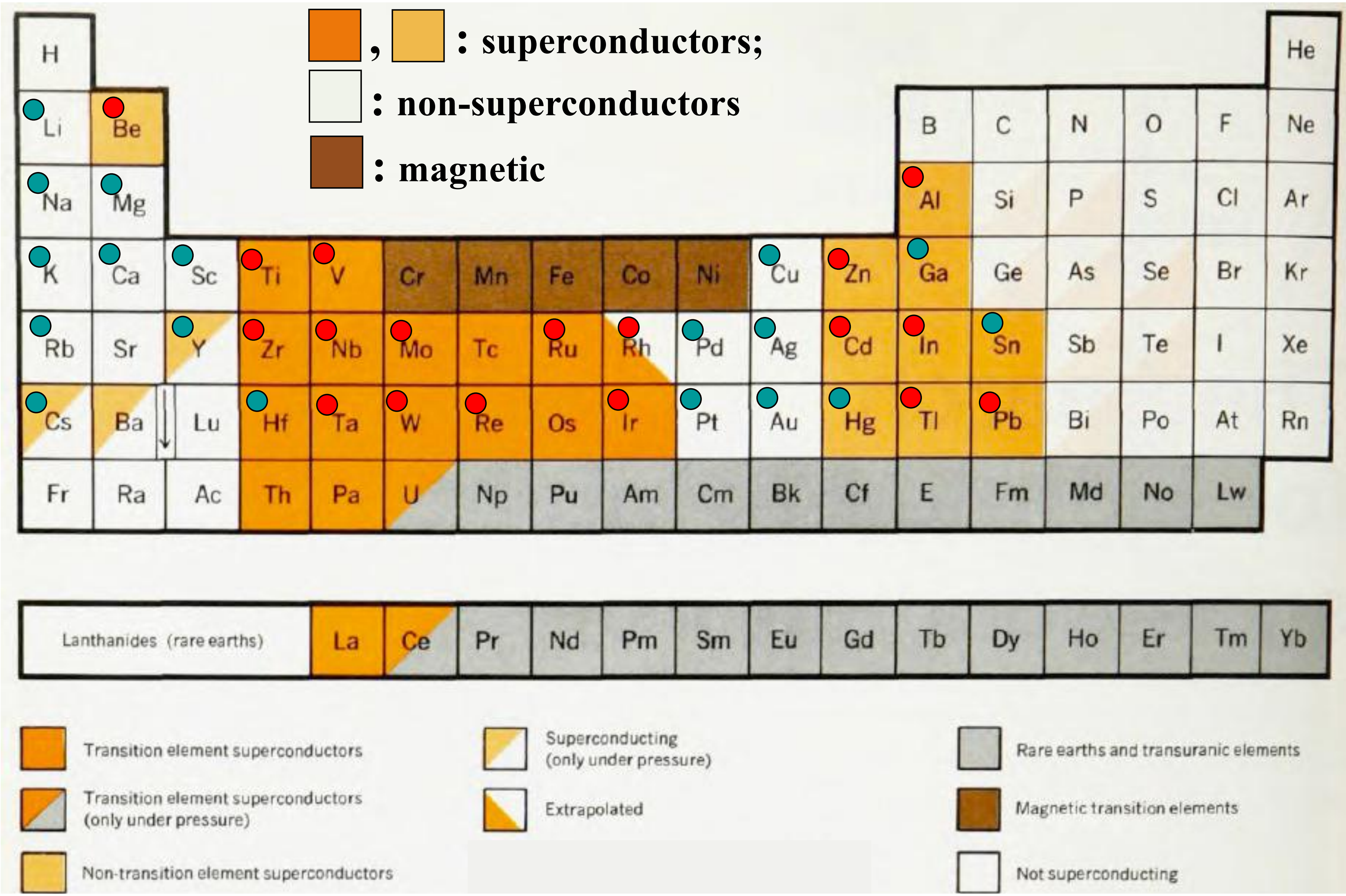
body rotation
•H
F_on-latt
N
electrons
F_latt
Lorentz
λ_L
F_E
ṙ_0
F_H
super current
E_F
E_F
ions
S
r_0
ṙ_0
ṙ_0
holes
λ_L
F_E
F_H
ṙ_0



Threshold curve
Normal state
H_c
Pure superconducting state
H
T
T_c
Threshold curve
Normal state
H_c
Pure superconducting state
H
T
T_c
(a)
body rotation
H
$\dot{r}_0$
$F_{on\text{-}latt}$
F_H
F_E
F_{latt}
N
λ_L
electrons
E_F
super current
ions
E_F
Lorentz
λ_L
S
$\dot{r}_0$
r_0
$\dot{r}_0$
F_H
F_E
(b)
body rotation
H
$F_{on\text{-}latt}$
N
electrons
F_{latt}
Lorentz
λ_L
F_E
$\dot{r}_0$
F_H
E_F
super current
E_F
ions
S
r_0
$\dot{r}_0$
$\dot{r}_0$
holes
λ_L
F_E
F_H
$\dot{r}_0$

Negative Hall coefficient=electron carriers

Positive Hall coefficient=hole carriers



1932

Hall Effect and Superconductivity.

As can be seen from these data, *the superconductors show usually a relatively small value of R and especially of $R\sigma$.*

I. KIKOIN.
BORIS LASAREW.

Magnetic Department,
Physical-Technical Institute,
Sosnovka 2, Leningrad (21).

ON A POSSIBLE CRITERION FOR SUPERCONDUCTIVITY

1962

I. M. Chapnik

Novosibirsk State University

(Presented by Academician I. K. Kikoin, June 1, 1961)
Translated from Doklady Akademii Nauk SSSR, Vol. 141, No. 1, pp. 70-73, November, 1961
Original article submitted February 1, 1961

Thus, we have as criteria for the appearance of superconductivity: the presence of a sufficient concentration of $\boxed{\text{holes}}$ $N_D > 10^{19}$ cm^{-3}, a restriction on the min-

ON THE EMPIRICAL CORRELATION BETWEEN THE SUPERCONDUCTING T_c AND THE HALL COEFFICIENT

I.M. CHAPNIK
Cavendish Laboratory, Cambridge CB3 OHE, England

(1979)

favorable condition for superconductivity would apparently be a positive value of the Hall coefficient.

R. Feynman, Rev.Mod.Phys.29, 205 (1957)

There may be small regions in momentum space, for instance, where the electrons behave as positively charged particles, that is, places where the conductivity is by holes and other regions where they behave normally. There is some indication that this is the case because it has been noticed that the Hall effect is very small when the material has a tendency to be superconductive. The Hall effect is very small when the positive and negative carriers cancel. Thus some people think that this, in conjunction with the lattice vibrations, may have something to do with superconductivity. Of course, that makes the problem more complicated, because it would mean that if Frohlich and Bardeen could solve their model exactly, they still would not find superconductivity, since it would still involve only negative carriers.

(1948)

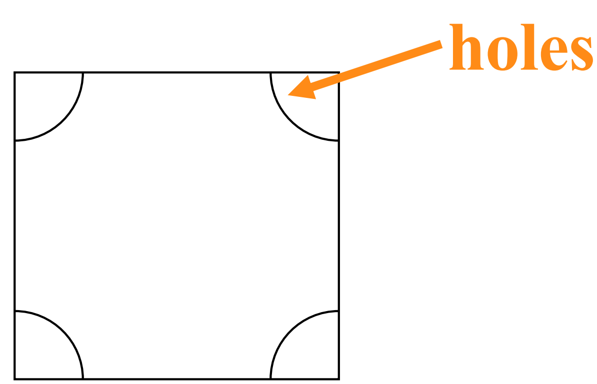
Theory of Superconductivity

On the other hand, we have found an empirical rule that indicates a correlation between superconductivity and lattice structure; namely, that those metals are superconductive for which the Fermi surface, supposed to be a sphere, lies in very close proximity to one set of the corners formed by the boundary planes of a Brillouin zone.

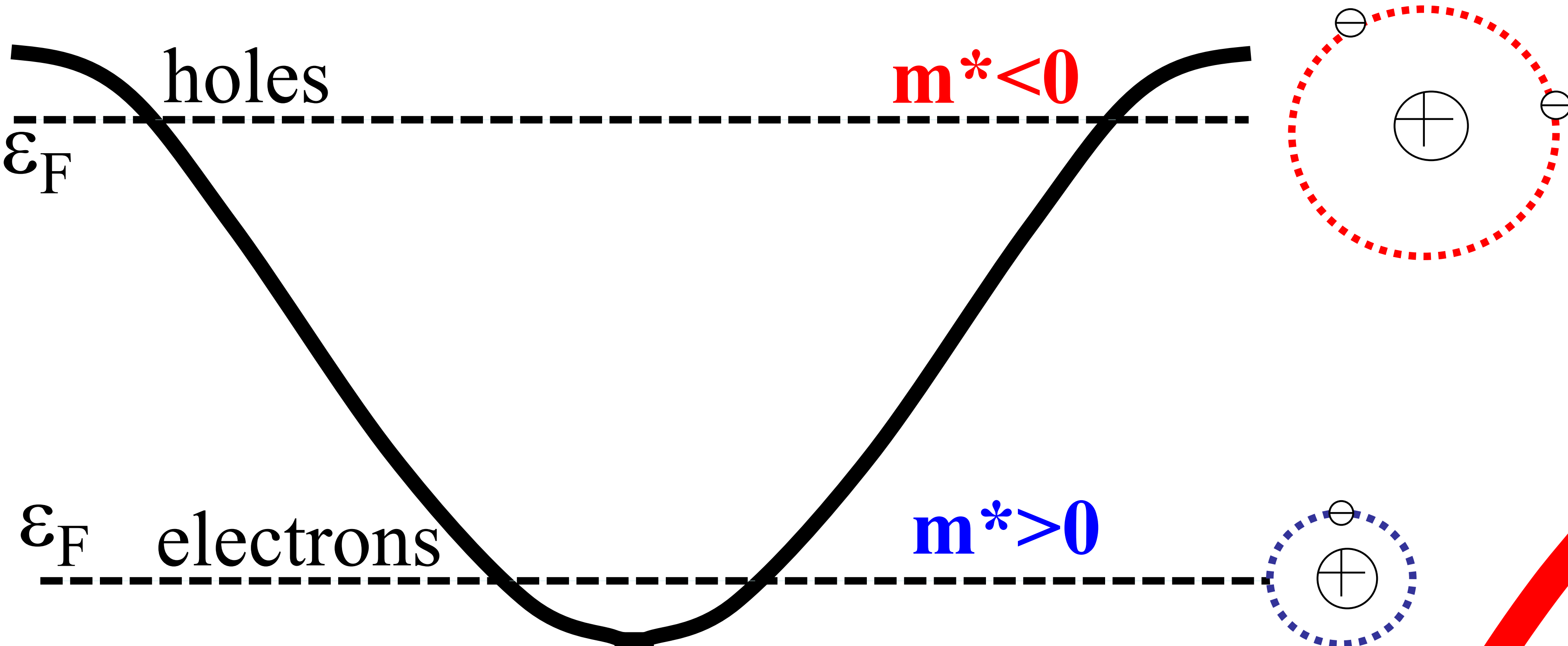
This table encourages the view that a correct theory of superconductivity should be based on the ionic forces. It is known that these ionic forces have predominant influence on the behaviour of the electrons, if the Fermi surface is close to the boundary planes of the Brillouin zone.

June 19, 1948

MAX BORN
KAI CHIA CHENG



Why hole carriers give rise to superconductivity and electron carriers do not



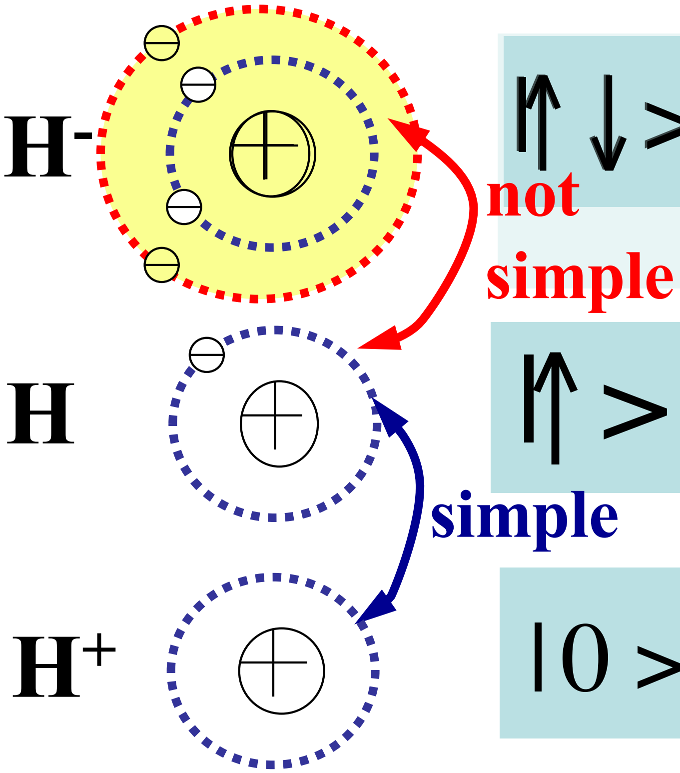
(1) Effective mass is negative near the top of the band

necessary to explain how momentum is conserved in Meissner effect

(2) Orbital expands when it is doubly-occupied

leads to pairing driven by lowering of kinetic energy - no phonons

Orbital expansion upon double-occupancy

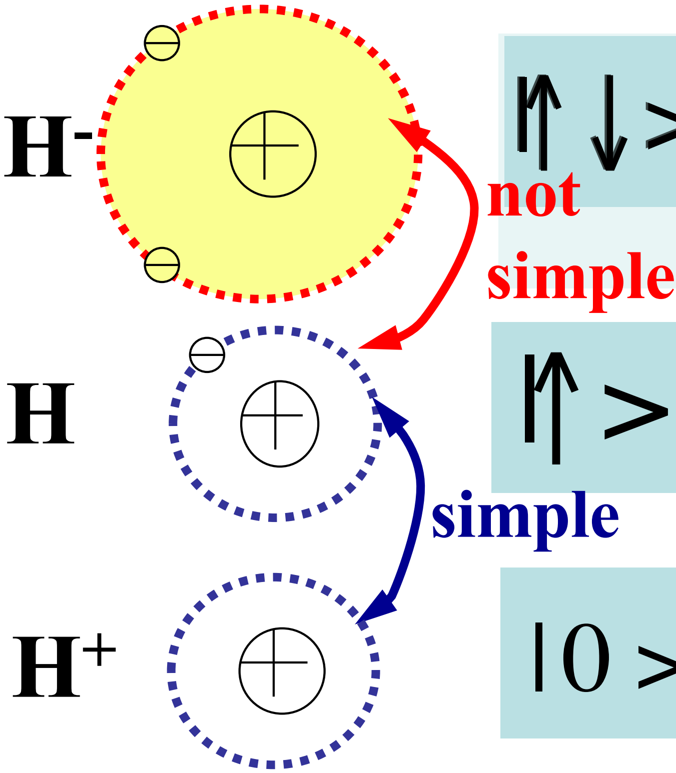


$$|\uparrow\downarrow> = \sum_{n,m} |\uparrow>_n \, |\downarrow>_m \, a_{nm}$$

$$|\uparrow>$$

$$|0>$$

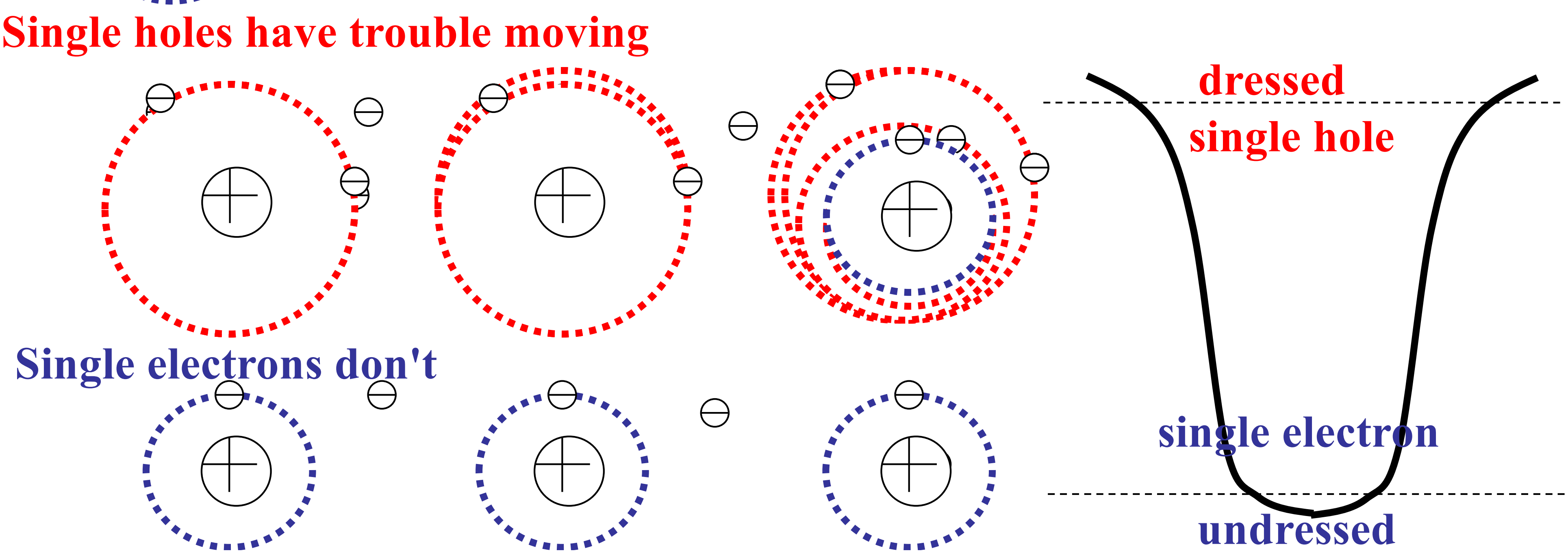
Orbital expansion upon double-occupancy

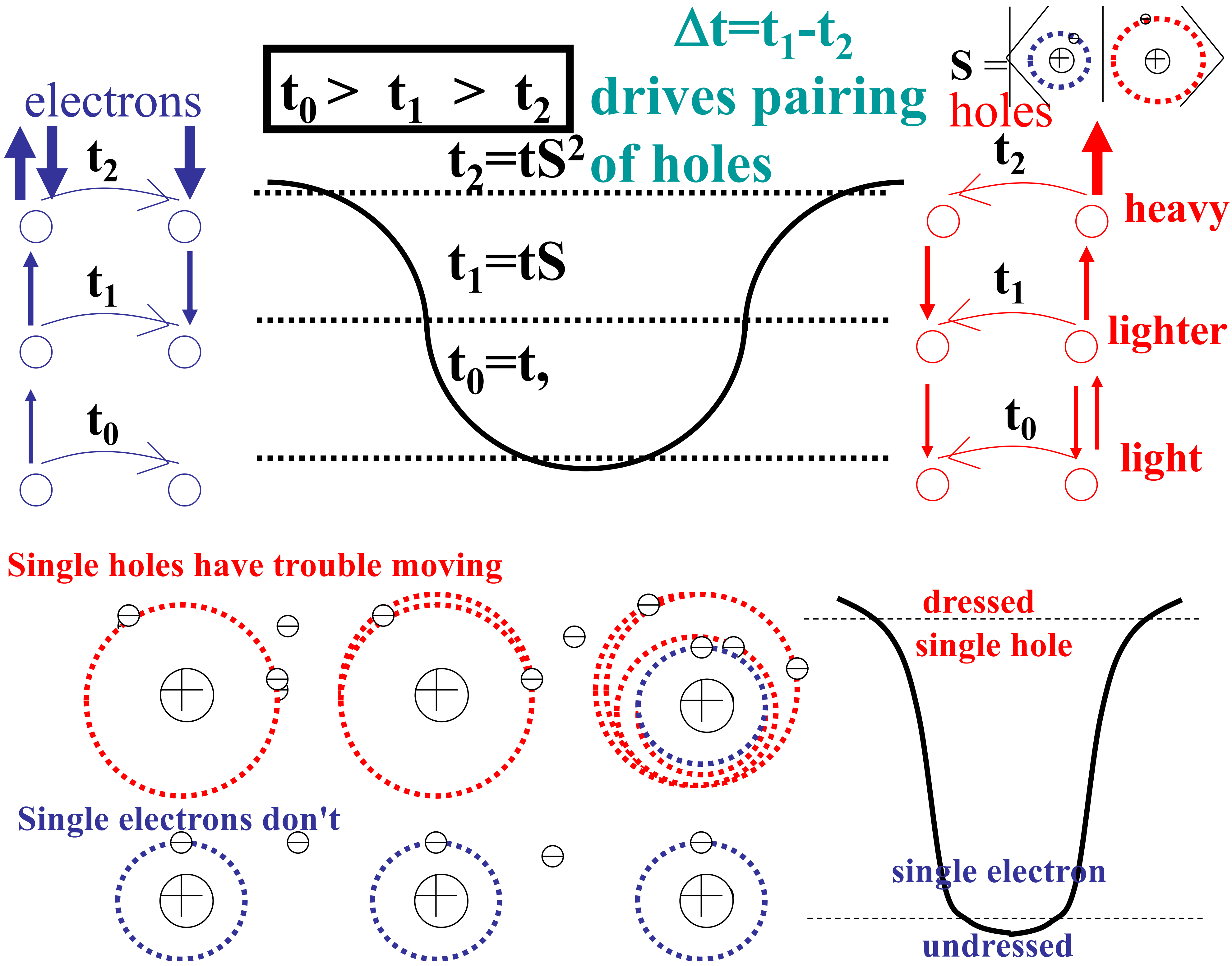


$$|\Uparrow\downarrow> = \sum_{n,m} |\Uparrow>_n \; |\Downarrow>_m \; a_{nm}$$

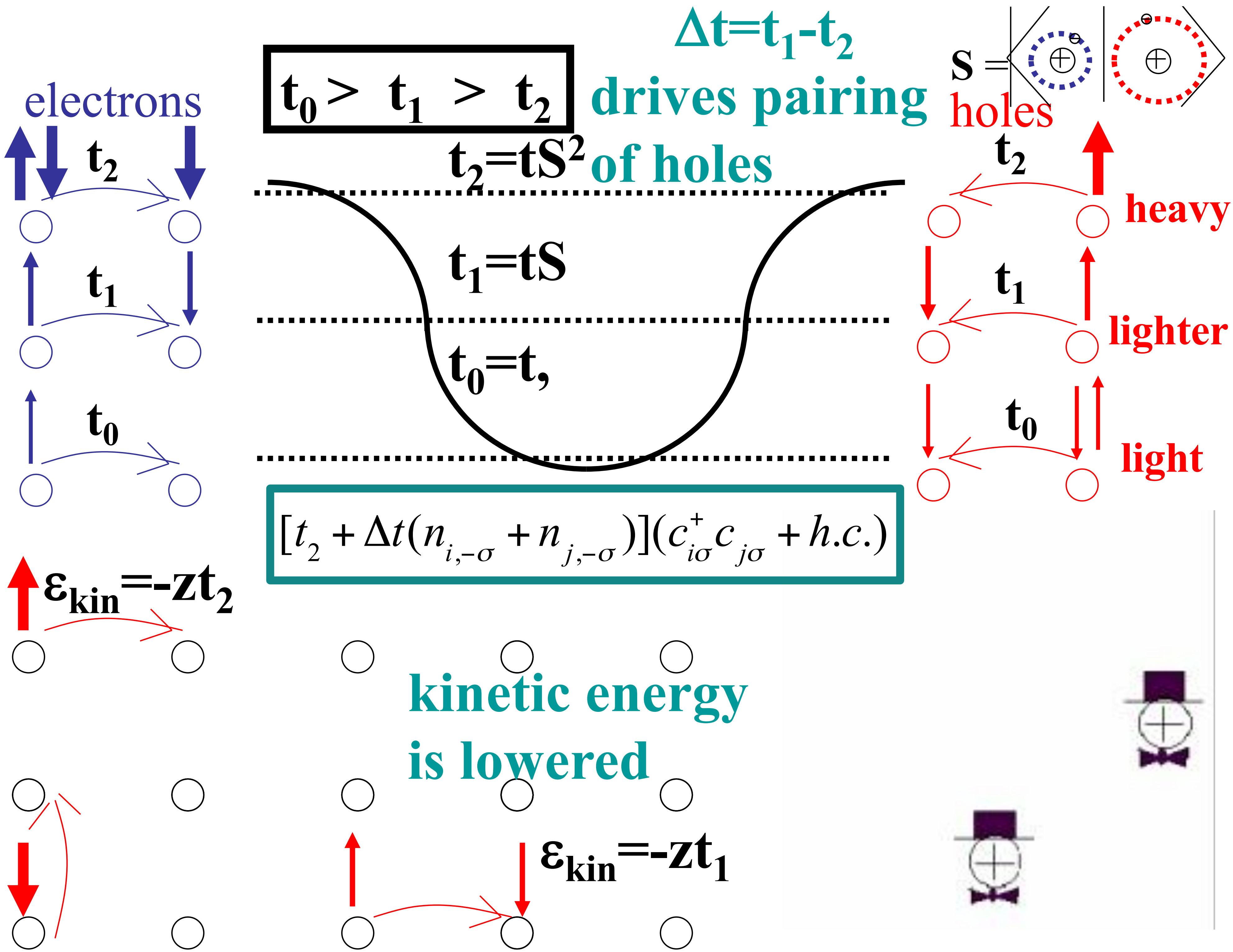
$$|\Uparrow>$$

$$|0>$$





electrons
$t_0 > t_1 > t_2$
$\Delta t = t_1 - t_2$
drives pairing
of holes
S =
holes
t_2
$t_2 = tS^2$
t_1
$t_1 = tS$
t_0
$t_0 = t,$
t_2
heavy
t_1
lighter
t_0
light
Single holes have trouble moving
Single electrons don't
dressed
single hole
single electron
undressed



$\Delta t = t_1 - t_2$
drives pairing
of holes
$t_0 > t_1 > t_2$
electrons
$S = \langle \oplus | \oplus \rangle$
holes
t_2
$t_2 = tS^2$
$t_1 = tS$
$t_0 = t,$
t_1
t_0
heavy
lighter
light
$[t_2 + \Delta t(n_{i,-\sigma} + n_{j,-\sigma})](c^+_{i\sigma} c_{j\sigma} + h.c.)$
$\varepsilon_{kin} = -zt_2$
kinetic energy
is lowered
$\varepsilon_{kin} = -zt_1$

Generalized Hubbard model

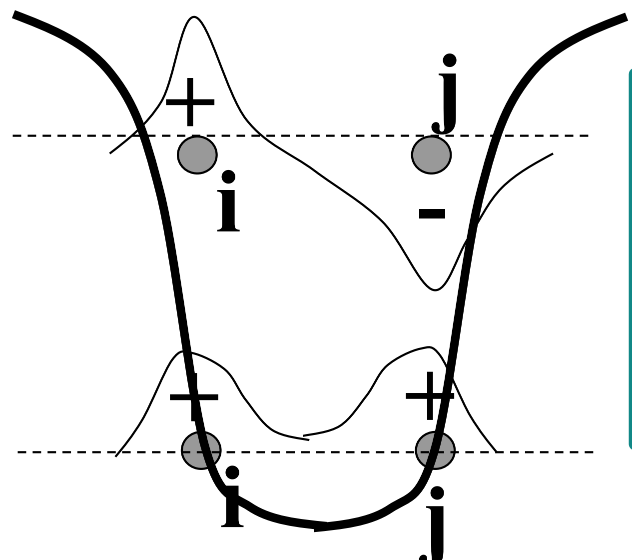
$$H = -\sum_{ij\sigma} t_{ij}[c^+_{i\sigma} c_{j\sigma} + h.c.] + \sum (ij\,|1/r|\,kl) c^+_{i\sigma} c^+_{j\sigma'} c_{l\sigma'} c_{k\sigma}$$

$$H = -\sum_{ij\sigma} t_{ij}[c^+_{i\sigma} c_{j\sigma} + h.c.] + U\sum_{i} n_{i\uparrow} n_{i\downarrow} + V\sum_{<ij>} n_i n_j + \Delta t \sum_{<ij>} (n_{i,-\sigma} + n_{j,-\sigma})(c^+_{i\sigma} c_{j\sigma} + h.c.)$$

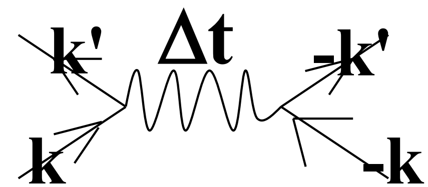
$$\Delta t \equiv (ii\,|1/r|\,ij) = \int |\varphi_i(r)|^2 \frac{e^2}{|r-r'|} \varphi_i(r')\varphi_j(r')$$

correlated hopping

$$n_{i,-\sigma} c^+_{i\sigma} c_{j\sigma} \text{ is } \begin{cases} < 0 \\ > 0 \end{cases}$$



attractive for holes

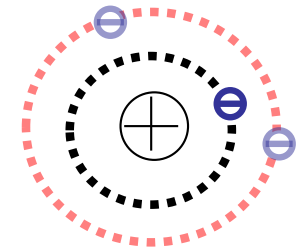


repulsive for electrons

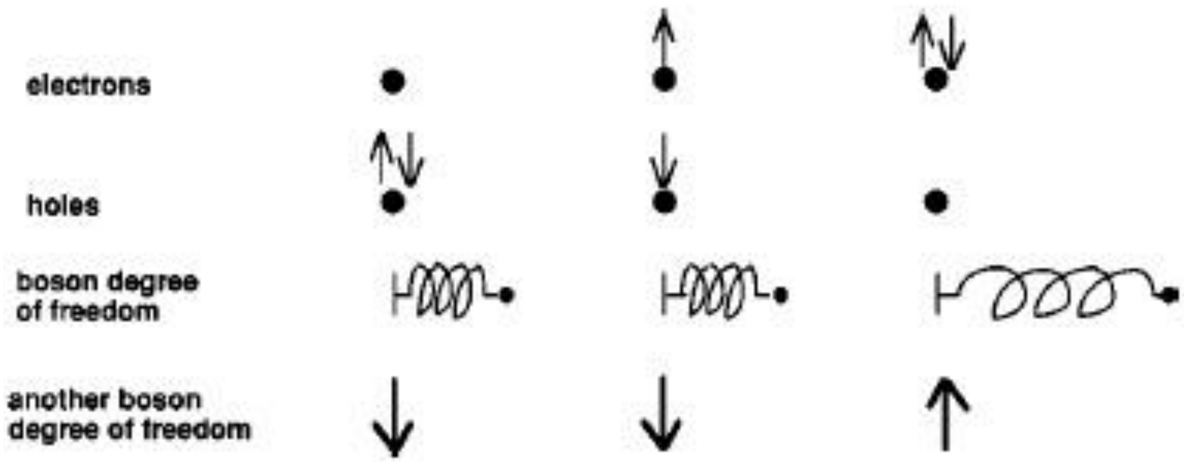
- **Δt breaks electron hole symmetry**
- **Δt lowers the kinetic energy of hole pairs**

Dynamic Hubbard models

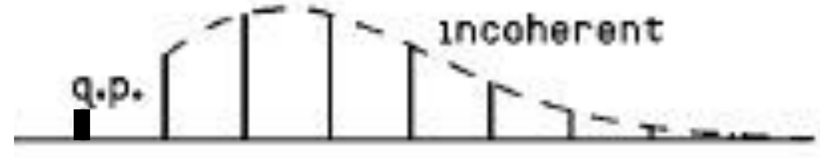
Phys. Rev. Lett. **87**, 206402 2001



1) Hubbard model + auxiliary boson degree of freedom



spectral function for hole creation



spectral function for electron creation

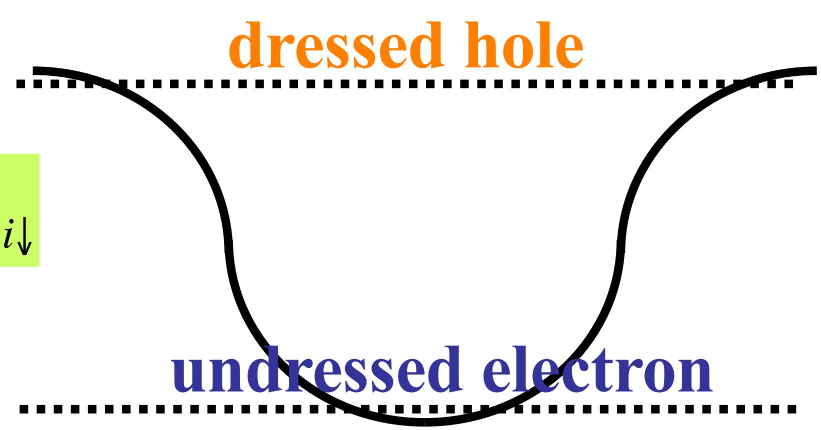
(i) Harmonic oscillator:

$$H_i = \frac{p_i^2}{2M} + \frac{1}{2}Kq_i^2 + (U + \alpha q_i)n_{i\uparrow}n_{i\downarrow}$$

(ii) Spin 1/2 degree of freedom

$$H_i = \omega_0\sigma_x^i + g\omega_0\sigma_z^i + [U - 2g\omega_0\sigma_z^i]n_{i\uparrow}n_{i\downarrow}$$

$$H = -\sum_{ij} t_{ij}c_{i\sigma}^+ c_{j\sigma} + \sum_i H_i$$



Hamiltonian is, in hole representation

$$H = \sum_{k\sigma} (\varepsilon_k - \mu) c^\dagger_{k\sigma} c_{k\sigma} + \frac{1}{N} \sum_{kk'q} \left(V(q) + \alpha(\varepsilon_k + \varepsilon_{k+q} + \varepsilon_{k'} + \varepsilon_{k'-q})\right) c^\dagger_{k+q\uparrow} c^\dagger_{k'-q\downarrow} c_{k'\downarrow} c_{k\uparrow} \quad \text{(59a)}$$

$$V(q) = \sum_j e^{iqR_j} V_{0j} \qquad V_{00} = U, \text{ and } \alpha = \Delta t_{ij}/\bar{t}_{ij}$$

$$V_{01} = V$$

$$H_{red} = \sum_{k\sigma} (\varepsilon_k - \mu)\, c^\dagger_{k\sigma} c_{k\sigma} + \sum_{kk'} V_{kk'}\, c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} c_{-k'\downarrow} c_{k'\uparrow}$$

$$D = 2z\bar{t},$$

$$K = 2z\Delta t$$

$$W = zV.$$

$$V_{kk'} = V(\varepsilon_k, \varepsilon_{k'}) = U + \frac{K}{D/2}(\varepsilon_k + \varepsilon_{k'}) + \frac{W}{D/2}\varepsilon_k \varepsilon_{k'}$$

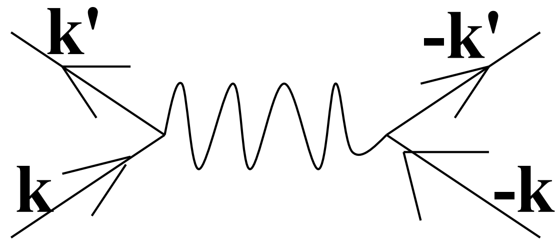
$$\boxed{\Delta_k = -\frac{1}{N} \sum_{k'} V(\varepsilon_k, \varepsilon_{k'}) \Delta_{k'} \frac{\tanh(\beta E_{k'}/2)}{2E_{k'}}}$$

$$\boxed{\Delta(\varepsilon_k) = \Delta_m \left(-\frac{\varepsilon_k}{D/2} + c\right)}$$

$$\boxed{\begin{gathered} 1 = K(I_1 + cI_0) - W(I_2 + cI_1) \\ c = K(I_2 + cI_1) - U(I_1 + cI_0) \\ I_\ell = \frac{1}{N} \sum_k \left(-\frac{\varepsilon_k}{D/2}\right)^\ell \frac{\tanh(\beta E_{k'}/2)}{2E_{k'}} \end{gathered}}$$

$$\boxed{1 = 2KI_1 - WI_2 - UI_0 + (K^2 - WU)(I_0 I_2 - I_1^2)}$$

$$V_{kk'} = U - \frac{2\Delta t}{t}(\varepsilon_k + \varepsilon_{k'})$$

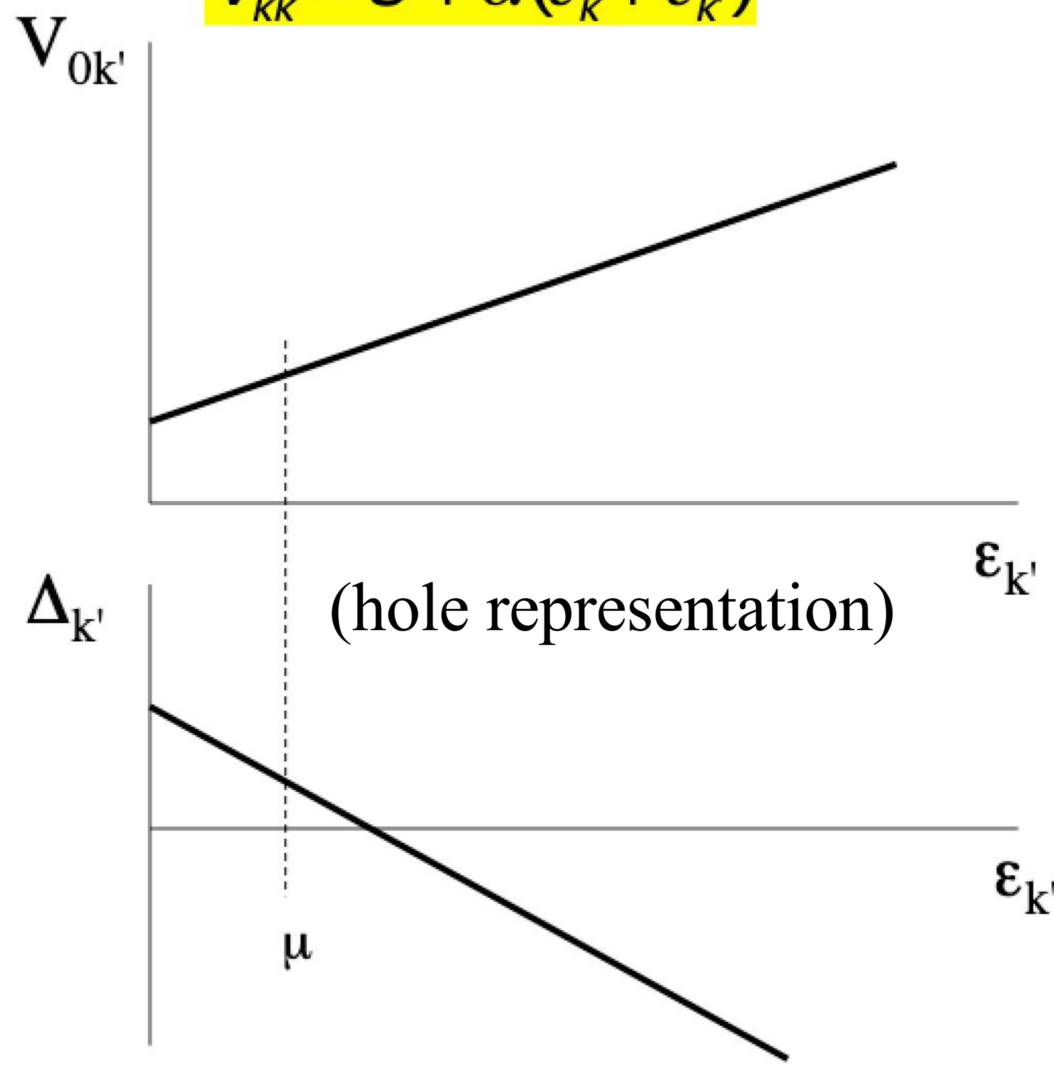


Is repulsive/attractive for $\varepsilon_k<0$ (electrons) / $\varepsilon_k>0$ (holes)

$$V_{kk'} = U + \alpha(\varepsilon_k + \varepsilon_{k'})$$

Superconductivity from repulsive interactions ('pseudopotential effect')

$$\Delta_k = -\sum_{k'} V_{kk'} \Delta_{k'} \frac{(1-2f(\varepsilon_{k'}))}{2\varepsilon_{k'}}$$



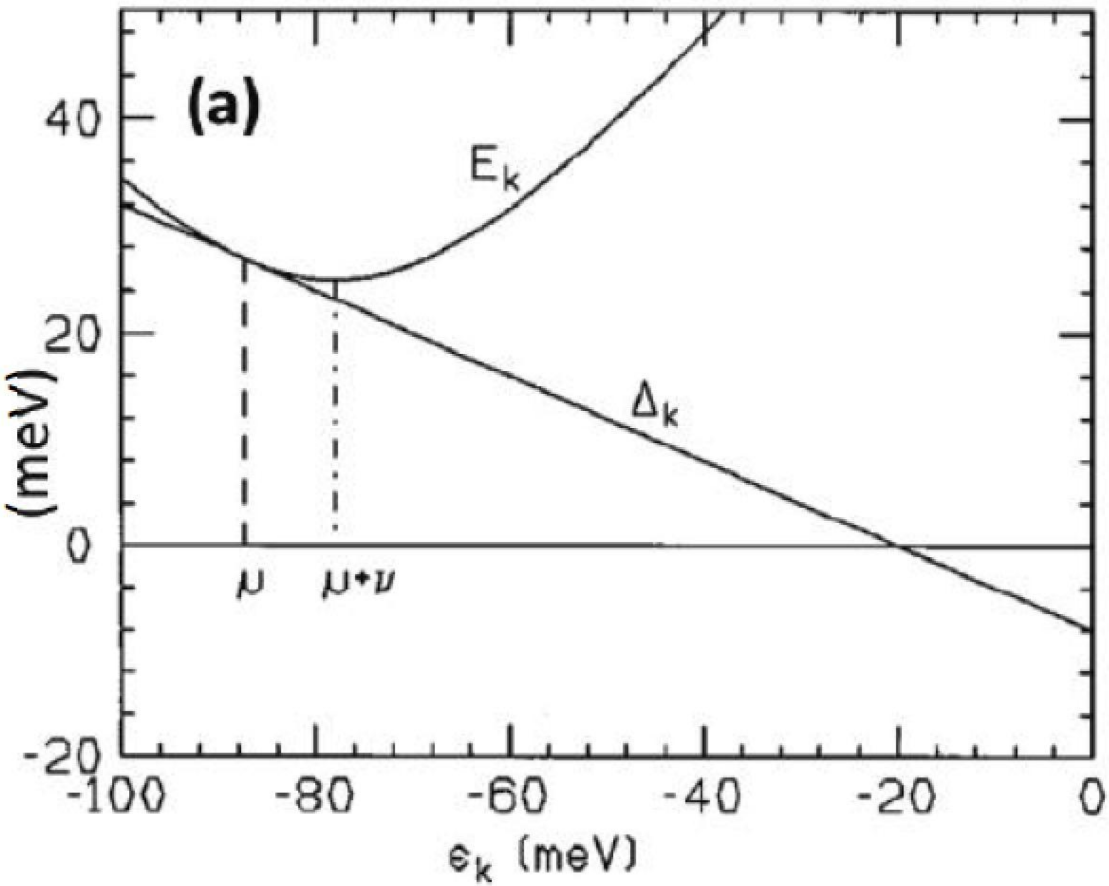
$$1 = 2KI_1 - WI_2 - UI_0 + \left(K^2 - WU\right)\left(I_0 I_2 - I_1^2\right)$$

$$k > \sqrt{(1+u)(1+w)} - 1$$

$$k = K / D \qquad D = 2z\bar{t},$$

$$u = U / D \qquad K = 2z\Delta t$$

$$w = W / D \qquad W = zV.$$



$$\boxed{\Delta(\varepsilon_k) = \Delta_m\left(-\frac{\varepsilon_k}{D/2} + c\right)}$$

$$E_k = \sqrt{(\varepsilon_k - \mu)^2 + \Delta_k^2}. \qquad E_k = \sqrt{a^2(\varepsilon_k - \mu - \nu)^2 + \Delta_0^2}$$

$$a = \sqrt{1 + \left(\frac{\Delta_m}{D/2}\right)^2}, \quad \Delta_0 = \frac{\Delta(\mu)}{a} \quad \text{and} \quad \nu = \frac{1}{a}\frac{\Delta_m}{D/2}\Delta_0$$

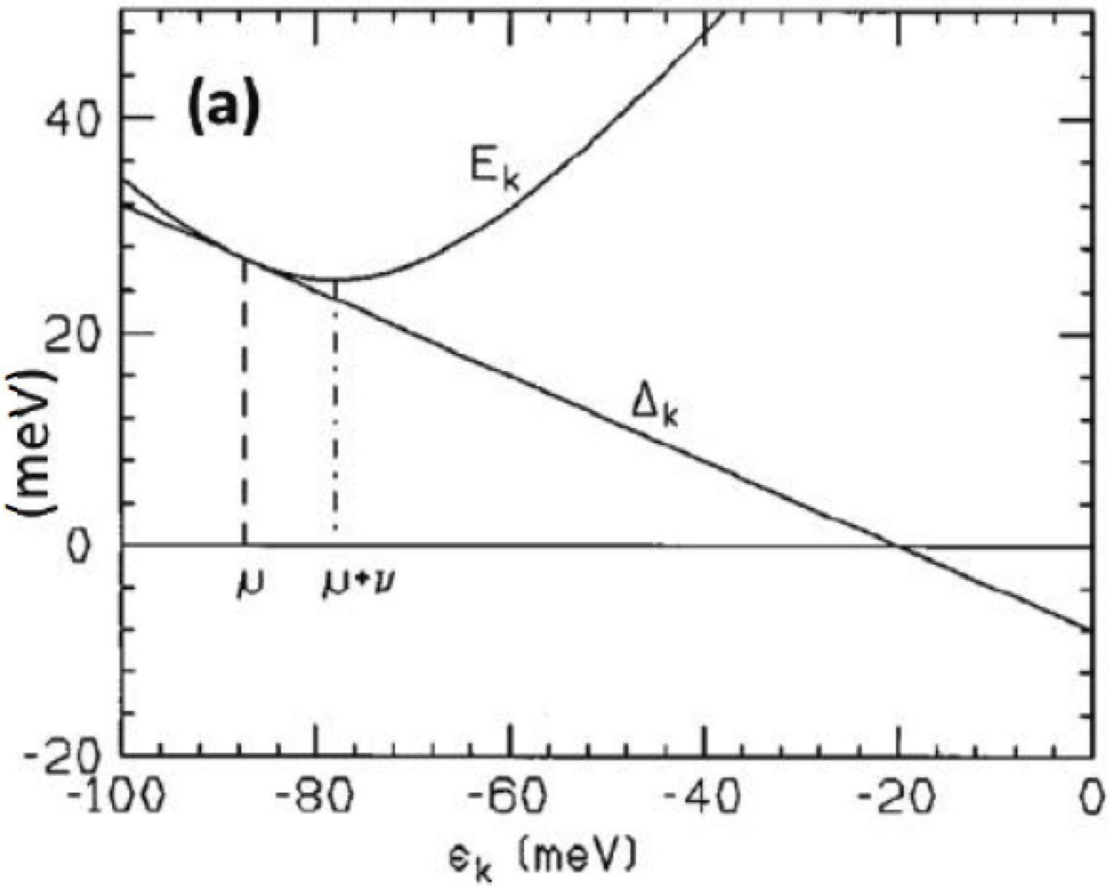
$$1 = 2KI_1 - WI_2 - UI_0 + \left(K^2 - WU\right)\left(I_0 I_2 - I_1^2\right)$$

$$k > \sqrt{(1+u)(1+w)} - 1$$

$$k = K / D \qquad D = 2z\bar{t},$$

$$u = U / D \qquad K = 2z\Delta t$$

$$w = W / D \qquad W = zV.$$



$$T_c = (e^{\gamma}/\pi)\sqrt{n(2-n)}\, D e^{-a/b},$$

$$a = 1 + 2k(1-n) - w(1 - 3n + \tfrac{3}{2}n^2)$$

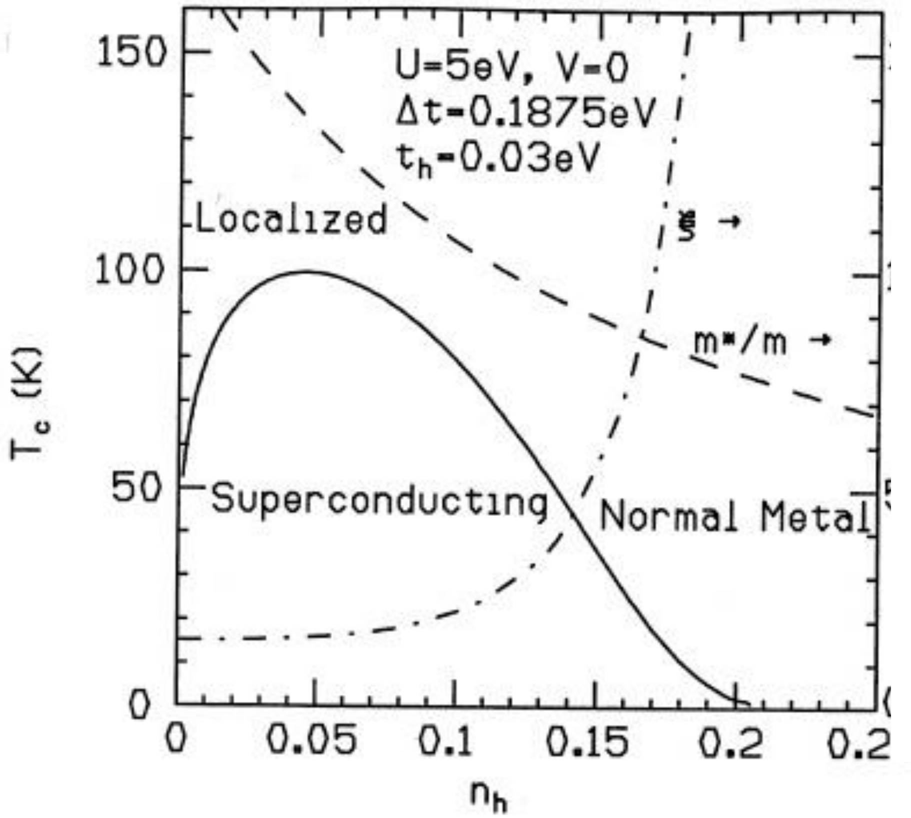
$$+ (k^2 - wu)(1-n)^2,$$

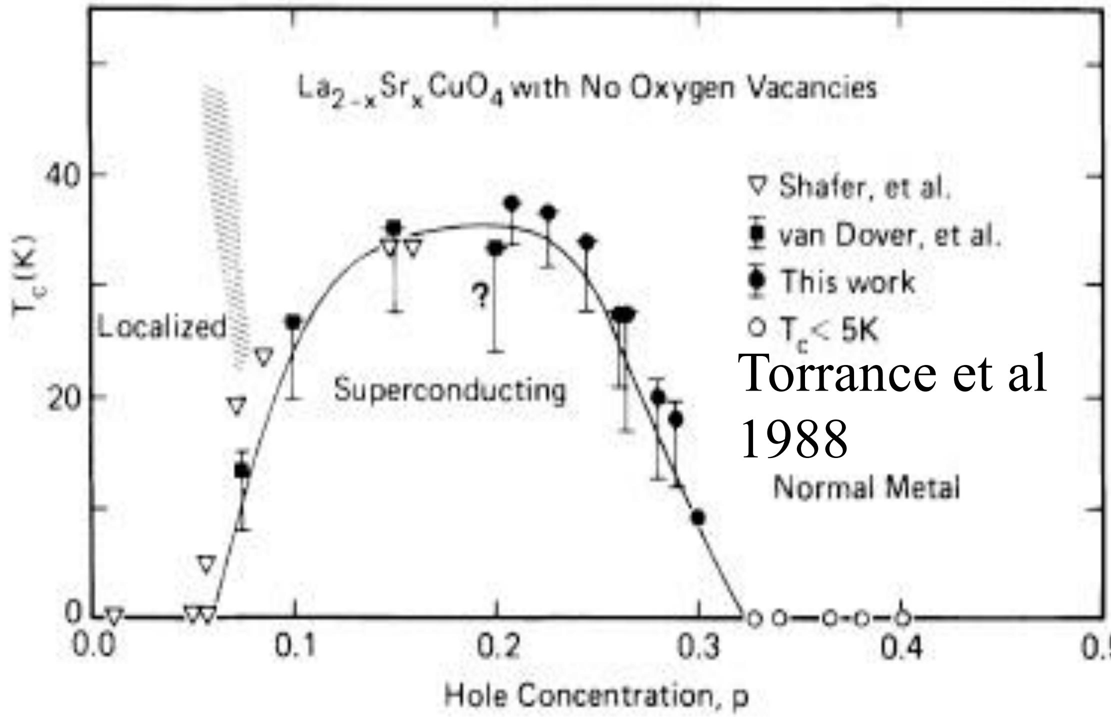
$$b = 2k(1-n) - w(1-n)^2 - u$$

$$+ (k^2 - wu)(1 - n + \tfrac{1}{2}n^2),$$

$$E_k = \sqrt{(\varepsilon_k - \mu)^2 + \Delta_k^2}. \qquad E_k = \sqrt{a^2(\varepsilon_k - \mu - \nu)^2 + \Delta_0^2}$$

$$a = \sqrt{1 + \left(\frac{\Delta_m}{D/2}\right)^2}, \quad \Delta_0 = \frac{\Delta(\mu)}{a} \quad \text{and} \quad \nu = \frac{1}{a}\frac{\Delta_m}{D/2}\Delta_0$$





Torrance et al 1988

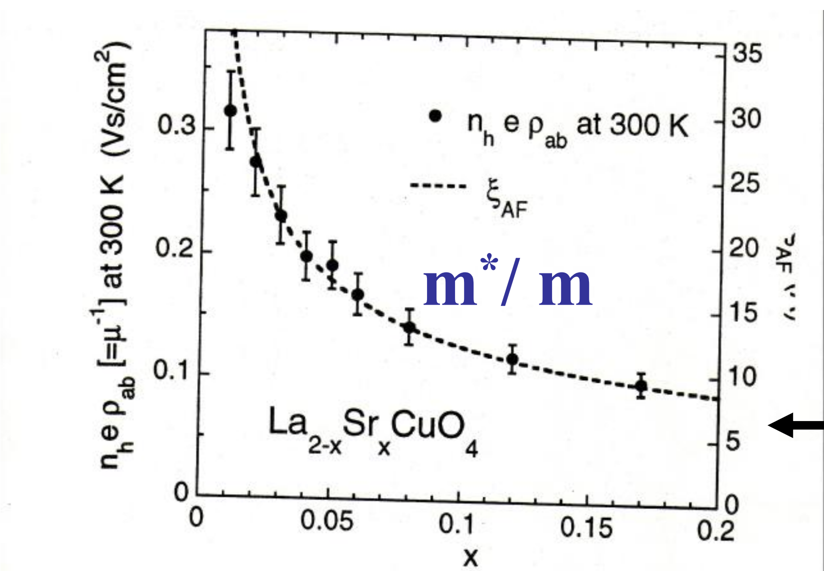
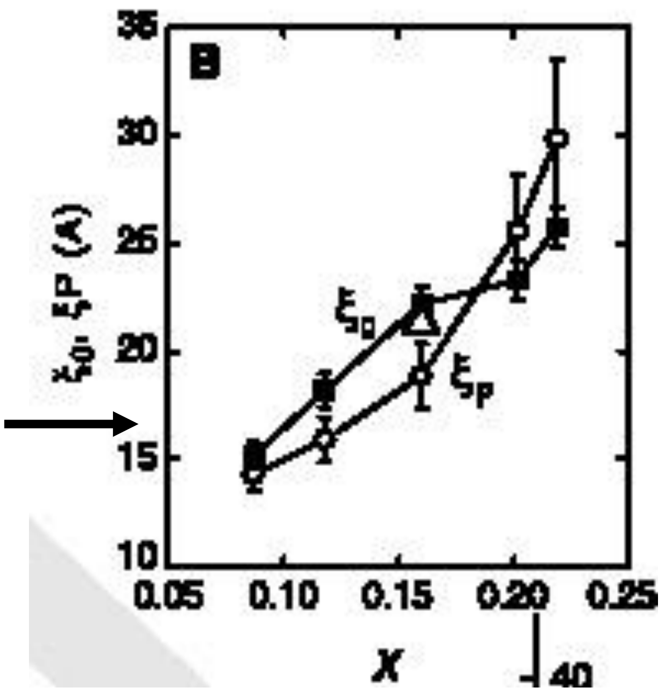
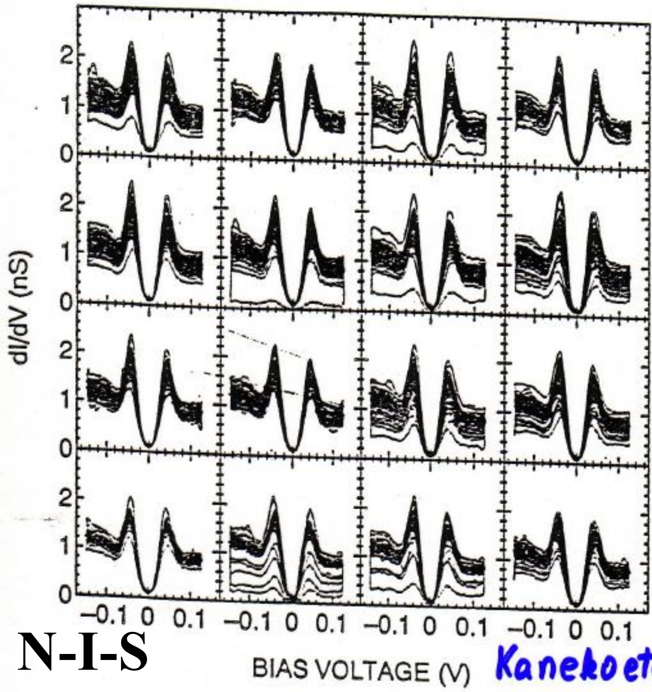
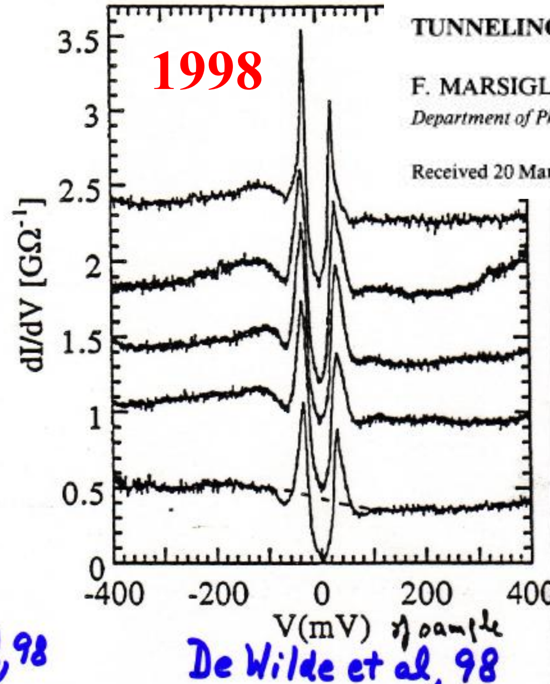


FIG. 3. x dependence of the inverse mobility (left axis) the LSCO crystals. The dashed line shows the x dependence ξ_{AF} (right axis), which is reported to be

Ando et al, 2001, 2003







N-I-S

current is larger for negatively biased sample

TUNNELING ASYMMETRY: A TEST OF SUPERCONDUCTIVITY MECHANISMS

(1989)

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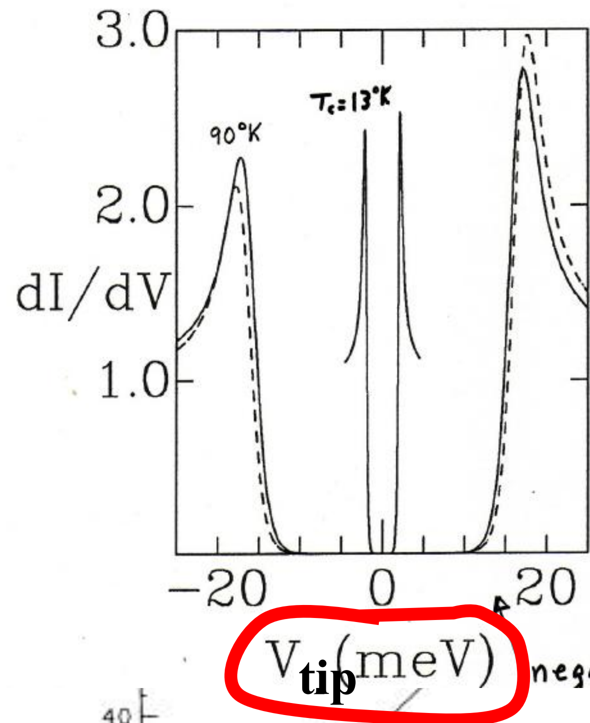
Received 20 March 1989



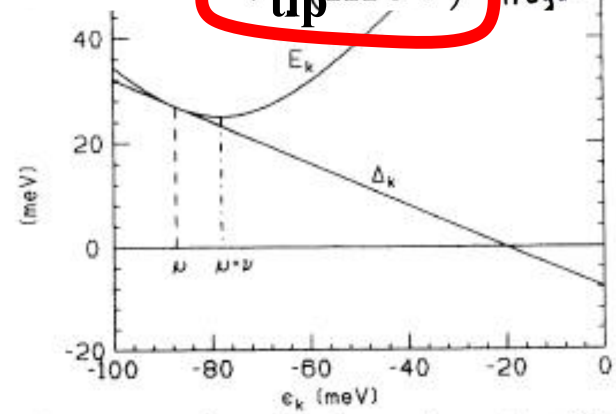
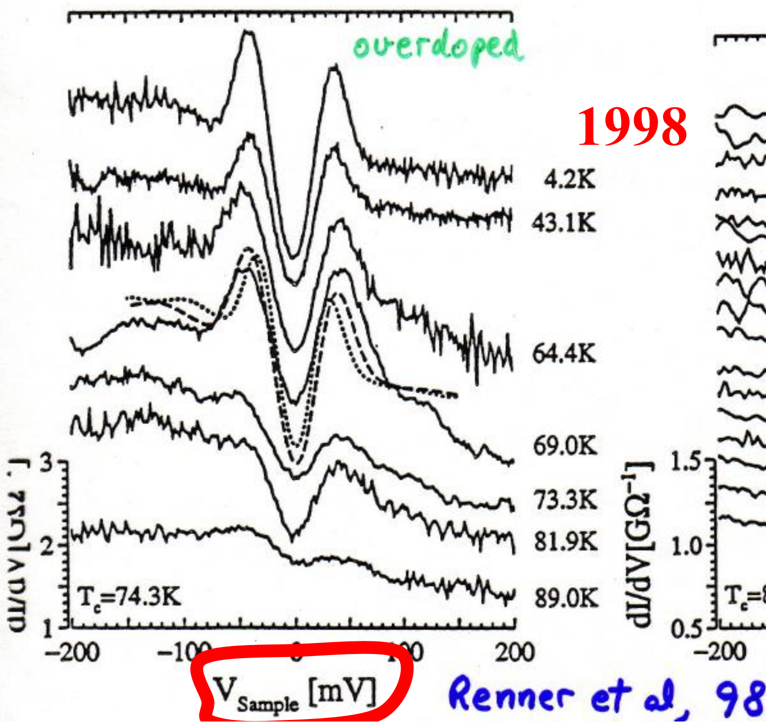
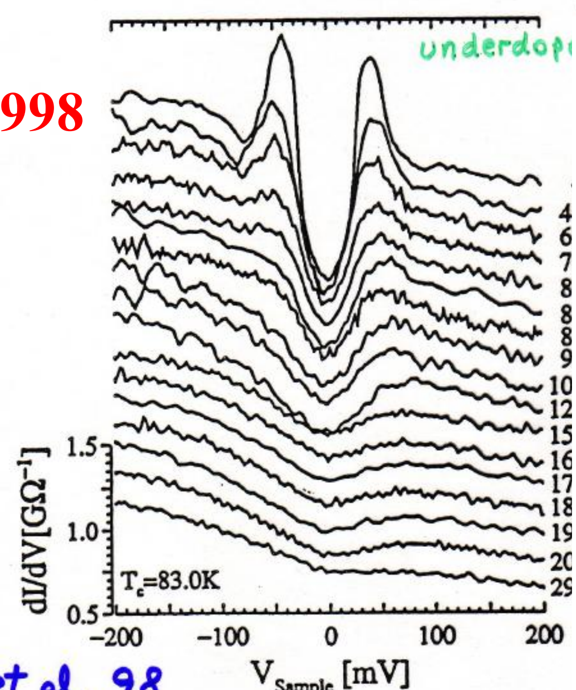


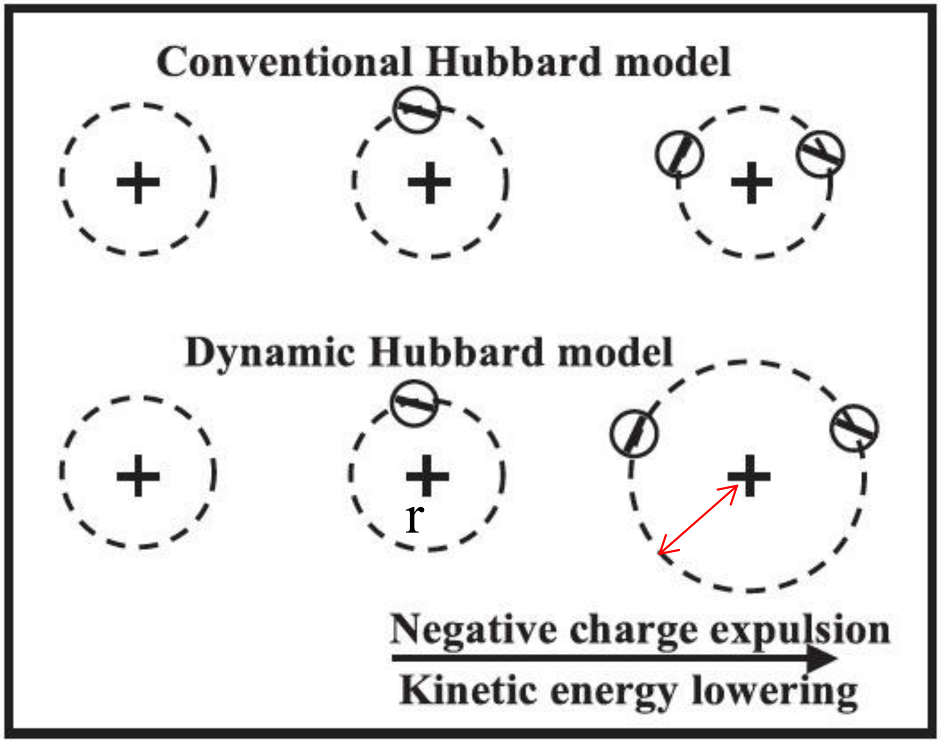
FIG. 1. Energy gap function Δ_k and quasiparticle energy E_k versus hole kinetic energy ϵ_k in the model of hole superconductivity (schematic). Only the lower half of the hole band (upper half of the electron band) is shown. Note that the minimum in the quasiparticle energy is shifted from the chemical potential μ to $\mu + \nu$.



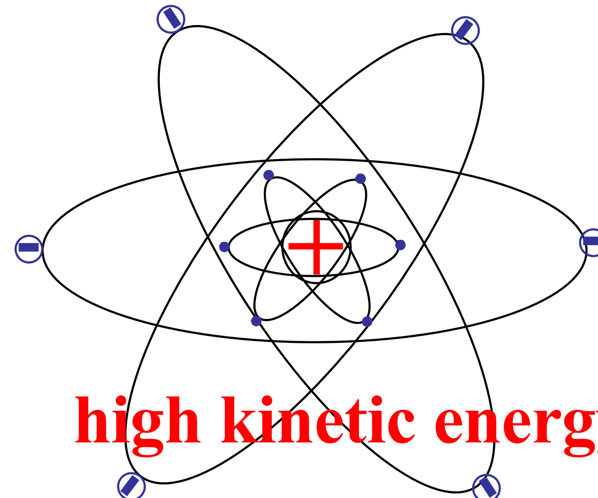


Microscopic physics: Dynamic Hubbard model

PRL 87, 206402 (2001)
PRB 87, 184506 (2013)



$$K = \frac{\hbar^2}{2m_e r^2}$$



high kinetic energy

kinetic energy lowering
wavefunction expansion

Effective low energy Hamiltonian:
Hubbard model with correlated hopping

$$H_{eff} \cong -\sum_{ij\sigma}[t_h + \Delta t(\tilde{n}_{i,-\sigma} + \tilde{n}_{j,-\sigma})][\tilde{c}^+_{i\sigma}\tilde{c}_{j\sigma} + h.c.] + U\sum_i \tilde{n}_{i\uparrow}\tilde{n}_{i\downarrow}$$

Leads to, when a band is almost full:

* pairing and superconductivity
* negative charge expulsion from interior to surface

driven by kinetic energy lowering

Negative charge expulsion in dynamic Hubbard model

PRB 87, 184506 (2013)

$$H = -\sum_{ij\sigma} t_{ij}^{\sigma}[c_{i\sigma}^{\dagger}c_{j\sigma} + \mathrm{H.c.}] + U\sum_{i} n_{i\uparrow}n_{i\downarrow},$$

$$t_{ij}^{\sigma} = t_h + \Delta t(n_{i,-\sigma} + n_{j,-\sigma}) + \Delta t_2 n_{i,-\sigma}n_{j,-\sigma}.$$

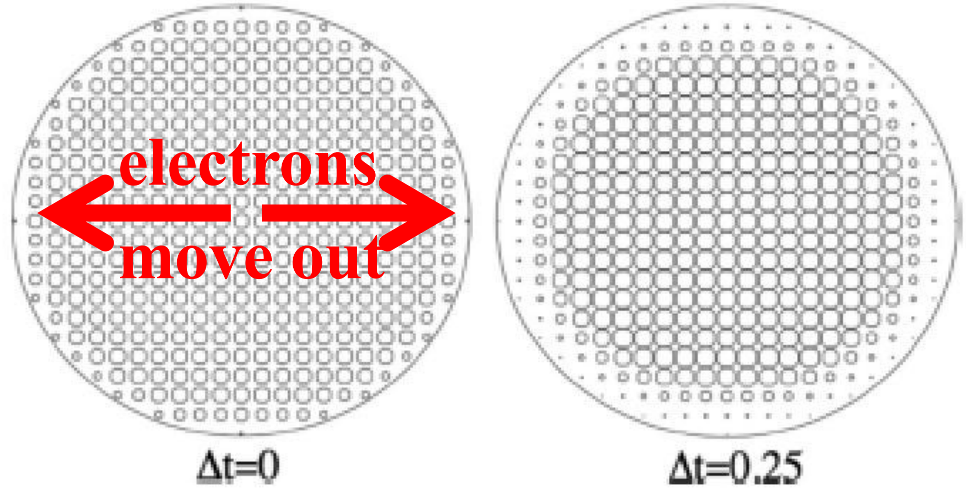


FIG. 4. Diameters of the circles are proportional to the hole occupation at the site. Note that for finite Δt the hole occupation increases in the interior and is depleted near the surface. Parameters correspond to the cases shown in Fig. 3.

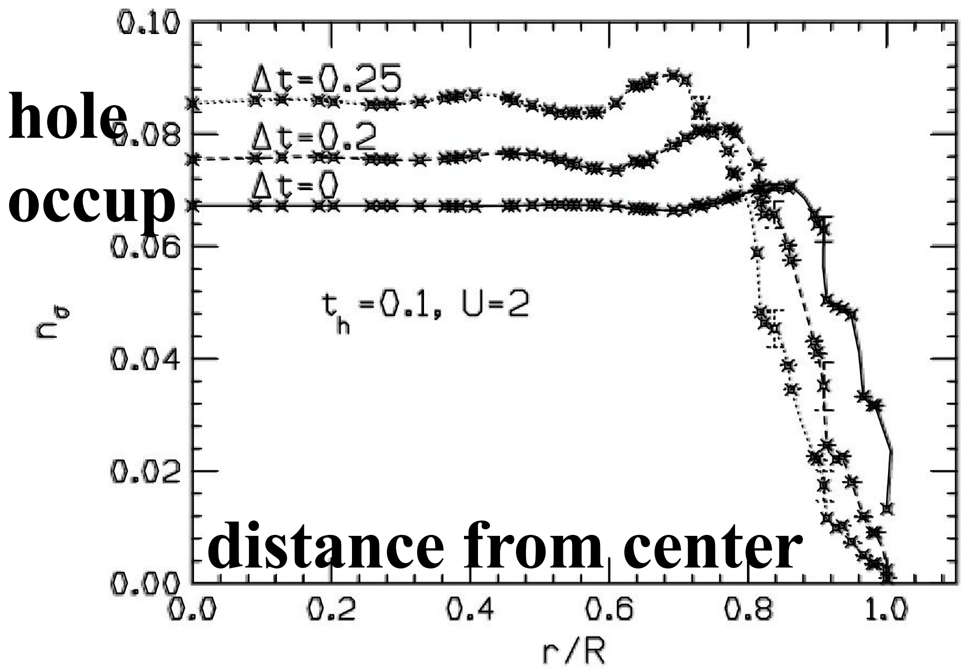


FIG. 3. Hole site occupation per spin for a cylinder of radius $R = 11$ as a function of r/R, with r the distance to the center, for a cubic lattice of side length 1. There are 377 sites in a cross-sectional area ($\pi R^2 = 380.1$). The average occupation (both spins) is $n = 0.126$ hole per site and the temperature is $k_B T = 0.02$.

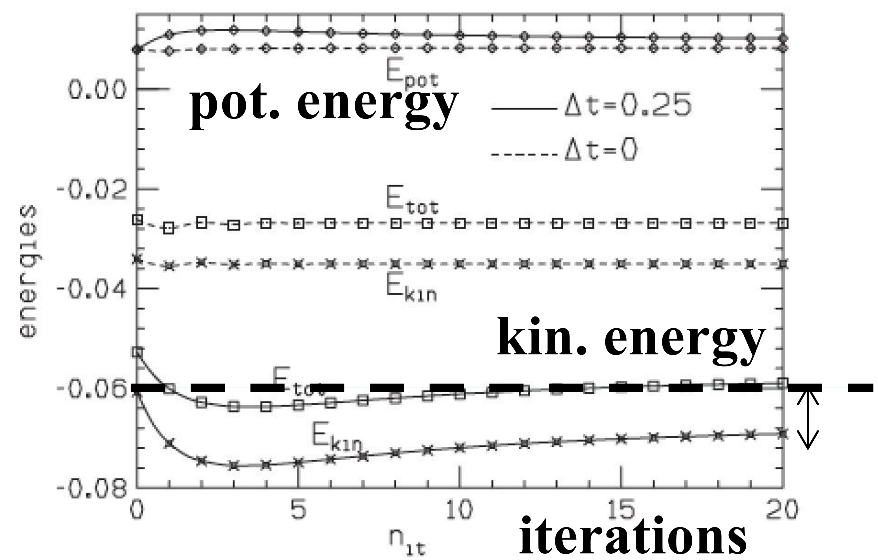
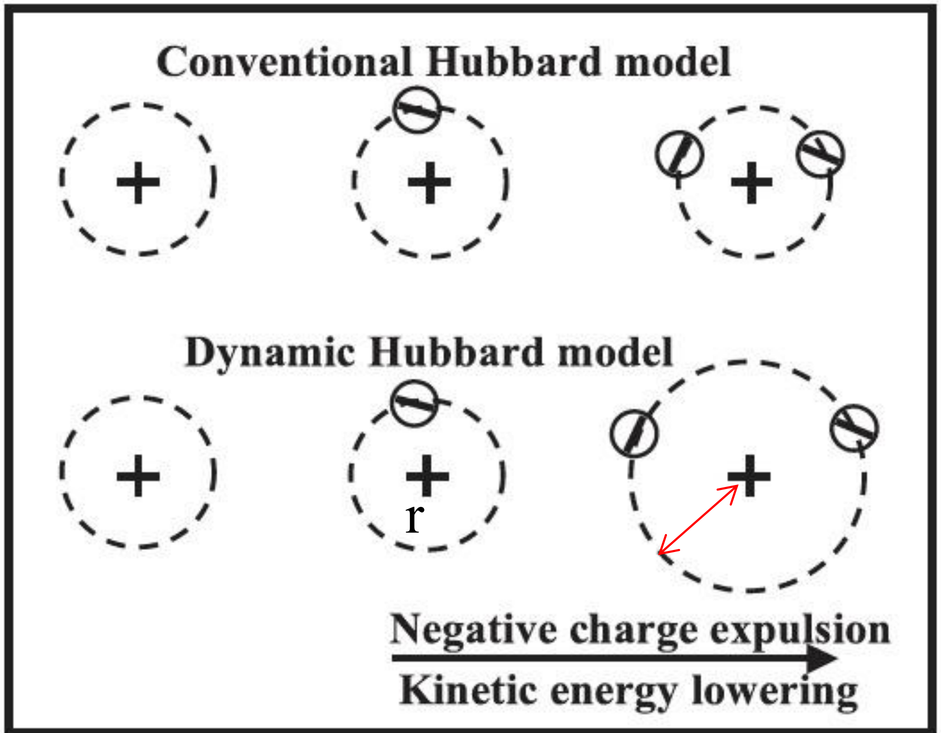


FIG. 5. Kinetic, potential, and total energy per site for $\Delta t = 0.25$ as a function of the number of iterations starting with a uniform hole distribution.

$t(n_h)=t_h+n_h\Delta t$

Negative charge expulsion in dynamic Hubbard model

PRB 87, 184506 (2013)



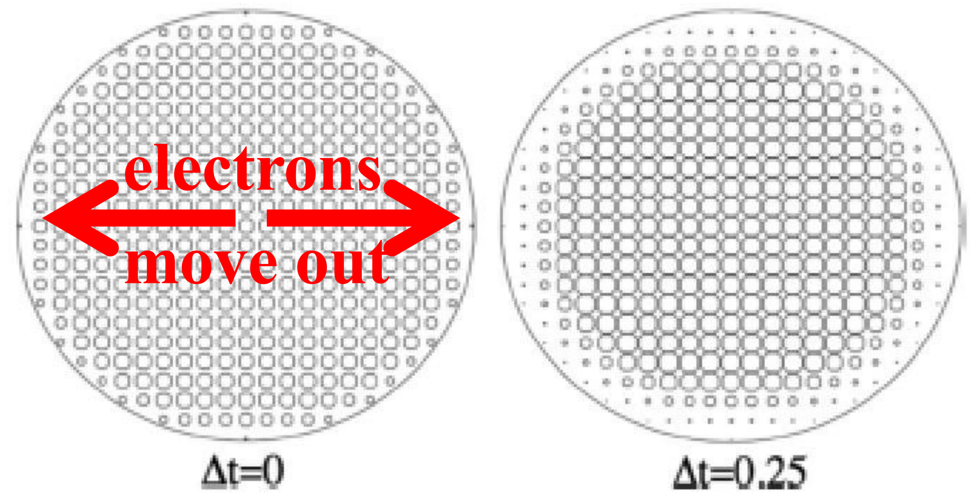
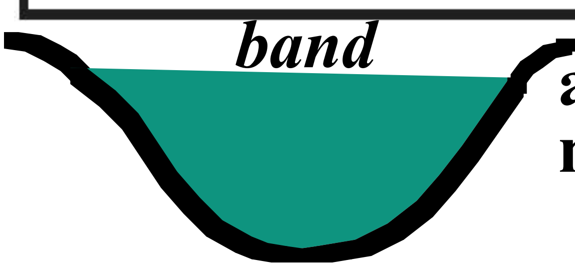
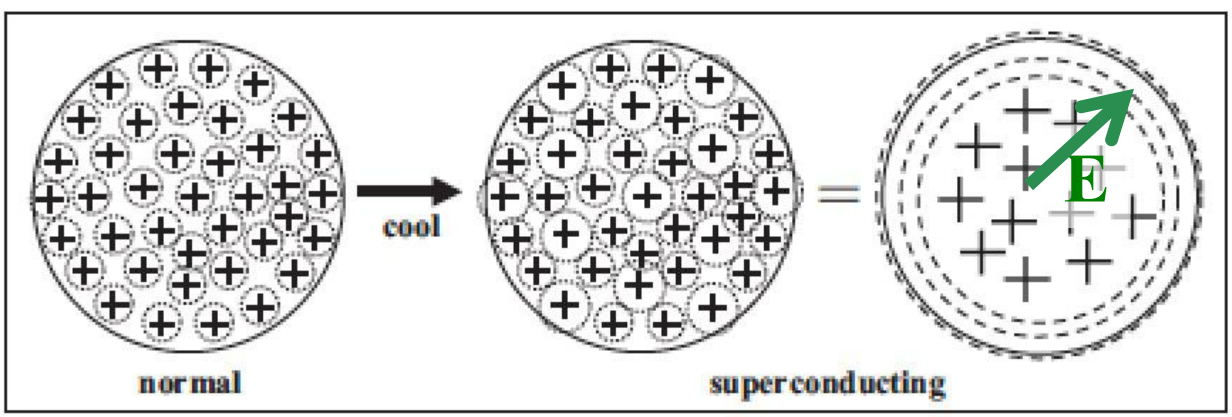


FIG. 4. Diameters of the circles are proportional to the hole occupation at the site. Note that for finite Δt the hole occupation increases in the interior and is depleted near the surface. Parameters correspond to the cases shown in Fig. 3.



almost full band ➔many electrons, high kin.energy
negative ions ➔ a lot of negative charge
➔ system expels electrons



macroscopic charge inhomogeneity

An outward-pointing electric field exists in the interior of superconductors at zero temperature

The Electromagnetic Equations of the Supraconductor **(1935)**

SUPRALEITUNG UND DIAMAGNETISMUS **(1935)**

von F. und H. LONDON

diese noch unbekannte Koppelung eine Verfestigung der Elektronenwellenfunktion in erster Näherung auch gegen elektrische Störungen zustande bringt [1]). Dann würde man zu einer Gleichung

ρ=charge density $$\rho = -\frac{e^2 n}{mc^2}\varphi \qquad (12b)$$ **φ=electric potential**

An Experimental Examination of the Electrostatic Behaviour of Supraconductors **(1936)**

By H. LONDON, Clarendon Laboratory, Oxford

It follows from these measurements that no electrostatic fields exist in a pure supraconductor, not even in a thin surface layer, at least to the approximation to which this is true for normal conductors. Accordingly

Derivation of conventional London equation:

$J = nev$ **(n=density, v=speed, J=current)**

$$m\frac{dv}{dt} = eE \quad ==> \quad \cancel{\frac{\partial J}{\partial t} = \frac{ne^2}{m}E}$$

free acceleration of electrons

$$\frac{\partial J}{\partial t} = \frac{ne^2}{m}E \quad ==> \quad \frac{\partial}{\partial t}\nabla\times J = \frac{ne^2}{m}\nabla\times E = -\frac{ne^2}{mc}\frac{\partial B}{\partial t}$$

Integrate, <u>ignore integration constant</u>, gives London eq.

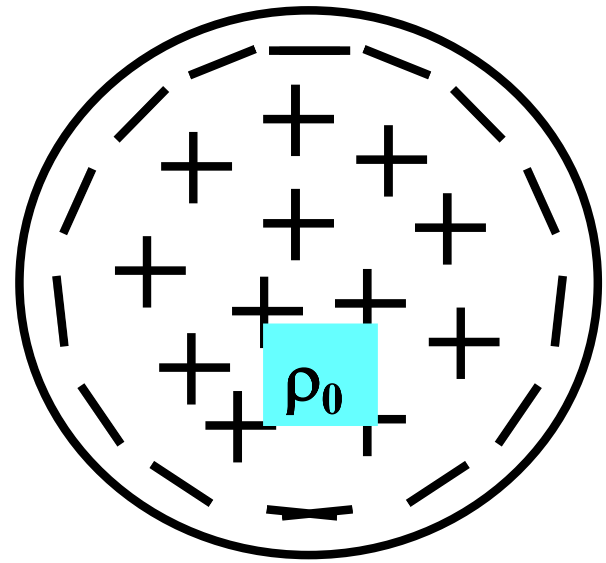
$$\boxed{\nabla\times J = -\frac{ne^2}{mc}B}\text{, with } \nabla\times B = \frac{4\pi}{c}J \quad ===> \quad \nabla^2 B = \frac{1}{\lambda_L^2}B = \frac{4\pi ne^2}{mc^2}B$$

$$\boxed{J = -\frac{ne^2}{mc}A} \qquad \boxed{\vec{\nabla}\cdot\vec{A} = 0}$$

Note: $$\boxed{\frac{\partial J}{\partial t} = -\frac{ne^2}{mc}\frac{\partial A}{\partial t}}, \quad \boxed{E = -\nabla\phi - \frac{1}{c}\frac{\partial A}{\partial t}} \quad ===> \quad \boxed{\frac{\partial J}{\partial t} = \frac{ne^2}{m}(E + \nabla\phi)}$$

New London-like equations for superconductors (JEH, PRB69, 214515(2004))

1) $$J=-\frac{ne^2}{mc}A=-\frac{c}{4\pi\lambda_L^2}A \quad ; \quad \frac{1}{\lambda_L^2}\equiv\frac{4\pi ne^2}{mc^2}$$



2) $$\nabla\cdot A+\frac{1}{c}\frac{\partial\phi}{\partial t}=0 \quad ; \quad \text{(Lorenz gauge)}$$

$$\nabla\cdot J=-\frac{c}{4\pi\lambda_L^2}\nabla\cdot A$$ **, continuity equation:** $\nabla\cdot J+\frac{\partial\rho}{\partial t}=0$ ==>

$$\frac{\partial\rho}{\partial t}=-\frac{1}{4\pi\lambda_L^2}\frac{\partial\phi}{\partial t}$$ **integrate in time, 1 integration constant ρ_0 , ...**

==> $$\boxed{\rho(r,t)-\rho_0=-\frac{1}{4\pi\lambda_L^2}[\phi(r,t)-\phi_0(r)] \quad \Big| \quad \phi_0(r)=\int d^3r'\frac{\rho_0}{|r-r'|}}$$

Electrostatics:

(JEH, PRB69, 214515(2004)

$$\nabla^2(\phi(r) - \phi_0(r)) = \frac{1}{\lambda_L^2}(\phi(r) - \phi_0(r))$$

$$\nabla^2(\rho(r) - \rho_0) = \frac{1}{\lambda_L^2}(\rho(r) - \rho_0)$$

$$\nabla^2\phi(r) = -4\pi\rho(r) \qquad \nabla^2\phi_0(r) = -4\pi\rho_0$$

$$\nabla^2(\vec{E} - \vec{E}_0) = \frac{1}{\lambda_L^2}(\vec{E} - \vec{E}_0)$$

$$\nabla^2\phi(r) = 0$$

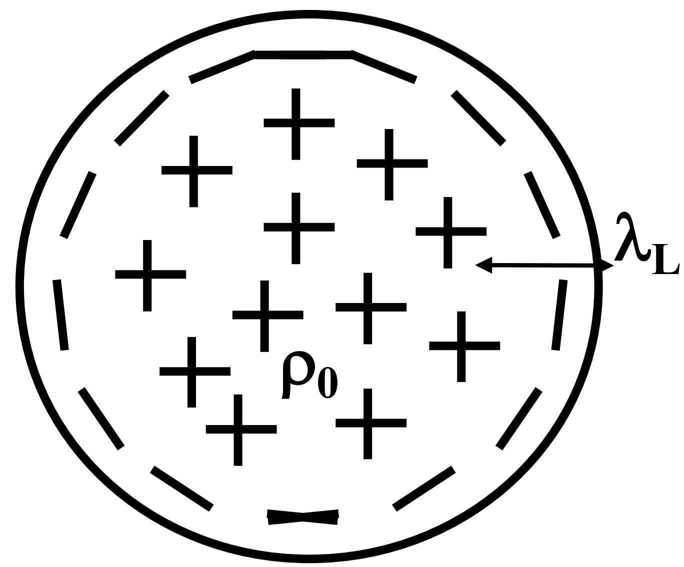
outside supercond.

+assume ϕ(r) and its normal derivative are continuous at surface

Solution for sphere of radius R:

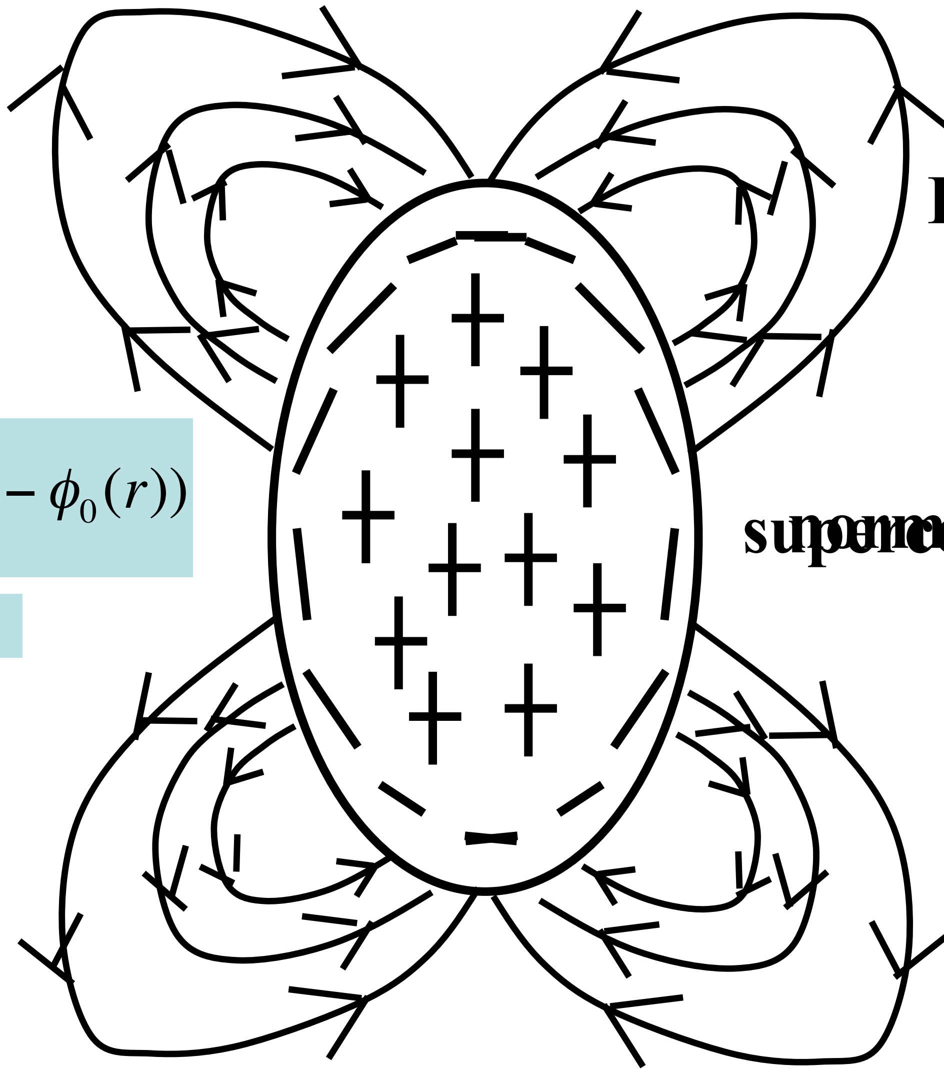
$$\rho(\mathrm{r}) = \rho_0\left(1 - \frac{R^3}{3\lambda_L^2}\frac{\sinh(r/\lambda_L)}{R/\lambda_L\cosh(R/\lambda_L) - \sinh(R/\lambda_L)}\right)$$

$$\vec{E}(\mathrm{r}) = \frac{4}{3}\pi\rho_0\left[1 - \frac{R^3}{r^3}\frac{r/\lambda_L\cosh(r/\lambda_L) - \sinh(r/\lambda_L)}{R/\lambda_L\cosh(R/\lambda_L) - \sinh(R/\lambda_L)}\right]\vec{r}$$



No electric field outside sphere

Elliptical shape



$$\nabla^2(\phi(r) - \phi_0(r)) = \frac{1}{\lambda_L^2}(\phi(r) - \phi_0(r))$$

$$\nabla^2\phi_0(r) = -4\pi\rho_0$$ inside

$$\nabla^2\phi(r) = 0$$ outside

test experimentally by measuring electric fields in the neighborhood of superconducting small particles

Electrostatics:

$$\nabla^2(\phi(r) - \phi_0(r)) = \frac{1}{\lambda_L^2}(\phi(r) - \phi_0(r))$$

$$\nabla^2(\rho(r) - \rho_0) = \frac{1}{\lambda_L^2}(\rho(r) - \rho_0)$$

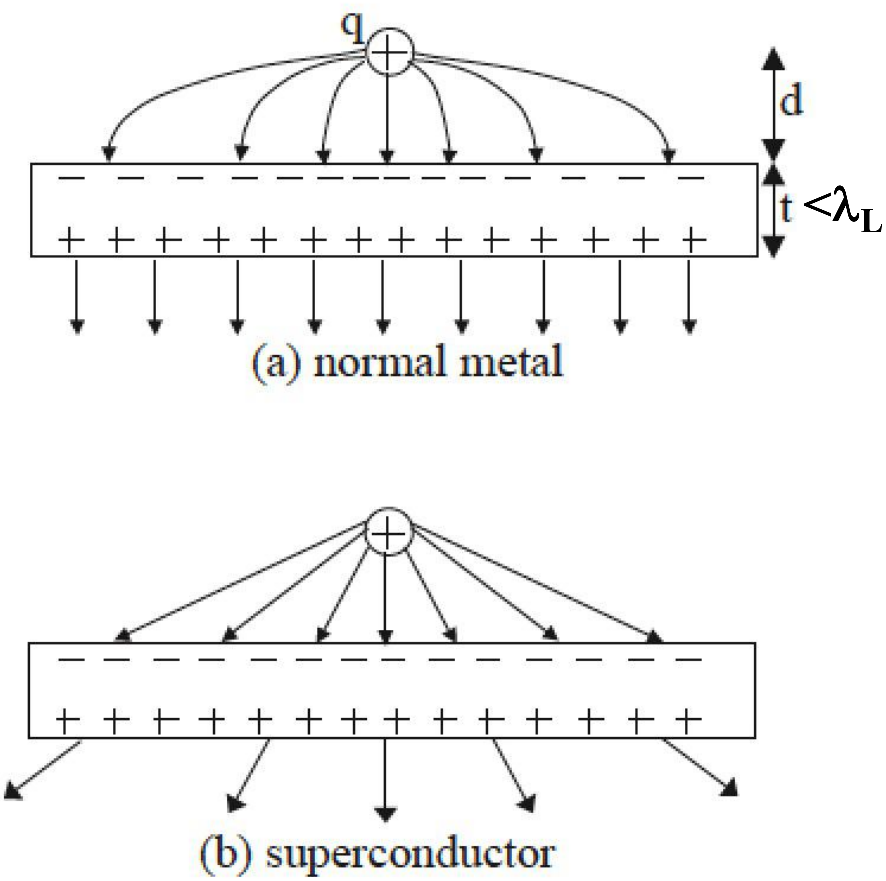
$$\nabla^2\phi(r) = -4\pi\rho(r)$$

$$\nabla^2\phi_0(r) = -4\pi\rho_0$$

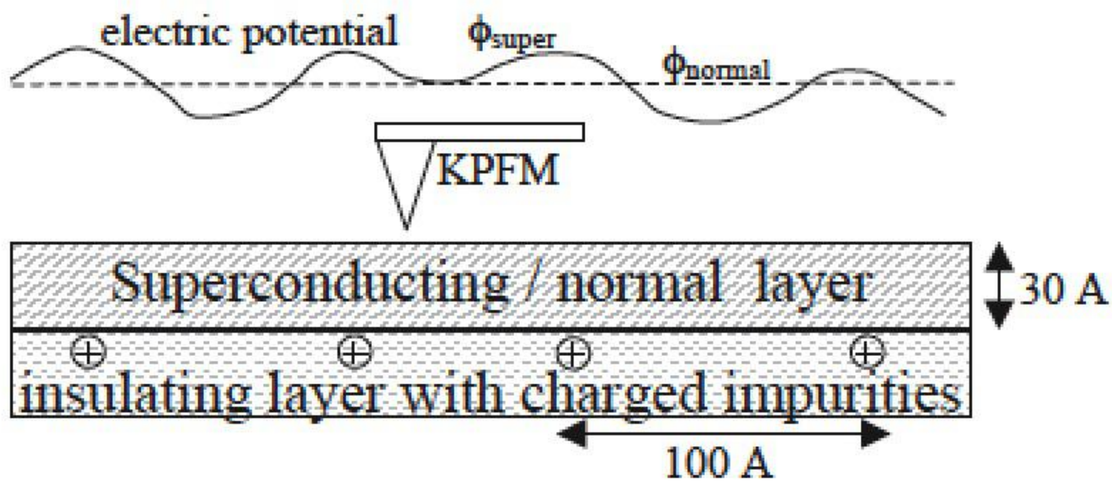
$$\nabla^2(\vec{E} - \vec{E}_0) = \frac{1}{\lambda_L^2}(\vec{E} - \vec{E}_0)$$

$$\nabla^2\phi(r) = 0$$

electric screening length is λ_L

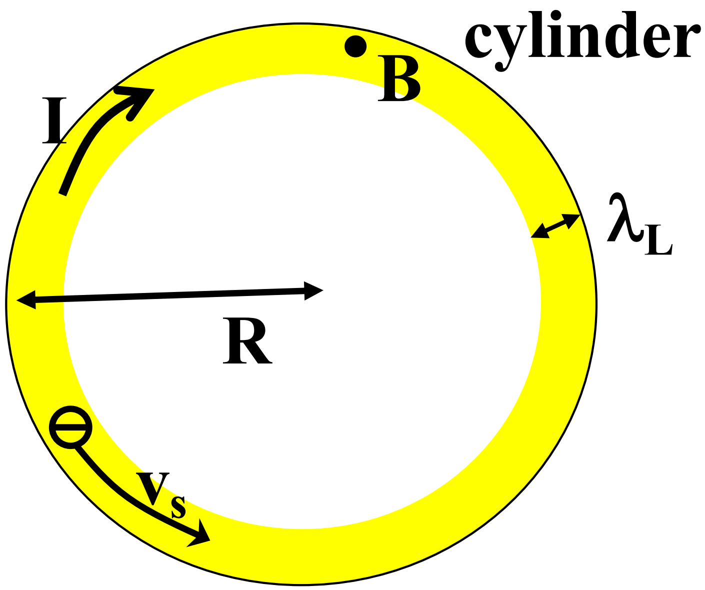


Experiment to test it



Physica C 508, 21 (2015)

Dynamics of the Meissner effect



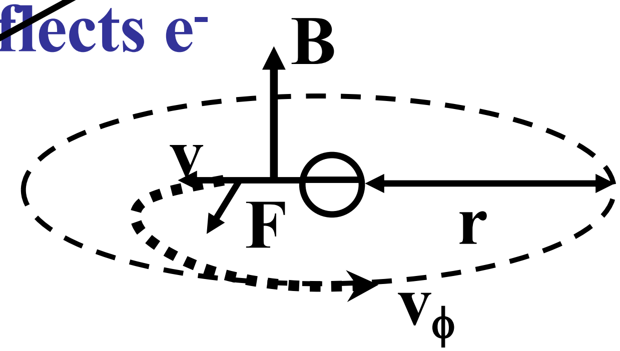
BCS / London :

$$v_s = \frac{1}{m_e}\left(p - \frac{e}{c}A\right)$$

$$\langle p \rangle = 0 \quad ==> v_s = \frac{e}{m_e c}A$$

$$A = \lambda_L B \quad \boxed{==> v_s = \frac{e\lambda_L}{m_e c}B}$$

Electron moving radially out: Lorentz force deflects e$^-$



$$\vec{F} = \frac{e}{c}\vec{v} \times \vec{B} + \vec{F}_r = m_e \frac{d\vec{v}}{dt}$$

$$\frac{d}{dt}(\vec{r} \times \vec{v}) = -\frac{e}{2m_e c}(\vec{r} \cdot \vec{v})\vec{B} = -\frac{e}{2m_e c}\frac{d}{dt}(r^2)\vec{B}$$

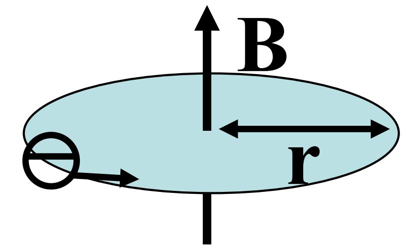
$$=> v_\phi = -\frac{er}{2m_e c}B$$

r=2λ_L

$$\boxed{==> v_\phi = \frac{e\lambda_L}{m_e c}B}$$

Diamagnetic susceptibility

$$\chi_{Larmor} = -\frac{n_s e^2}{4 m_e c^2} < r^2 >$$



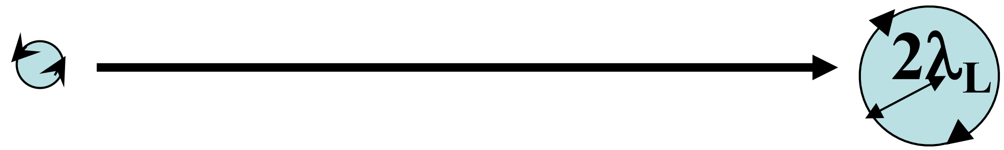
Normal state:

$$\chi_{Landau} = -\frac{1}{3}\mu_B^2 g(\varepsilon_F) = -\frac{n_s e^2}{4 m_e c^2} < (k_F^{-1})^2 >$$

Superconducting state:

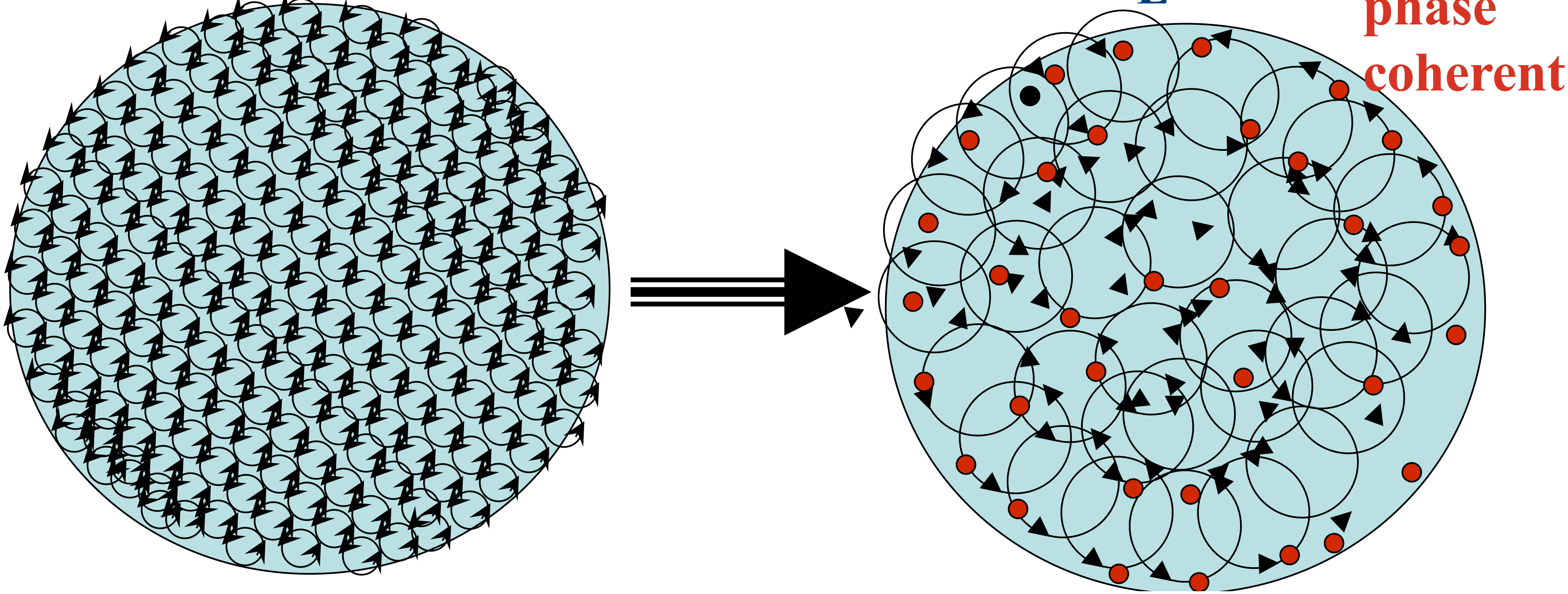
$$\chi_{London} = -\frac{1}{4\pi} = -\frac{n_s e^2}{4 m_e c^2} < (2\lambda_L)^2 >$$

orbit expansion: k_F^{-1}

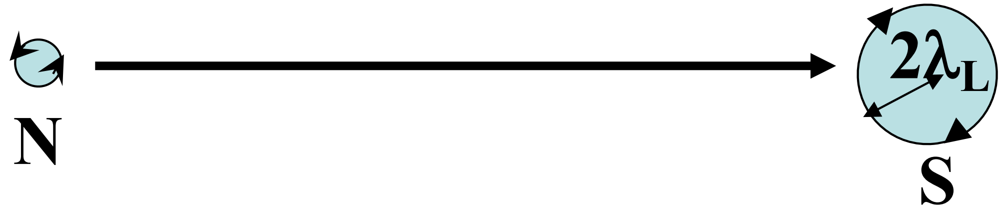


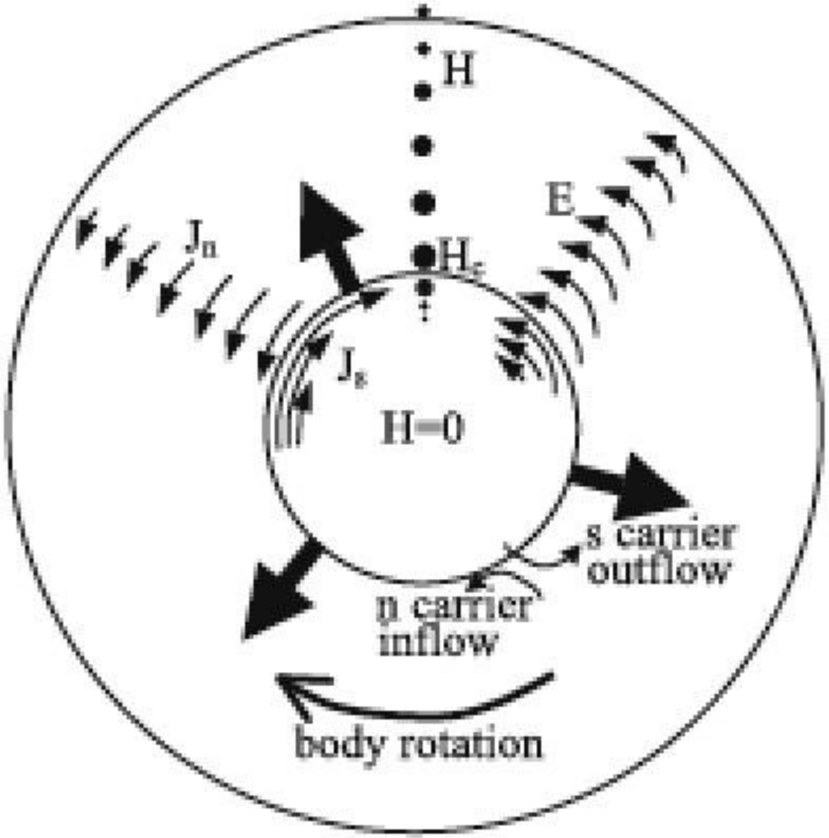
$r=k_F^{-1}$ orbits

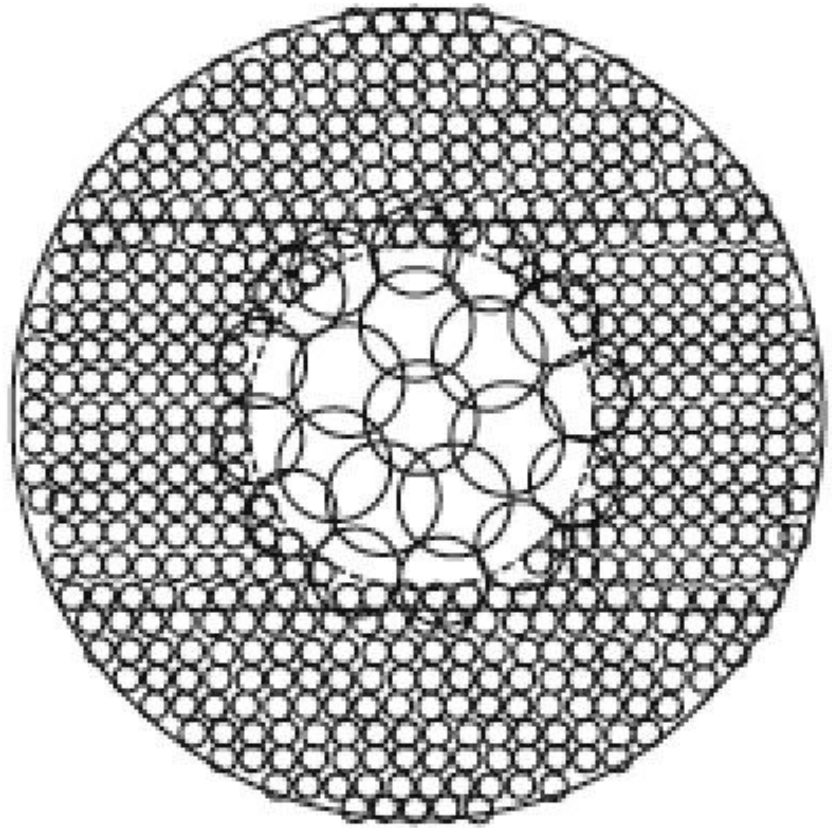
$r=2\lambda_L$ orbits



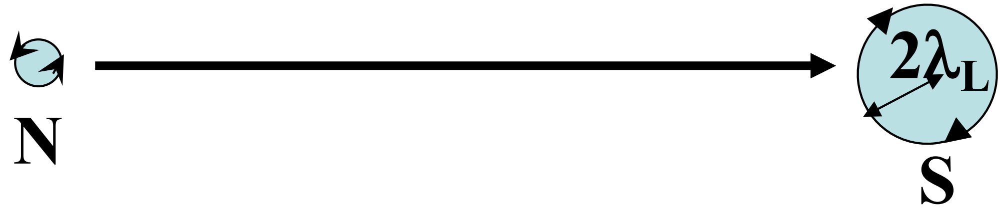
orbit expansion

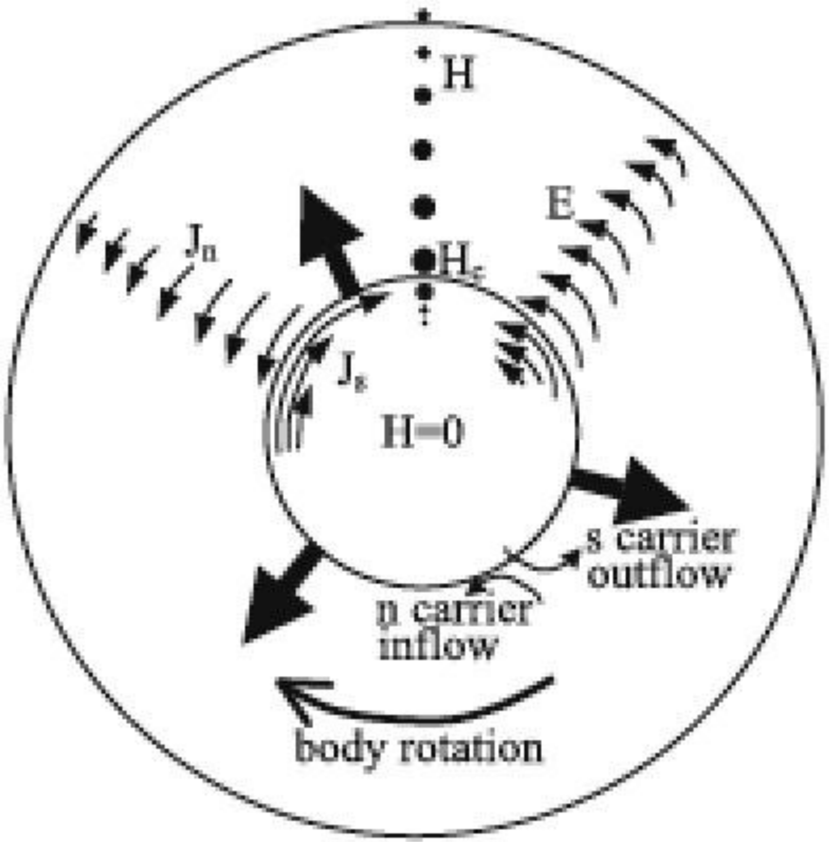


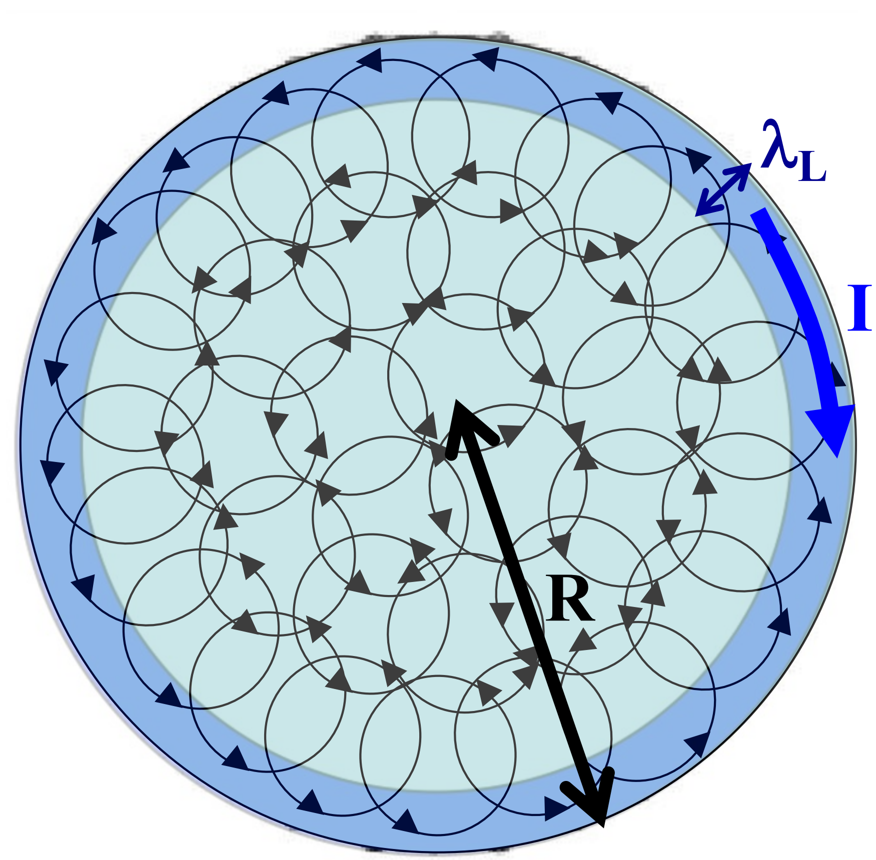




orbit expansion



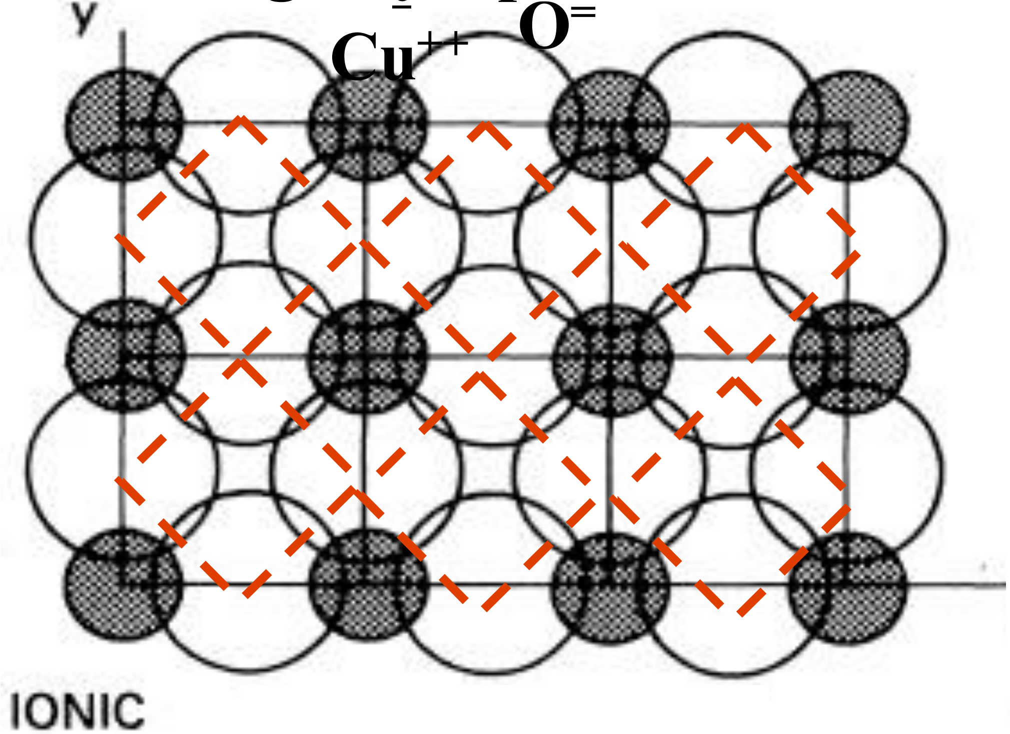


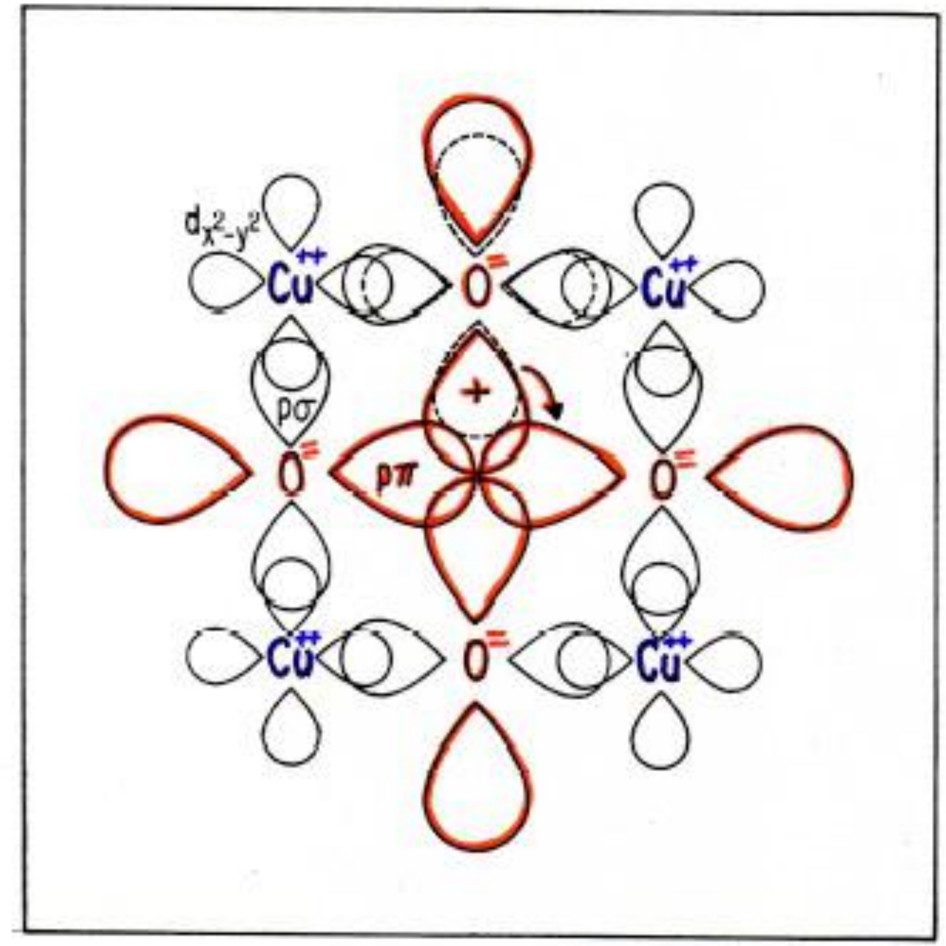


angular momentum of supercurrent:

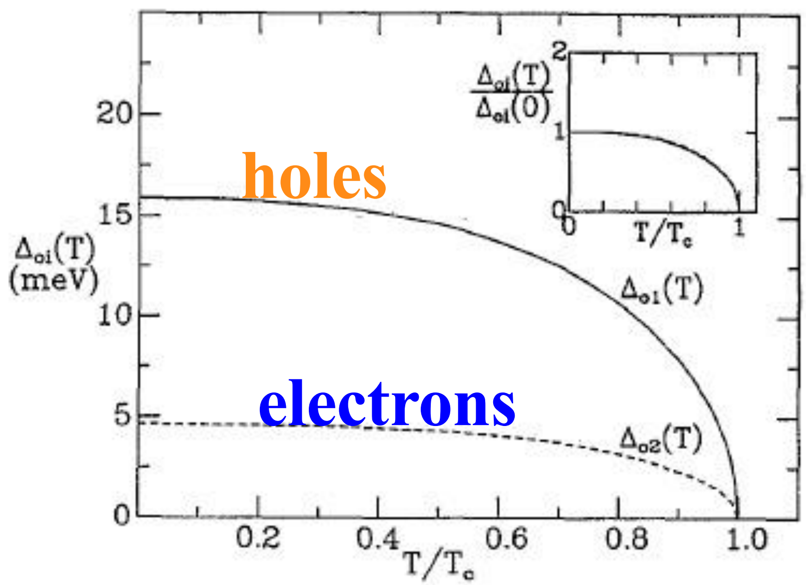
$$L = (m_e v_s R) n_s (2\pi R \lambda_L h) \; = \; L = (m_e v_s 2\lambda_L) n_s (\pi R^2 h)$$

High T_c cuprates

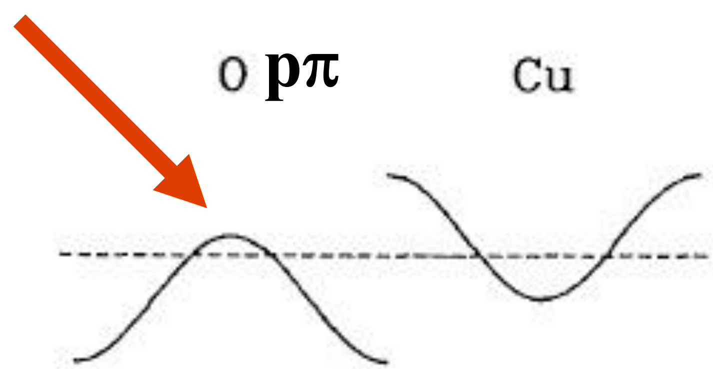




S.Tang, J.H. (1989)



F.M.,J.H., Phys.Rev.B43, 424 (1991)



doped

F.Marsiglio, J.H. (1991)

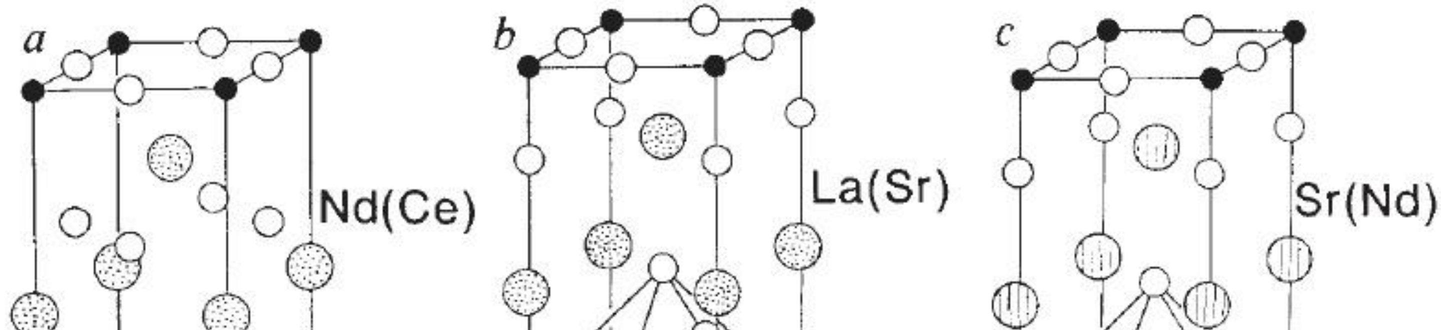
Electron-doped cuprates

letters to nature

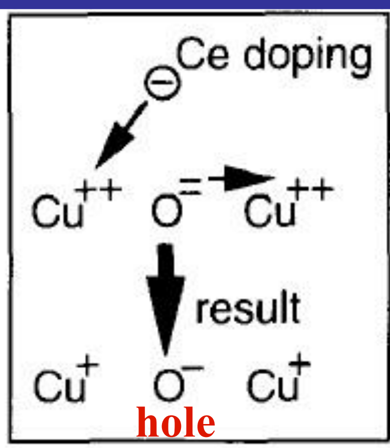
Nature **337**, 345 - 347 (26 January 1989); doi:10.1038/337345a0

A superconducting copper oxide compound with electrons as the charge carriers

Y. TOKURA*, H. TAKAGI† & S. UCHIDA†



With regard to the "electron-doped" oxide superconductors,[21] our model has a specific prediction: oxygen hole carriers will be found in all the samples that go superconducting.
(JEH 1989)



Physica C243, 319 (1995)

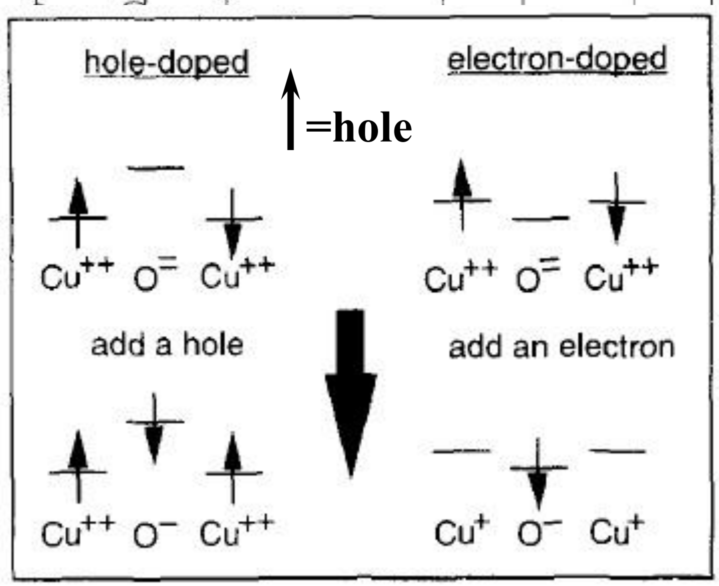


Fig. 1. Schematic depiction of how holes are created by electron doping. The electron added to Cu^{2+} repels an electron from O^{2-} to the neighboring Cu^{2+}, leaving behind a hole in oxygen (O^{-}).

Electron-doped cuprates have hole carriers

VOLUME 73, NUMBER 9 PHYSICAL REVIEW LETTERS 29 AUGUST 1994

Anomalous Transport Properties in Superconducting $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$

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(Received 4 February 1994)

We report a comprehensive study of the in-plane transport properties of $Nd_{2-x}Ce_xCuO_{4\pm\delta}$ epitaxial thin films and crystals by both increasing and decreasing δ with Ce content fixed at $x \approx 0.15$. We find a remarkable correlation between the appearance of superconductivity and (1) a positive magnetoresistance in the normal state, (2) a positive contribution to the otherwise negative Hall coefficient, and (3) an anomalously large Nernst effect. These results strongly suggest that both holes and electrons participate in the charge transport for the superconducting phase of $Nd_{2-x}Ce_xCuO_{4\pm\delta}$.

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Hole superconductivity in the electron-doped superconductor $Pr_{2-x}Ce_xCuO_4$

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We measure the resistivity and Hall angle of the electron-doped superconductor $Pr_{2-x}Ce_xCuO_4$ as a function of doping and temperature. The resistivity ρ_{xx} at temperatures $100\ K < T < 300\ K$ is mostly sensitive to the electrons. Its temperature behavior is doping independent over a wide doping range and even for nonsuperconducting samples. On the other hand, the transverse resistivity ρ_{xy}, or the Hall angle θ_H, where $\cot(\theta_H) = \rho_{xx}/\rho_{xy}$, is sensitive to both holes and electrons. Its temperature dependence is strongly influenced by doping, and $\cot(\theta_H)$ can be used to identify optimum doping (the maximum T_c) even well above the critical temperature. These results lead to a conclusion that in electron doped cuprates holes are responsible for the superconductivity.

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CONDENSED MATTER PHYSICS

Hole pocket–driven superconductivity and its universal features in the electron-doped cuprates

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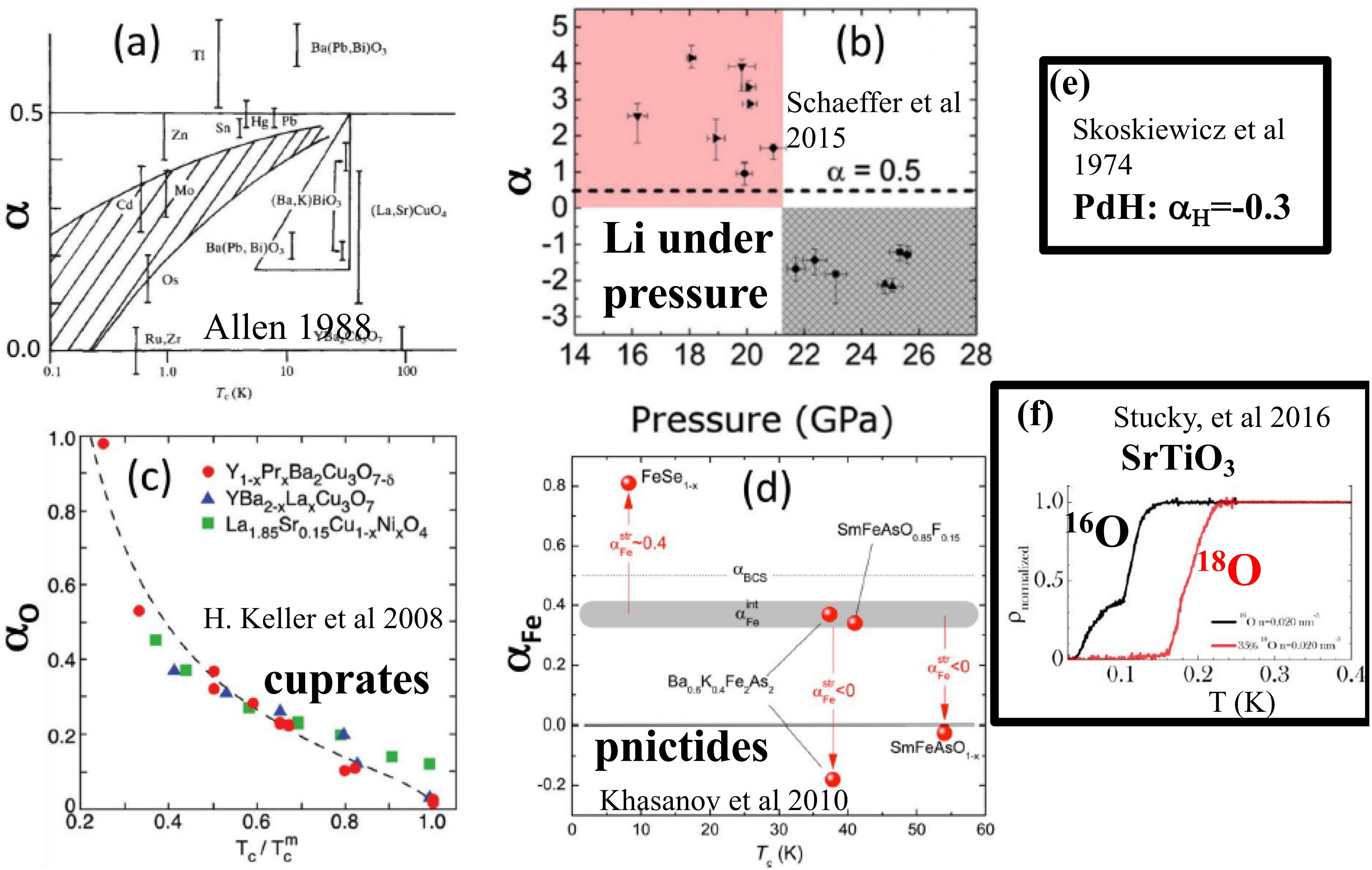
After three decades of intensive research attention, the emergence of superconductivity in cuprates remains an unsolved puzzle. One major challenge has been to arrive at a satisfactory understanding of the unusual metallic "normal state" from which the superconducting state emerges upon cooling. A second challenge has been to achieve a unified understanding of hole- and electron-doped compounds. Here, we report detailed magnetoresistance measurements for the archetypal electron-doped cuprate $Nd_{2-x}Ce_xCuO_{4+\delta}$ that, in combination with previous data, provide crucial links between the normal and superconducting states and between the electron- and hole-doped parts of the phase diagram. The characteristics of the normal state (magnetoresistance, quantum oscillations, and Hall coefficient) and those of the superconducting state (superfluid density and upper critical field) consistently indicate two-band (electron and hole) features and point to hole pocket–driven superconductivity in these nominally electron-doped materials. We show that the approximate Uemura scaling between the superconducting transition temperature and the superfluid density found for hole-doped cuprates also holds for the small hole component of the superfluid density in electron-doped cuprates.

Isotope effect: $T_c \sim M^{-\alpha}$



To the same natural effects we must, as far as possible, assign the same causes.

Summary

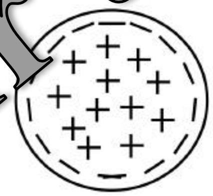
* The Meissner effect is the most fundamental property of supercond.

* Expulsion of magnetic field requires radial flow of charge

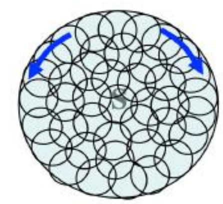
* Only hole carriers can transfer momentum to body without dissipati

* Hole carriers pair through kinetic energy lowering, electrons don’t

* Superconductors are like “giant atoms”



* Superconductors have macroscopic zero-point motion



* The spin-orbit interaction is essential to understand superconductivi

* Superfluid electrons have orbital angular momentum $L = \hbar/2$

* The electron-phonon interaction is irrelevant to superconductivity

* It is impossible for BCS theory to explain the Meissner effect!

* A lot remains to be understood!

Thank you for your attention

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The Bohr superconductor

The Dirac superconductor

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PACS 74.25.N- – Response to electromagnetic fields

Abstract – Superconductors have often been described as "giant atoms". The simplest description of atoms that heralded their quantum understanding was proposed by Bohr in 1913. The Bohr atom starts from some simple assumptions and deduces that the angular momentum of the electron in Bohr orbits is quantized in integer units of $\hbar$. This remarkable result, which does not appear to be implicit in the assumptions of the model, can be interpreted as a "theoretical proof" of the model's validity to describe physical reality at some level. Similarly we point out here that from some simple assumptions it can be deduced that electrons in superconductors reside in mesoscopic orbits with orbital angular momentum $\hbar/2$. This implies that both in superconductors and in ferromagnets the long-range order results from elementary units of identical angular momentum. Similarly to the case of the Bohr atom we propose that this remarkable result is compelling evidence that this physics, which is not part of conventional BCS theory, describes physical reality at some level and heralds a qualitatively new understanding of superconductors.