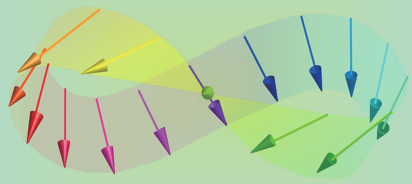
Nanoelectronics

14



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THE UNIVERSITY *of York*

12:00 Thursday, 02/March/2023 (P/T 005A)

Quick Review over the Last Lecture

	Fermi-Dirac distribution	Bose-Einstein distribution
Function	$f(E) =$	$f(E) =$
Energy dependence		

Contents of Nanoelectonics

14 Quantum Statistics 2

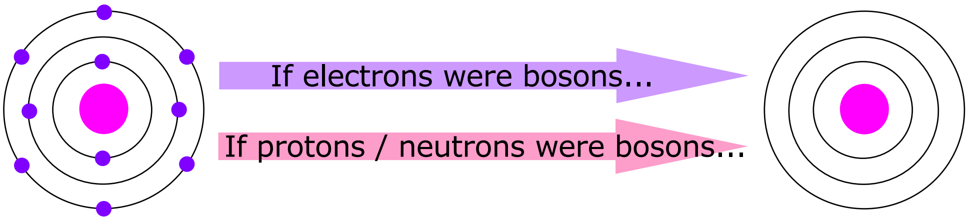
- Boson
- Fermion
- Bose-Einstein condensation
- Fermi degeneracy
- Fermi liquid
- Ideal quantum gas

Fermions / Bosons

In particle physics,

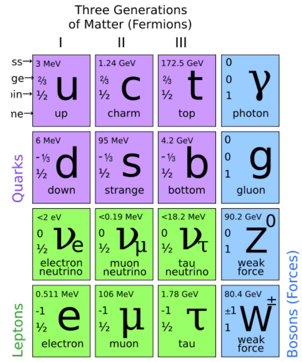
Fermions : 1 fermion occupies 1 quantum state (Fermi-Dirac statistics)

Particles, which consist of materials; *e.g.*, protons, neutrons and electrons



Bosons : Several bosons occupy 1 quantum state (Bose-Einstein statistics)

Particles, which transfer particle-interactions; *e.g.*, photons and gluons



* http://www.wikipedia.org/

Superconducting Elements

In the periodic table,

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pd	Bi	Po	At	Rn
Fr	Ra																
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Superconductors and high-pressure-phase superconductors

Superconducting transition temperature :

Al : 1.19 K, Nb : 9.2 K, In : 3.4 K, Sn : 3.7 K, Pb : 7.2 K

Superconductors

Major properties :

Zero electrical dc resistance : H. K. Onnes in 1911 (Hg)

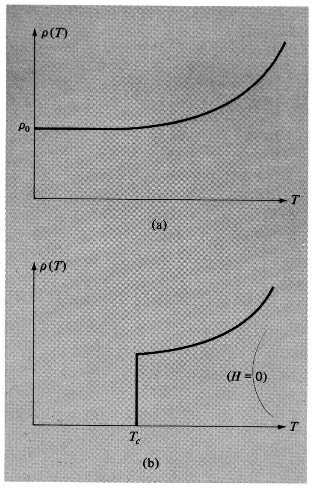


Figure 34.1
(a) Low-temperature resistivity of a normal metal ($\rho(T) = \rho_0 + BT^5$) containing nonmagnetic impurities (b) Low-temperature resistivity of a superconductor (in zero magnetic field) containing nonmagnetic impurities. At T_c, ρ drops abruptly to zero.

→ Superconducting phase transition at T_c

→ BCS theory

Persistent current :

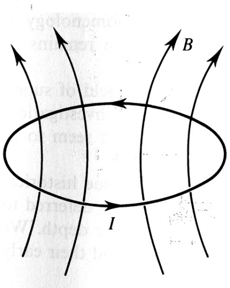
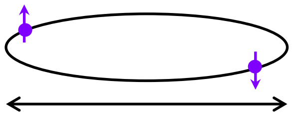


FIGURE 1.1
Schematic diagram of persistent current experiment.

Cooper pair :



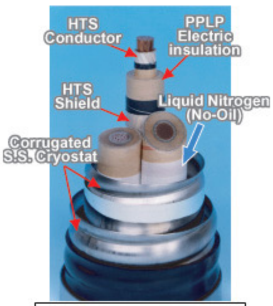
~ 1 μm

* N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Thomson Learning, London, 1976);

Superconductor Applications

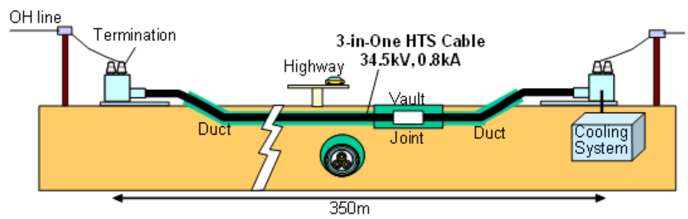
Using a persistent current,

Superconducting cable :



Structure of "3-in-One" Superconducting Cable

System Schematic



Superconducting flywheel :

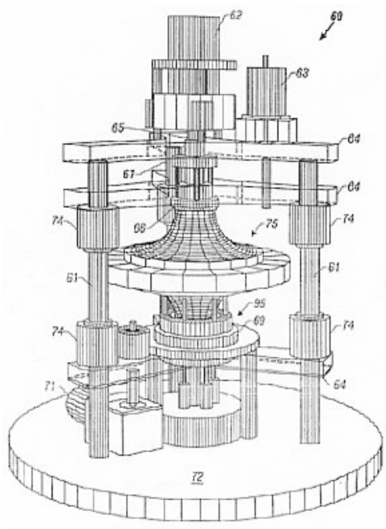
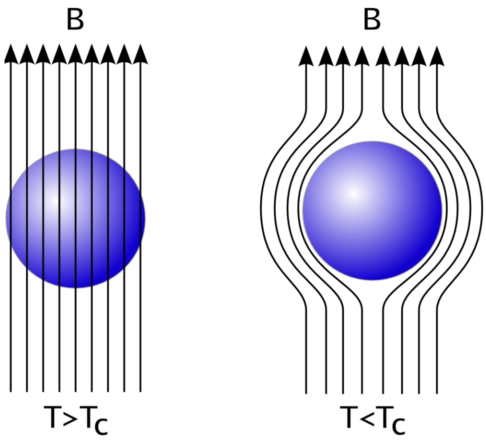


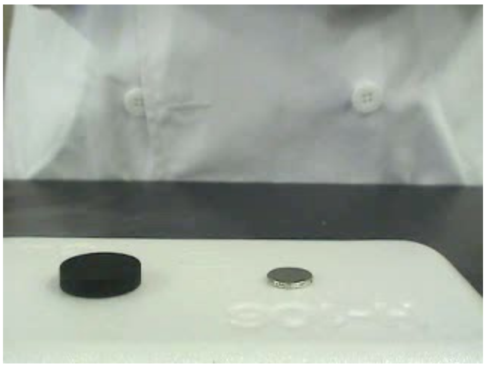
FIG. 5

* http:// www.sei.co.jp/; ** U.S. Patent 6,231,011 B1.

Meissner Effect

Expulsion of a magnetic field from a superconductor :





→ Perfect diamagnetism

→ London equation

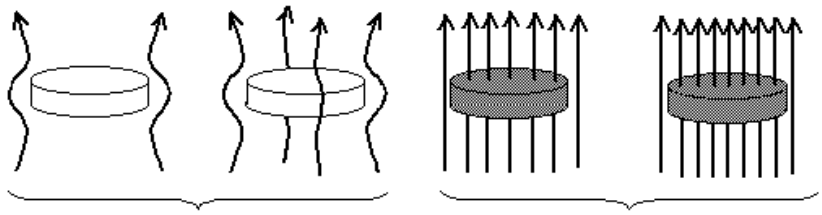
→ Magnetic levitation
(581 km/h, 2003)

* http://www.wikipedia.org/;

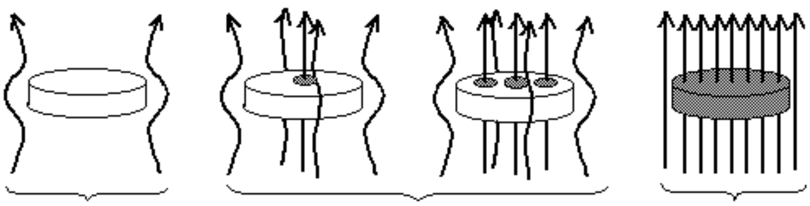
Magnetic Levitation

Type I / II Superconductors

Type I superconductors : *e.g.*,



Type II superconductors : *e.g.*, $YBa_2Cu_3O_{7-\delta}$, $Bi_2Sr_2Ca_2Cu_3O_{10}$, ...



* http://www.wikipedia.org/

Magnetic Field Dependence of Type I / II Superconductors

Flux penetration in type I and II superconductors :

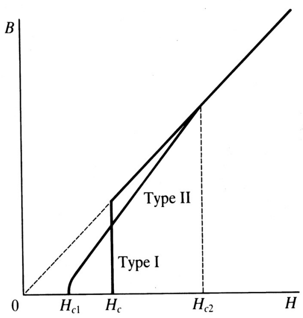
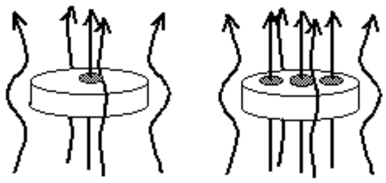


FIGURE 1.5
Comparison of flux penetration behavior of type I and type II superconductors with the same thermodynamic critical field H_c. $H_{c2} = \sqrt{2}\kappa H_c$. The ratio of B/H_{c2} from this plot also gives the approximate variation of R/R_n, where R is the electrical resistance for the case of negligible pinning, and R_n is the normal-state resistance.

Flux quantization in a superconductor :

h / 2e

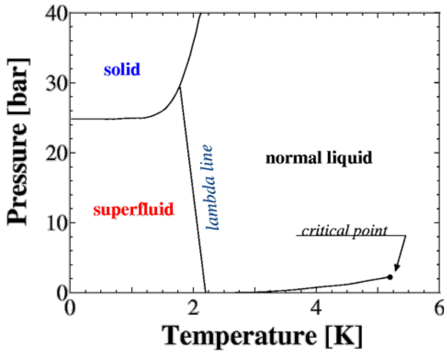


* M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1996).

Fermions / Bosons Transition

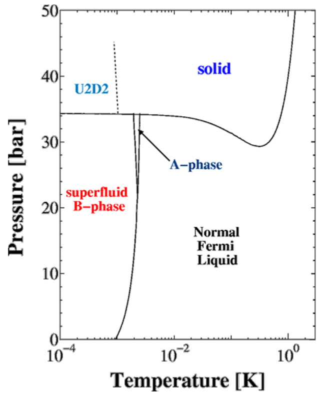
Particles consisting of even numbers of fermions : bosons

e.g.,



Particles consisting of odd numbers of fermions : fermions

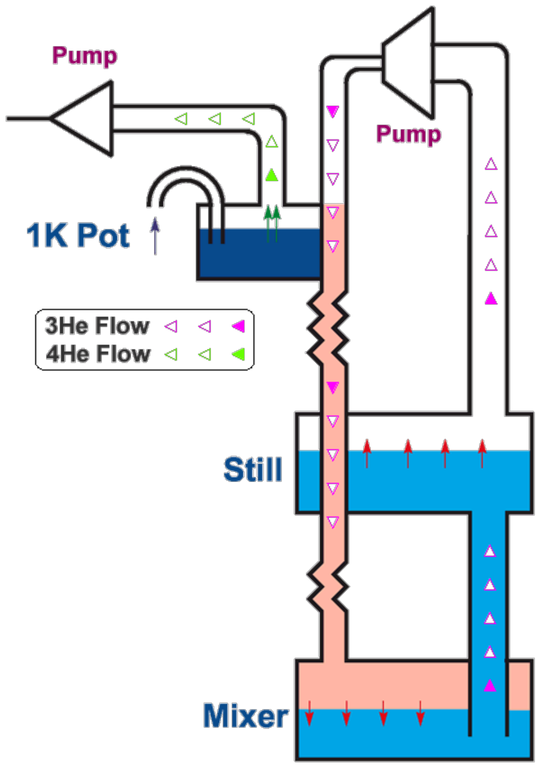
e.g.,

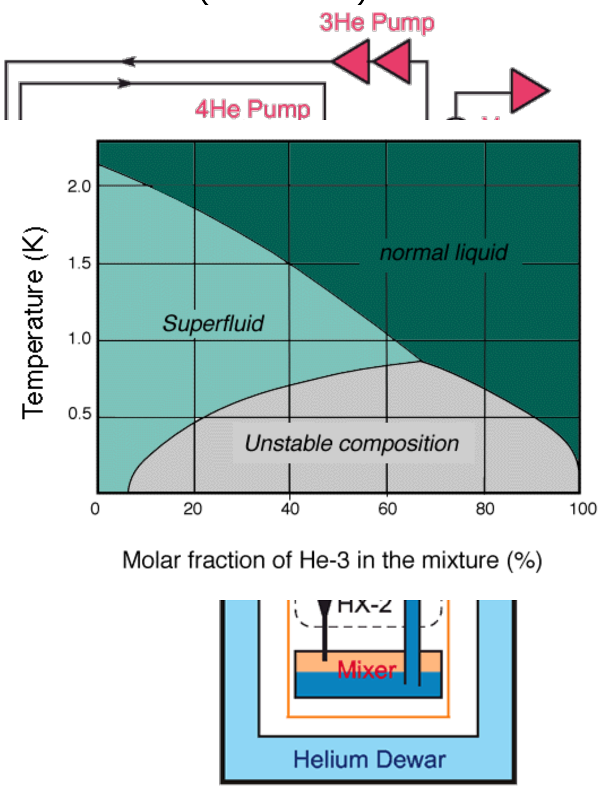


* http://www.sci.osaka-cu.ac.jp/phys/ult/invitation/helium/helium.html

Low-Temperature Generation

By using 3-He and 4-He, a dilution refrigerator is realised (< 100 mK) :





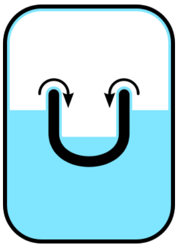
* http://www.sci.osaka-cu.ac.jp/phys/ult/invitation/cryo/dr.html

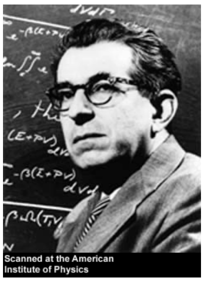
Bose-Einstein Condensation - He 3 superfluid

In boson systems, all bosons fall into the lowest energy state at very low temperature.

→ Bose-Einstein condensation

e.g., (1938 Fritz W. London)





e.g., (1972 Douglas D. Osheroff, Robert C. Richardson and David M. Lee)

2 He-3 fermions form a Cooper pair

→ quasi-particle

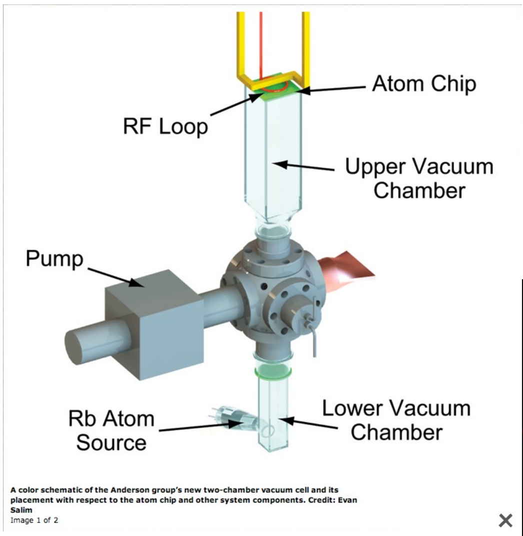
→ state

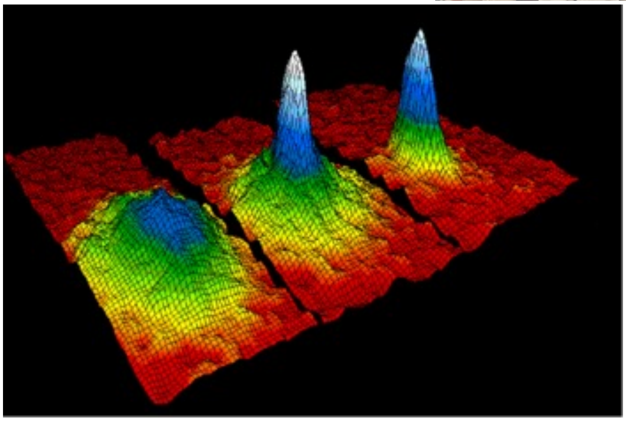
* http://photos.aip.org/

Bose-Einstein Condensation - He 4 superfluid

Bose-Einstein Condensation - Rb atom

In 1995, B-E condensation observed in Rb atom by Eric A. Cornell and Carl E. Wieman :





← Reduced speed by photon-momentum absorption

* http://www.wikipedia.org/

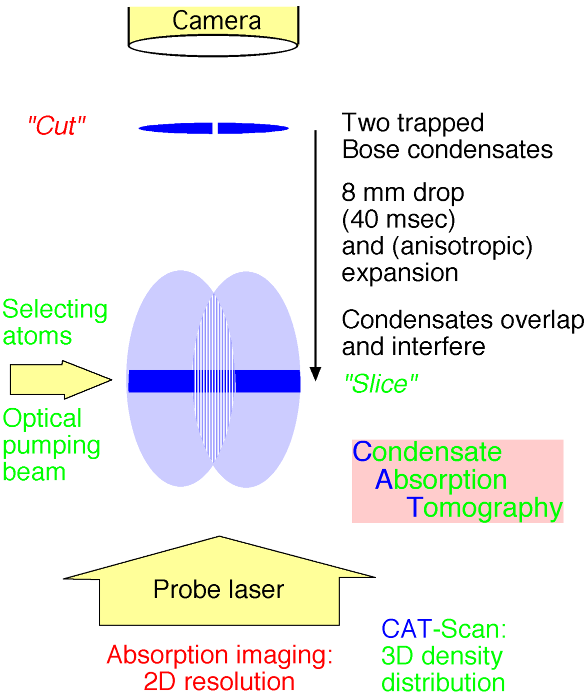
** http://jila.colorado.edu/content/bec-transporter

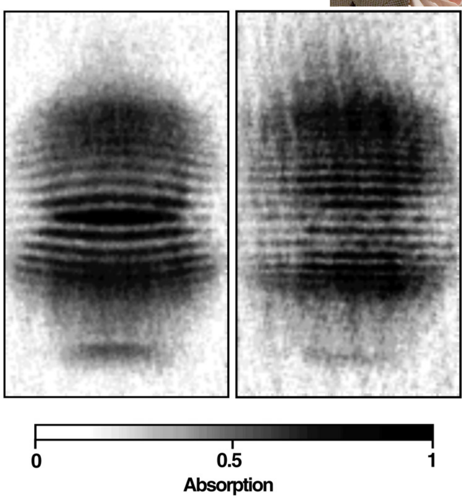
*** R. Baierlein, *Thermal Physics* (Cambridge University Press, Cambridge, 1999).

Bose-Einstein Condensation - Na atom

In 1995, Wolfgang Ketterle also observed B-E condensation in Na atom :

Interference of two condensates



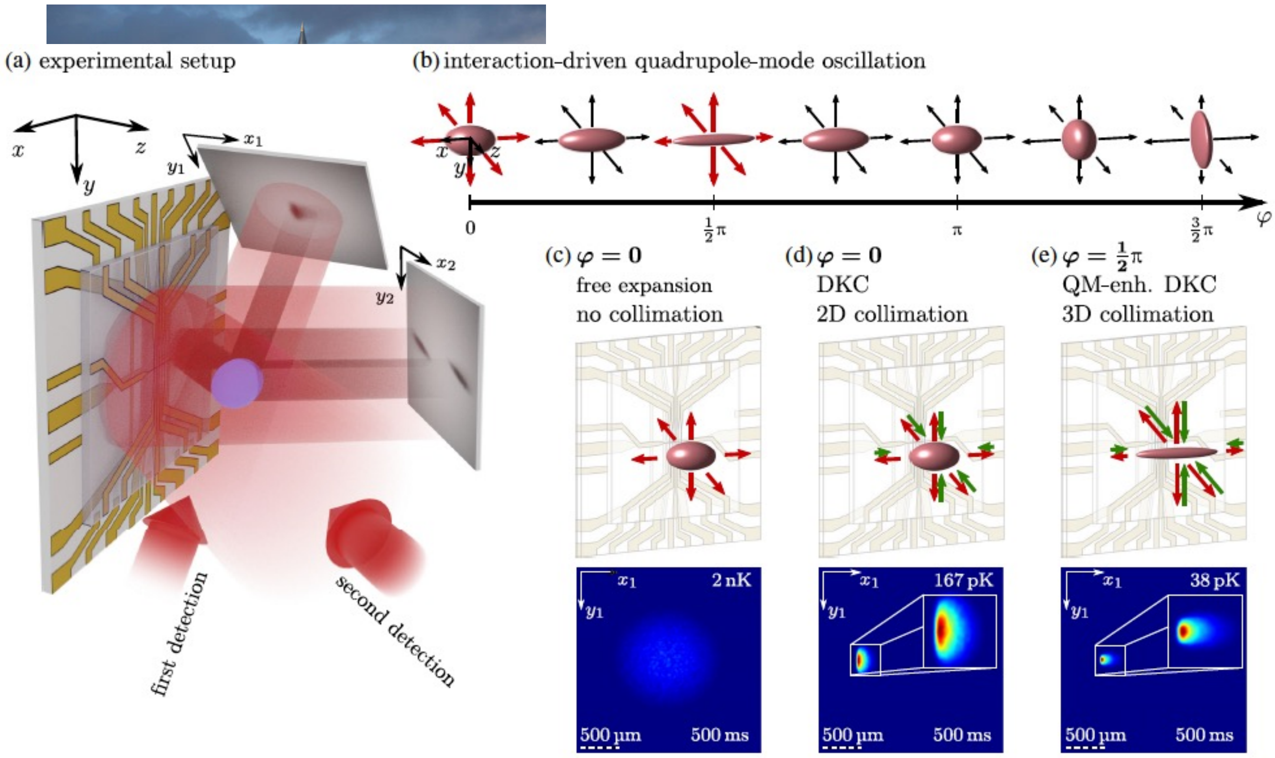


* http://www.wikipedia.org/

** http://cua.mit.edu/ketterle_group/Projects_1997/Interference/Interference_BEC.htm

Bose-Einstein Condensation - Rb atom

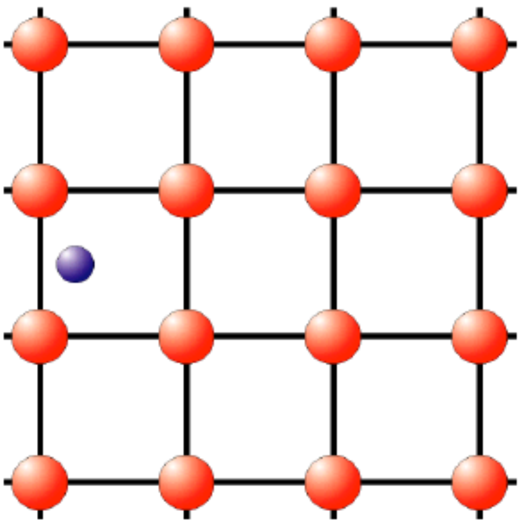
In 2021, 120 m freefall was used to achieve 38pK by switching a magnetic field on/off to freeze 0.1M Rb atoms :

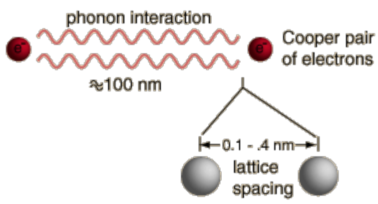


* C. Deppner *et al.*, *Phys. Rev. Lett.* 127, 100401 (2021).

Bose-Einstein Condensation - Superconductor

Cooper pair in a superconductor :

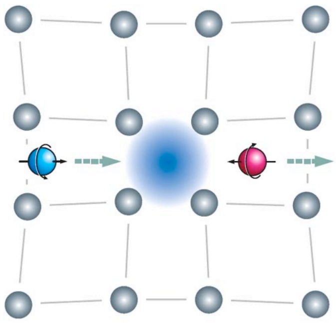




* http://www.phys.shimane-u.ac.jp/mutou_lab/
** http://hyperphysics.phy-astr.gsu.edu/Hbase/solids/coop.html

Superconductor and Heavy-Electron System

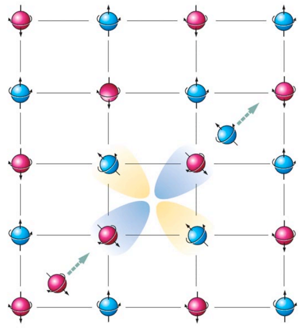
Cooper pair in a superconductor :



→ Lattice deformation

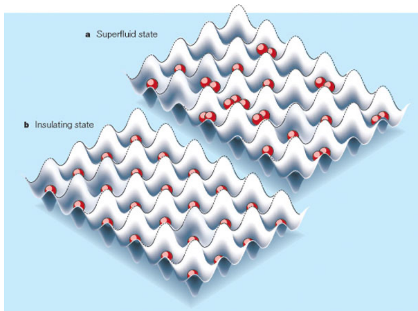
→ Dipole Cooper pair

Heavy-electron system :



→ Quadra-pole rigid lattice

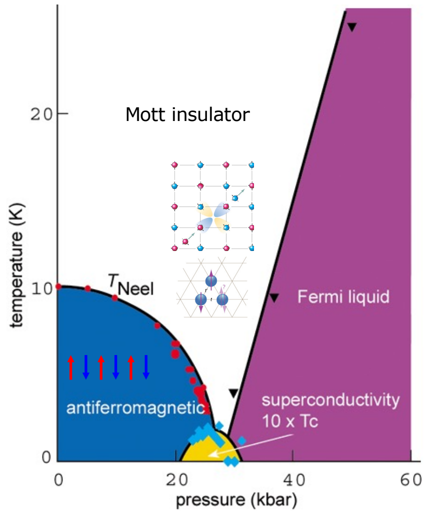
→ Mott insulator



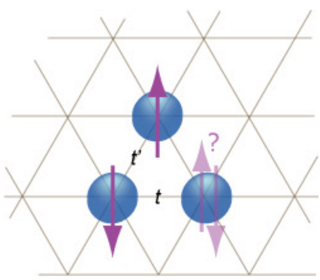
* http://www.lanl.gov/news/index.php/fuseaction/1663.article/d/20075/id/10392
** http://www.lorentz.leidenuniv.nl/~pjhdent/

Magnetic Quantum Critical Point

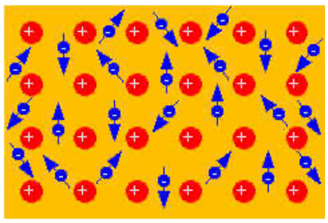
Phase diagram :



Frustrated spin system :



Fermi liquid :



→ Conventional metals

* http://physicsworld.com/cws/article/print/3504/1/pw1501092
** http://kotai2.scphys.kyoto-u.ac.jp/index.php?Research
*** http://www.jst.go.jp/kisoken/presto/complete/soshiki/theme/first_r/07nantoh/link011.htm

Fermi Liquid

In 2D and 3D, Landau proposed electron behaviour as liquid :

Electron states can be defined by the competition among ;

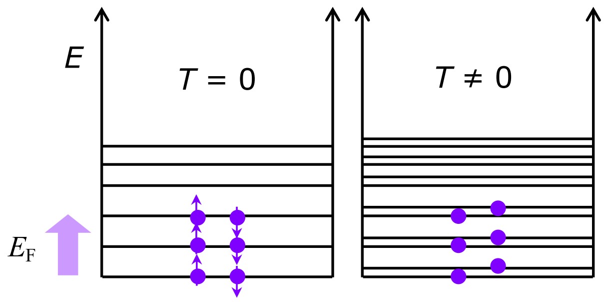
- Kinetic energy →
- Coulomb interaction →
- Potential randomness →

At very low temperature,

Coulomb interaction becomes negligible. →

Fermi Degeneracy

Fermi-Dirac distribution :



Pauli exclusion principle → Fermi degeneracy

- Free electrons in a metal at room temperature
  - » Higher energy states are occupied.
  - » Heat capacity becomes smaller than expected from the classical model.
  - » Magnetic susceptibility becomes smaller (Pauli paramagnetism).
- Star cores even at 10^9 K
  - » Very high density → degeneracy pressure
  - » After nuclear fusion,
    - › white dwarf stars by electron degeneracy pressure
    - › neutron stars by electron degeneracy pressure → black holes

Equation of states for ideal gas :

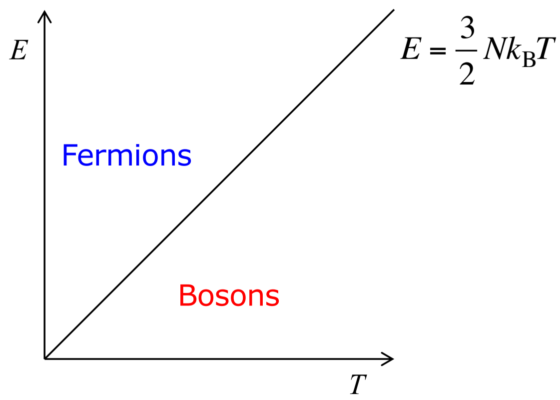
$$PV = Nk_B T$$

where P : gas pressure, V : volume, N : number of particles,
k_B : Boltzman constant and T : temperature

Energy E satisfies :

$$PV = \frac{2}{3}E$$

$$\therefore E = \frac{3}{2}Nk_B T \quad \text{(classical model)}$$



Fermions :

Compared with the classical model

E increases / P increases

= Repulsive force between particles
← Pauli exclusion law

Bosons :

Compared with the classical model

E decreases / P decreases = Attractive force between particles