Visualizing the Amazing Quantum World

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The Quantum Scale
Micro-Scale

- Viruses (.003-.05 microns)
- Tobacco Smoke (.1-1 microns)
- Bacteria (3-5 microns)
- Fungus Spores (5-30 microns)
- Plant Spores (10-80 microns)
- Rain Droplet (600-10,000 microns)

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Nano-Scale

Less than a nanometer
Individual atoms are up to a few angstroms, or up to a few tenths of a nanometer, in diameter.

Nanometer
Ten shoulder-to-shoulder hydrogen atoms (blue balls) span 1 nanometer. DNA molecules are about 2.5 nanometers wide.

Thousands of nanometers
Biological cells, like these red blood cells, have diameters in the range of thousands of nanometers.

A million nanometers
The pinhead sized patch of this thumb (circled in black) is a million nanometers across.

Billions of nanometers
A two meter tall male is two billion nanometers tall.
It’s a different world
Classical Ball
Classical Ball
Classical Ball
Quantum Ball
Quantum Ball
Quantum Ball

Quantum Tunneling
Ball rolling past a hill
Classical Particle

High Temperature

Absolute Zero
Classical Particle

High Temperature

Absolute Zero
Classical Particle
Quantum Particle

Absolute Zero
Quantum Particle

Absolute Zero
Quantum Particle

Zero point motion

Absolute Zero
Classical Dude
Classical Dude

Where are you?
Classical Dude

Where are you?

Here I am!!
Quantum Dude
Quantum Dude
Where are you?

Here I am !!
Classical Duet
Classical Duet
Classical Duet

What’s your color?
Classical Duet

What’s your color?
Classical Duet
What’s your color?

RED!!
Classical Duet

What’s your color?

RED!!  BLUE!!
Quantum Duet
Quantum Duet
What’s your color?
Quantum Duet
What’s your color?

Depends!!!
Quantum Duet

What’s your color?

Quantum Entanglement

Action at a distance
Wave-Particle Duality

Quantum Particles can be in multiple places at once
Wave-Particle Duality
Quantum Particles can be in multiple places at once
Wave-Particle Duality

Quantum Particles can be in multiple places at once

Better to think of a particle as a wave
Wave-Particle Duality

Quantum Particles can be in multiple places at once

Better to think of a particle as a wave

A probability wave: \( p(x) \)
Where the height \( p \) represents the probability of finding the particle at a given point \( x \)
Quantum phenomena with macroscopic consequences

Superfluidity and Superconductivity
Superfluidity
Superfluidity

Bose–Einstein condensate
In a 1959 speech entitled ‘There’s Plenty of Room at the Bottom’, Richard Feynman invited scientists to a new field of research: to see individual atoms distinctly, and to arrange the atoms the way we want. Feynman envisioned that, by achieving those goals, one could synthesize any chemical substance that the chemist writes down, resolve many central and fundamental problems in biology at the molecular level, and dramatically increase the density of information storage.

Some 20 years later, those goals began to be achieved through the invention and application of the Scanning Tunneling Microscope (STM).

The inventors of STM, two physicists at IBM Research Division, Gerd Binnig and Heinrich Rohrer, shared the 1986 Nobel Prize in physics for this discovery.
The Scanning Tunneling Microscope
Scanning Tunneling Microscopy (STM)

The STM measures the number of electrons that tunnel across the Vacuum barrier (tunnel current) at a fixed real space position.

Imaging Atoms

Precision Spectroscopy
The STM measures the number of electrons that tunnel across the Vacuum barrier (tunnel current) at a fixed real space position.
Scanning Tunneling Microscope
Scanning Tunneling Microscope
Scanning Tunneling Microscope

Tip

Temp Magnet Field Pressure Chemically

Diagram shows a scanning tunneling microscope setup with a tip and various parameters like temperature, magnet field, pressure, and chemical conditions.
Scanning Tunneling Microscope

Temp
Magnet Field
Pressure
Chemically
The chance of tunneling is based exponentially on distance.
The chance of tunneling is based exponentially on distance.
Binning and Rohrer et al. 1983
Atomic Resolution Imaging

(30Å X 30 Å)  Si(100)
Au(111)

W. Chen, V. Madhavan, T. Jamneala, M.F. Crommie
Atomic Manipulation by STM

STM setup

Long-range forces
van der Waals, etc.

Adsorbate

Short-range forces
'tunable chemical bond'

Z

X

V

I
Cobalt Atoms on Au(111)
Atomic Manipulation

M.F. Crommie, C.P. Lutz, D.M. Eigler

Corrals and Waves
Superconductivity
Electrical resistance
Pure Metals (Au, Cu, Ag)

\[ R = \rho \frac{L}{A} \]

Resistivity (\(\rho\))

Residual Resistivity (\(\rho_r\))

Room temperature

Temperature
Super-conductor

Resistivity ($\rho$)

Room temperature

$R = \rho \frac{L}{A}$

$T_C$
Discovered in 1911 by the Dutch physicist, Heike Kammerlingh Onnes

Onnes (left) and Van der Waals (right) in Leiden at the helium 'liquefactor' (1908)
Cooper pairs are two electrons bound by glue (vibrations in the BCS case).
Cooper pairs are bosons ($S=0$) so they can condense into the SC state (no Pauli-X).
Cooper pairs are coherent.
The energy of the SC state is less than that of the Normal State.

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High Temperature Superconductors

High Temperature Superconductors

Copper
Oxygen
Layered Materials Called "cuprates"

BCS low Temp SC 1986

Year

## Cuprate-Oxide “High-\( T_c \)” Superconductors

<table>
<thead>
<tr>
<th>Compound</th>
<th>( T_c ) (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 )</td>
<td>-235</td>
</tr>
<tr>
<td>( \text{YBa}_2\text{Cu}<em>3\text{O}</em>{7-x} )</td>
<td>-180</td>
</tr>
<tr>
<td>( \text{Bi}_2\text{Sr}_2\text{CaCu}<em>2\text{O}</em>{8+x} )</td>
<td>-179</td>
</tr>
<tr>
<td>( \text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}<em>3\text{O}</em>{10} )</td>
<td>-148</td>
</tr>
<tr>
<td>( \text{HgBa}_2\text{Ca}_3\text{Cu}<em>4\text{O}</em>{10} )</td>
<td>-136</td>
</tr>
</tbody>
</table>

Temperature at which Nitrogen gas becomes a liquid: \(-196 \text{ C}\)
Superconducting Magnets
MRI (Magnetic Resonance Imaging)
Dissipationless transport
Meissner Effect
High Temperature superconductor
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

T = 4.2K, B = 0T
100pA, -100mV
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2\text{K}, B = 0\text{T}$

$100\text{pA}, -100\text{mV}$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2\text{K}, B = 0\text{T}$

$100\text{pA}, -100\text{mV}$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2K, B = 0T$

$100pA, -100mV$
STM on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

Topography

Electronic Structure: energy

Electronic Structure: space

dl/dV map at 18meV

dl/dV map at 39meV
Mechanism of Pairing

Room Temperature Superconductivity