A Synopsis on Science
A Journey through
1.37 billion years of “Matter”
from The Big Bang to a Green Earth

Lectures 4-6

The University of Tokyo
Institute for Solid State Physics
Yasuhiro Iye

Lecture Plan

Lectures 4-6: Yasuhiro Iye “The Properties of Matter”

Lecture 4:Modern Society and Material Science

- What does the discipline of Solid-State Physics do?

Lecture 5: From an Atom to a Solid Object

- Diverse Matter, Varied Physicality

Lecture 6:

Manipulating Atoms, Manipulating Quanta

- High-Tech and Nano-Science

Today's Talk

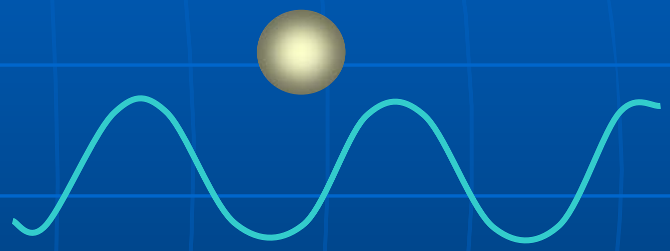
- About Quantum Mechanics
  - Quantum Interference, Tunnel Effect
- Nano-science
  - Mesoscopic Physics
  - Scanning Probe Microscope
- Macroscopic Quantum Phenomena
  - Super-fluidity
  - Bose Condensation
  - Super-conduction
- Summary

About Quantum Mechanics

Quantum Mechanics

Body of theory describing the workings of the micro world

Structure of Atoms/Molecules
Behavior of electrons in solids
Light and Substance



Light: both a wave and a particle
Electron: both a particle and wave

In saying particles and waves, it is a reflection that these are the only suitable words we have when we try and imagine quantum mechanics with everyday (classical mechanical) analogies.

Particle nature: separate, individual
Wave nature: superposition, interference

Quantum mechanical particles also display the behavior of waves

de Broglie Wavelength $\lambda = \frac{h}{p}$

Momentum

de Broglie Wavelength of an electron that is accelerated at 100V

$$E = \frac{p^2}{2m} \quad \Rightarrow \quad p = \sqrt{2mE}$$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$$

$$= \frac{6.62 \times 10^{-34}}{\sqrt{2 \times 0.91 \times 10^{-30} \times 100 \times 1.6 \times 10^{-19}}}$$

$$= 1.23 \times 10^{-10}\,\mathrm{m} \qquad \lambda = 0.12\,\mathrm{nm}$$

de Broglie Wavelength of a classical particle (e.g. tennis ball) is extremely short

Wave Function

The state of a particle is
Described by its wave function

$$\psi(x, y, z, t)$$

The existing probability of a particle is expressed by $\left|\psi(x, y, z, t)\right|^2$

The time evolution of a wave function obeys Schrödinger's equation

$$i\hbar\frac{d}{dt}\psi(x,y,z,t)=\left(-\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)+V(r)\right)\psi(x,y,z,t)$$

Linear equation => Superposition Principle

$$\psi_1, \quad \psi_2 \quad \Rightarrow \quad \psi_1+\psi_2$$

=>Quantum Interference

Measurement in Quantum Mechanics

Generally, although quantum mechanics provides a probabilistic distribution of a measurable value when the measurement of a physical quality in the "same situation" is repeated, it doesn't provide a measurable value in individual cases.

By measurement, the condition becomes one of the eigenstates of that physical observable.
=> "the Collapse of wavefunction"

Time evolution is described by Schrödinger's equation and the Collapse of wavefunction occurs by measurement
Standard interpretation of quantum mechanics
(Copenhagen Interpretation)

Interpretation problem, observation problem of quantum mechanics
Many-Worlds Interpretation

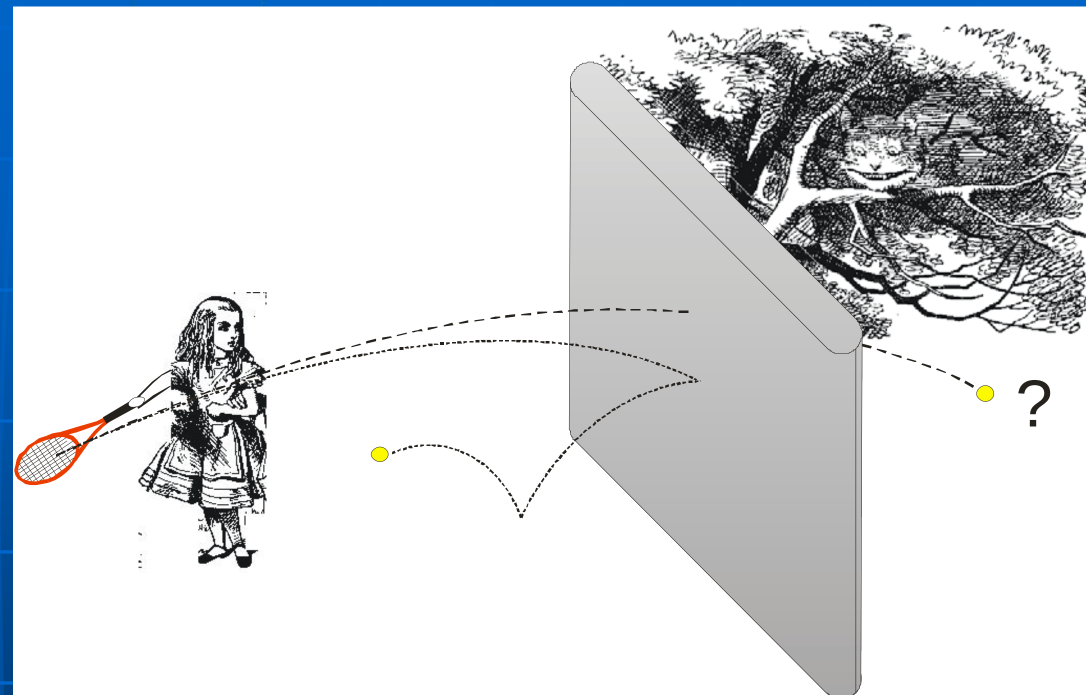
Characteristic Phenomena of Quantum Mechanics

Tunnel Effect

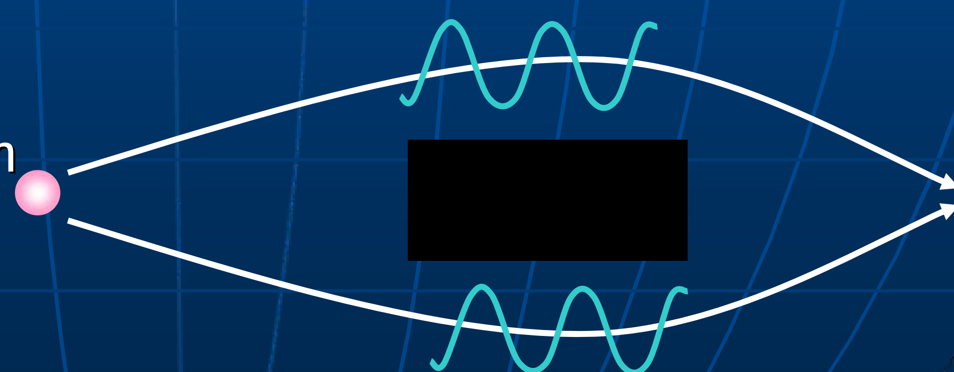
- Passes through a potential wall it shouldn't pass through in classical dynamics

Quantum Interference Effect

- Superposition of states that pass through different paths =>Quantum Interference



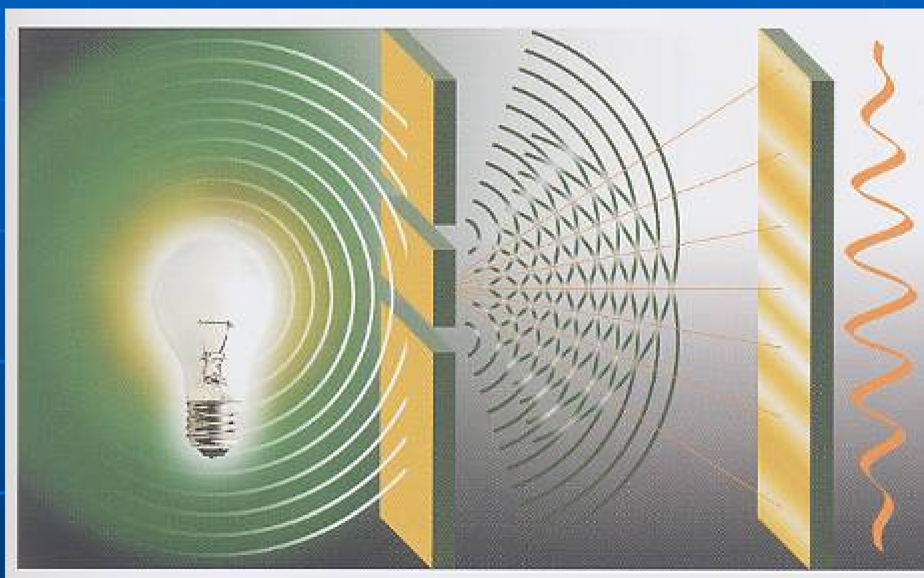
Yasuhiro, IE, 2006,"Aris' Quantum Mechanics", Maruzen



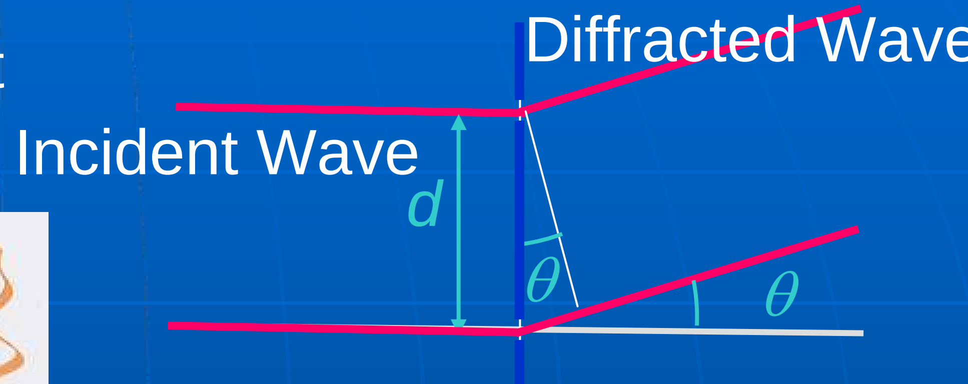
Quantum Interference

Interference of Light Waves

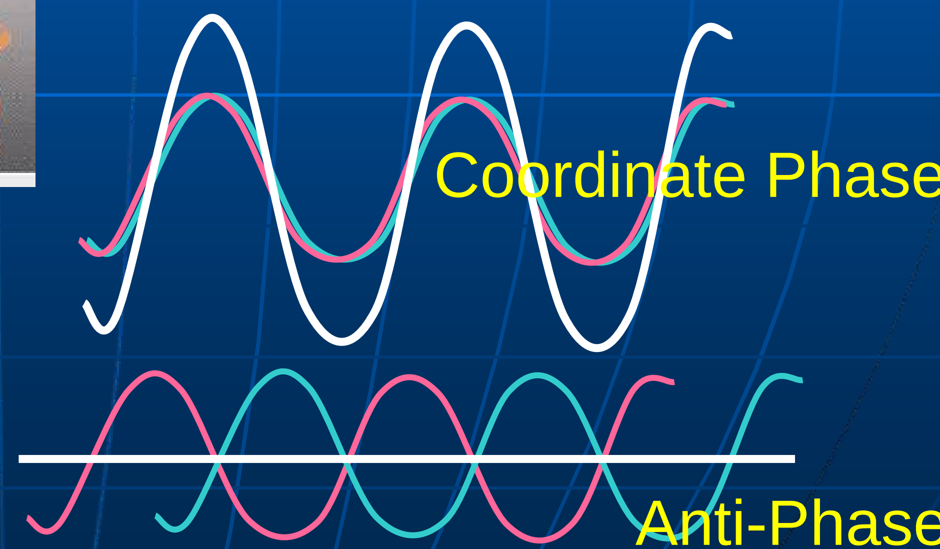
Young's double-slit experiment
(1805)



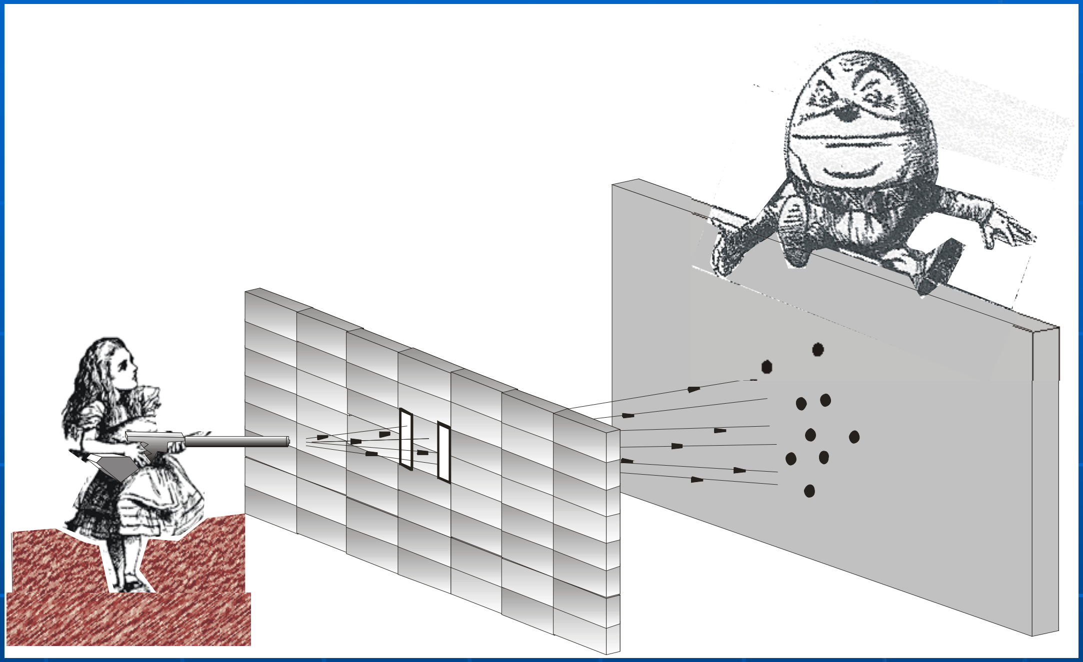
Interference of waves
that passed through each slit



$$d\sin\theta = \begin{cases} n\lambda & \text{positive} \\ \left(n+\frac{1}{2}\right)\lambda & \text{negative} \end{cases}$$

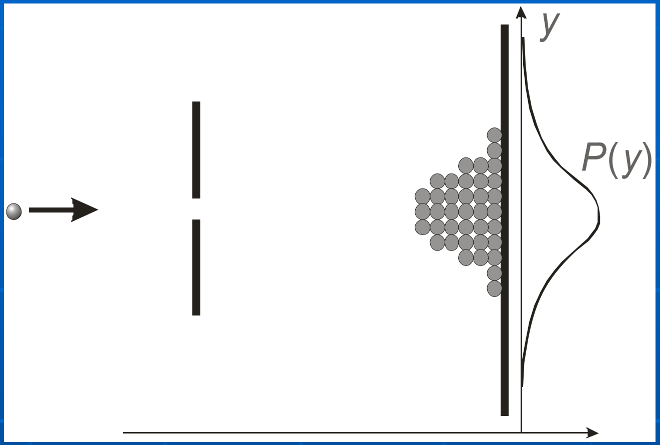


The Case of Classical Particles

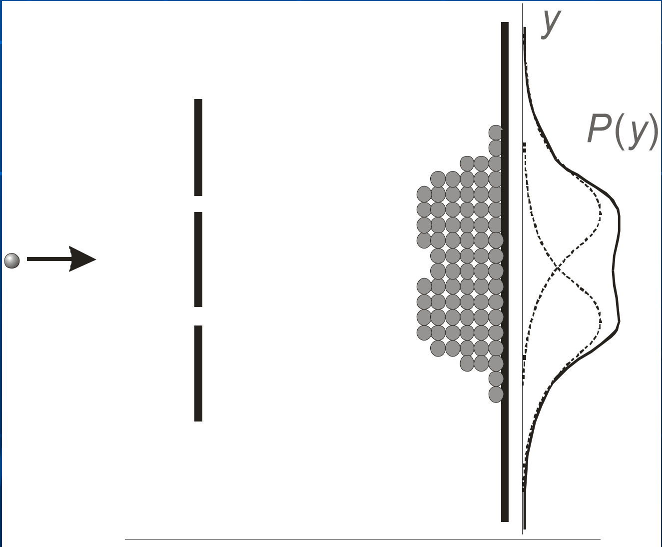


Yasuhiro, IE, 2006,"Aris' Quantum Mechanics", Maruzen‡

One slit



Two slit

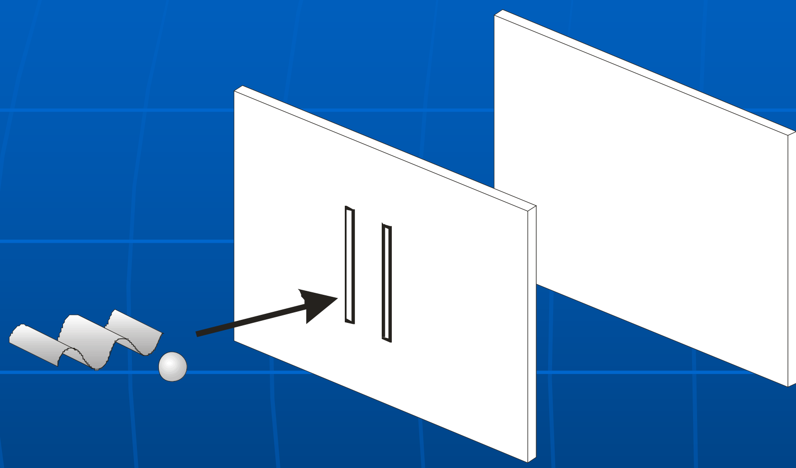


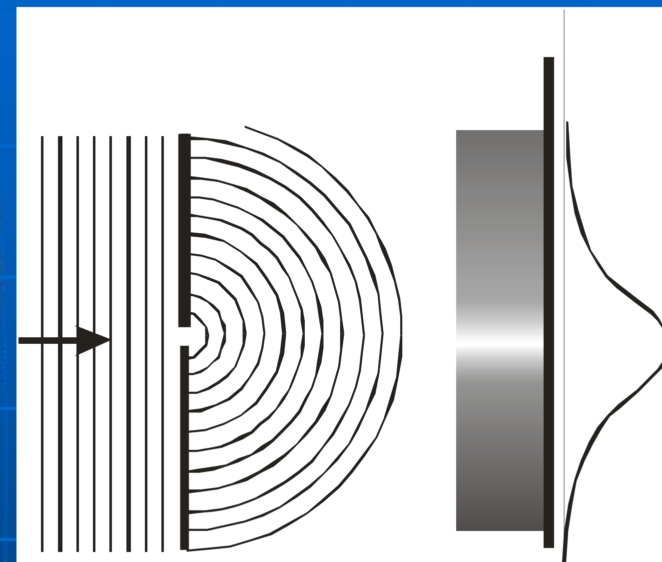
Probability of a bullet hitting a particular spot
＝Probability of it hitting the spot passing through the right slit
＋Probbility of it hitting the spot passing through the left slit

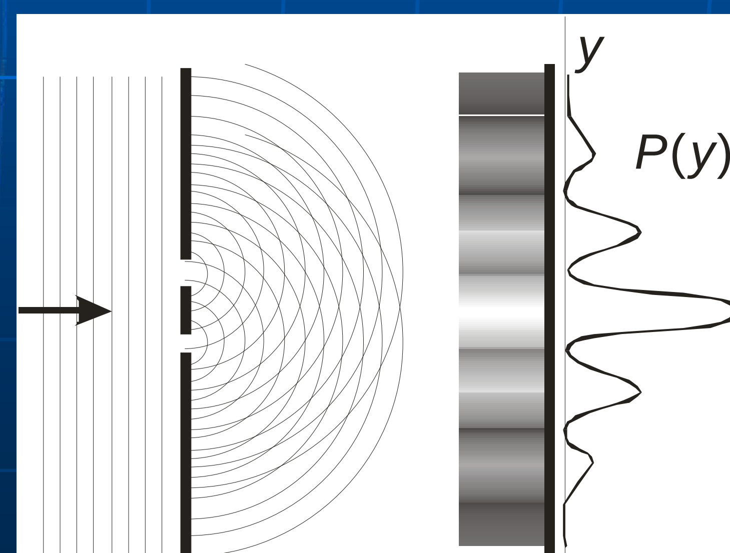
$$P_{\text{total}}(y) = P_{\text{R}}(y) + P_{\text{L}}(y)$$

Summation of Probability

Incident Waves







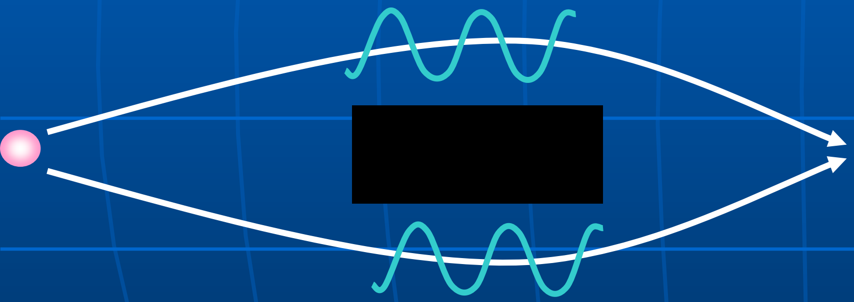
Summation of
Waves’ Amplitudes

Interference Pattern

The Case of Quantum Mechanical Particles

$$\Psi_{\text{total}} = \Psi_{\text{R}} + \Psi_{\text{L}}$$

Wave Function = Wave Function passing through right-hand slit
+ Wave Function passing through right-hand slit

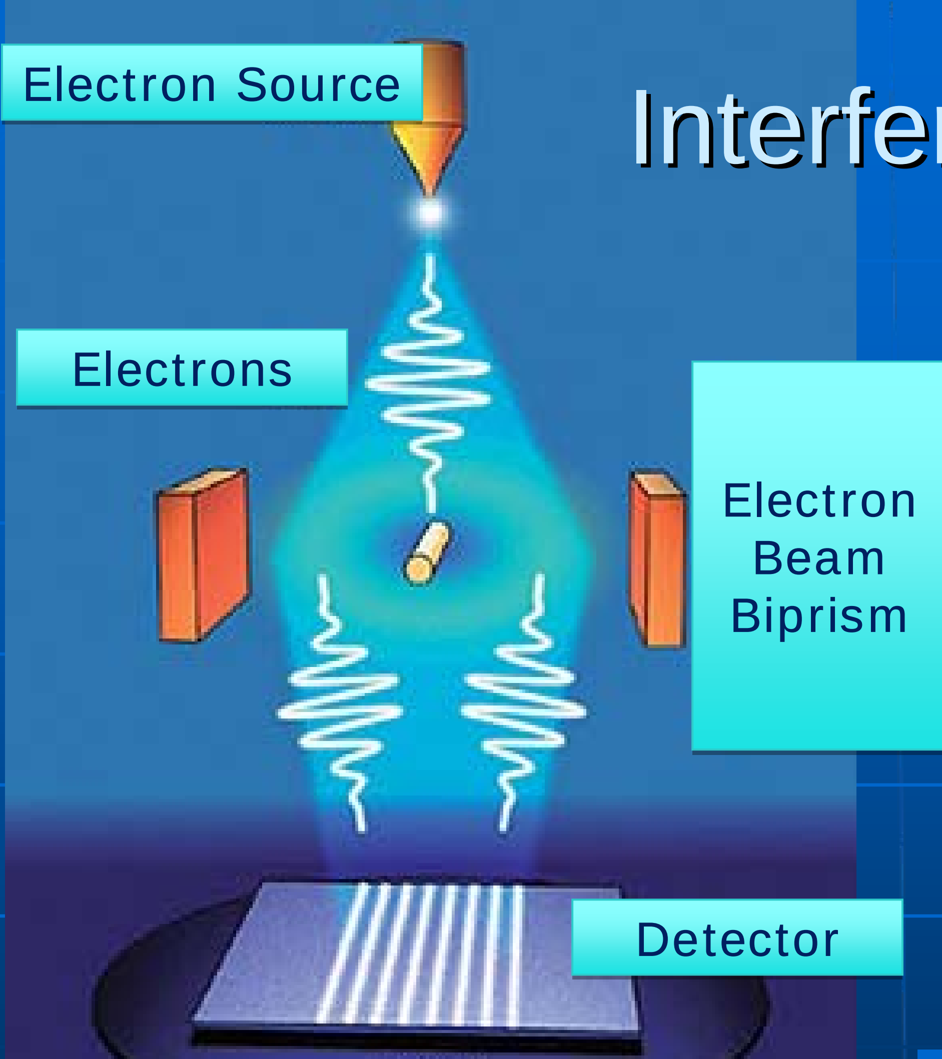


Probability = |Wave Function| ^{2}

$$\left|\Psi_{\text{total}}\right|^2 = \left|\Psi_{\text{R}} + \Psi_{\text{L}}\right|^2$$

$$= \left|\Psi_{\text{R}}\right|^2 + \left|\Psi_{\text{L}}\right|^2 + \underbrace{\Psi_{\text{R}}^{*}\Psi_{\text{L}} + \Psi_{\text{R}}\Psi_{\text{L}}^{*}}_{\text{Quantum Interference Terms}}$$

Interference of Electrons

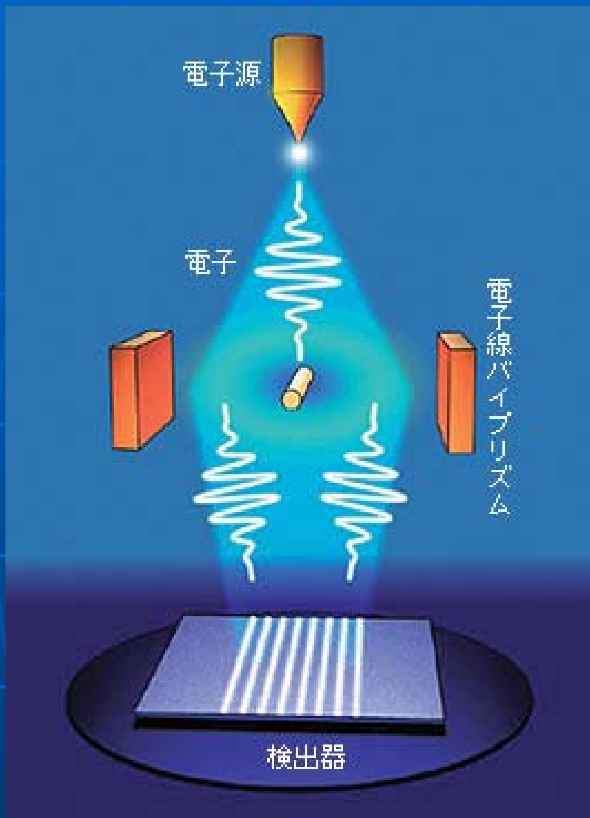


Dig. 3 Representation of Electron Two-Slit Experiment
In this experiment an electron beam bi-prism is used in place of a slit. This type of experiment is technically difficult and at one time was thought of as a thought experiment that could only be done in your head.

Dr Akira Tonomura (Hitachi Advanced Research Laboratory)

Double-Slit Experiment with Electrons (Dr Akira Tonomura)

Interference of Electrons

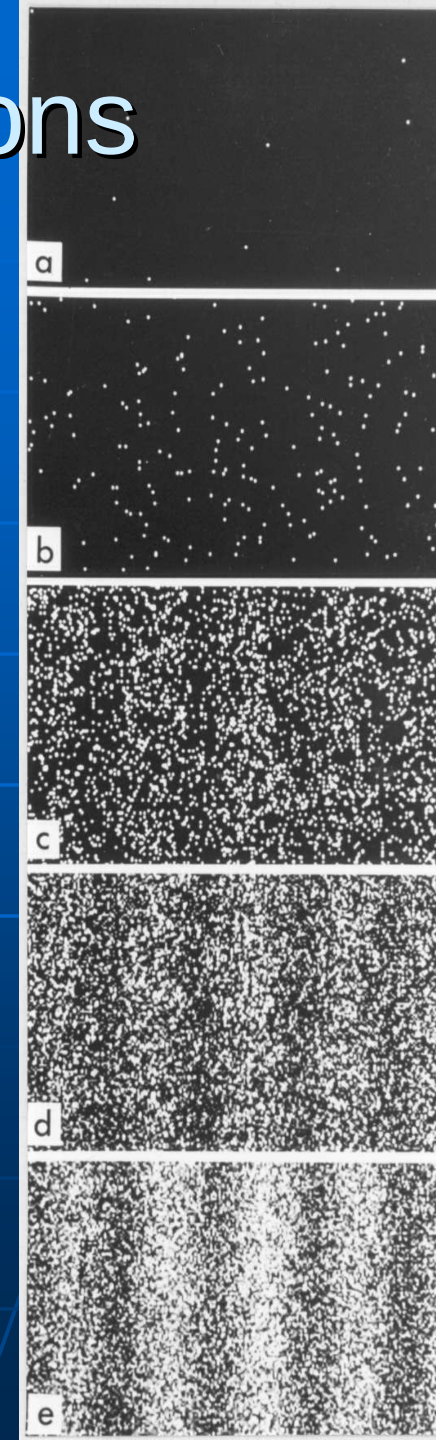


Dr Akira Tonomura (Hitachi Advanced Research Laboratory)‡

Electrons reach the screen one-by-one

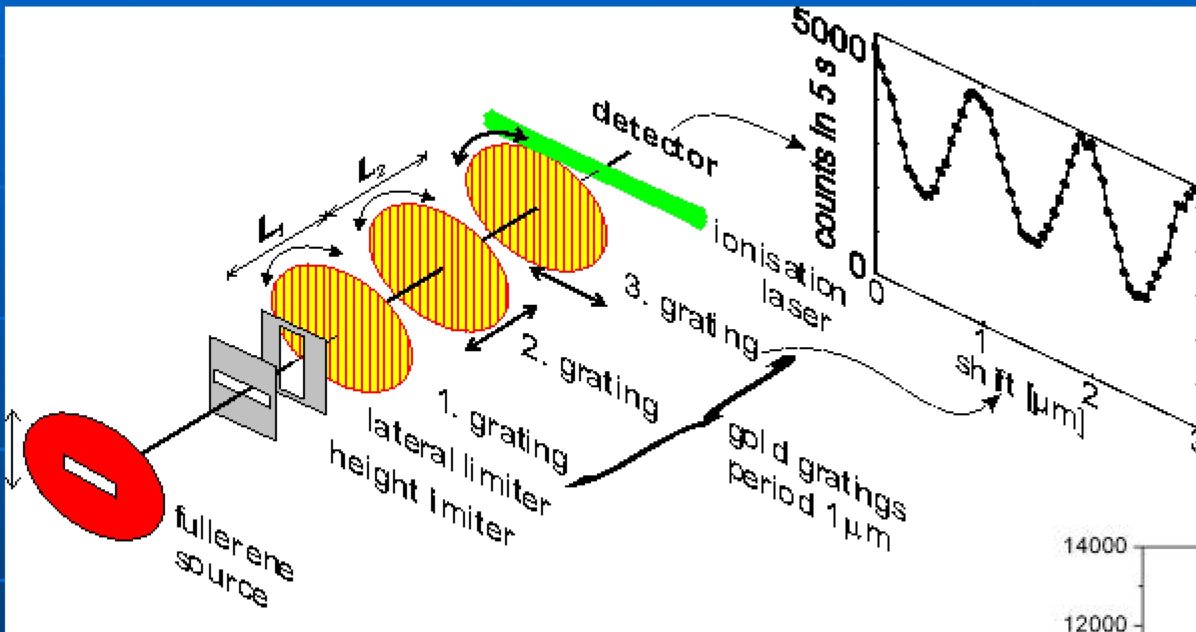
An Interference Pattern will appear

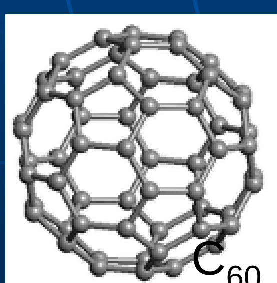
Clear proof of the wave properties of electrons



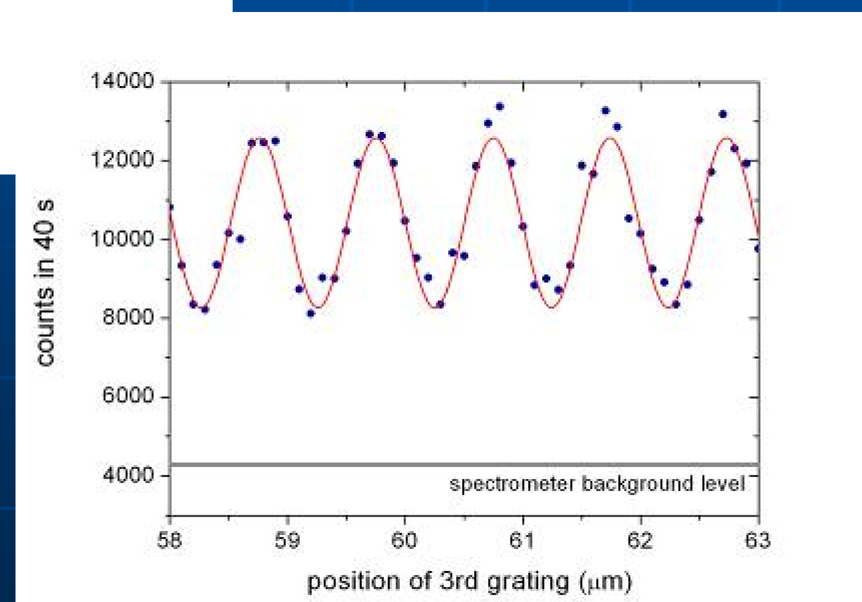
How big can something be to still Interfere?

A.Zeilinger
Vienna University of Technology‡





C_{60} Fullerene molecule

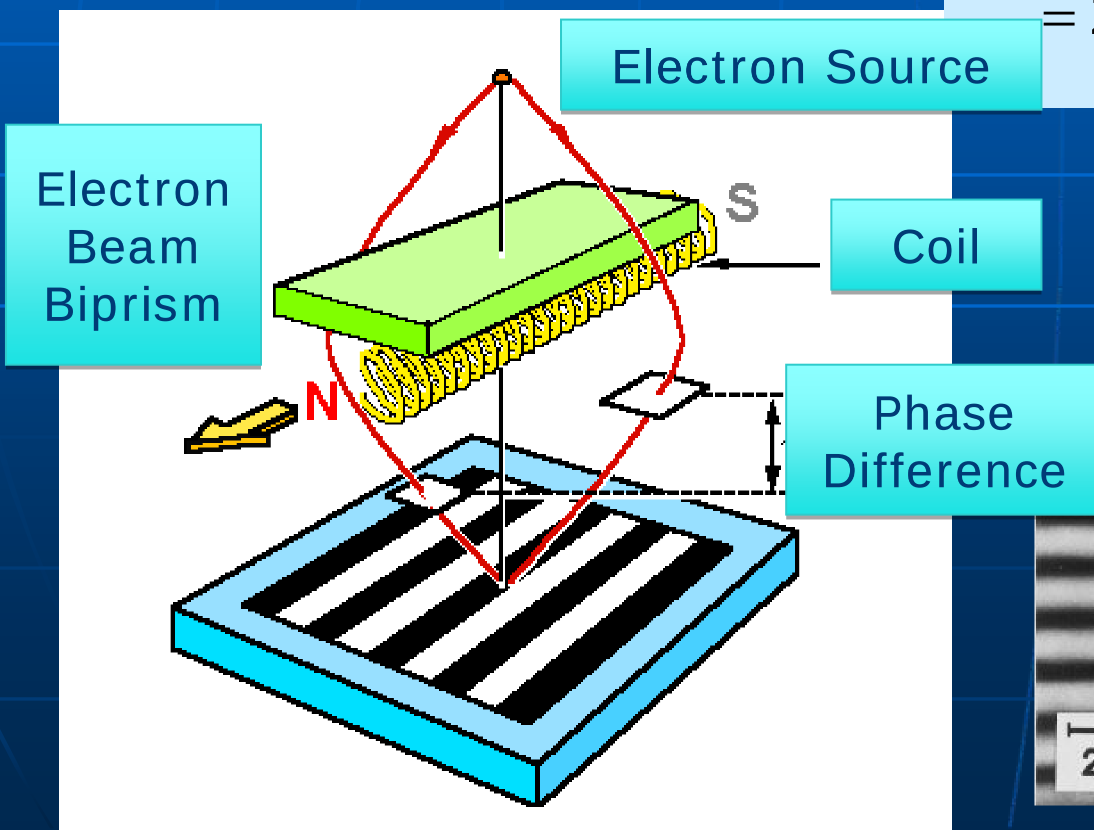


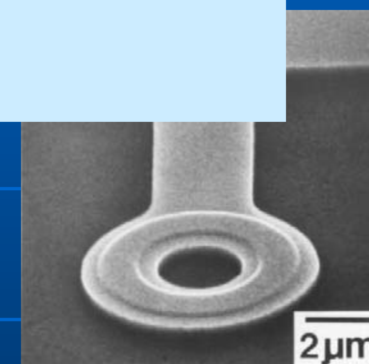
Aharonov-Bohm (AB) Effect

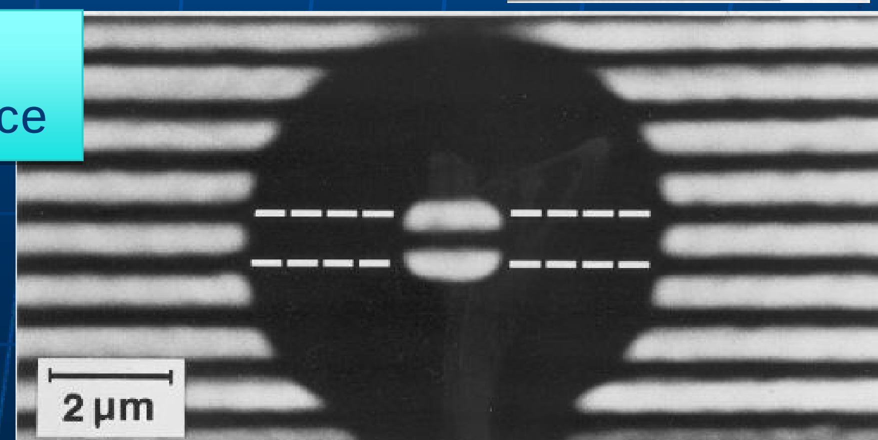
An electron's phase changes according to a magnetic field (vector potential)

$$\psi \Rightarrow \psi e^{i\frac{e}{\hbar}\int \mathbf{A}(\mathbf{r})\cdot d\mathbf{r}}$$

$$\begin{aligned}\Delta\theta &= \frac{\hbar}{e}\int_{\mathrm{L}} \mathbf{A}(\mathbf{r})\cdot d\mathbf{r} - \frac{\hbar}{e}\int_{\mathrm{R}} \mathbf{A}(\mathbf{r})\cdot d\mathbf{r} \\ &= \frac{\hbar}{e}\oint_{\mathrm{loop}} \mathbf{A}(\mathbf{r})\cdot d\mathbf{r} = \frac{\hbar}{e}\int \mathbf{B}(\mathbf{r})\cdot d\mathbf{S} \\ &= 2\pi\frac{\phi}{\phi_0} \qquad \phi_0 = \frac{h}{e}\end{aligned}$$







Mesoscopic System

Nanotechnology

Mesoscopic Physics

Micro-Scale
(Microscopic)

Macro-scale
(Macroscopic)

Mesoscopic System

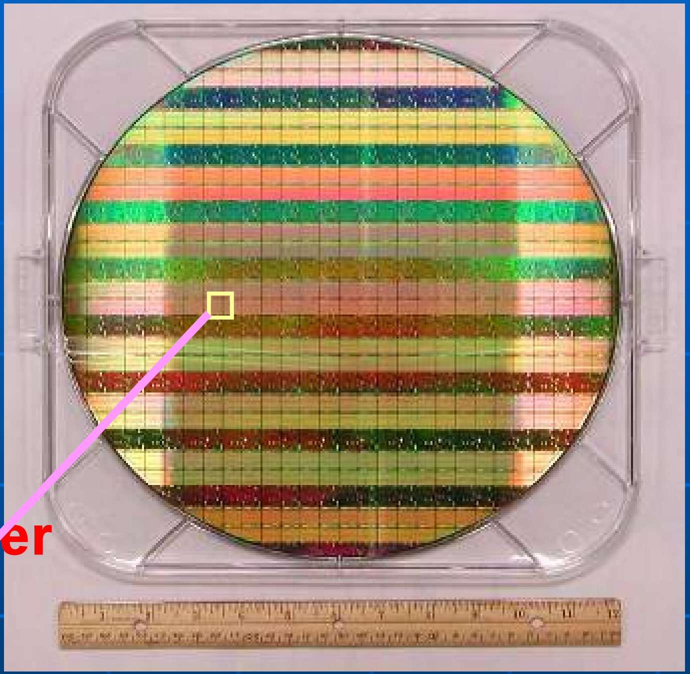
Scale between Micro and Macro
(meso: between)

The new Physics observed when the size of physical systems are comparable with or less than the scale that characterizes Physical phenomena

Miniaturisation of Semiconductor Devices

First Electrical Transistor
American Bell Laboratories
(1946)

50 years



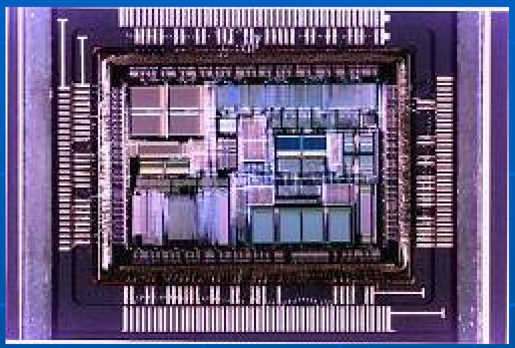
Silicon Wafer

12 inches (30 cm)

Progress of the
High-Tech Industry’s Science

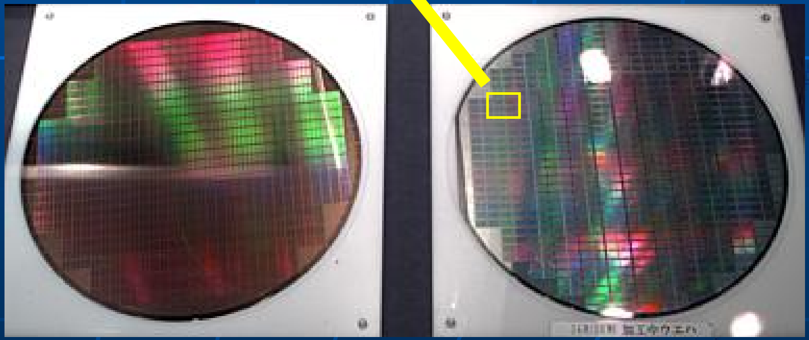
Silicon Monocrystal => Wafer => Super LSI

Super LSI (Large-Scale Integration)



Cut-out Monocrystal

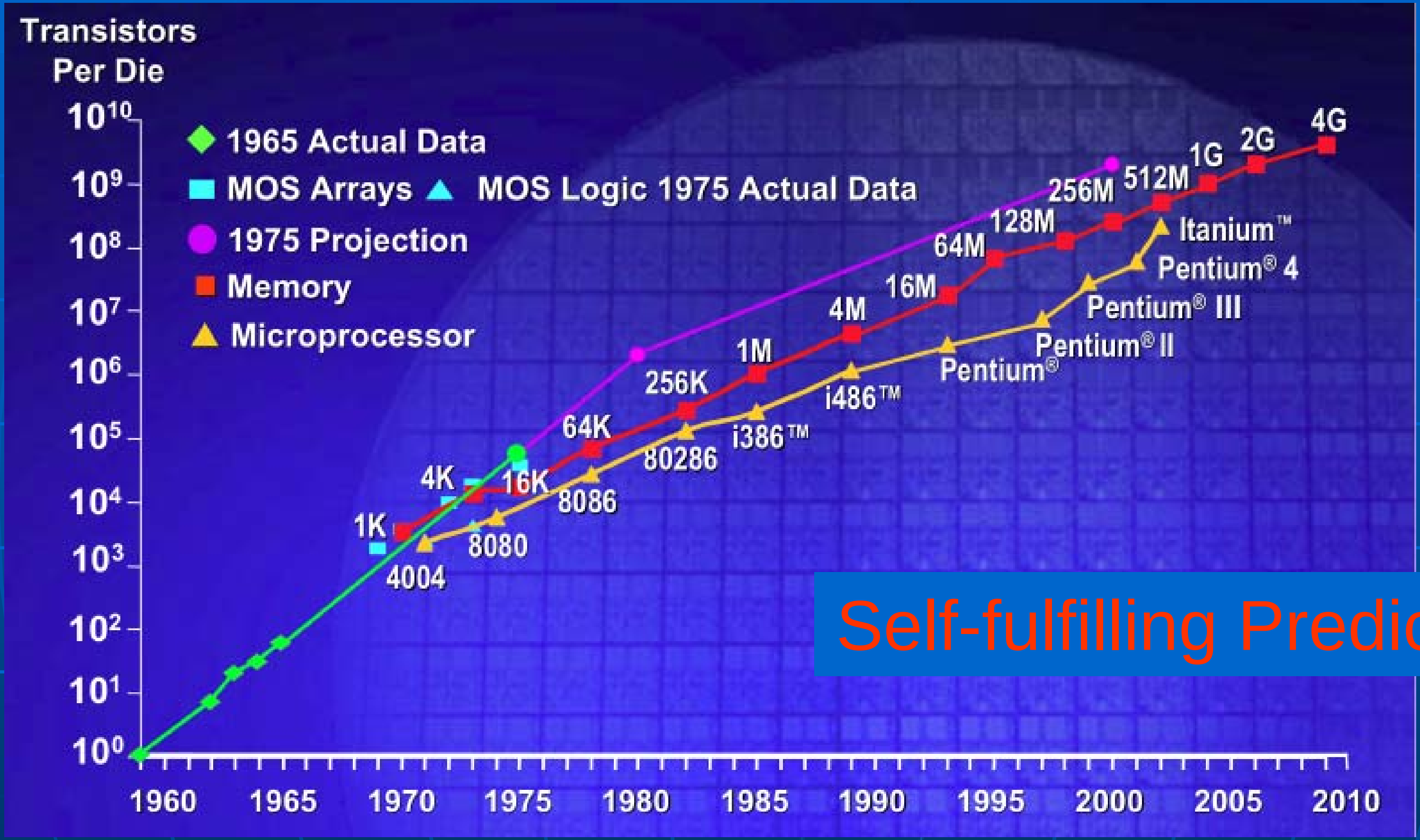
Wafer



Microfabrication

Moore's Law

"Integrated Circuit Complexity"



Self-fulfilling Prediction

Gordon E.Moore "NO EXPONENTIAL IS FOREVER…"

‡ Intel Copyright Permission Department

The degree of integration of LSI (Large Scale Integration), in other words, the number of transistors that can fit within a unit area will double approx. every one-and-a-half years.

Nano-science / Nanotechnology

- Semiconductor technology⇒ More than Moore

  Can't simply miniaturise
  - Problem of heat production
  - Problem of quantum fluctuation
- Nano-science
  - Observing atoms, Manipulating atoms
  - There are new quantum physics effect in the Nano world

    "There is plenty of room at the bottom."

    （Richard Feynman)

Mesoscopic Physics

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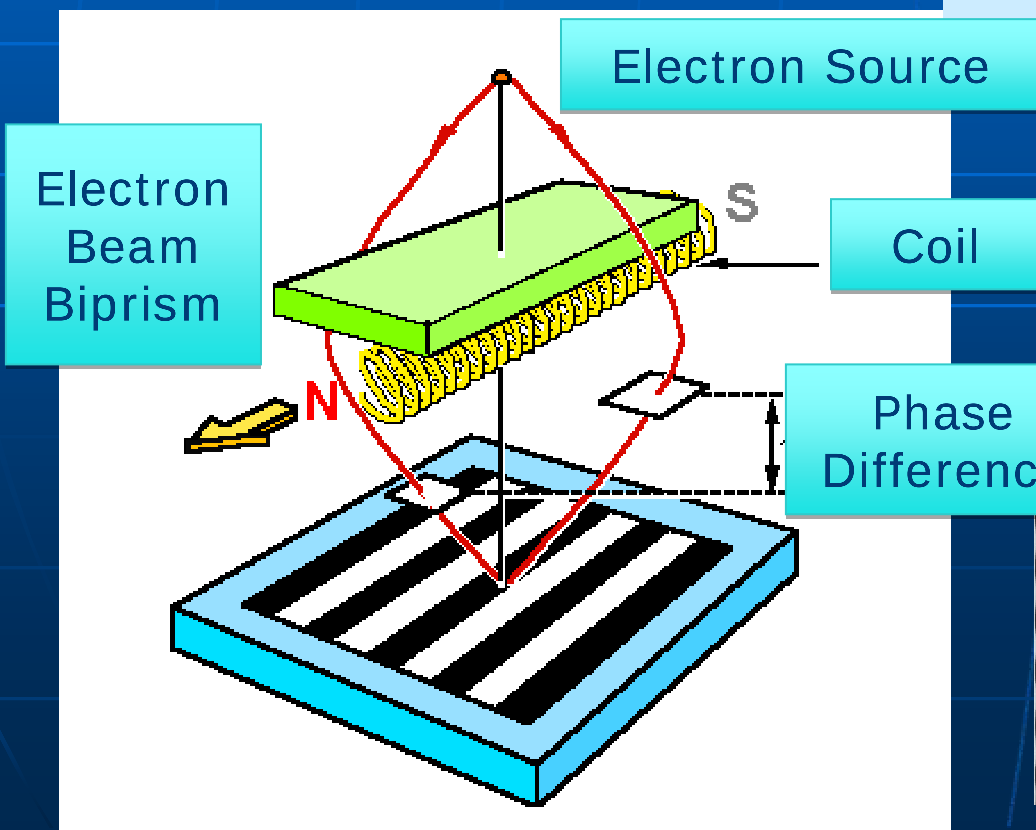
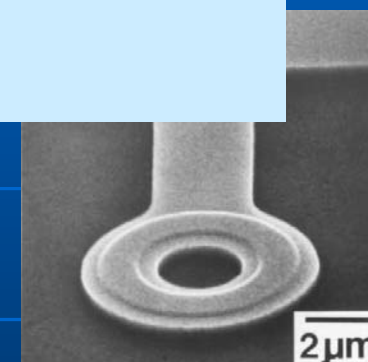
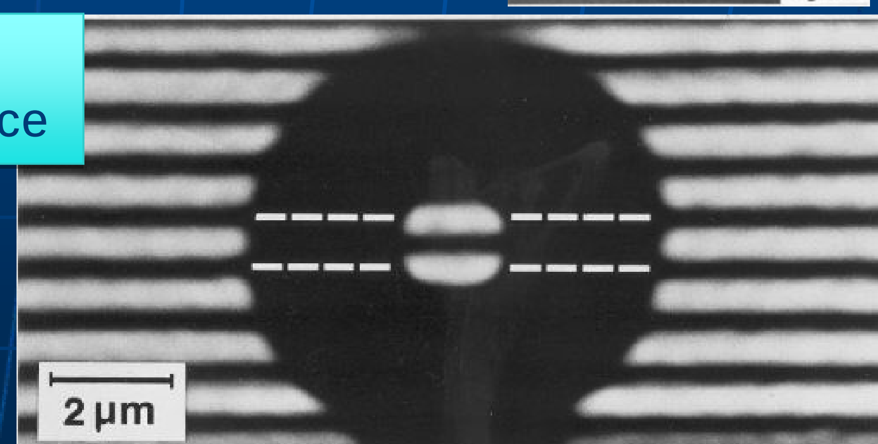
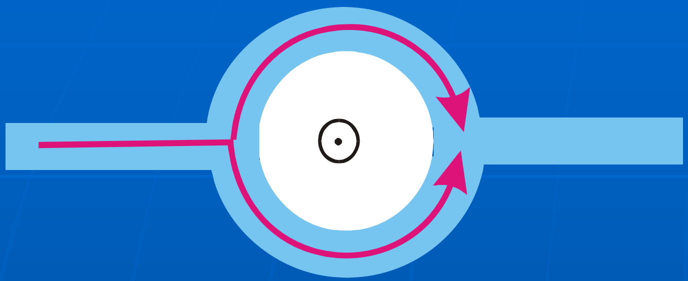






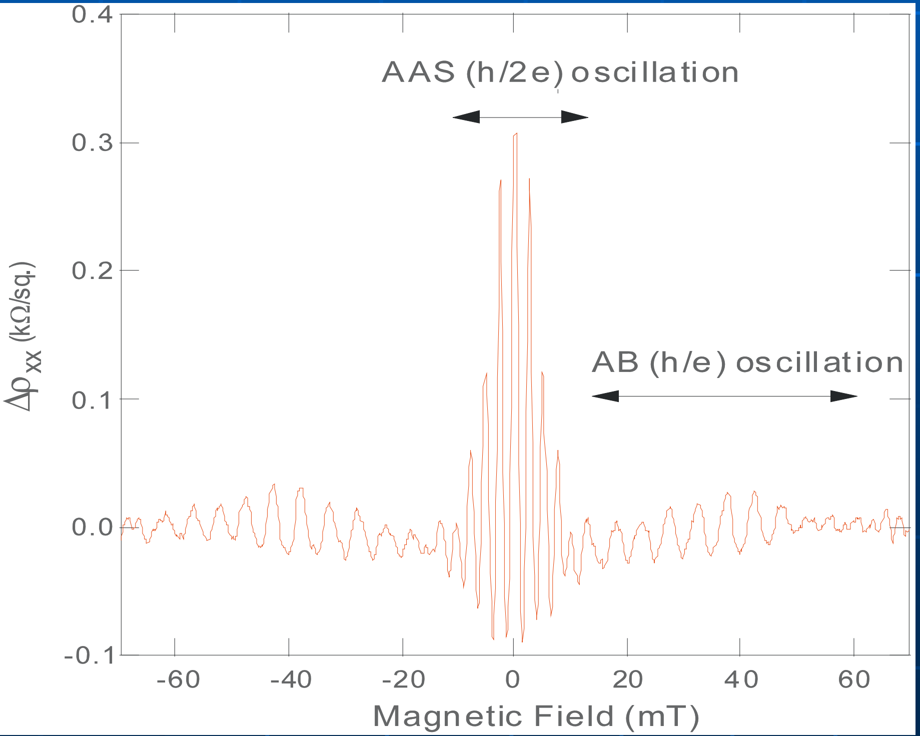
Aharonov-Bohm Oscillations



Mesoscopic Ring

$$|\Psi|^2 = |\Psi_+ + \Psi_-|^2$$
$$= |\Psi_+|^2 + |\Psi_-|^2 + \Psi_+\Psi_-^* + \Psi_+^*\Psi_-$$

Quantum Interference Item



$$\phi_0 = \frac{e}{h} = 4.14 \times 10^{-15}\,\mathrm{Wb}$$

Flux Quantum

Interference effect of electron waves that have passed through the paths on both sides of a ring

Electrical resistance changes cyclically to the magnetic flux Φ which passes through the ring

Quantum Resistance

Make quanta that have the dimensionality of electrical resistance from physical constants

$$\boxed{e} \qquad \textit{Charge } e = \text{Current} \times \text{Time}$$

$$\boxed{\frac{h}{e}} \qquad \textit{Flux } \Phi = \text{Voltage} \times \text{Time}$$

$$\boxed{\frac{h}{e^2}} \qquad \text{Flux/Charge} = \text{Voltage/Current} = \text{Resistance}$$

$$\frac{h}{e^2} = 25.813\ \mathrm{k\Omega}$$

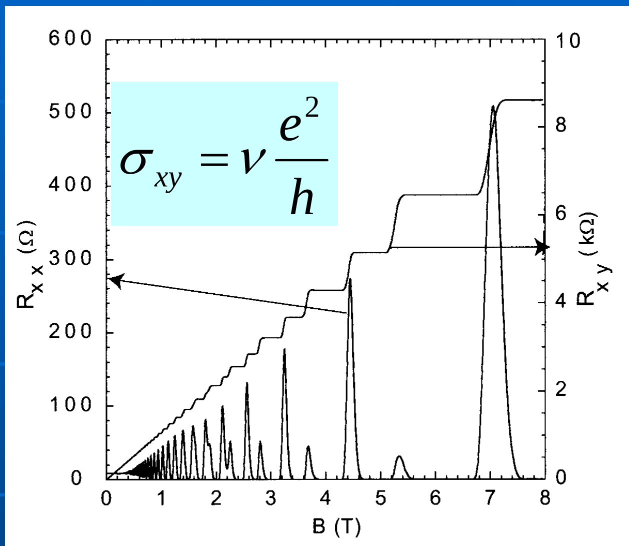
$$\frac{e^2}{h} = \frac{1}{25{,}813\ \mathrm{k\Omega}} = 38.7\,\mu\mathrm{S}$$

Quantum Resistance   Quantum Conductance

Quantum Conductance

$$\frac{e^2}{h} = \frac{1}{25.813\,\mathrm{k\Omega}}$$

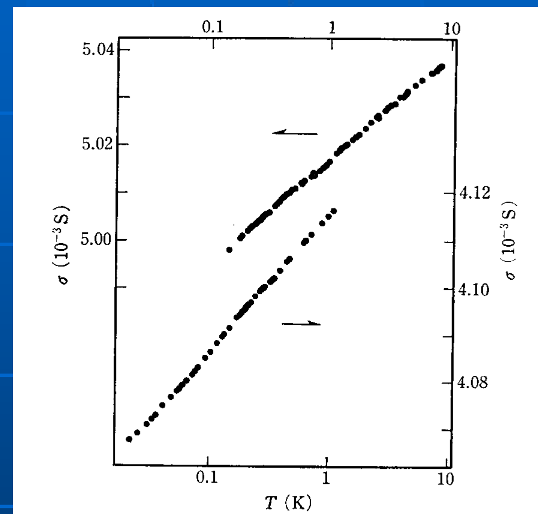
Quantum Hall Effect => International Standard of Resistance



$$\sigma_{xy} = \nu \frac{e^2}{h}$$

Superconductor-Insulator Transition

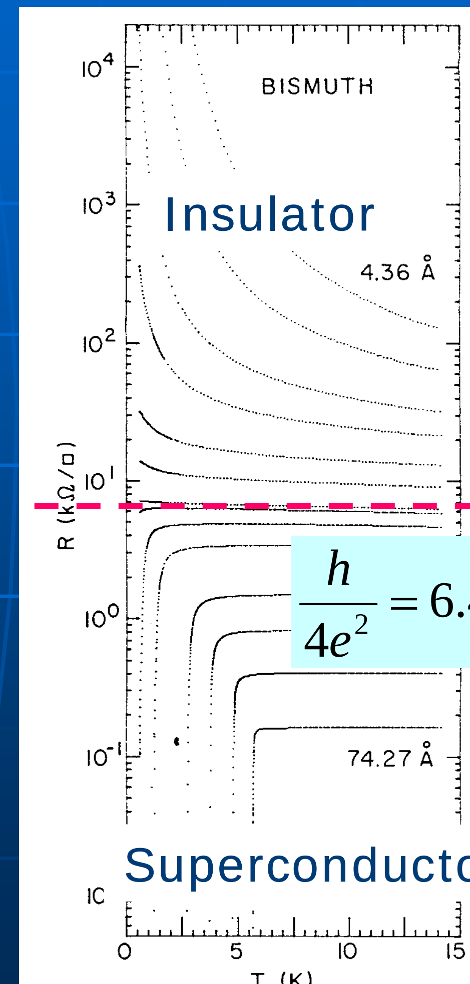
Electron Localization



$$\sigma_{2D} = \frac{ne^2\tau}{m} - \frac{P}{\pi}\frac{e^2}{h}\ln\frac{T}{T_0}$$

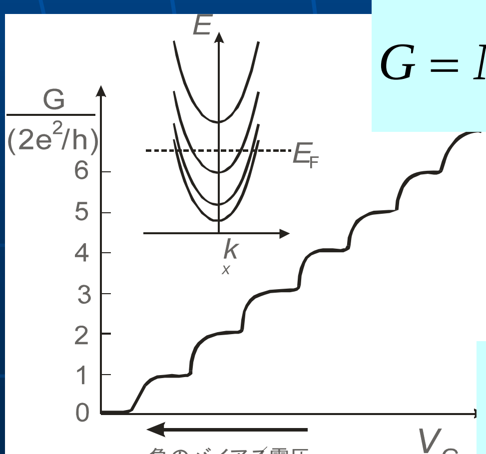
Classical conductivity
+Quantum Correction

‡ Provided by School of Science Ex-Kobayashi Lab



$$\frac{h}{4e^2} = 6.4\,\mathrm{k\Omega}$$

Quantization of Conductance

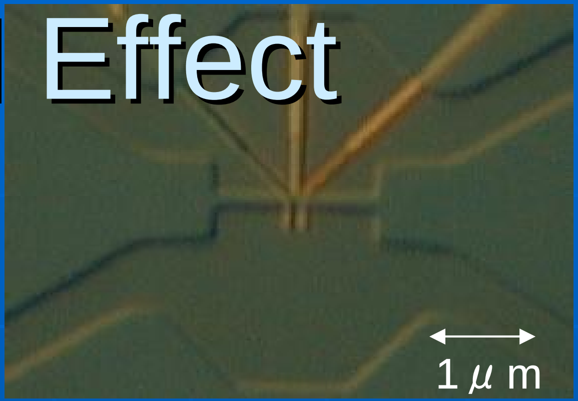


$$G = N\frac{2e^2}{h}$$

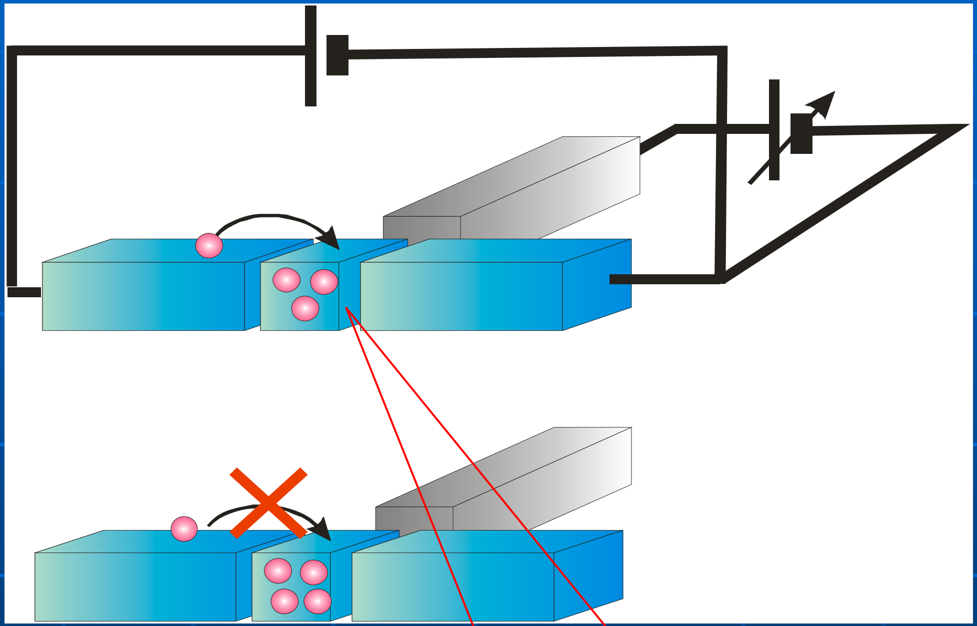
Universal Physics
not dependent on the material

‡ D.B.Haviland et,al " PHYSICAL REVIEW LETTERS"Vol62-Num18

Mono-Electron Tunnel Effect

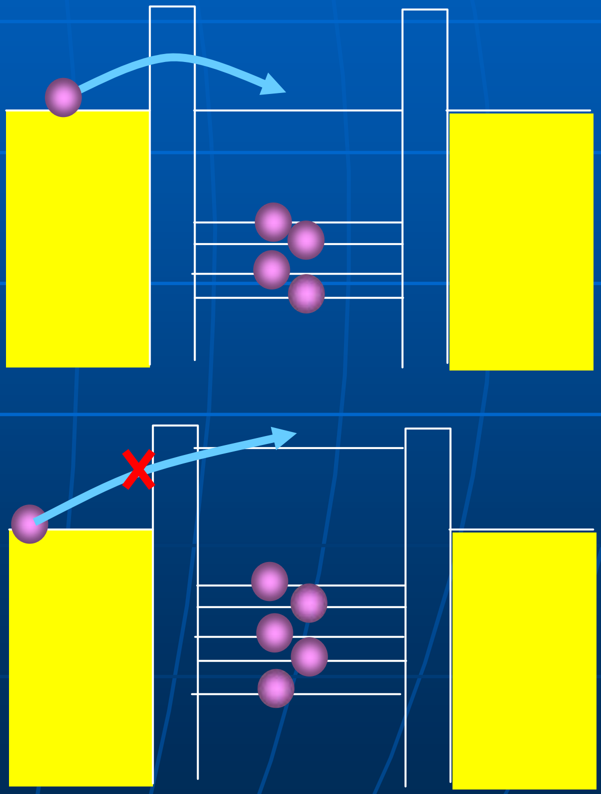


Nano-Tunnel Junction



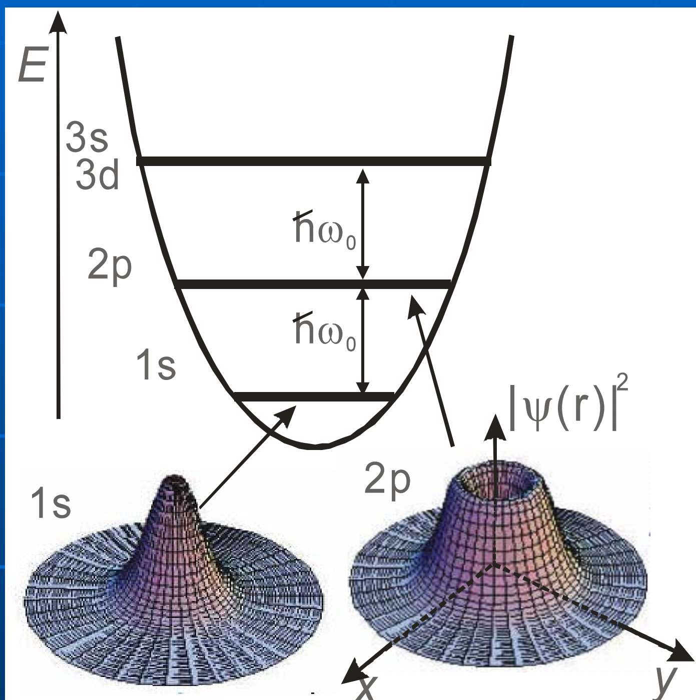
Coulomb Island (Quantum Dot)

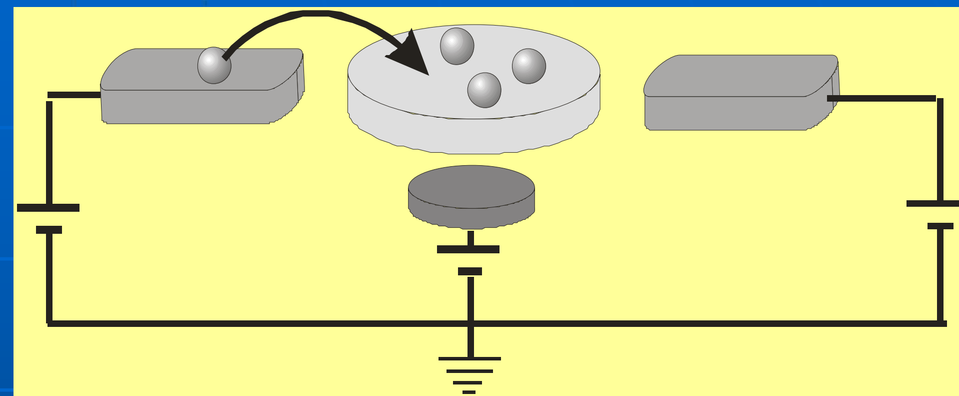
The electrostatic potential of the island increases as one electron tunnels => next electron can't enter

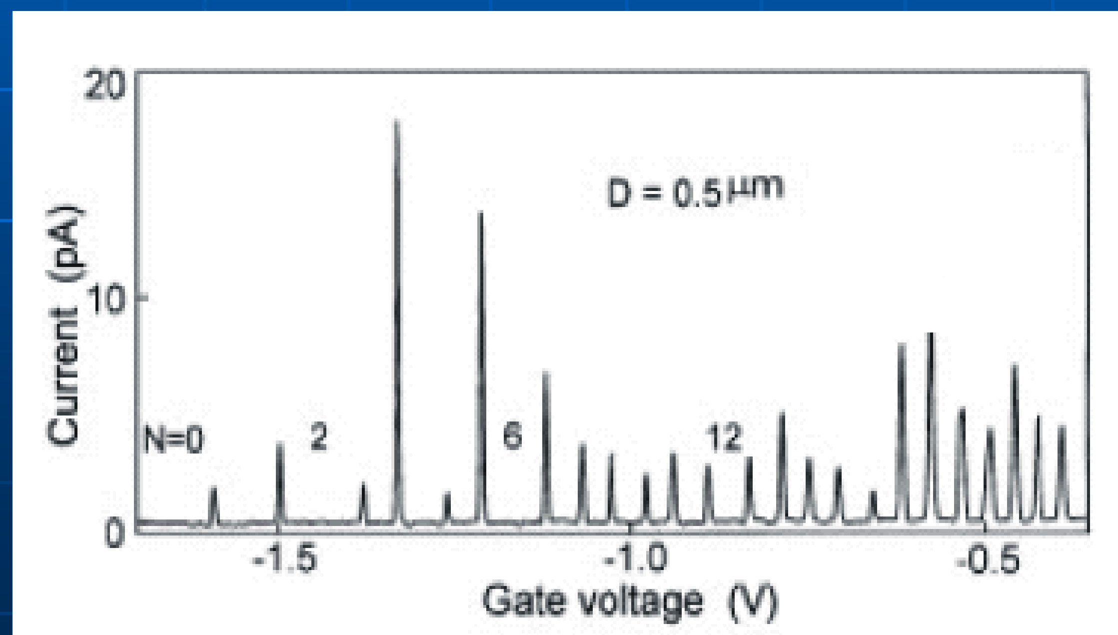


Coulomb Blockade

Quantum Dot (Artificial Atom)





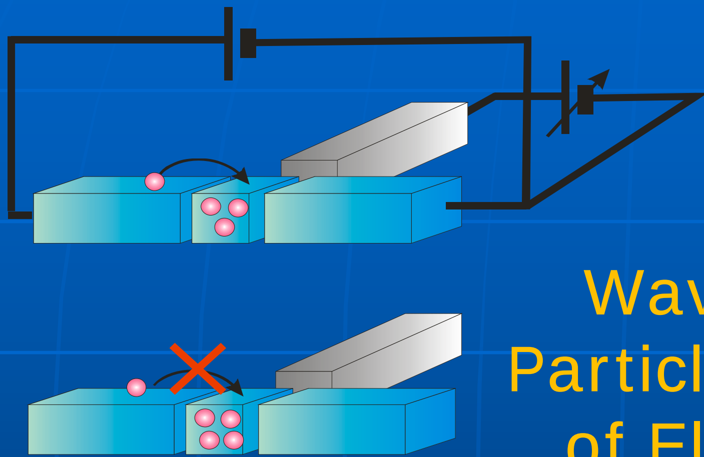


Periodic Law of Artificial Atoms

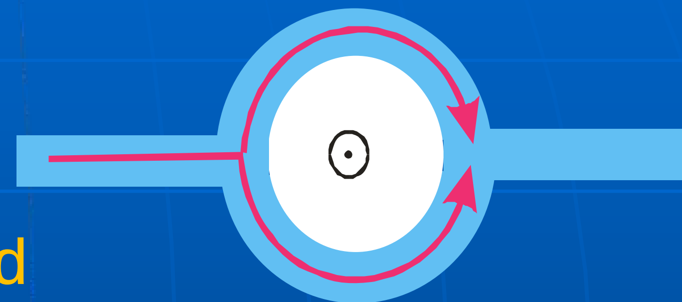
source : Shingo, Tarucha, Graduate school of Science

Quantum Physics of Mesoscopic Systems

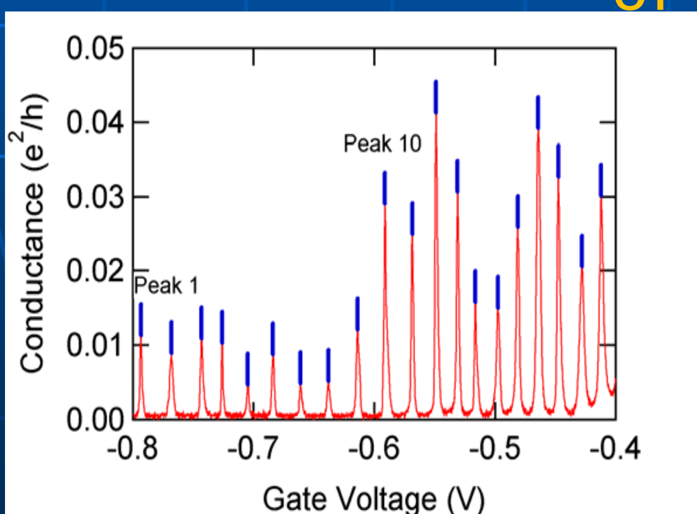
Mono-Electron Tunnel Effect

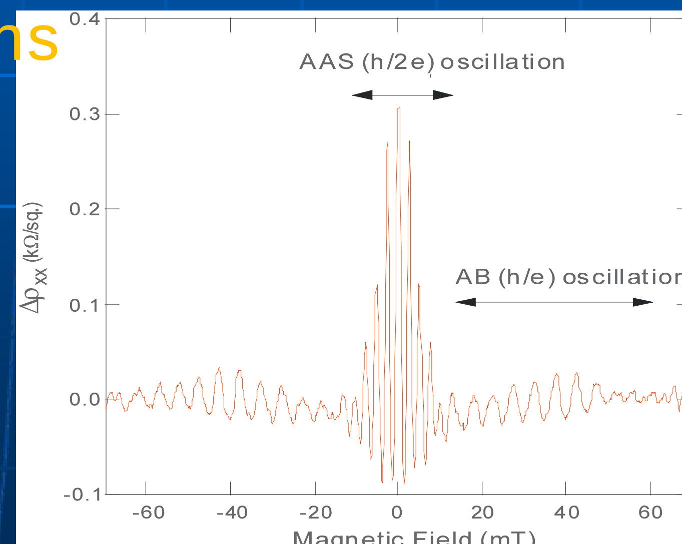


Quantum Interference Effect



Wave and Particle nature of Electrons





粒子性 ⟷ 波動性

Observing Atoms
Manipulating Atoms

The Small Scale

10^{-12} m | 10^{-9} m | 10^{-6} m | 10^{-3} m | 1 m

1 pm Picometer

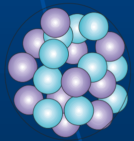
1 nm Nanometer

1 μm Micrometer (Micron)

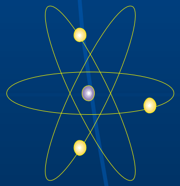
1 mm Millimeter

Virus

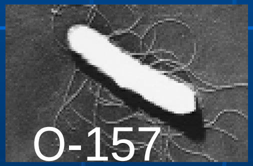
Size of a nucleus



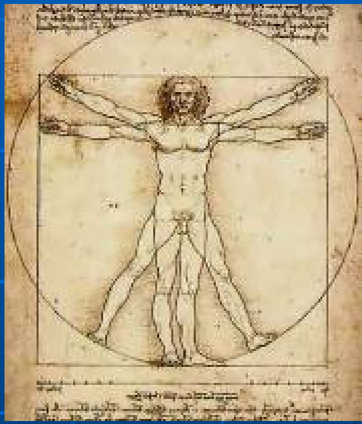
Size of an Atom



Bacteria



Eye of a Needle, Hair



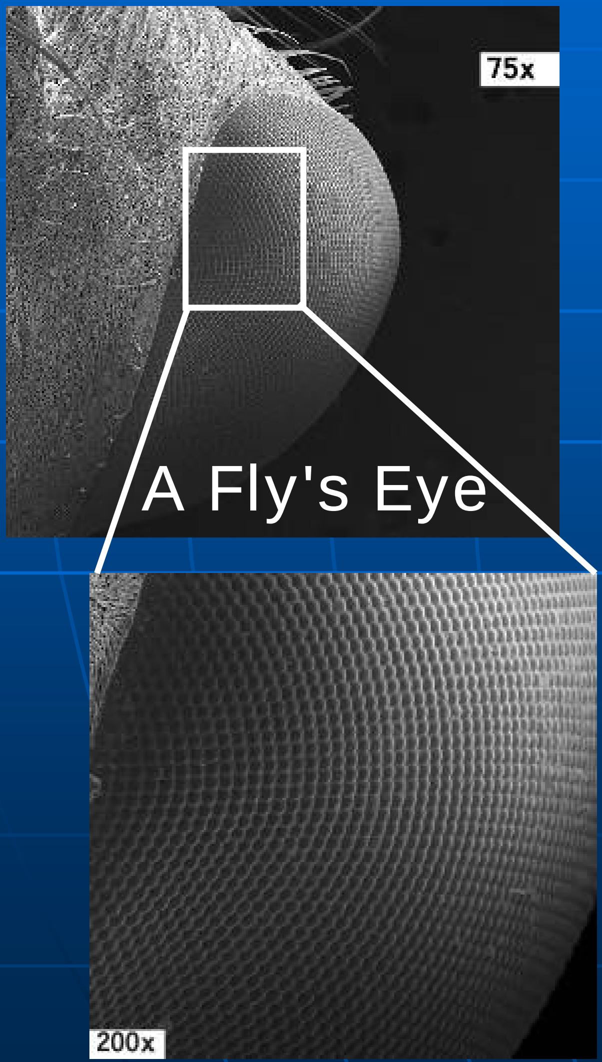
Visible Light Wavelength

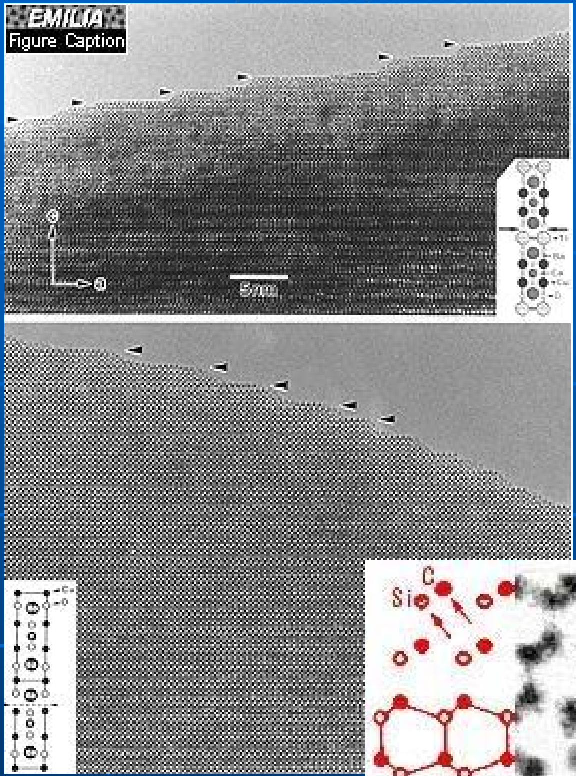
Light Microscope

Electron Microscope

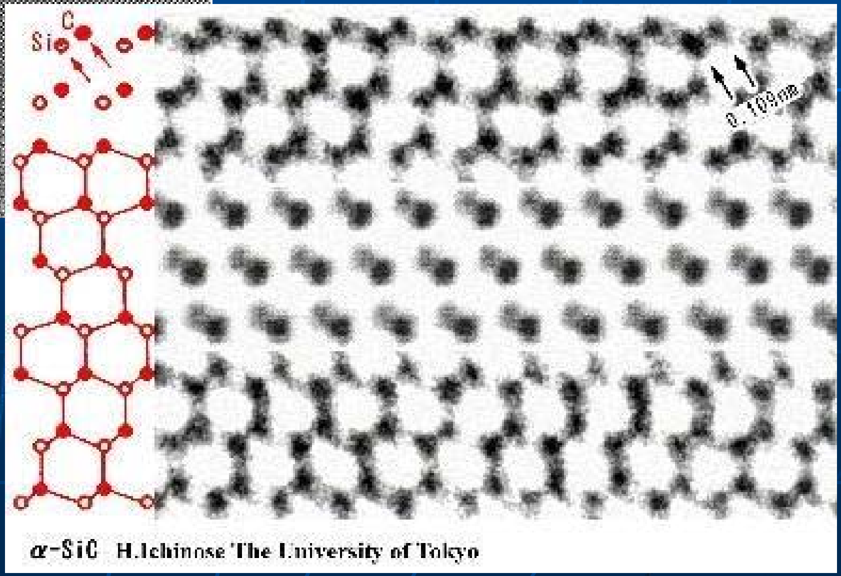
Scanning Probe Microscope

Observing Small Things : Electron Microscope

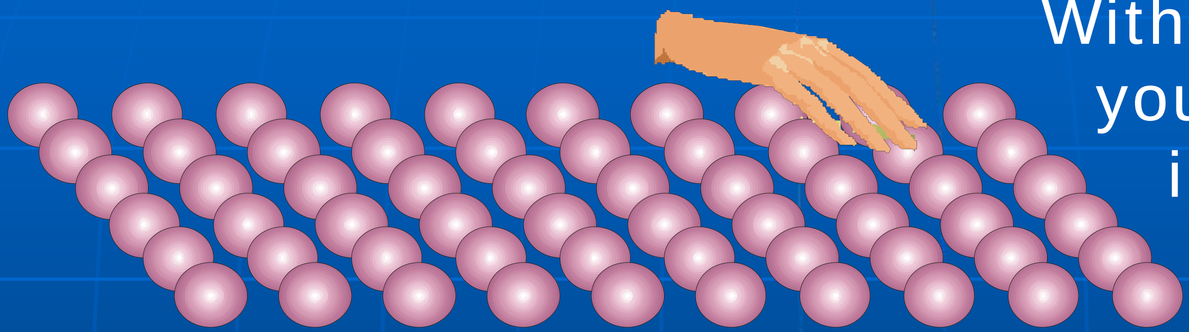




Observe the arrangement of atoms with a High-Resolution Electron Microscope



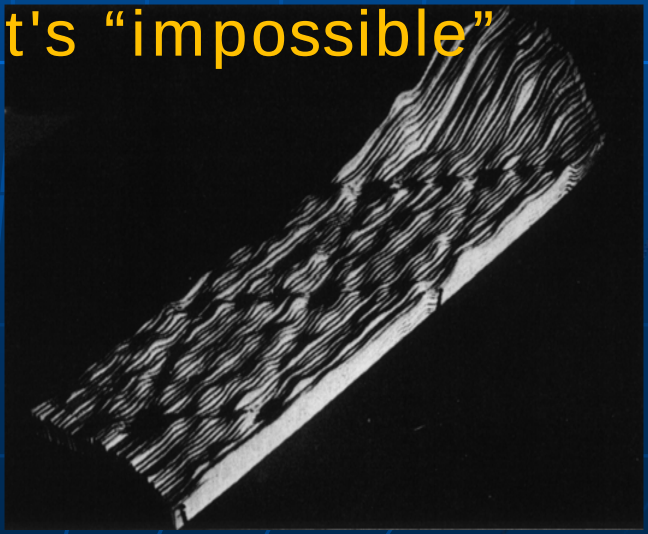
Observing the arrangement of atoms of a solid surface



With Macro things you can observe irregularity by touching it

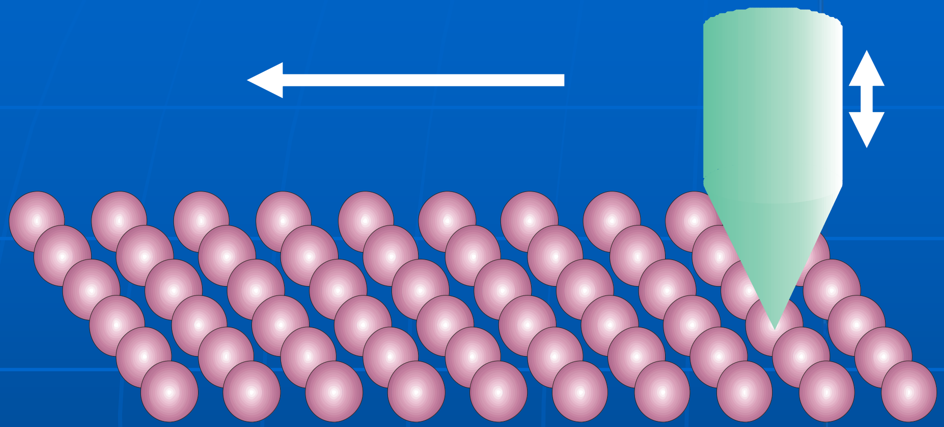
Is this type of thing possible on the atomic scale?
=> common sense tells us that it's “impossible”

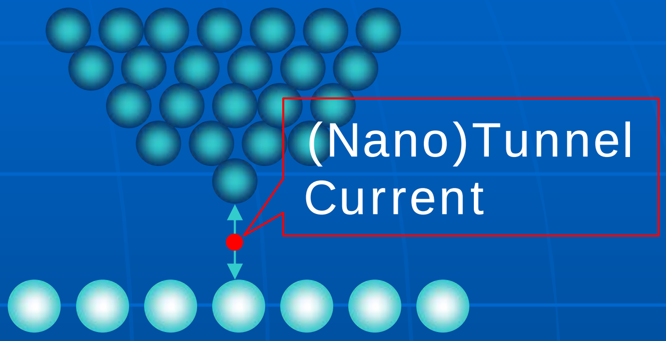
Scanning Tunnel Microscope
1984 Binnig and Rohrer



First picture taken of the arrangement of atoms on the surface of a silicon crystal

Scanning Tunnel Microscope (STM)

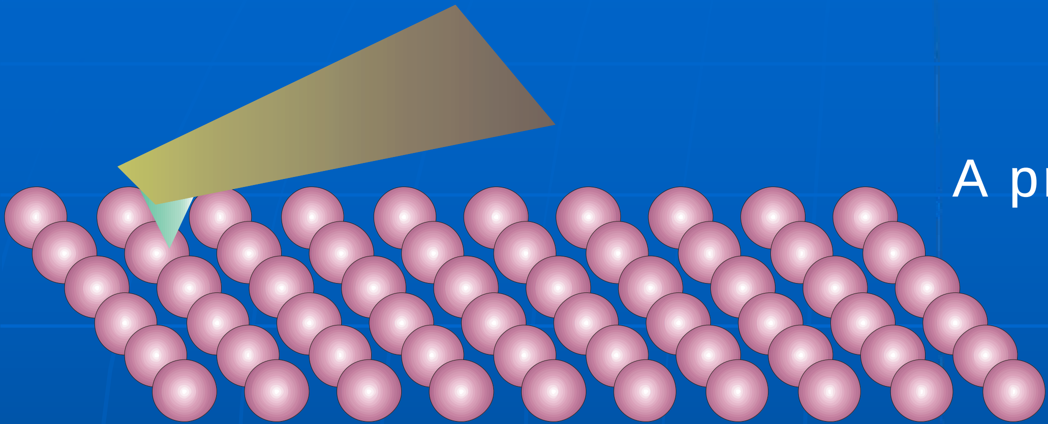




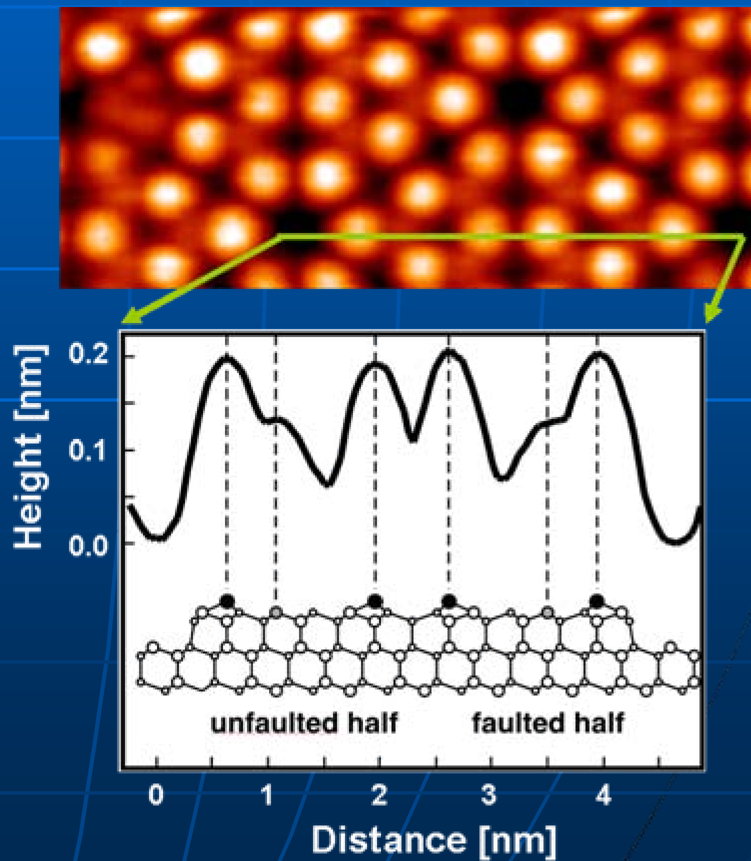
When the atoms of the needle tip and atoms of the surface get to within 1nM of each other, the Tunnel Current flows Similar to the tunnel current becoming constant, if the pin moves laterally as it rises and falls you can observe the irregularity of the atom scale

Problem of Stability
Mechanical Vibration
Electrical Noise

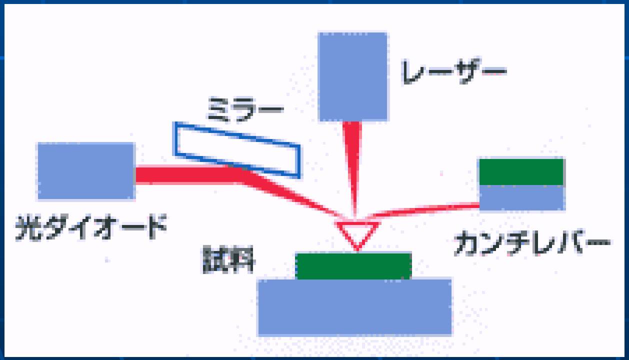
Atomic Force Microscope (AFM)



A probe on the end of a cantilever
(one-ended beam)



Detect the force when the atoms on the end of the probe get close to the atoms of the surface



Detect the force when the atoms on the end of the probe get close to the atoms of the surface

Manipulating Atoms

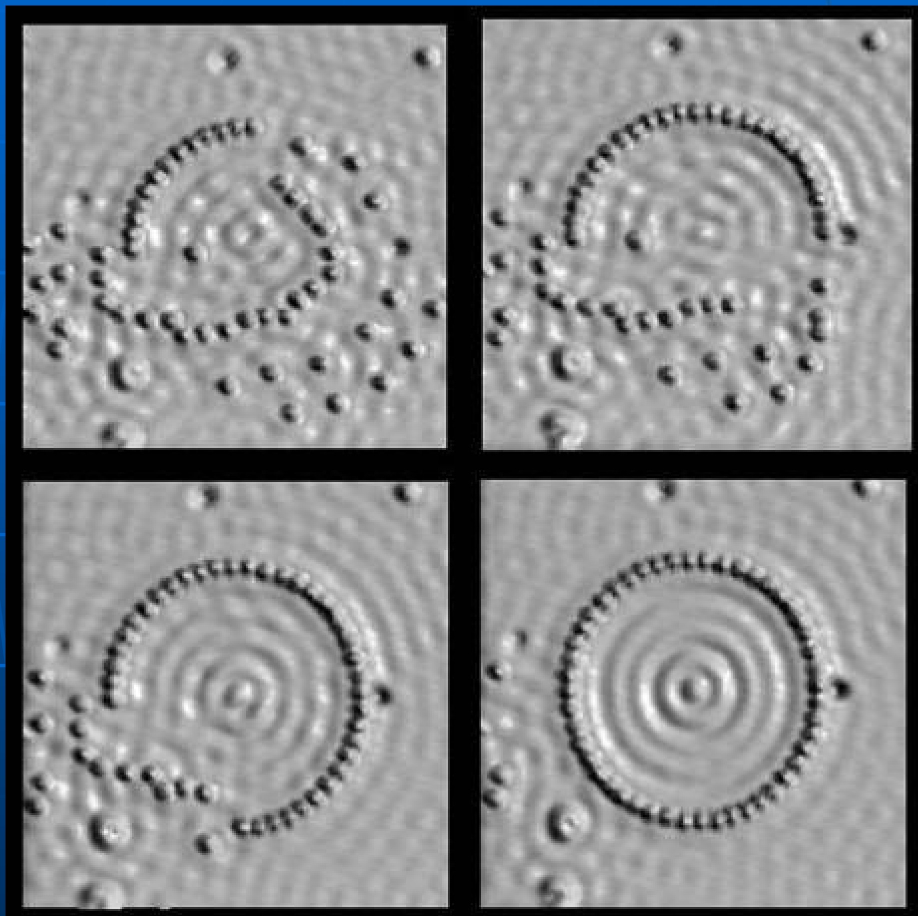


image © Crommie, Lutz & EiglerIBM

IBM Almaden Lab
Eigler Group

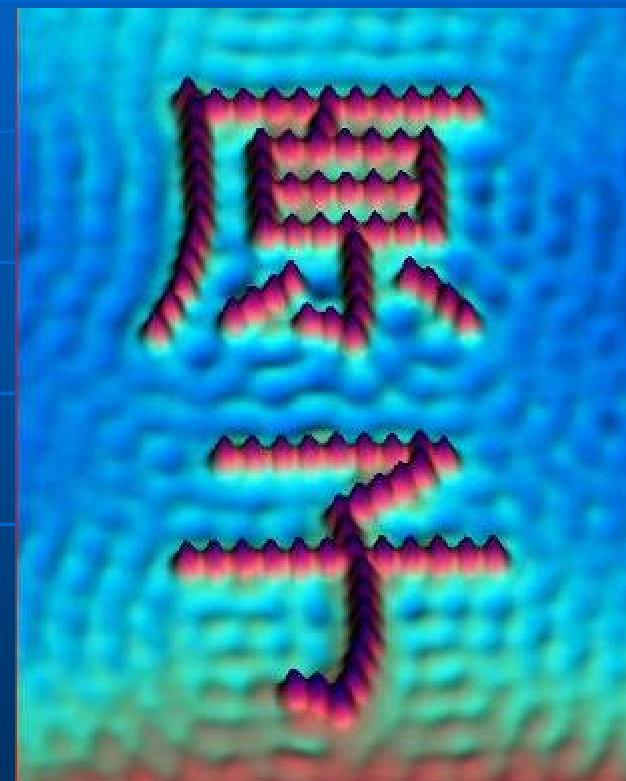


image © Lutz & Eigler IBM

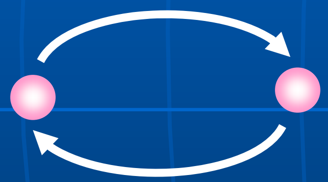
Arranging Iron atoms on a Copper surface.
The ripple-like appearance is due to the wave interference of the surface electrons

Macroscopic Quantum Phenomena
Bose Condensation and Super-conduction

Quantum Mechanical Particles

Cannot discriminate
between quantum mechanical particles of the same type

Even when two particles interchange,
the state remains the same as before
(However, the wave function will generally have a numerical factor)



$$\Psi(\mathrm{b,a}) = C\,\Psi(\mathrm{a,b})$$

$$\Psi(\mathrm{a,b}) = C\,\Psi(\mathrm{b,a}) = C^2\,\Psi(\mathrm{a,b})$$

$$\Rightarrow \quad C^2 = 1$$

$$\Rightarrow \quad C = 1 \quad \text{or} \quad -1$$

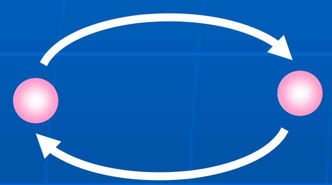
Bose Particle

Fermi Particle

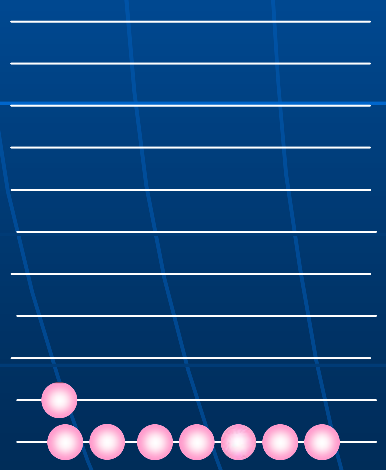
Quantum Statistics

Bose Particle (Boson)

Spin: 0,1,...



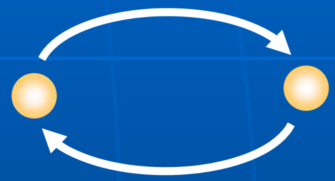
$$\Psi(\mathrm{b,a}) = \Psi(\mathrm{a,b})$$



Any number can enter the same state

Fermi Particle (Fermion)

Spin: ½, 3/2, ...

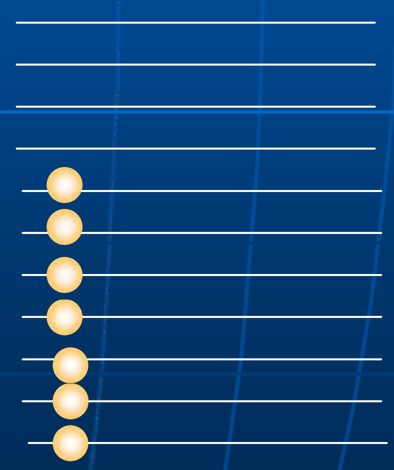


$$\Psi(\mathrm{b,a}) = -\Psi(\mathrm{a,b})$$

If a=b then

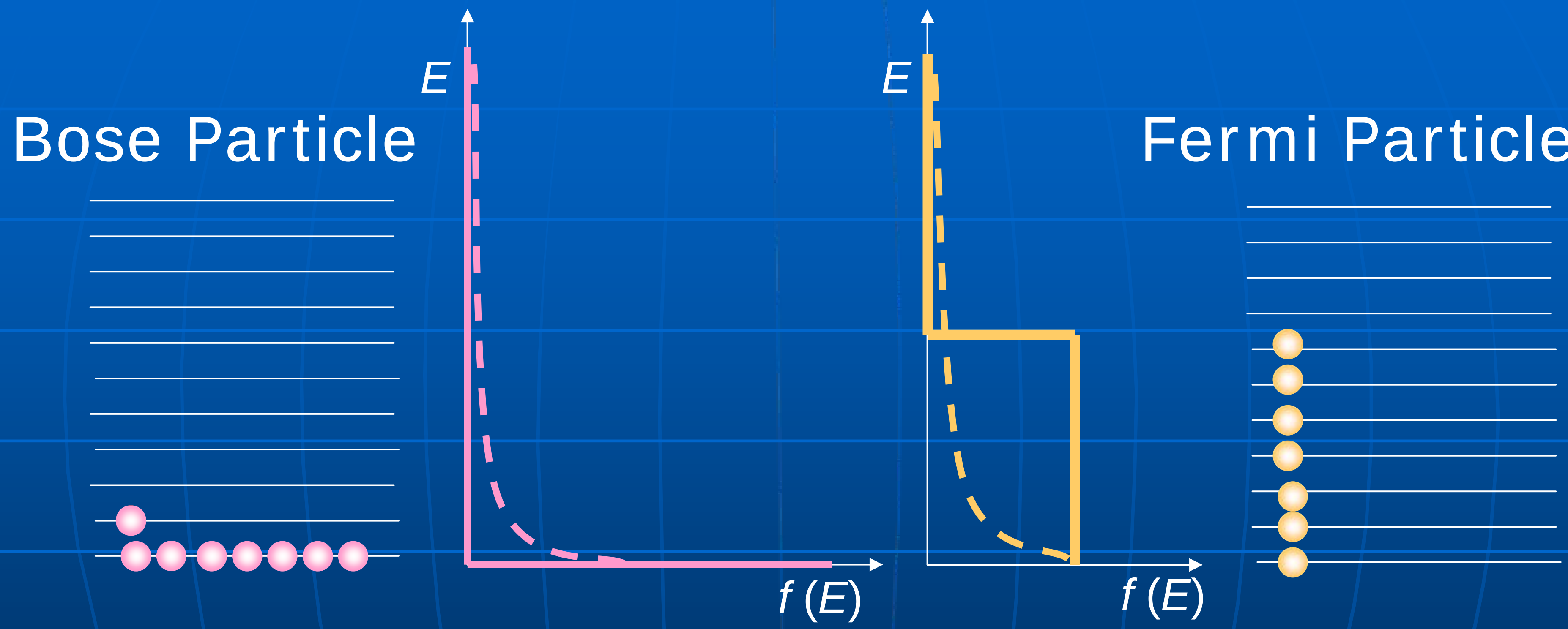
$$\Psi(\mathrm{a,a}) = -\Psi(\mathrm{a,a})$$

$$\Rightarrow \Psi(\mathrm{a,a}) = 0$$



Only one can enter the same state (Pauli Exclusion Principle)

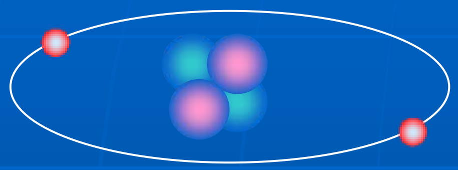
Bose-Einstein Distribution and Fermi-Dirac Distribution



Maxwell Boltzmann Distribution at the High Temperature Limit

$$f(E) = e^{-(E-\mu)/k_{\mathrm{B}}T}$$

Helium Isotopes

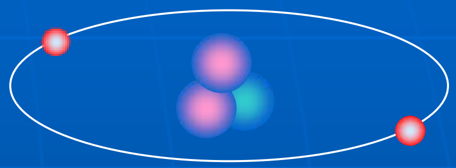


^{4}He

2 Protons
2 Neutrons
2 Electrons

Total Spin = 0

Bose Particle



^{3}He

2 Protons
1 Neutrons
2 Electrons

Total Spin = 1/2

Fermi Particle

Making Ultra-Low Temperatures

Ultra-low temperatures are required to observe phenomena that behave in a quantum statistical manner

Inner structure of a Liquid Helium Container

Liquid Nitrogen 77K

Liquid Helium (^{4}He) 4.2K

Decompression with a vacuum pump ~1.2K

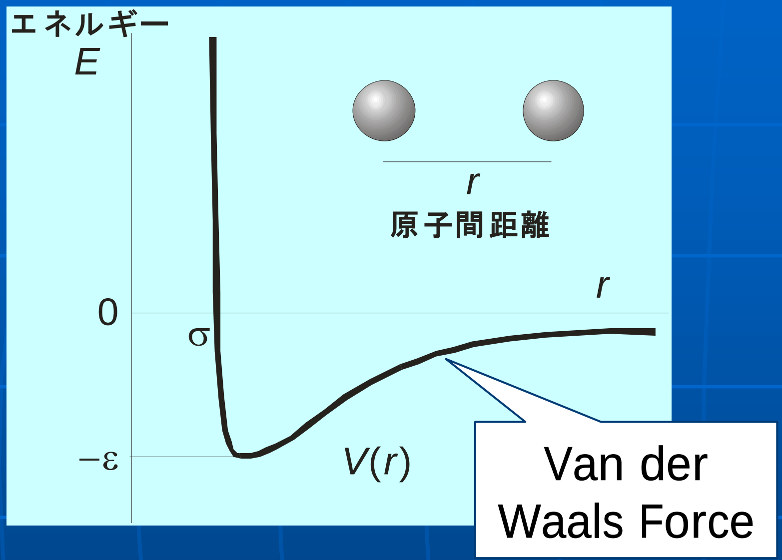
Liquid Helium (^{3}He) 3.2K

Decompression with a vacuum pump ~0.3K

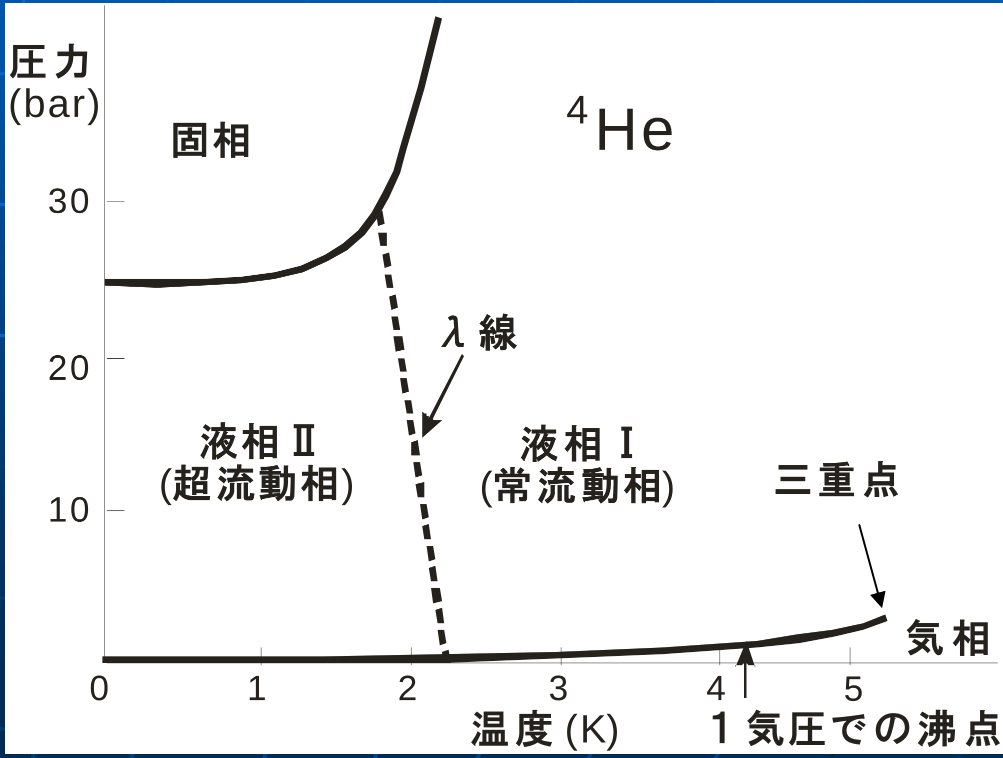
^{3}He-^{4}He Dilution Refrigerator ~ mK

Adiabatic Nuclear Demagnetization ~ μK

Phase Diagram of Helium

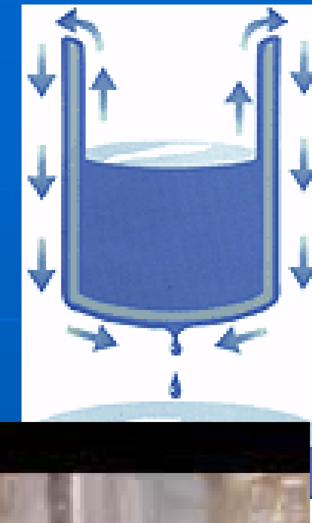


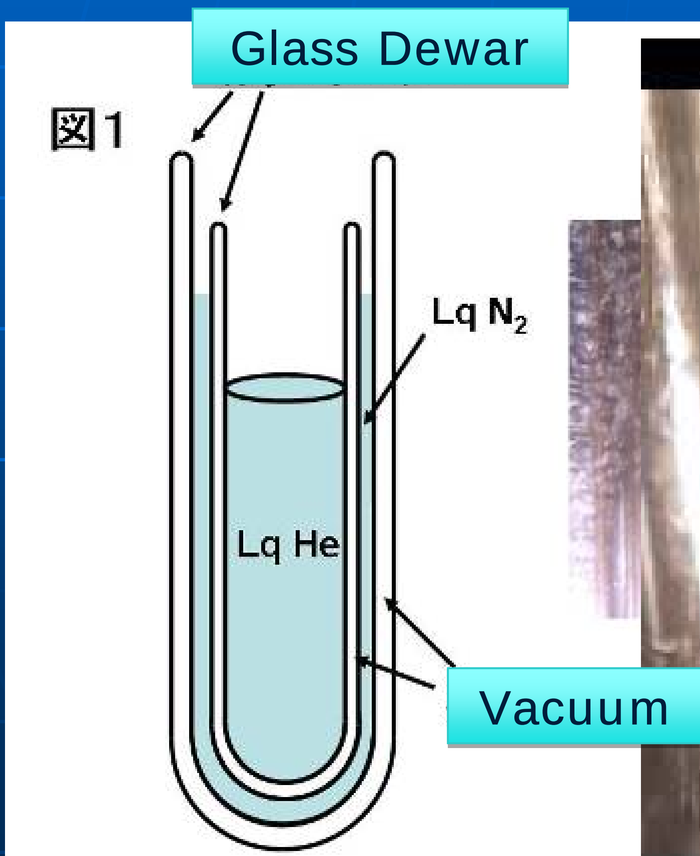
Helium (at normal pressure) will not become a solid even at absolute zero
=> Quantum Liquid



Helium atoms:
1)Light
2)Weak Interaction
 Kinetic Energy > Interaction Energy

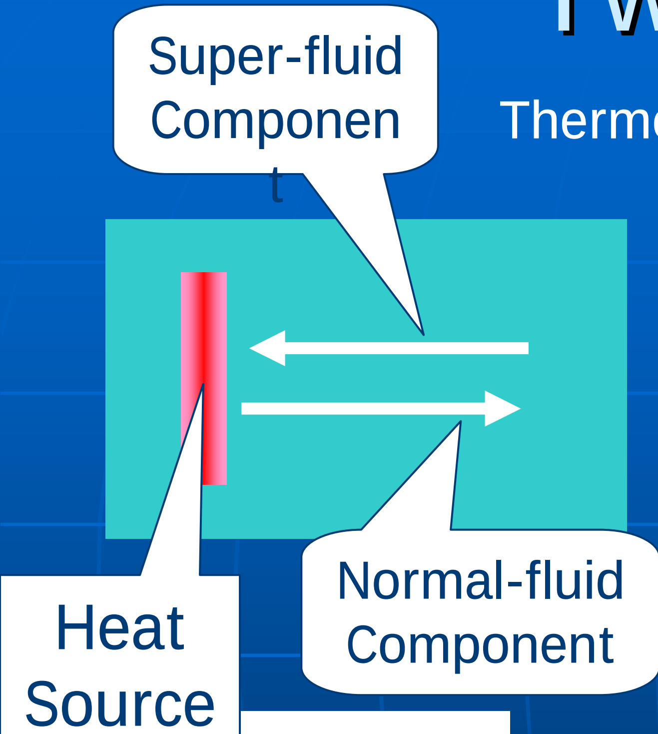
Super-fluidity of Liquid Helium



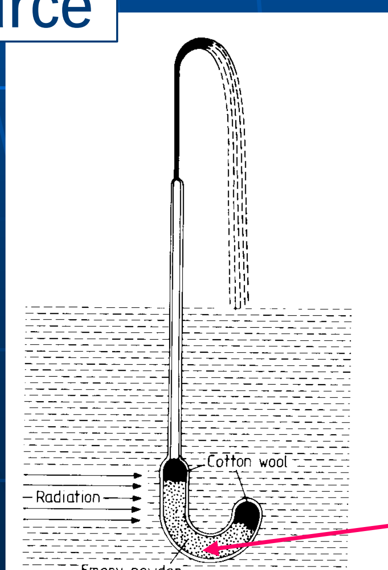


The University of Tokyo Cryogenic Research Center

Two-Fluid Model



Thermomechanical Effect (Internal Convection)



Fountain Effect

the University of Tokyo Cryogenic Research Center‡

”Super-fluid Component flows without friction in a gap which is too small for ordinary fluid to pass.”

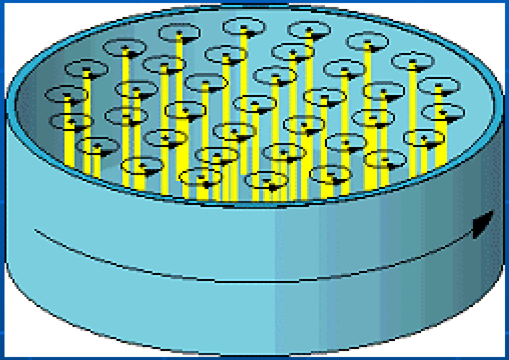
Quantum Vortex

Macroscopic Wave Function $\Psi = \Psi_0 e^{i\theta}$

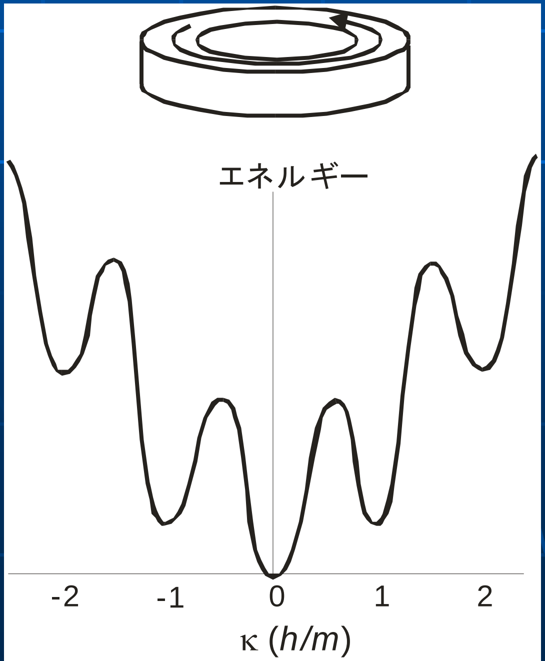
Quantization of Circulation

$$\kappa \equiv \oint_C \mathbf{v}_s \cdot d\mathbf{s} = \frac{\hbar}{m} \oint_C \nabla\theta \cdot d\mathbf{s} = \frac{\hbar}{m} 2\pi n = n\frac{h}{m}$$

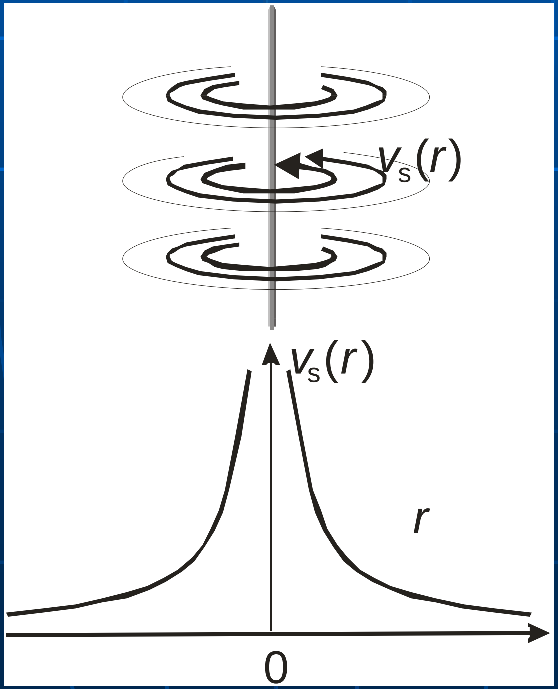
Rotating Buckets Experiment

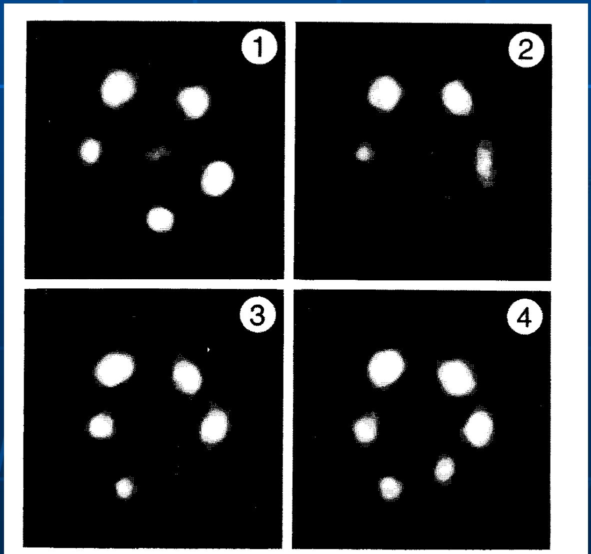


Permanent Current

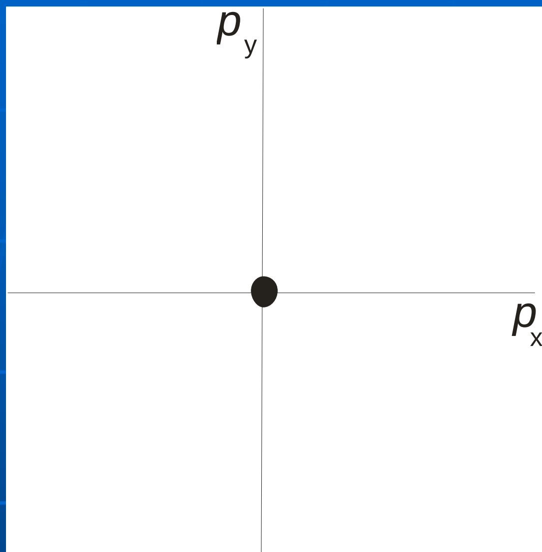


Quantum Vortex

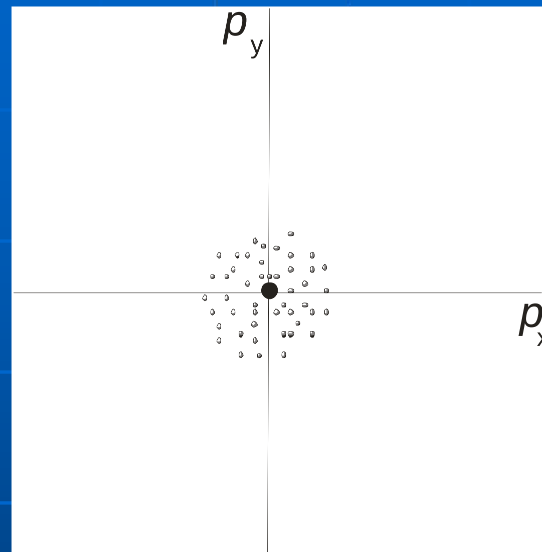




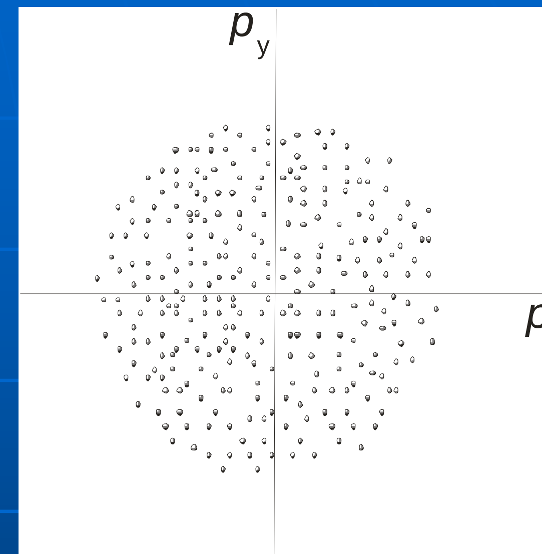
Bose-Einstein Condensation



$T = 0$



$T = T_{\mathrm{BE}}$



$T > T_{\mathrm{BE}}$

Thermal de Broglie Wavelength

$$\lambda_{\mathrm{T}} = \left(\frac{2\pi \hbar^2}{m k_B T} \right)^{1/2}$$

Bose Condensation when the Thermal de Broglie Wavelength becomes approx same as the inner-particle distance

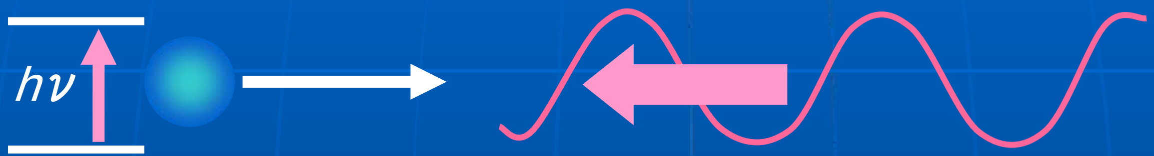
$$\lambda_T \approx n^{-\frac{1}{3}}$$

$$T_{\mathrm{BE}} = \frac{2\pi\hbar^2}{m k_{\mathrm{B}}} \left(\frac{n}{2.612} \right)^{\frac{2}{3}}$$

Laser Cooling of Atomic Gases

Collect and cool an atomic (e.g.Rb) gas (vapor) in a trap

Doppler Cooling



・Shine light at a frequency just below the resonance frequency of the atoms

・To the atoms travelling in the opposite direction to the light, the frequency of this light looks higher and becomes closer to the resonant frequency due to the Doppler effect, so the absorption probability becomes higher. The atoms decelerate due to the light absorbing the momentum.

・When the light is re-shone, it is shone isotropically so on average the atoms decelerate.

・Due to six laser beams being shone in x, y, z axes, Doppler cooling occurs in every direction

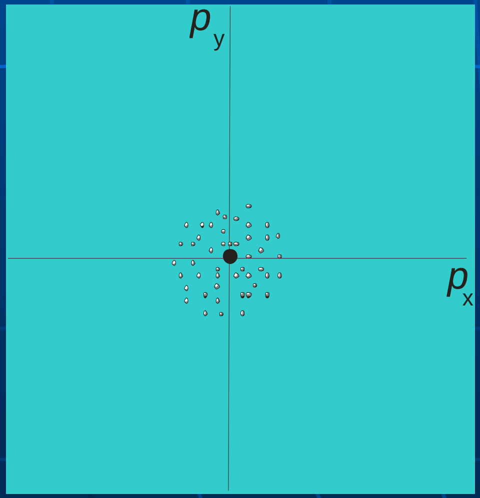
・The limit of Doppler Cooling is about T~100μK

=>this temperature can lower a further 3-4 orders of magnitude

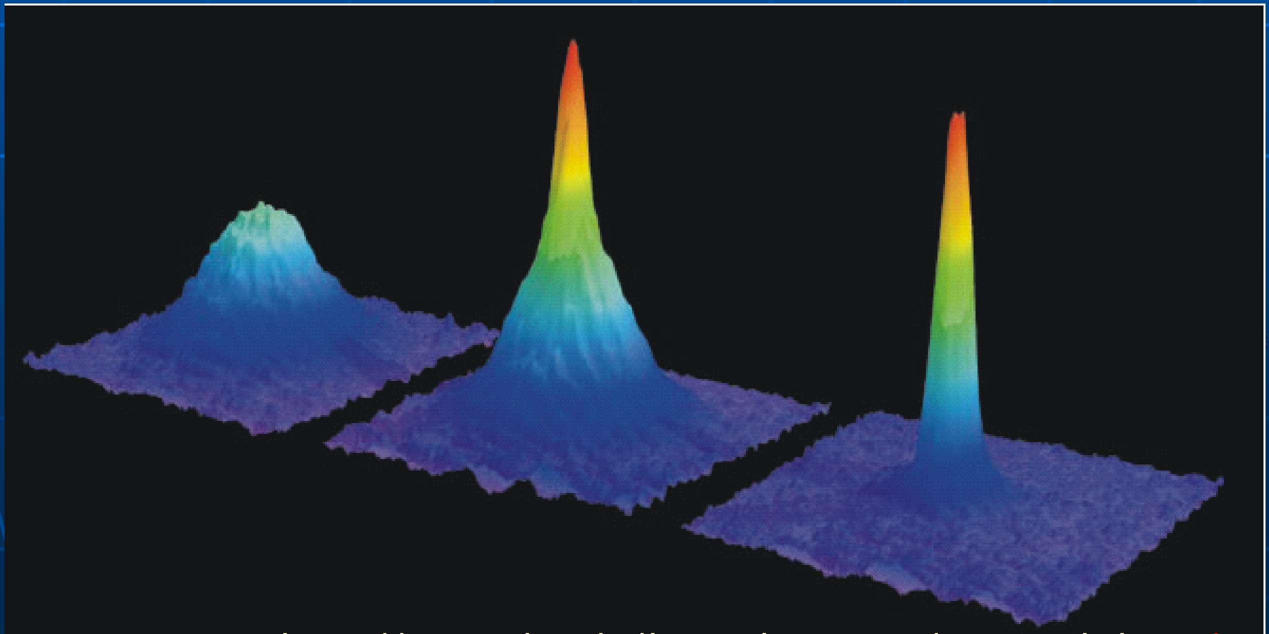
Bose-Einstein Condensation of Atomic Gases

Reducing the temperature and
achieving the conditions of Bose-Einstein Condensation by
Evaporative Cooling of atomic gas
cooled in a magnetooptical trap
$T \sim 10^{-7}$K
On shutting off the trap,
the velocity distribution consequently swells
as the atomic gas falls under the force of gravity.

$$\lambda_T \approx n^{-1/3}$$



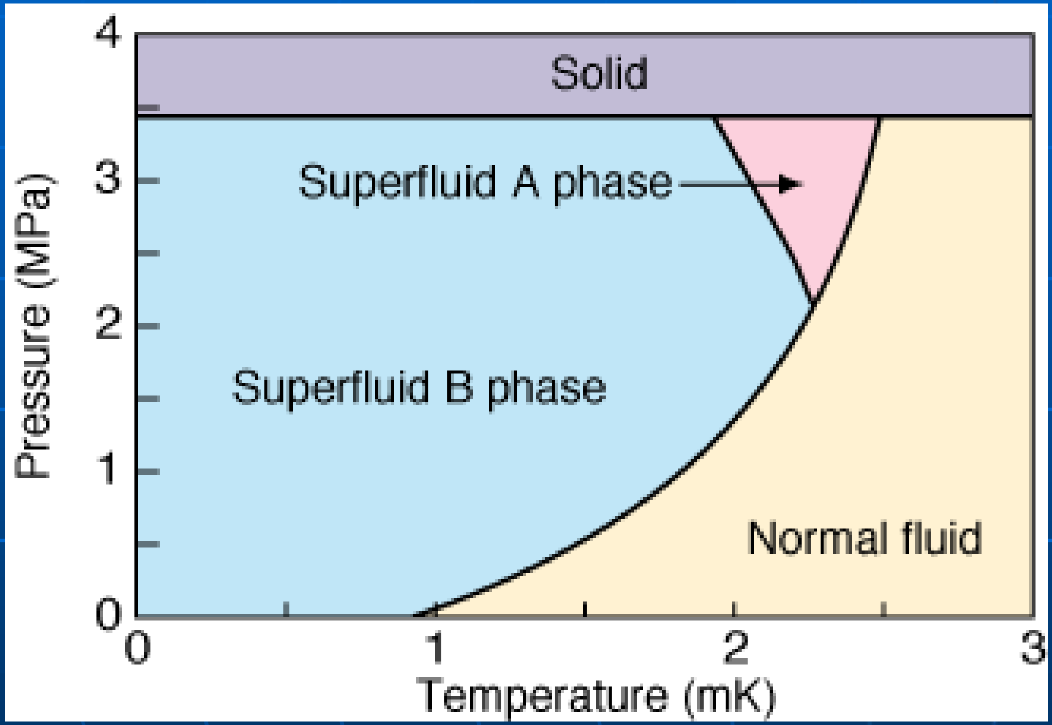
$T = T_{BE}$



http://cua.mit.edu/ketterle_group/research.htm ‡

Super-fluidity of ^3He

Phase diagram of ^3He

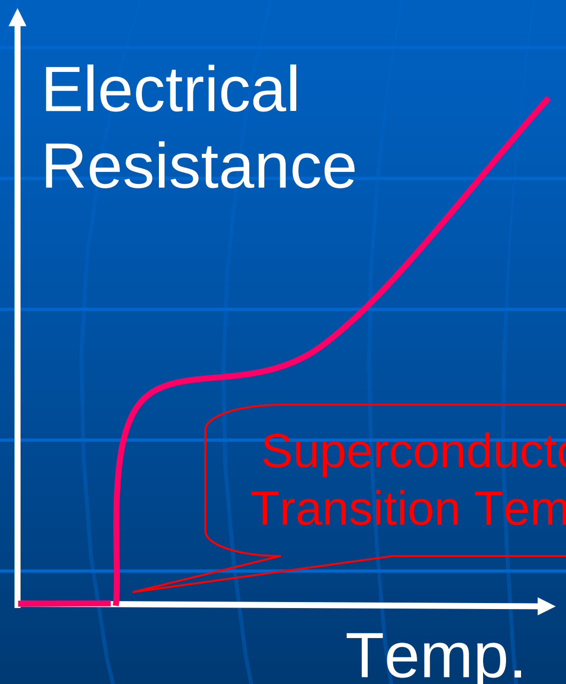


Although the ^3He Fermi particle doesn't undergo Bose Condensation, transition into Super-fluid state can occur when 2 ^3He molecules pair and behave like a Bose particle (Same mechanism as Super-Conduction)

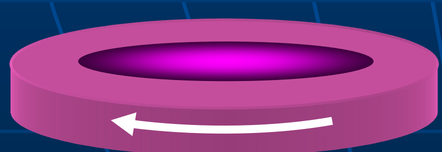
^3He becomes a super-fluid at the ultra-low temperature of ~2mK

Basic Properties of Super-Conduction

Perfect Conductor (Zero Resistance)

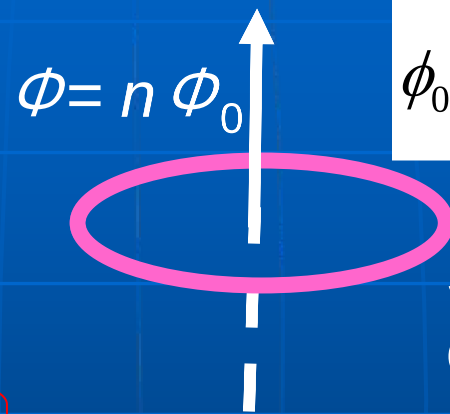


Permanent Electrical Current



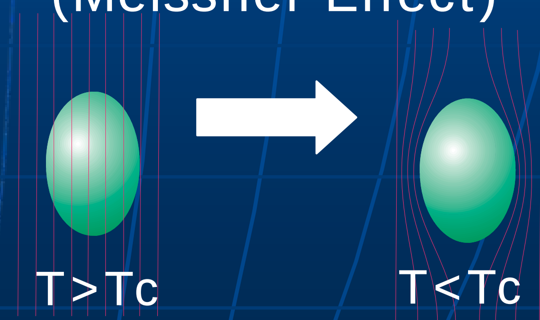
Quantization of Magnetic Flux

$$\phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\,\mathrm{Wb}$$



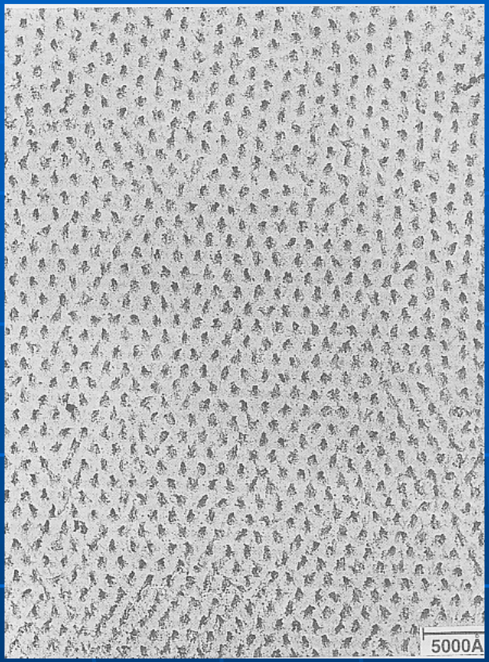
Same as quantization
of circulation
in Super-fluidity

Perfect Diamagnetism
(Meissner Effect)

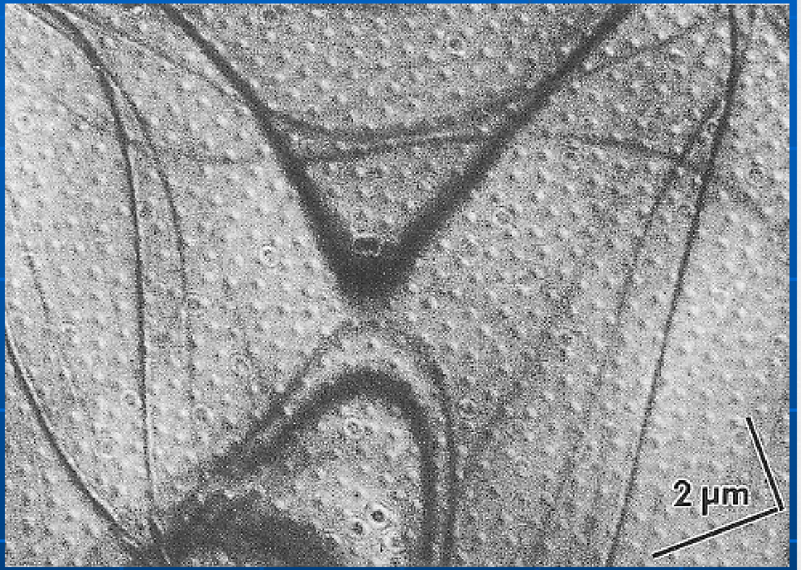


Magnetic Field if repelled in the Super-Conducting State

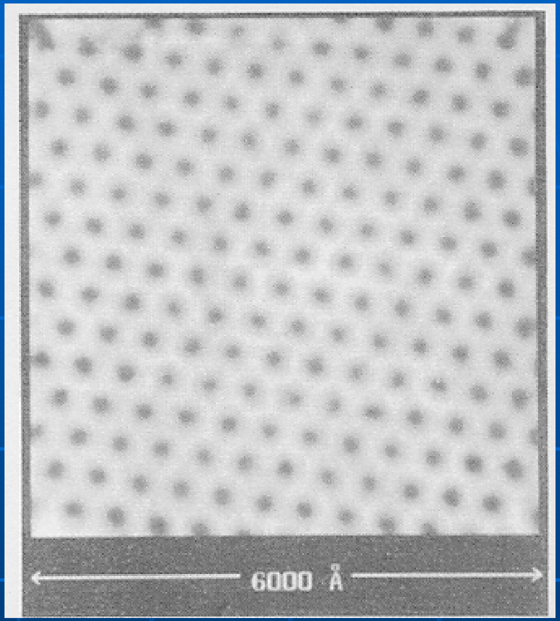
Observation of Magnetic Flux Particles



Bitter Method
(Essmann & Traeuble,1968)



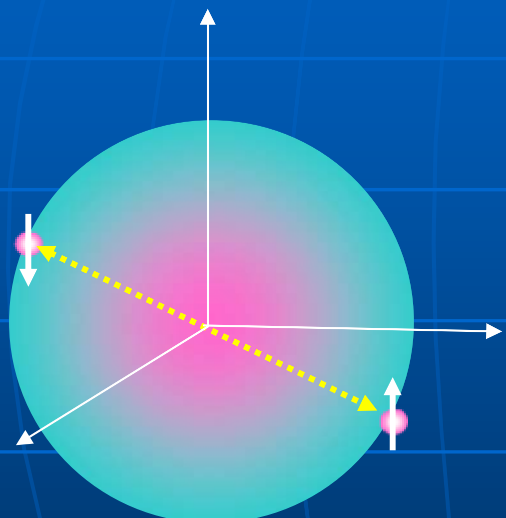
Lorentz Microscope
（Tonomura Akira, 1992）



Scanning Tunnel Microscope
（Hess, 1989）

Mechanisms of Super-conduction

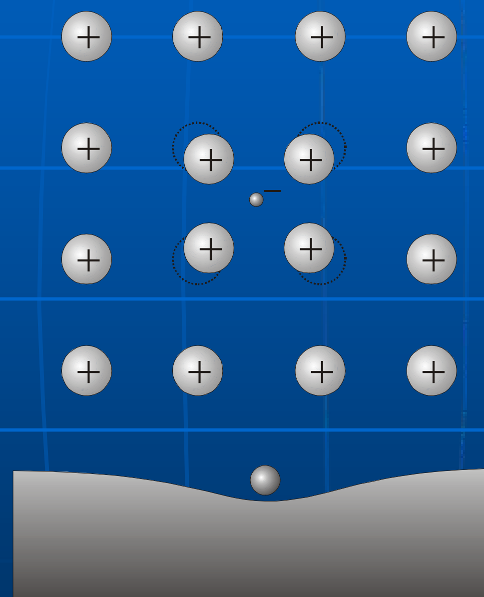
Cooper Pair Configuration

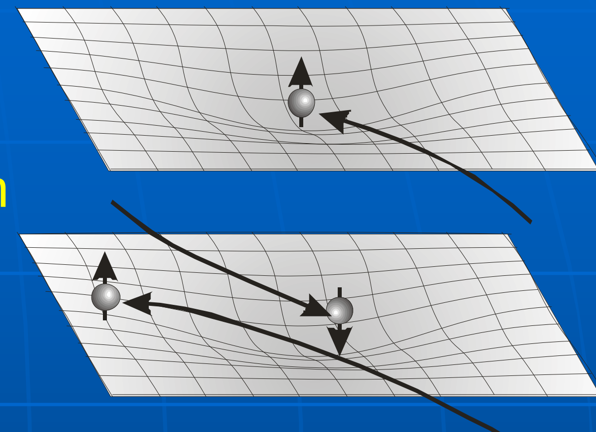


When attractive force acts on 2 electrons on the Fermi plane, a bound state (Cooper Pair) takes shape.

Origin of Attraction?

Electron Particle Interaction



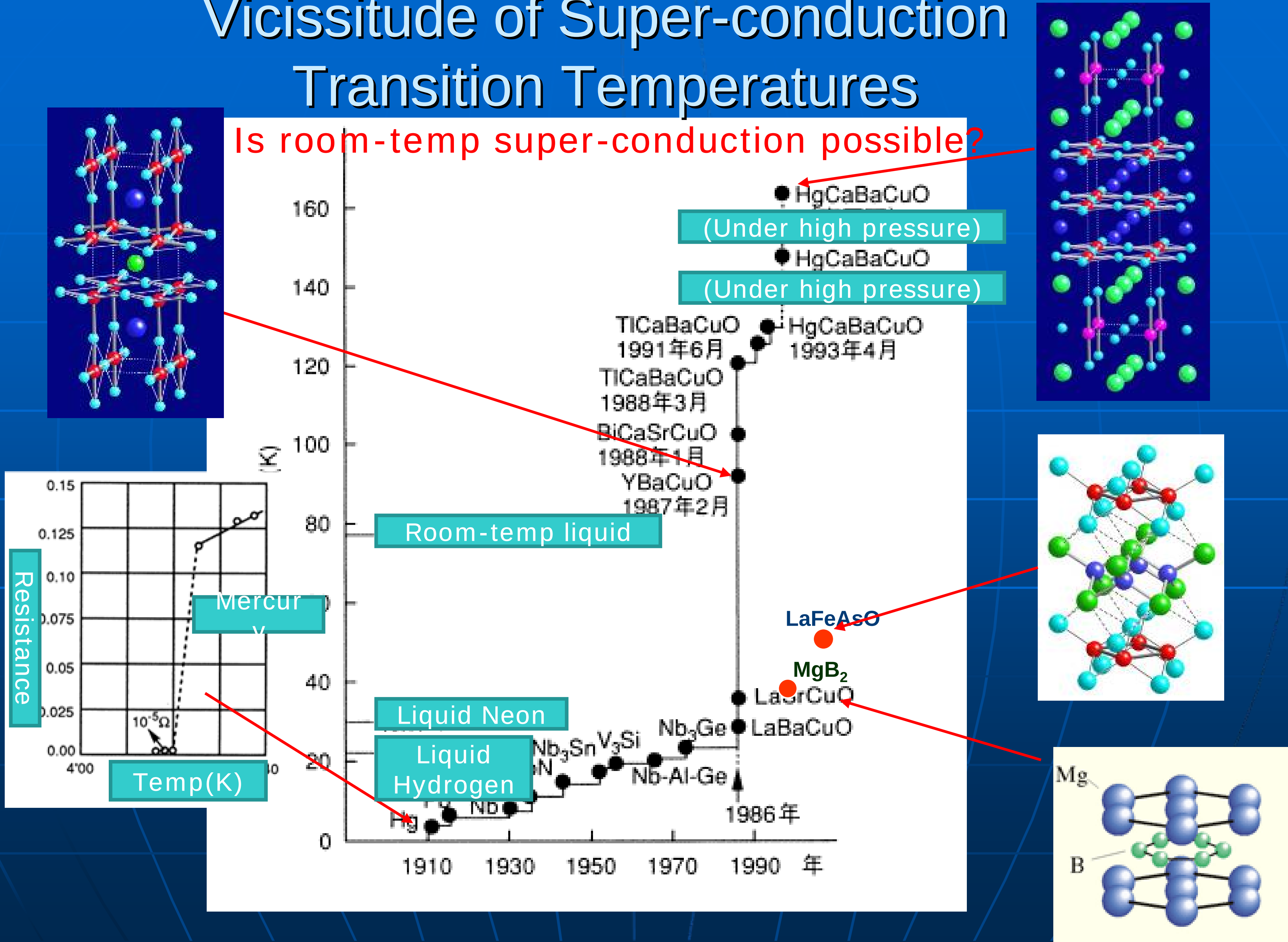


When the inter-electron attractive force mediated by electron lattice interaction over-powers the inter-electron Coulomb repulsive force, pure attraction is able to function.

Super-conduction Transition Temp.

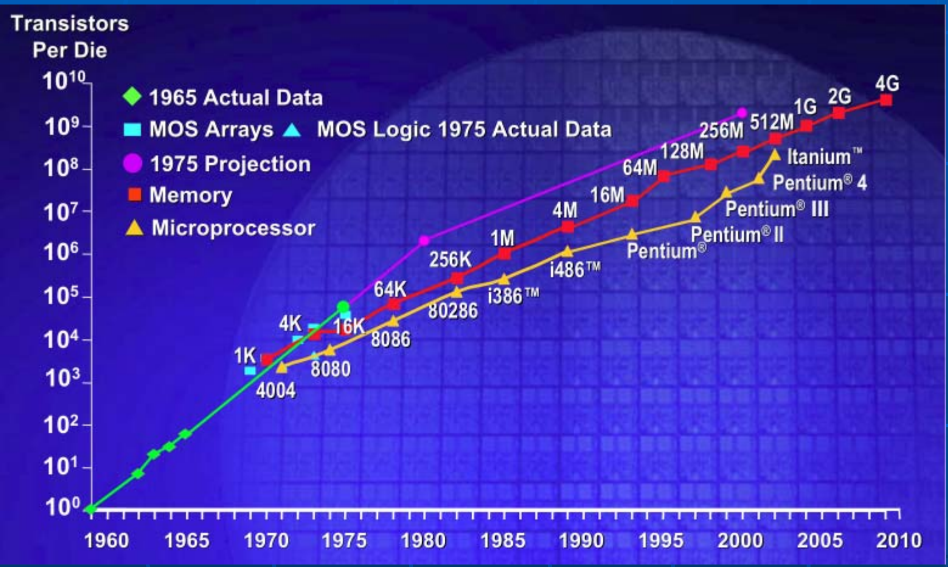
$$T_c = 1.14\Theta_D \exp\left(-\frac{1}{N(0)V}\right)$$

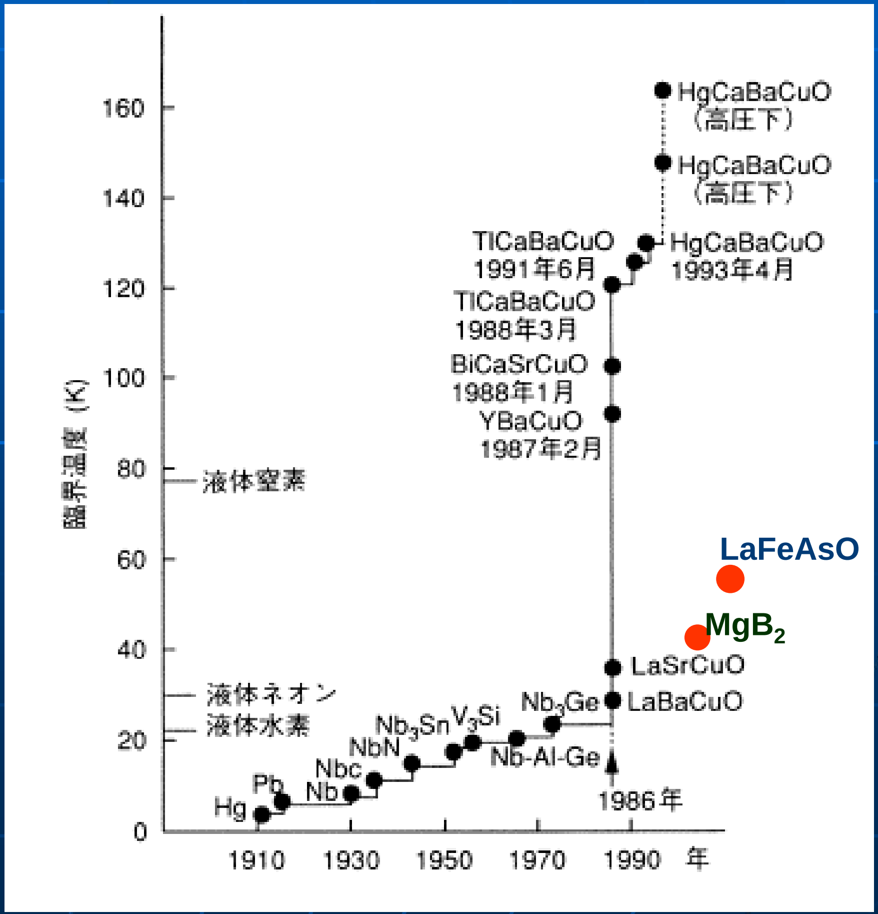
Vicissitude of Super-conduction Transition Temperatures



Future Predictions of Technological Development
vs
Predictions of the Development of Science

"Integrated Circuit Complexity"





Gordon E.Moore "NO EXPONENTIAL IS FOREVER…"

‡ Intel Copyright Permission Department

Load Map ⇒
Self-fulfillment Prophecy

Summary

- Characteristic of Quantum Mechanics
  - Quantum Interference, Tunnel Phenomenon
- Mesoscopic Physics
  - Quantum Conductance e^2/h
  - Quantum Interference AB Effect
  - Mono-electron Tunnel Effect
- Nanotechnology Nano-science
  - Observing Atoms, Manipulating Atoms
  - Scanning Probe Microscope
- Macroscopic Quantum Phenomena
  - Super-Fluidity
  - Bose Condensation
  - Super-Conduction

Positioning of Solid-State Ph ysics

- Understanding the various pr es of various substances (Solid-State P ties) based on the basic principles of ph (Quantum Physics)
- hase Transitio d Emergent Phenomena which r e uni ality and unity within variation and comp
- Becoming a also perform experiments that will close-in on the ations of Quantum Mechanics
- The concepts are nu that permeate the construction of the“Materi spective” and Sub-atomic and Astrophysics.
- Towards foundations for applications gineering

There are many interesting things!

Recommend a unification of the Humanities and Sciences!