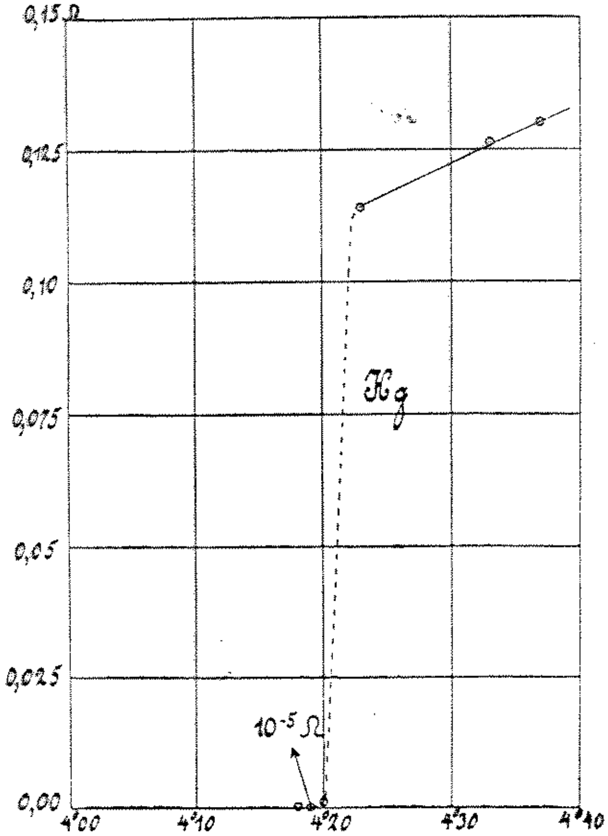


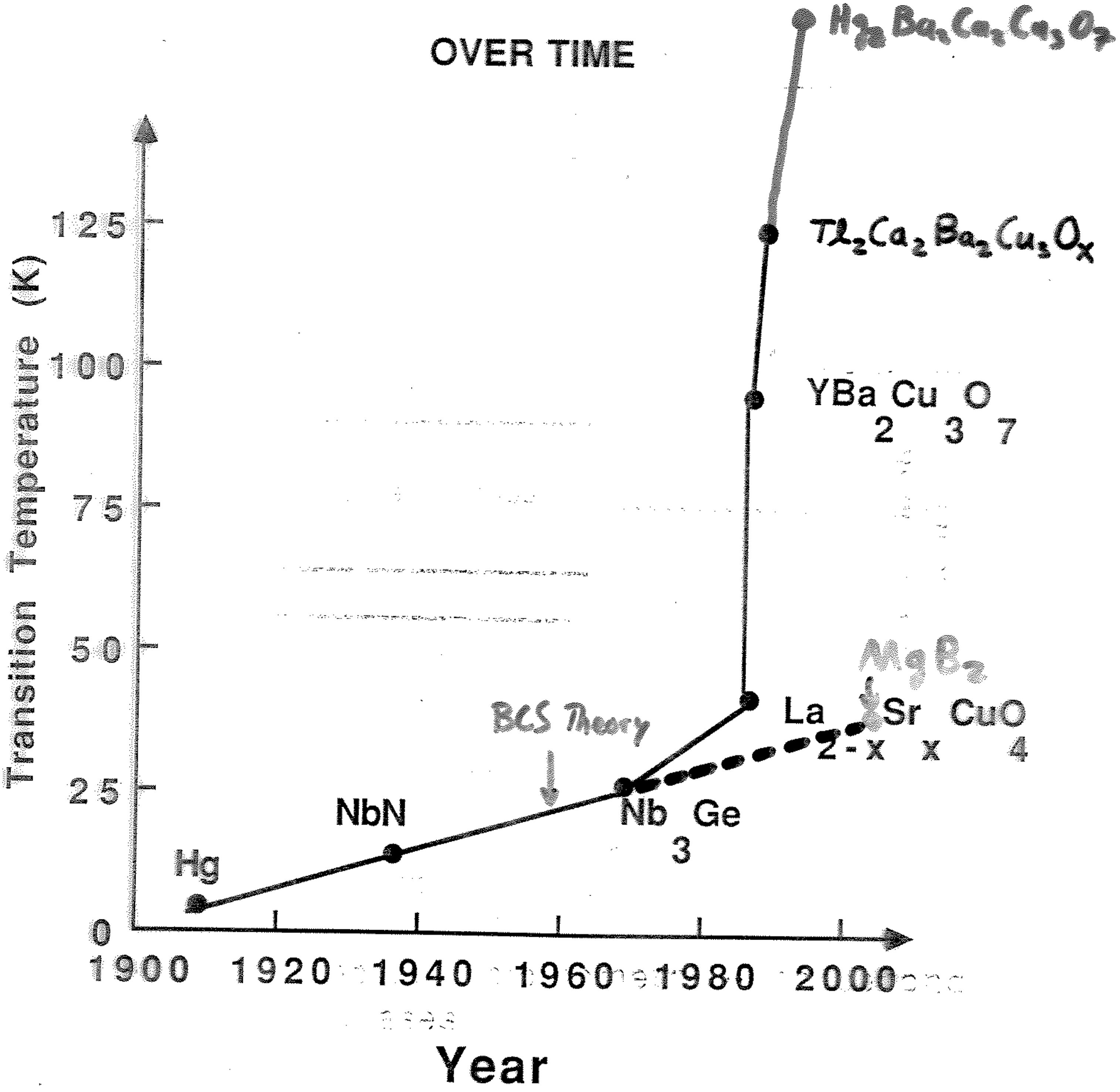
Figure 1 Resistance in ohms of a specimen of mercury versus absolute temperature. This plot by Kamerlingh Onnes marked the discovery of superconductivity.

bulk superconductor in a weak magnetic field will act as a perfect diamagnet, with zero magnetic induction in the interior. When a specimen is placed in a magnetic field and is then cooled through the transition temperature for superconductivity, the magnetic flux originally present is ejected from the specimen. This is called the **Meissner effect.** The sequence of events is shown in Fig. 2. The unique magnetic properties of superconductors are of central importance to the characterization of the superconducting state.

The superconducting state is known to be an ordered state of the conduction electrons of the metal. The order is in the formation of loosely associated pairs of electrons. The electrons are ordered at temperatures below the transition temperature, and they are disordered above the transition temperature. The nature and origin of the ordering was explained by Bardeen, Cooper, and Schrieffer.[3] In the present chapter we develop as far as we can in an elementary way the physics of the superconducting state. We shall also discuss the basic physics of the materials used for superconducting magnets, but not their technology.

SUPERCONDUCTING TRANSITION TEMPERATURE

OVER TIME



Classes of Superconductors

"Conventional" 3D BCS s-wave

Nb, Al, Pb, Sn, Nb_3Sn, Nb-Ti, etc. $T_c < 25$ K

A_3C_{60}, electronically-doped C_{60}, MgB_2 $T_c < 40$ K

"Organic" Quasi 1-D,2-D

$(TMTSF)_2X$, $(BEDT\text{-}TTF)_2X$ $T_c < 12$ K

"Oxide"

$Ba(Pb\text{-}Bi)_3O$, Ba-K-Bi-O $T_c < 30$ K

"Heavy Fermion" Anisotropic (p- or d-wave)

UPt_3, UBe_{13}, $CeCu_2Si_2$ $T_c < 2$ K

"Cuprates"

$T_c \rightarrow 154$ K (under pressure)

High-T_c:

Hg-Ba-Ca-Cu-O $T_c < 135$ K

Tl-Ba-Ca-Cu-O $T_c < 125$ K

Bi-Sr-Ca-Cu-O $T_c < 108$ K

★ Y-Ba-Cu-O $T_c < 93$ K

Low-T_c:

La-Sr-Cu-O $T_c < 36$ K

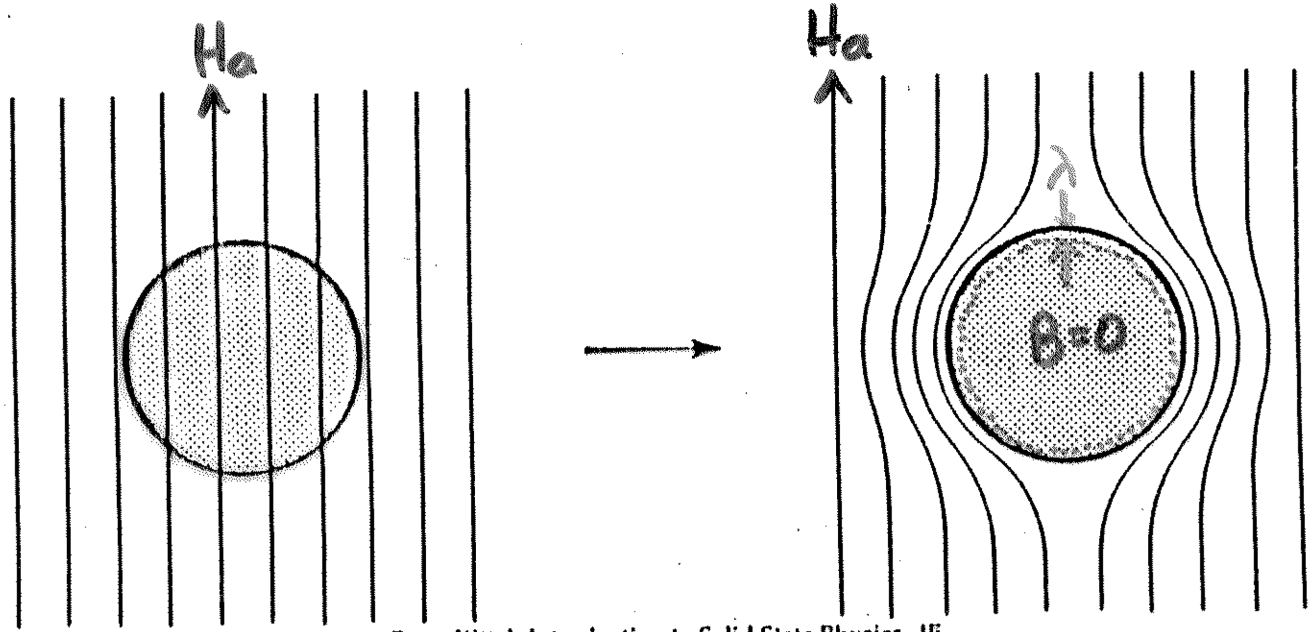
☆ Nd-Ce-Cu-O $T_c < 25$ K

"Ruthenates" Sr-Ru-O (p-wave) $T_c < 1.5$ K

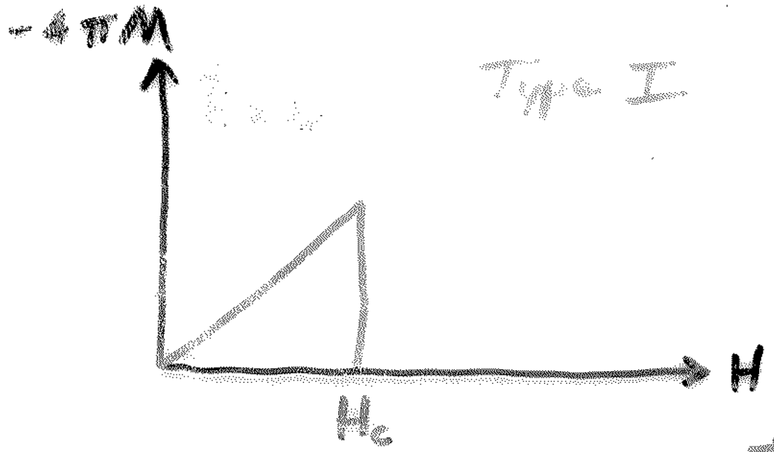
Superfluid ^4He -> Bose-Einstein condensate: $T_c \sim 2$ K

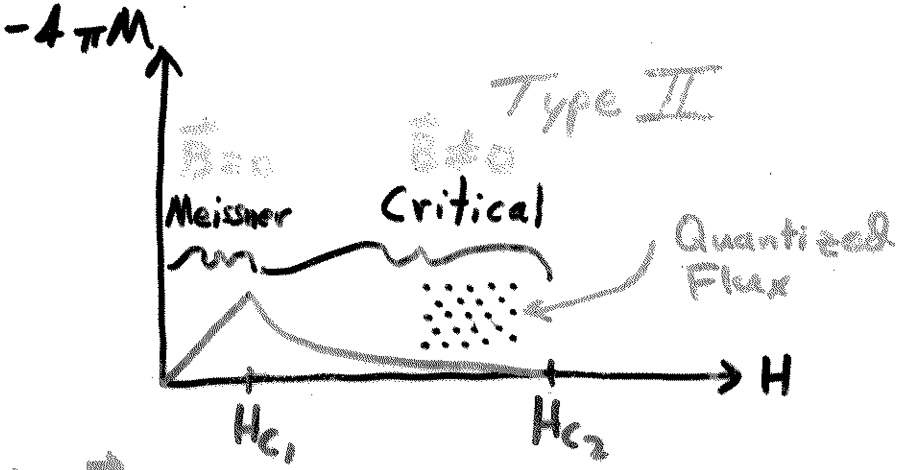
Superfluid ^3He -> S = 1 pairs, p-wave superfluid: $T_c \sim 10^{-3}$ K

Meissner Effect



From Kittel: Introduction to Solid State Physics, 4E

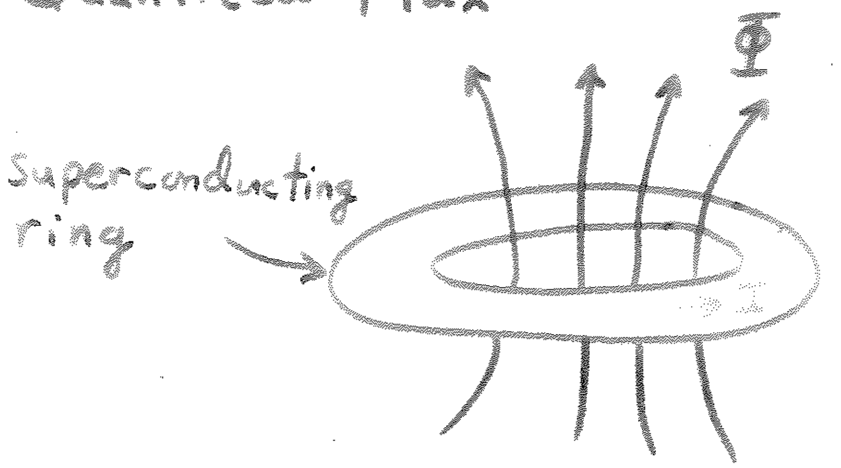




$\vec{B}=\vec{H}+4\pi\vec{M}$

Macroscopic Quantum Phenomena

Quantized Flux



But

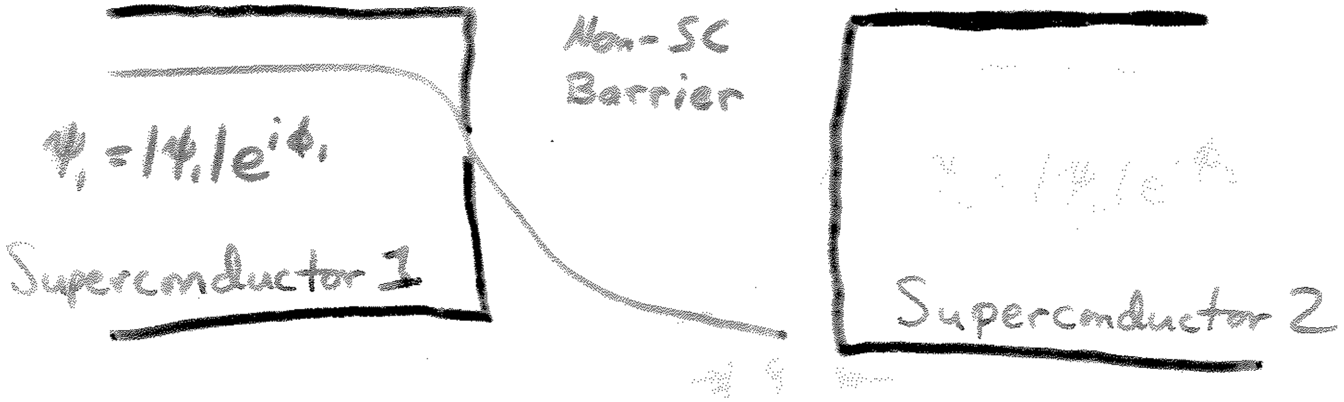
$$\Phi = n\Phi_0 = \frac{nh}{2e}$$

$n = 0, 1, 2, 3, \ldots$

$\Phi_0 = 2.07 \times 10^{-15}$ Wb

wf is single-valued

Josephson Effect

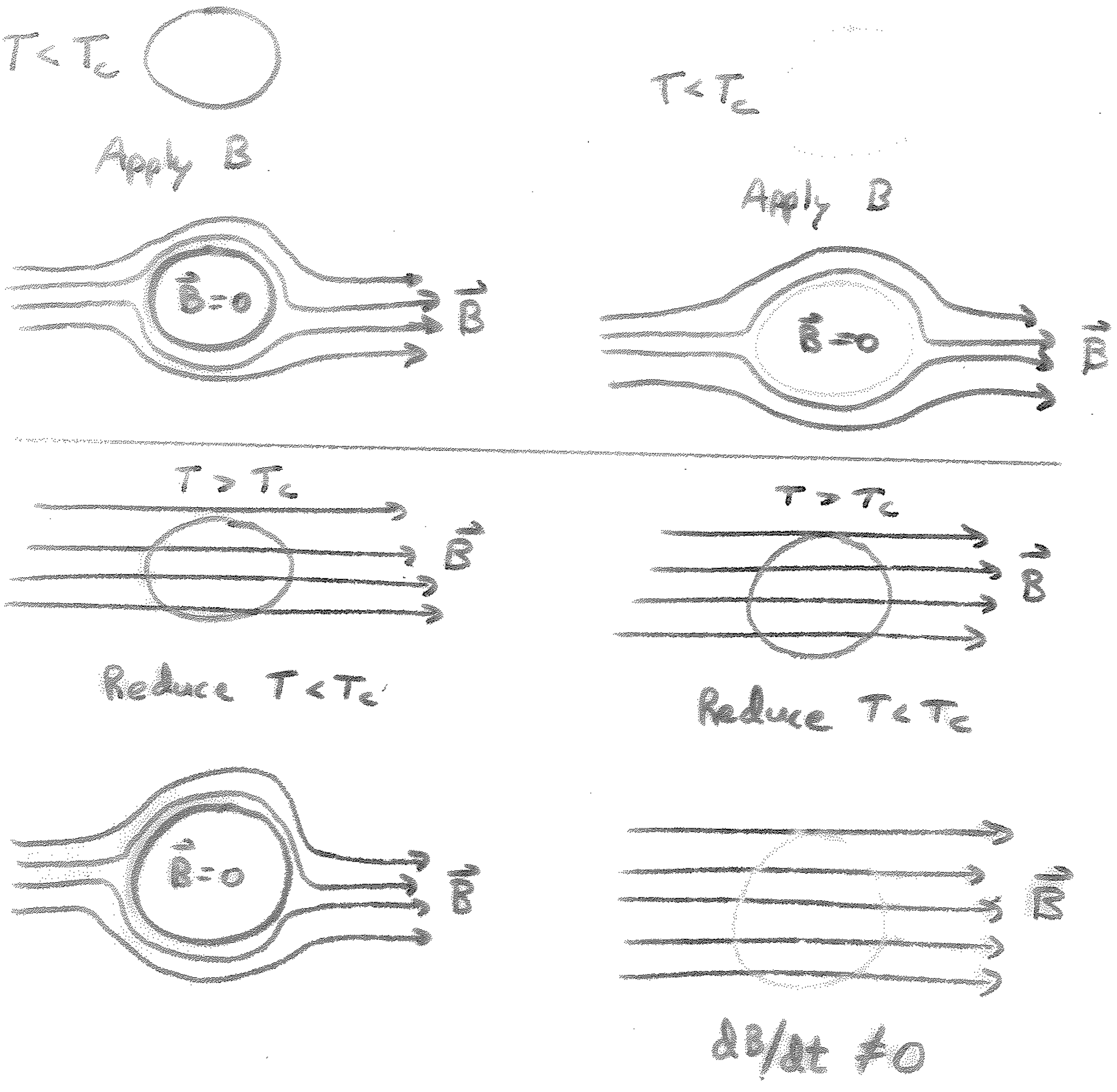


$$I = I_c \sin(\phi_2 - \phi_1) \qquad (V_{DC} = 0)$$

$$\frac{\partial(\phi_2 - \phi_1)}{\partial t} = \frac{2e}{h} V_{DC}$$

Zero Resistance and Perfect Diamagnetism

Superconductor vs Perfect Conductor



Flux Quantization in a High T_c SC

C. E. Gough, et al. Nature **326**, 855 (1987).

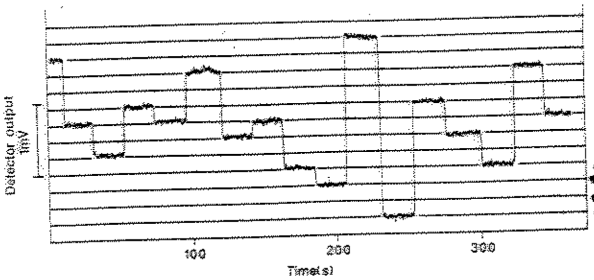
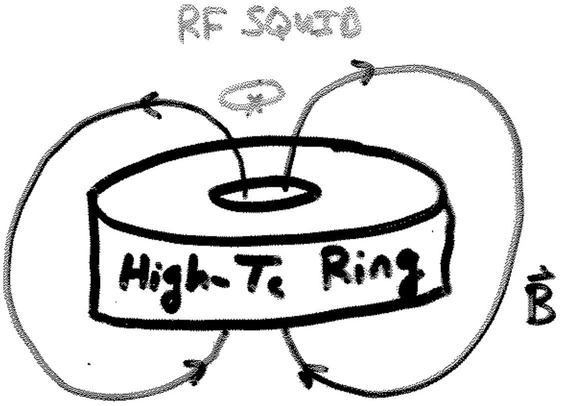


Fig. 2 Output of the r.f.-SQUID magnetometer showing small integral numbers of flux quanta jumping in and out of the ring.

$\updownarrow \; \Phi_0 = \frac{h}{2e}$

$YBa_2Cu_3O_7$
ceramic
4.2 K



Experimental value for the flux quantum

$$\Phi_0 = 0.97 \pm 0.04 \; \frac{h}{2e}$$

SQUID magnetometer output stable for 1000 s

$\Rightarrow R_{ring} < 10^{-13} \, \Omega$