Thank you, PER Community!

Physics Pedagogy

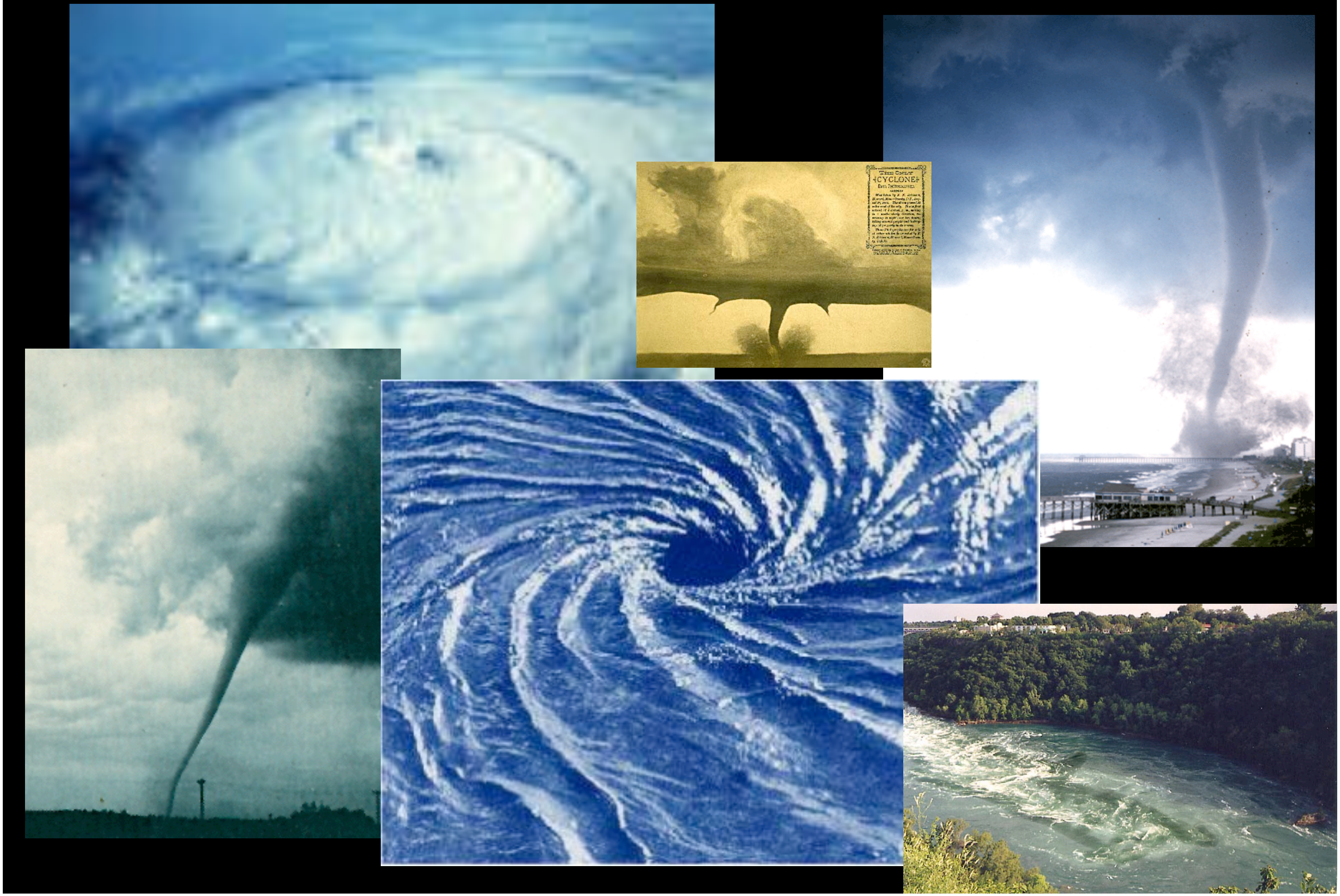
- Peer instruction
  - Pre-reading quizzes
  - Conceptual questions with clickers during class
  - Concepts on exams
- Computer graphics demos
- Backwards course design
- Project-based labs
- Focus on individuals
  - Learn and use names
  - Encourage use of office hours
  - Informal interactions

Specific Thanks to:

- Tobias Beetz
- Pat Burchat
- Marcelo Clerici-Arias
- Robyn Dunbar
- David Goldhaber-Gordon
- Chaya Nanavati
- Tom Woosnam
- All my students and TAs

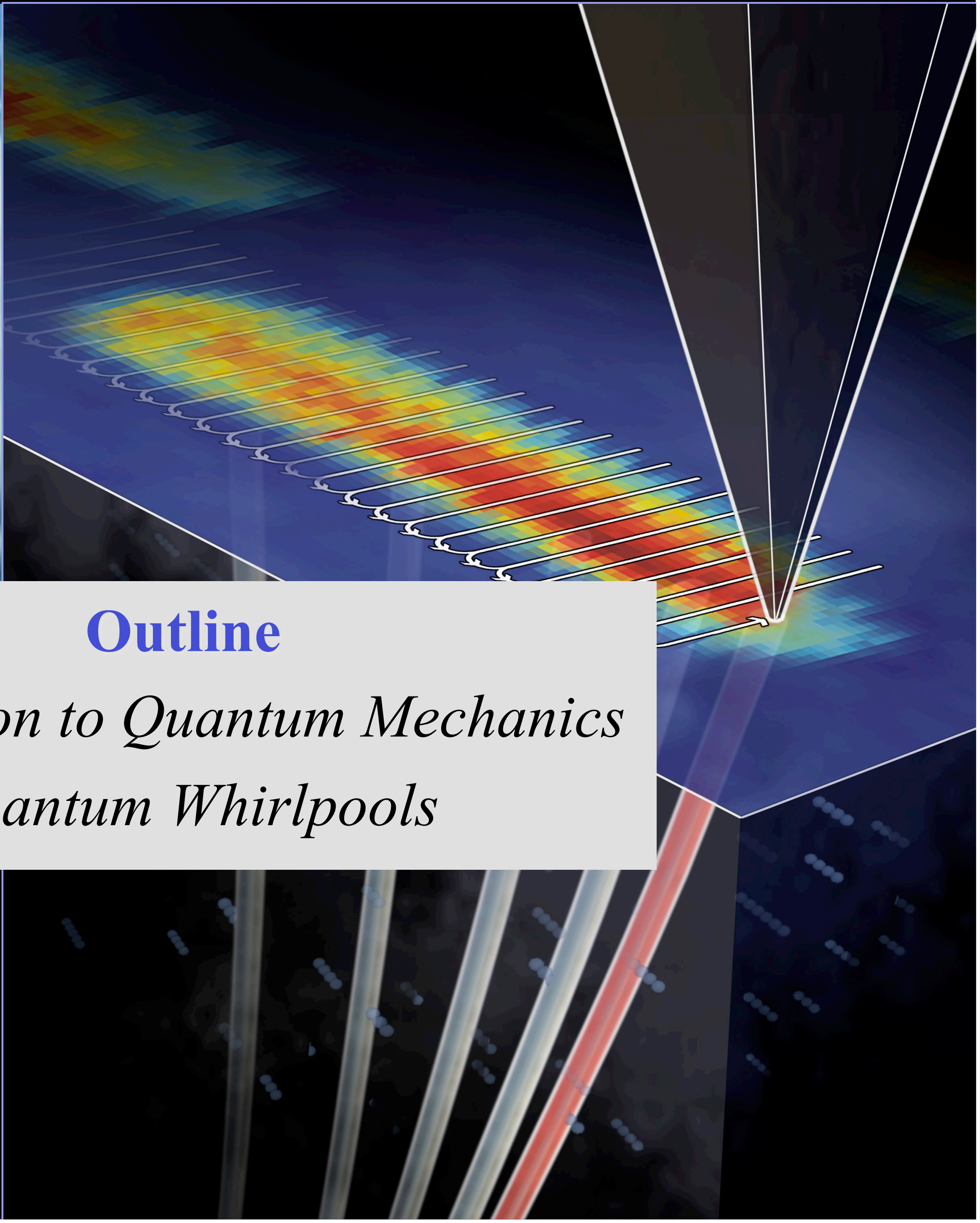
Quantum Whirlpools

Jacksonville,
1/11/10



Quantum Whirlpools

Jacksonville,
1/11/10

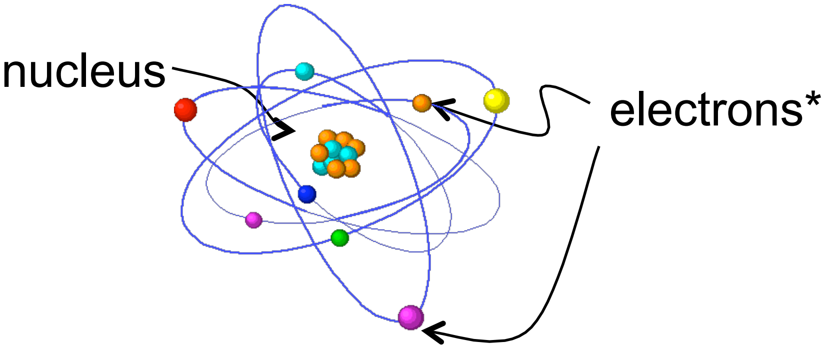


Outline

Introduction to Quantum Mechanics

Quantum Whirlpools

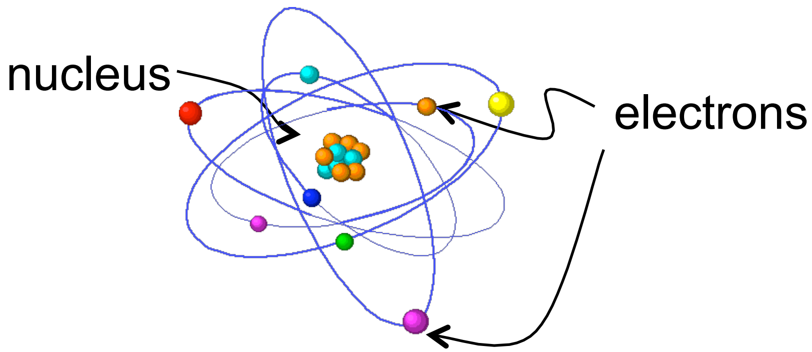
Classical view of the atom




The Economist, April 1, 2004

*An electron is a fundamental particle with mass m_e, charge e, and spin 1/2.

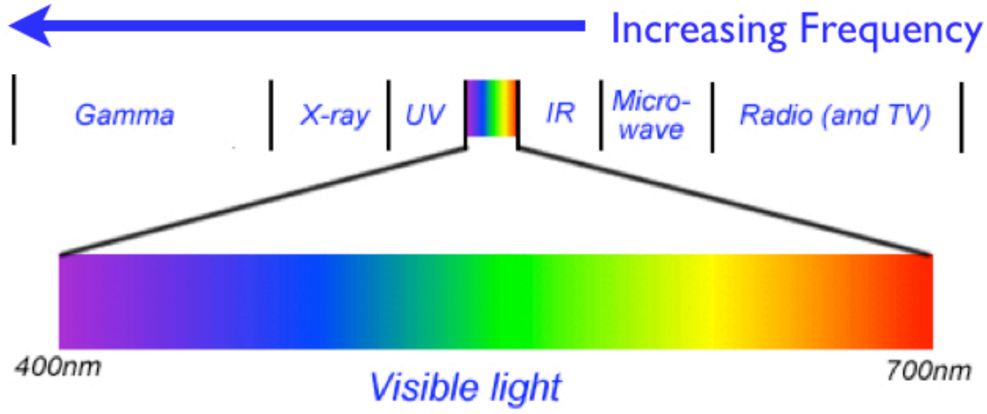
Problems with the classical view of the atom



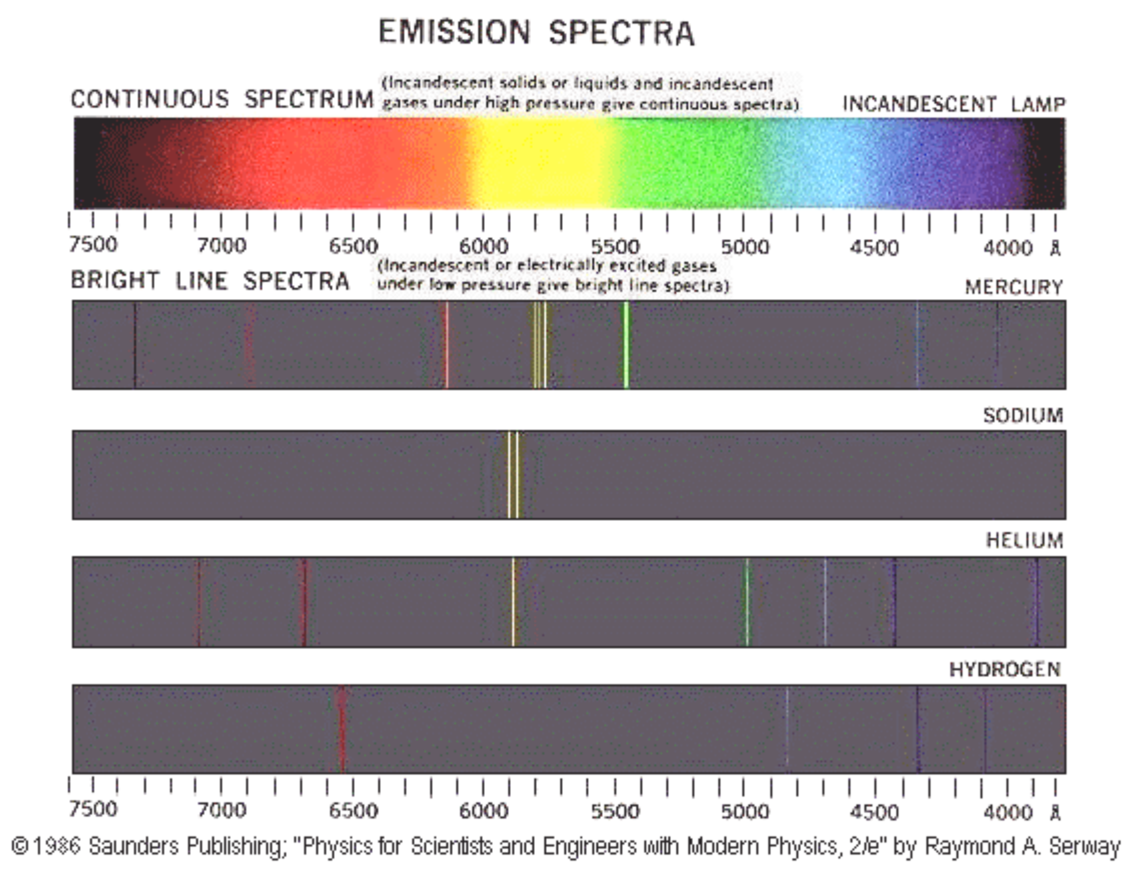
The classical (Newtonian) view of the atom would predict:

1. that the electron will spiral in and crash into the nucleus in a fraction of a second.
2. that the electron can orbit at any distance, so the energy of the atom can change by arbitrarily small amounts.

The color of light is related to its frequency:



Experimental reality: discrete (“quantized”) absorption and emission of light from atoms



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continuous spectrum
of visible light

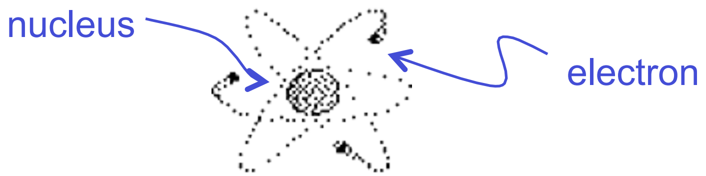
mercury (quantized)

sodium (quantized)

helium (quantized)

hydrogen (quantized)

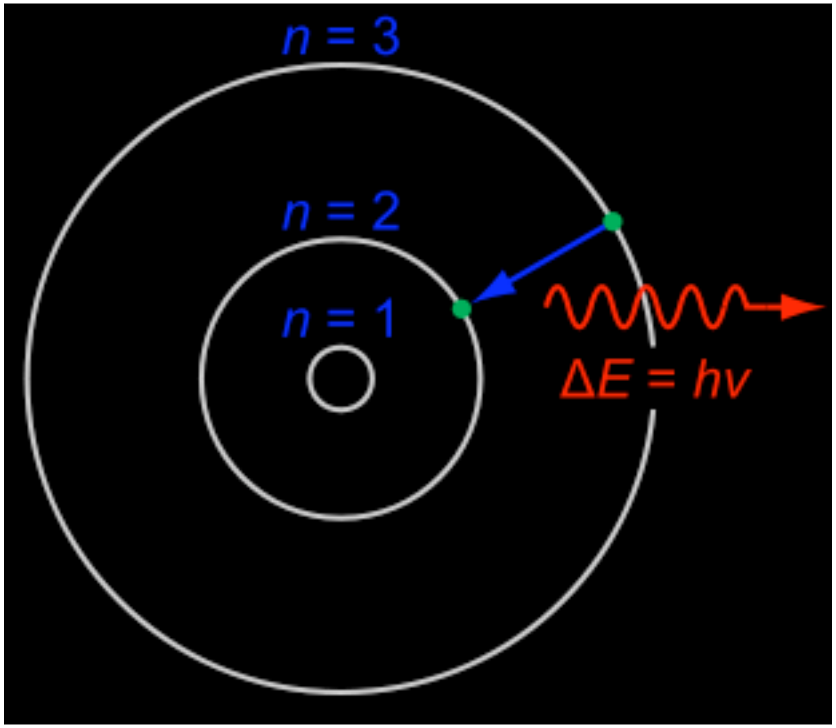
Bohr model of the hydrogen atom



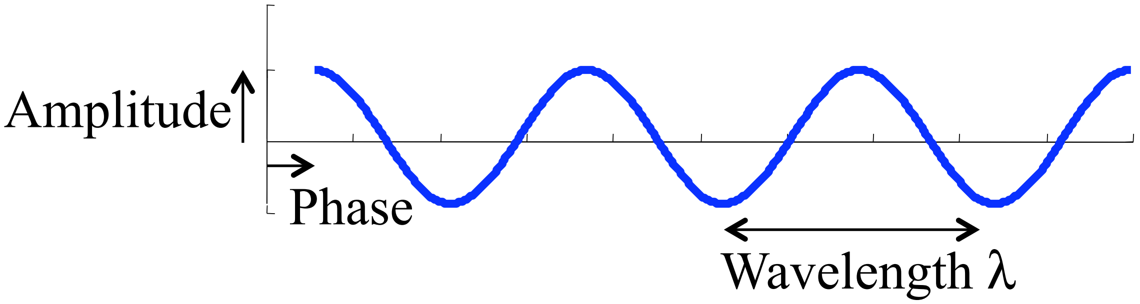
$$E_n = -\frac{13.6}{n^2}\,\mathrm{eV}$$

Only states with integer values of *n* are allowed.

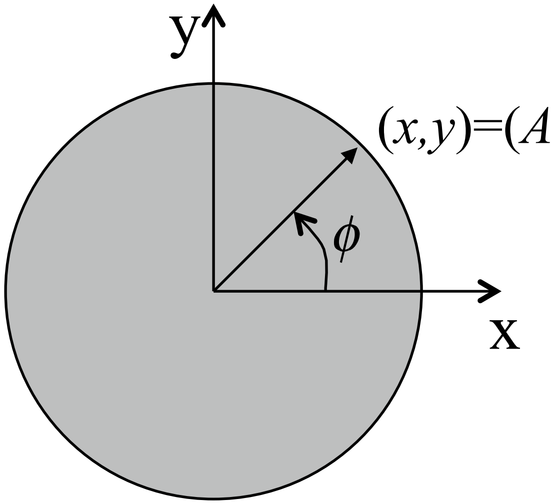
The energy is *quantized*.



A wave



Aside: *the quantum mechanical wave function has an* ***Internal*** *phase:*
think of a hand on a clock, or an oven timer



$(x,y)=(A\cos(t/T+\phi), A\sin(t/T+\phi))$

The wave function

$$\Psi(r,t)$$

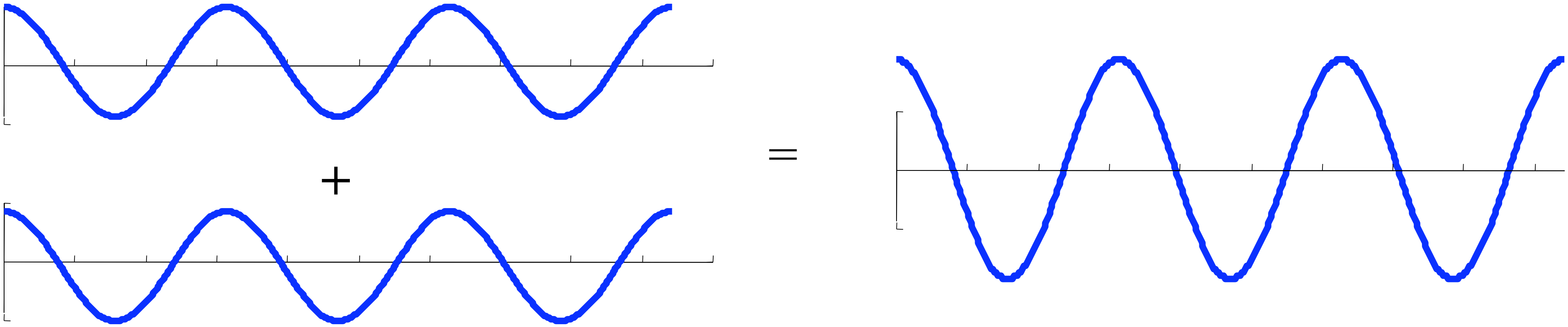
has an internal phase

$$\Psi = \psi e^{i\varphi}$$

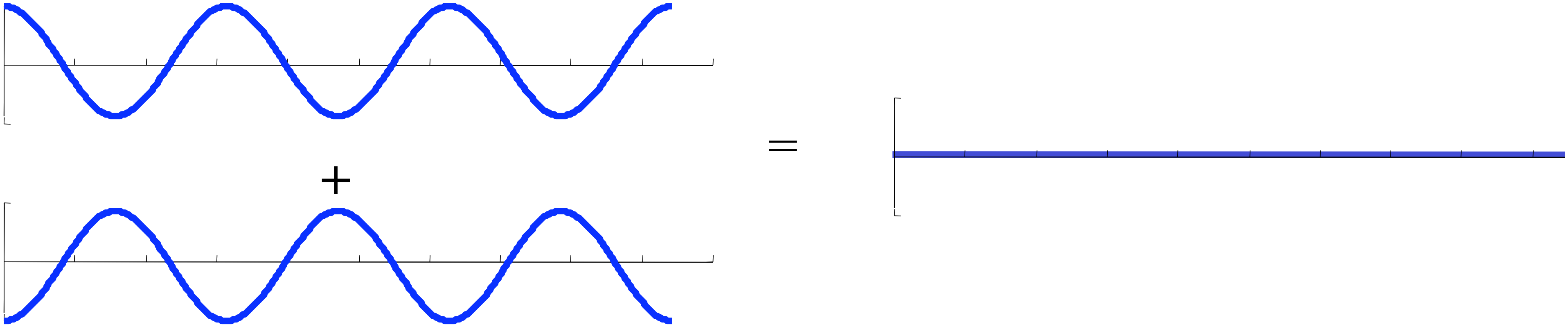
phase

amplitude

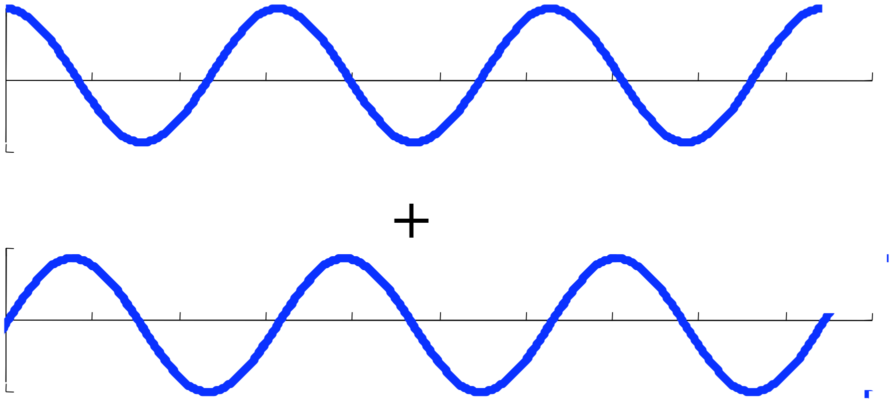
Waves: constructive interference



Waves: destructive interference

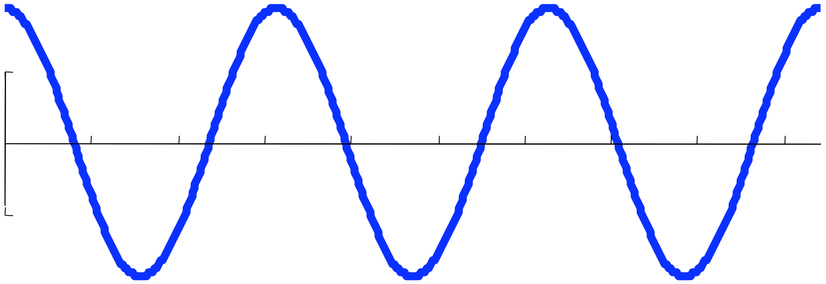


Test yourself!



$\overset{?}{=}$

①



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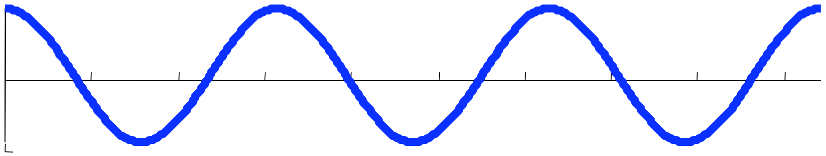

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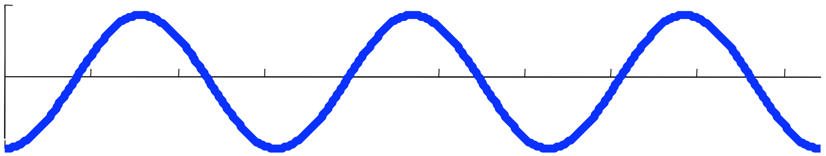

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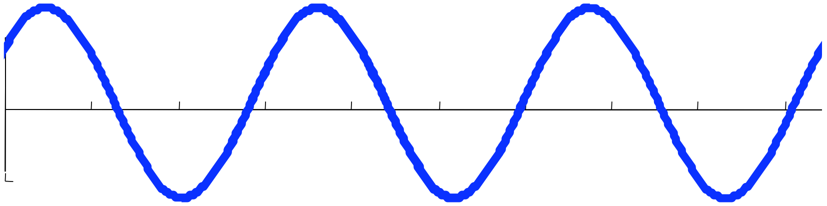

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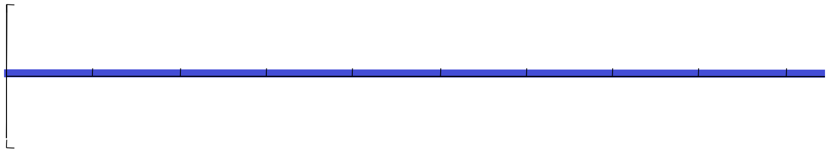
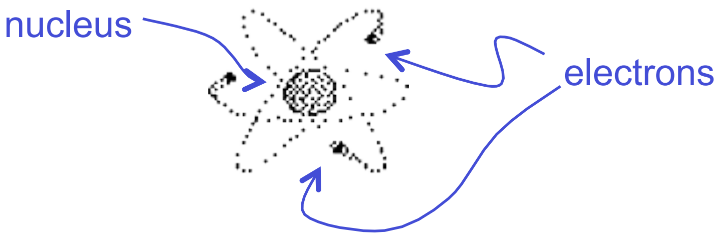


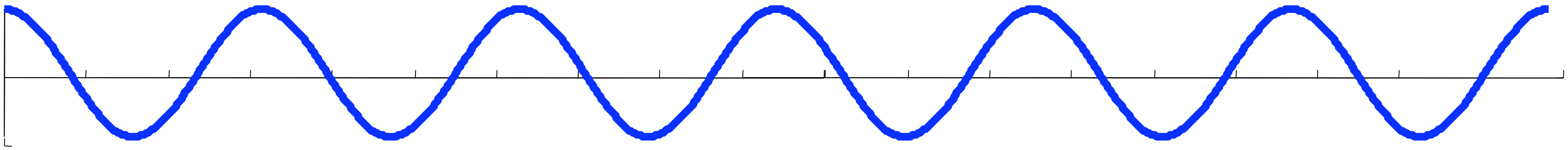
How does a wavelike electron lead to quantized orbitals in atoms?



The deBroglie hypothesis:

$$\lambda = \frac{h}{m_e v}$$

Imagine a wavelike electron wrapping many, many times around the nucleus:



The electron can only exist in orbits with no destructive interference!

Both the angular momentum and the energy are "quantized"

Quantum mechanics: wave-particle duality

Electrons are both waves and particles.

When detected, the electron appears to be a particle.

But the probability of finding the electron behaves like a wave.

Quantum mechanical view of the atom

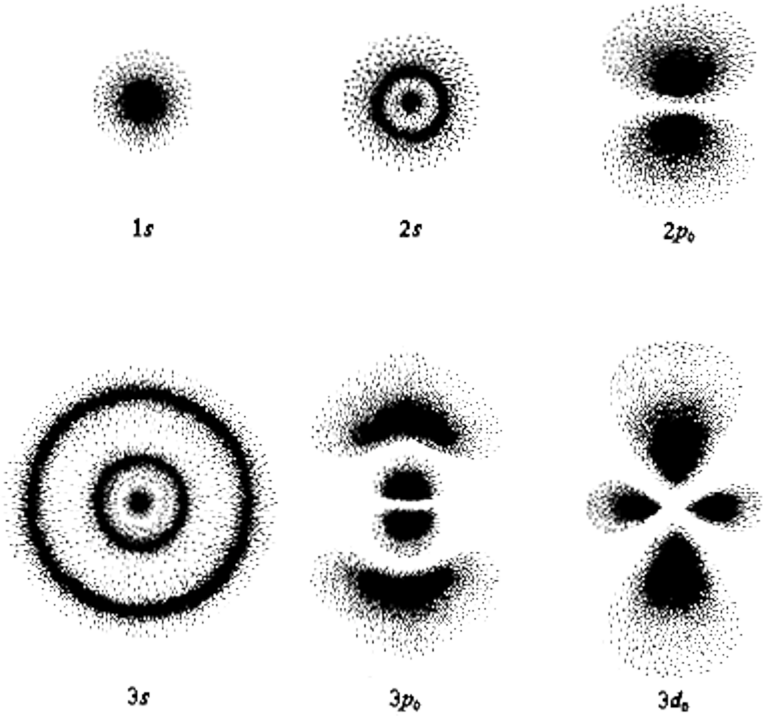


Figure 6-12. Probability density plots of some hydrogen atomic orbitals. The density of the dots represents the probability of finding the electron in that region.

© 1983 University Science Books; "Quantum Chemistry" by Donald A. McQuarrie

http://www.scot-canoe.org/touring/graphics/photocomp/2002/ripples.JPG

Young' s double slit experiment: demonstration of wave-like nature of light

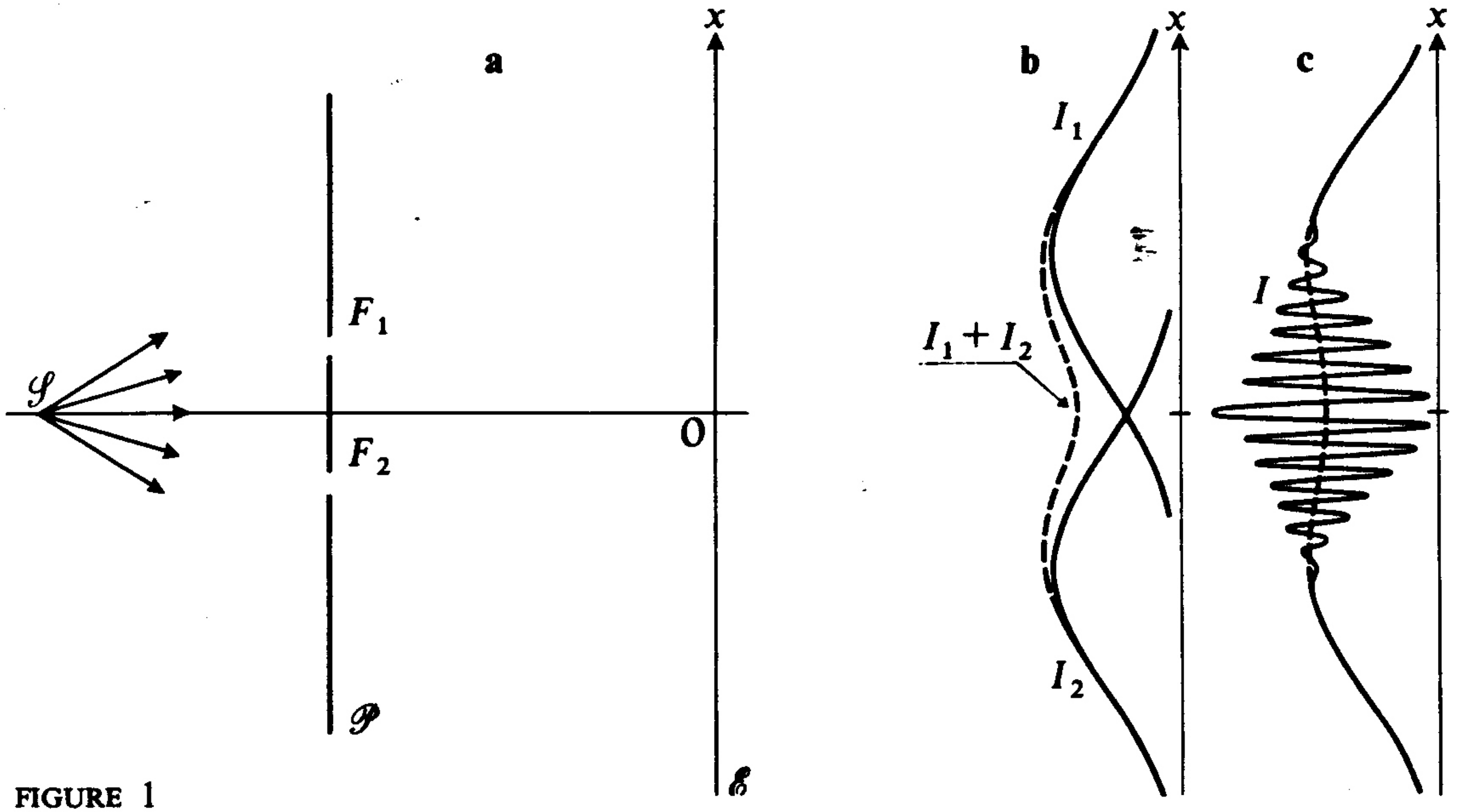


FIGURE 1

Diagram of Young's double-slit light interference experiment (fig. a). Each of the slits F_1 and F_2 produces a diffraction pattern on the screen $\mathcal{E}$. The corresponding intensities are $I_1(x)$ and $I_2(x)$ (solid lines in figure b). When the two slits F_1 and F_2 are open simultaneously, the intensity $I(x)$ observed on the screen is not the sum $I_1(x) + I_2(x)$ (dashed lines in figures b and c), but shows oscillations due to the interference between the electric fields radiated by F_1 and F_2 (solid line in figure c).

Double-slit experiment for electrons?

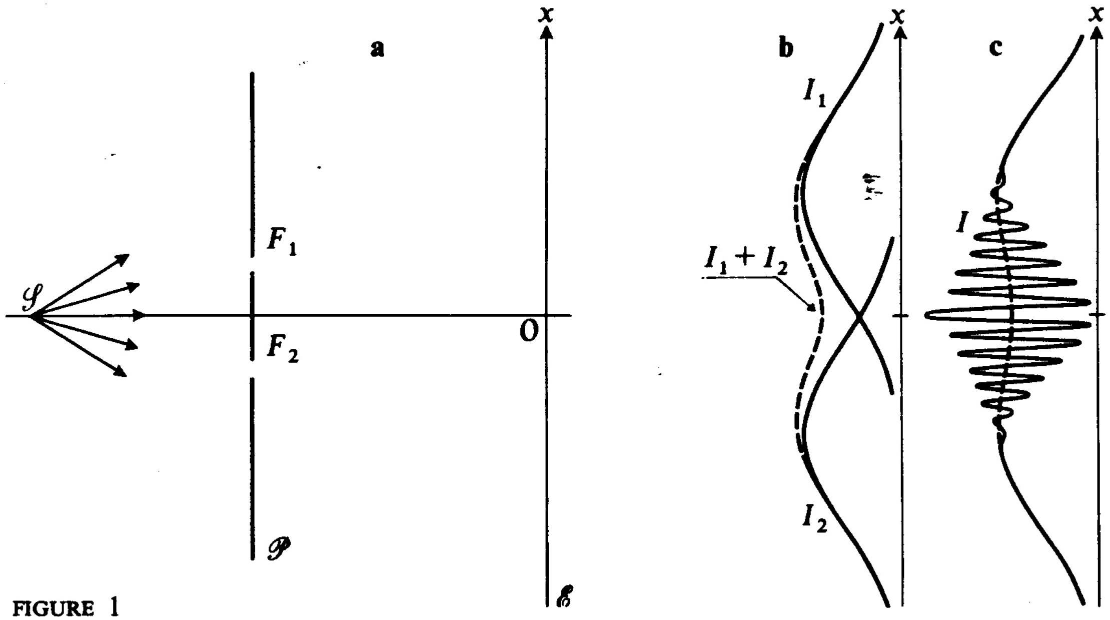


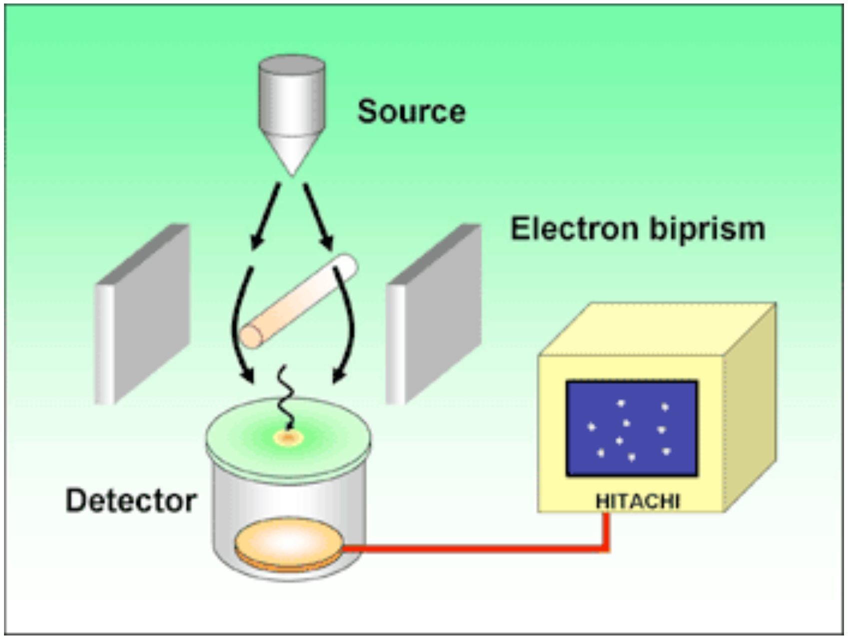
FIGURE 1

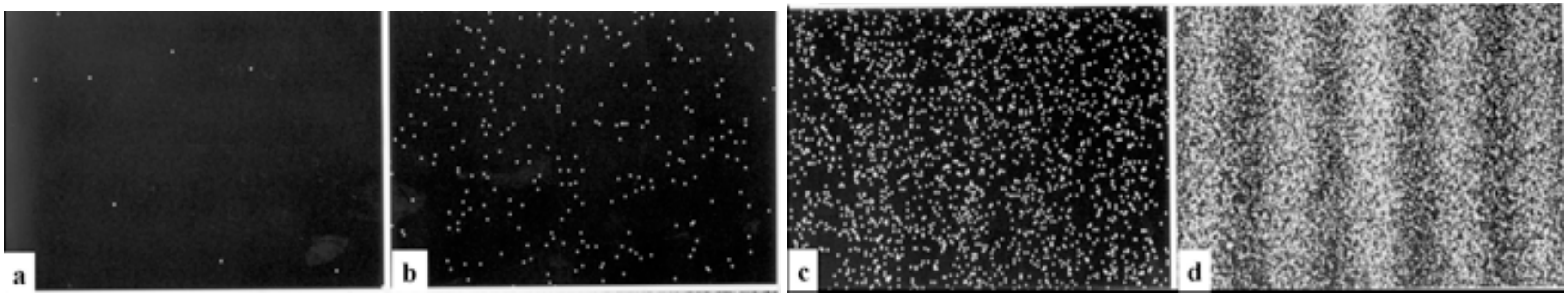
"We should say right away that you should not try to set up this experiment…The trouble is that the apparatus would have to be made on an impossibly small scale to show the effects we are interested in. We are doing a 'thought experiment,' which we have chosen because it is easy to think about."

--Feynman Lectures on Physics, 1961-1963
(Volume III, Section 1-4)

Möllenstedt-Düker electron biprism experiment

(Tonomura implementation)





Original experiments G Möllenstedt and H Düker 1955, 1956.

This data: http://www.hqrd.hitachi.co.jp/em/doubleslit.cfm, A. Tonomura, J. Endo. T. Matsuda, T. Kawasaki and H. Ezawa, "Demonstration of Single-Electron Buildup of an Interference Pattern" Amer. J. Phys. 57 (1989) 117-120.

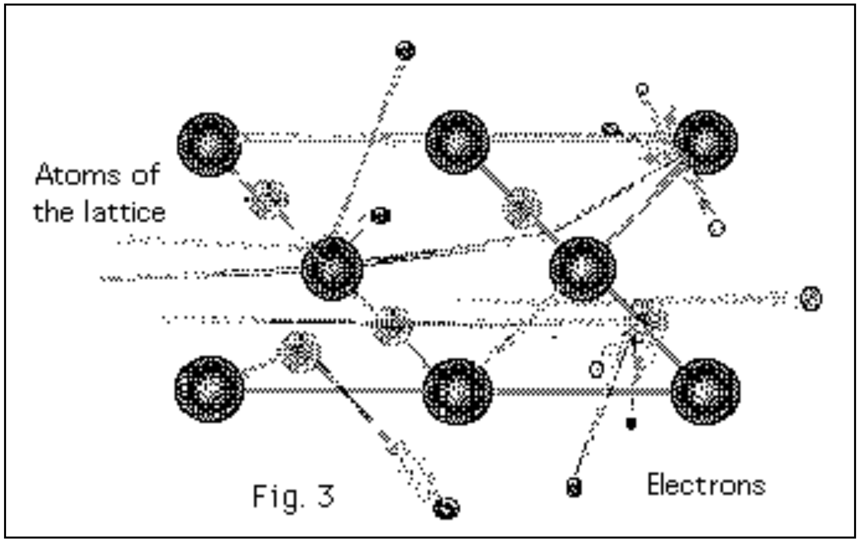
Why is wavelike electron behavior not obvious in every day metals and semiconductors?

Electrons typically have small wavelengths.

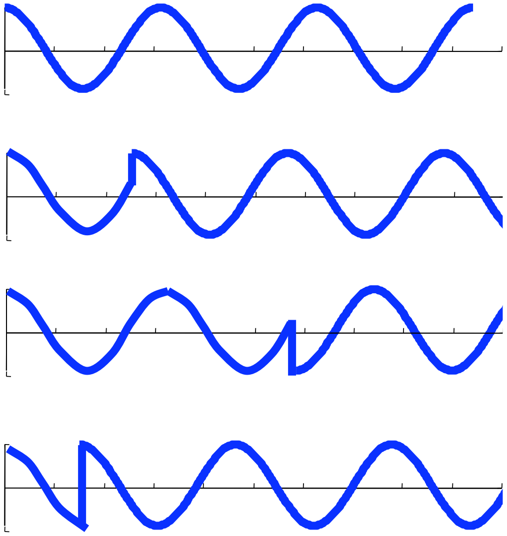
Electrons with different energies have different wavelengths.

Electrons lose phase coherence in various ways.

Artist's rendition of electrons colliding with lattice from Oak Ridge National Lab

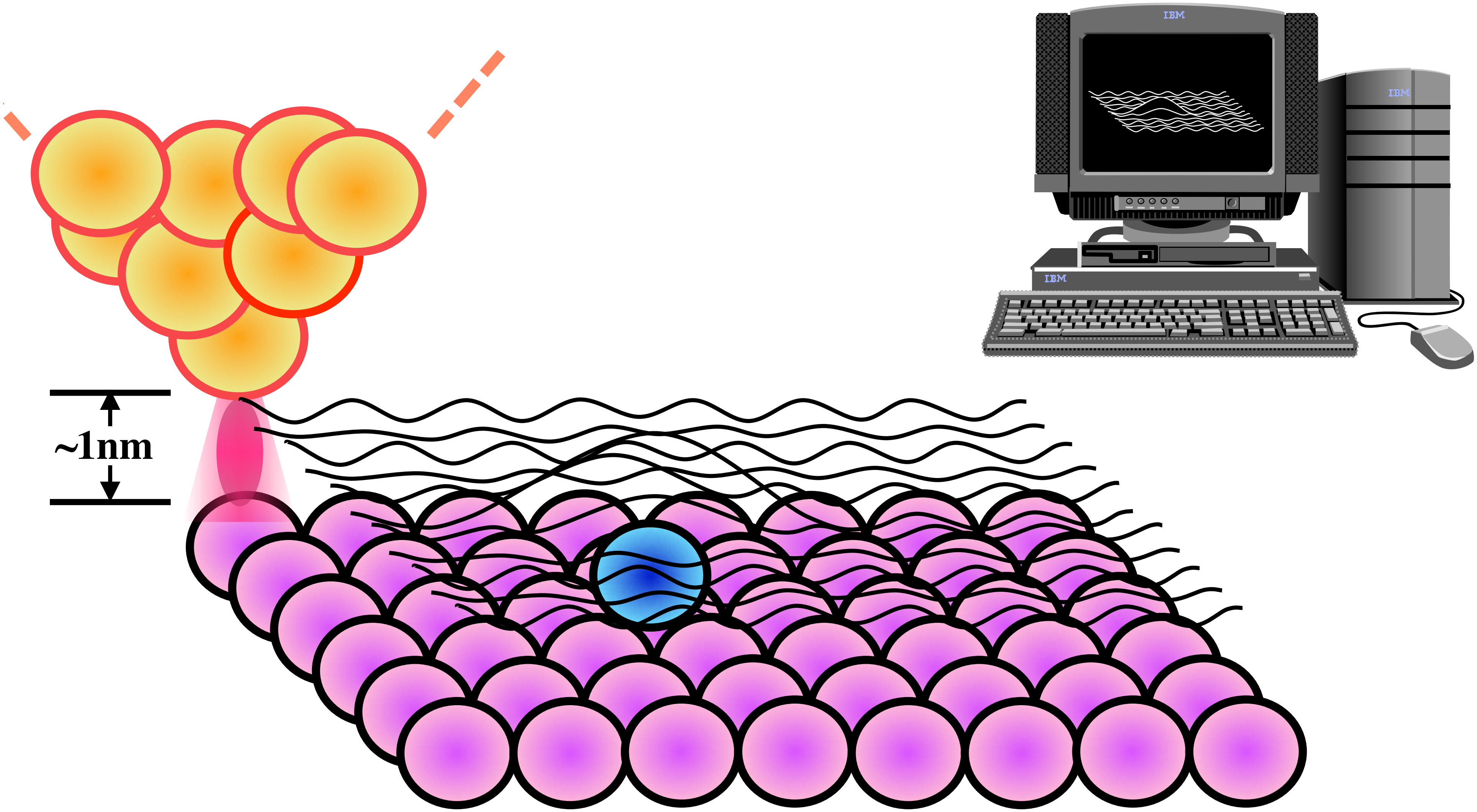


decoherence/dephasing

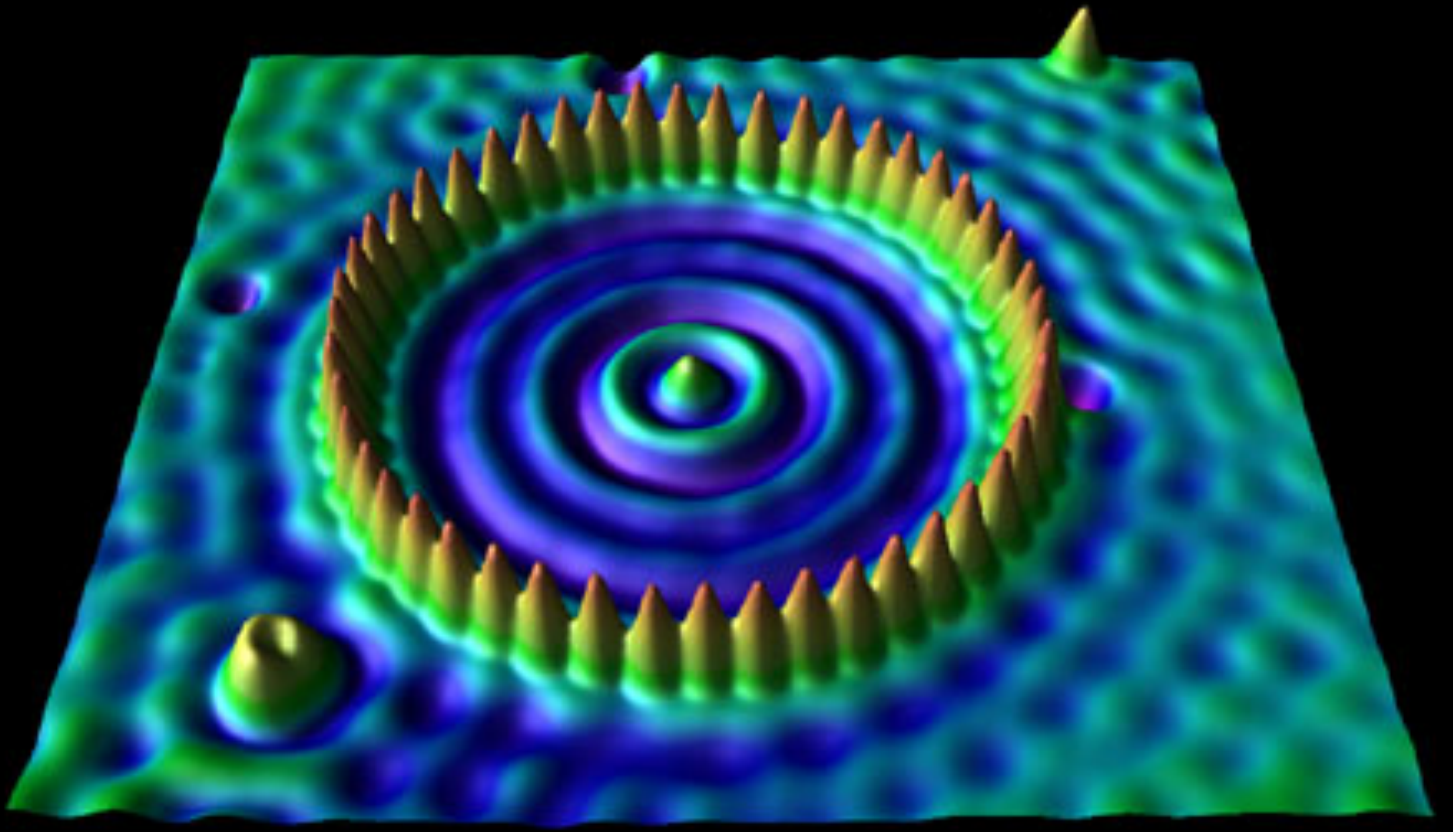


How can we see electron waves in real materials?

Scanning Probe Microscopy



Source: Don Eigler, Barbara Jones



“Fe on Cu(111)”
Crommie, Lutz, Eigler (1993)

Outline

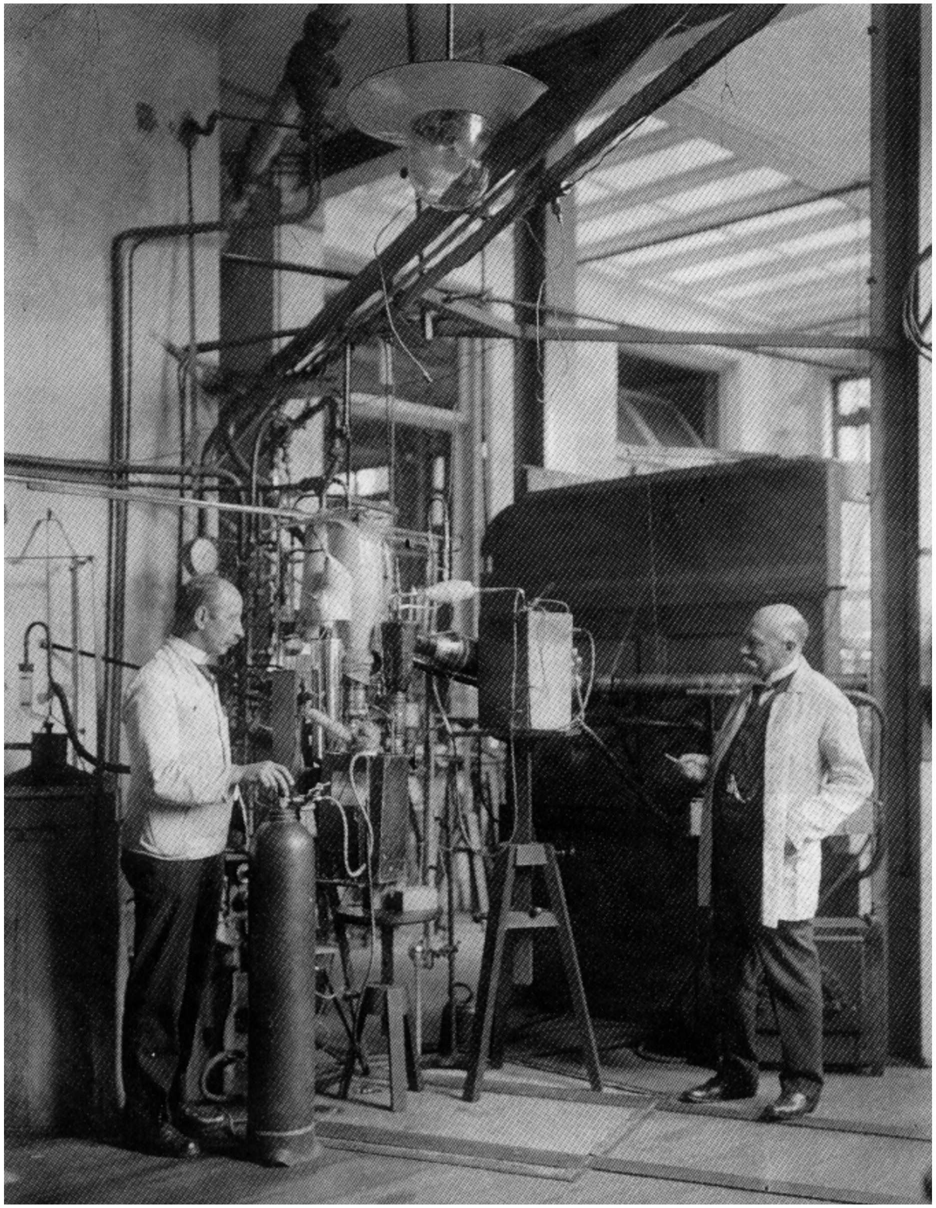
Introduction to Quantum Mechanics

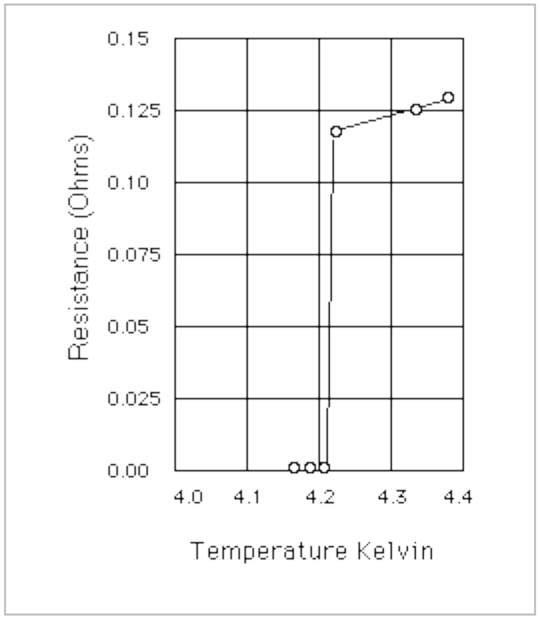
- *Wavelike electrons save the atom*
- *Show me a real wave!*
- *Why we don't usually experience wavelike/quantized behavior: Decoherence*
- *To see wavelike behavior in normal metals and semiconductors, we usually need to look at very small length scales (the nanoscale)*

Quantum Whirlpools

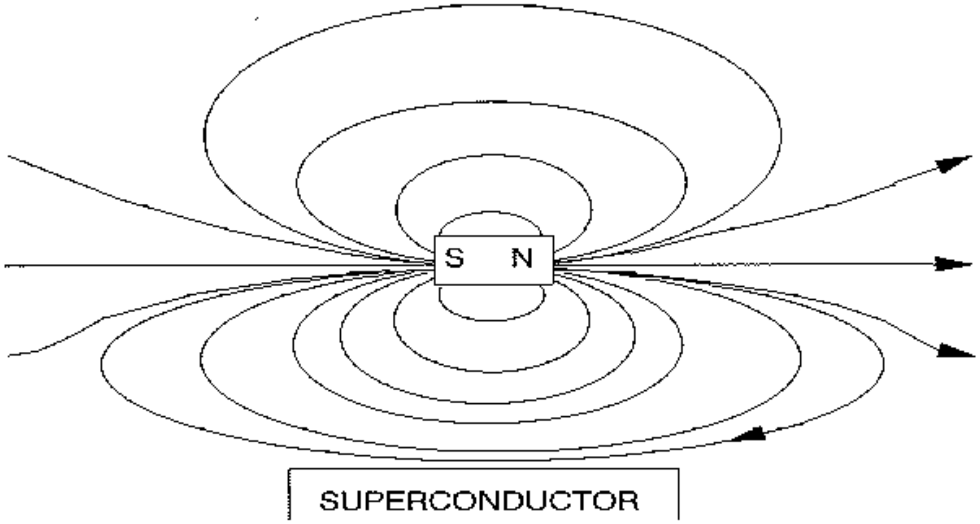
- *Superconductivity: A charged macroscopic quantum fluid*
- *Vortices in superconductors*

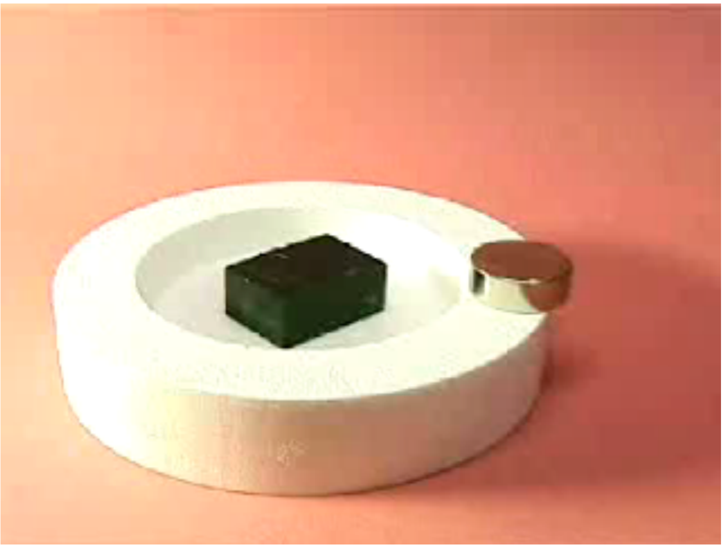
Discovery of Superconductivity 1911





Meissner Effect (1933) and Levitation



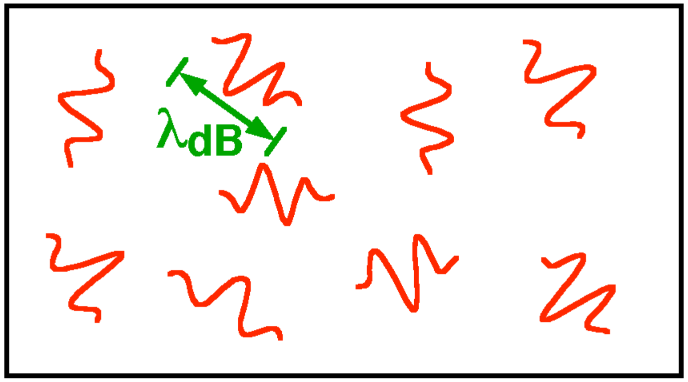


Note: complete analysis of levitation effect requires not only gravity and the Meissner effect, but also vortex pinning

Image at left:
http://www.ornl.gov/info/reports/m/ornlm3063r1/pt2.html
Movie at right:
Original source unknown to me, widely available on web

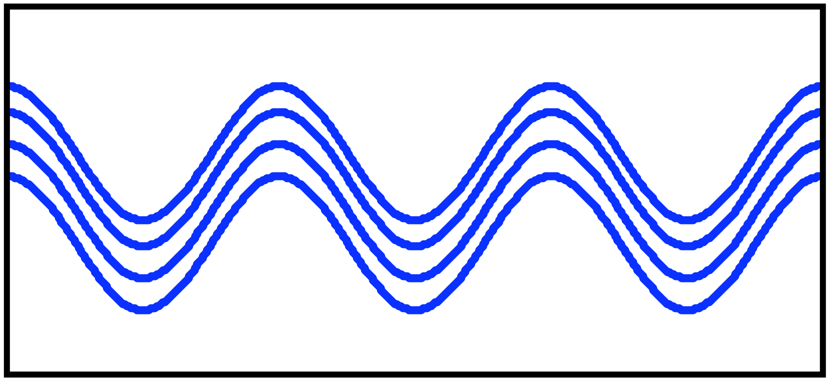
Superconductor = Macroscopic Quantum Superfluid that carries charge

Ordinary Gas or Fluid



particles move somewhat independently
many small waves
doesn’t look wavelike over large distances

Quantum “Superfluid”



particles “march in lockstep”
one big wave made of many particles
coherent, wavelike behavior over large distances

Superconductors are superfluids made of *charged* particles.

Aside: the phrase “macroscopic quantum” has multiple uses.
A “macroscopic quantum state” has long-range (macroscopic) coherence.
However, the phrase “macroscopic quantum coherence” is usually reserved for Schrödinger cat states.

Vortices

Vortices

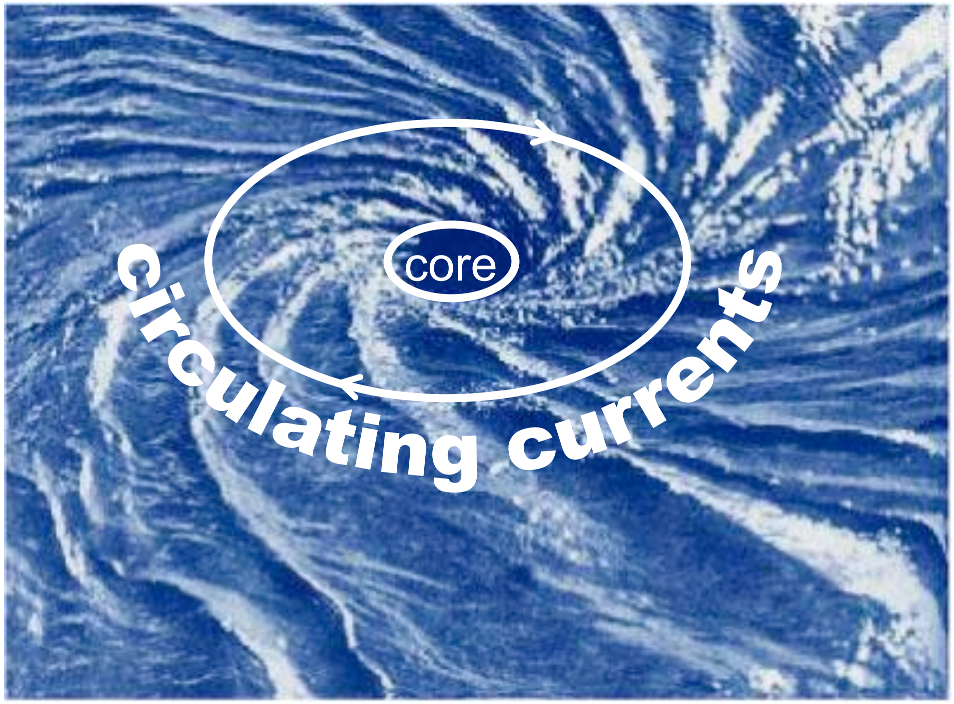
- cylindrical symmetry
- fluid swirling around a core

Vortices in Quantum Fluids

- persistent
- quantized

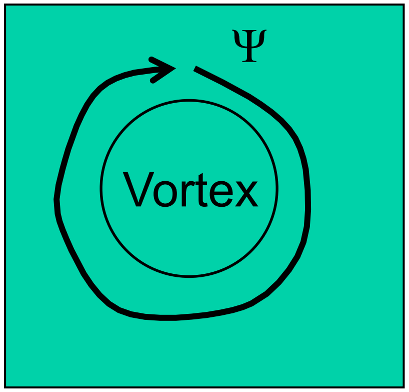
Vortices in Superconductors

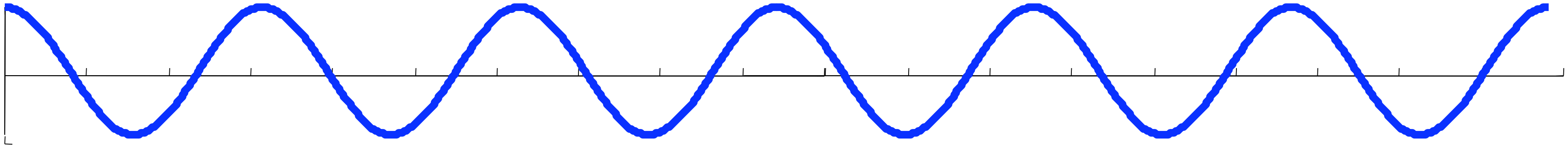
- generate a local magnetic field



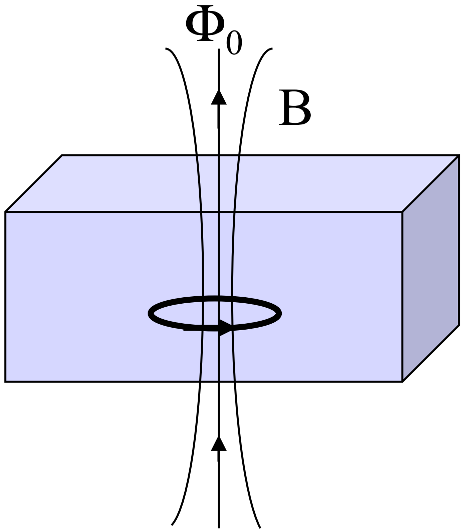
A Quantum Vortex Is *Quantized*

The “pseudowavefunction” is a wave. If you imagine wrapping it around the vortex core, the phase can only change by multiples of 2π





In the lowest energy configuration, it changes by exactly 2π



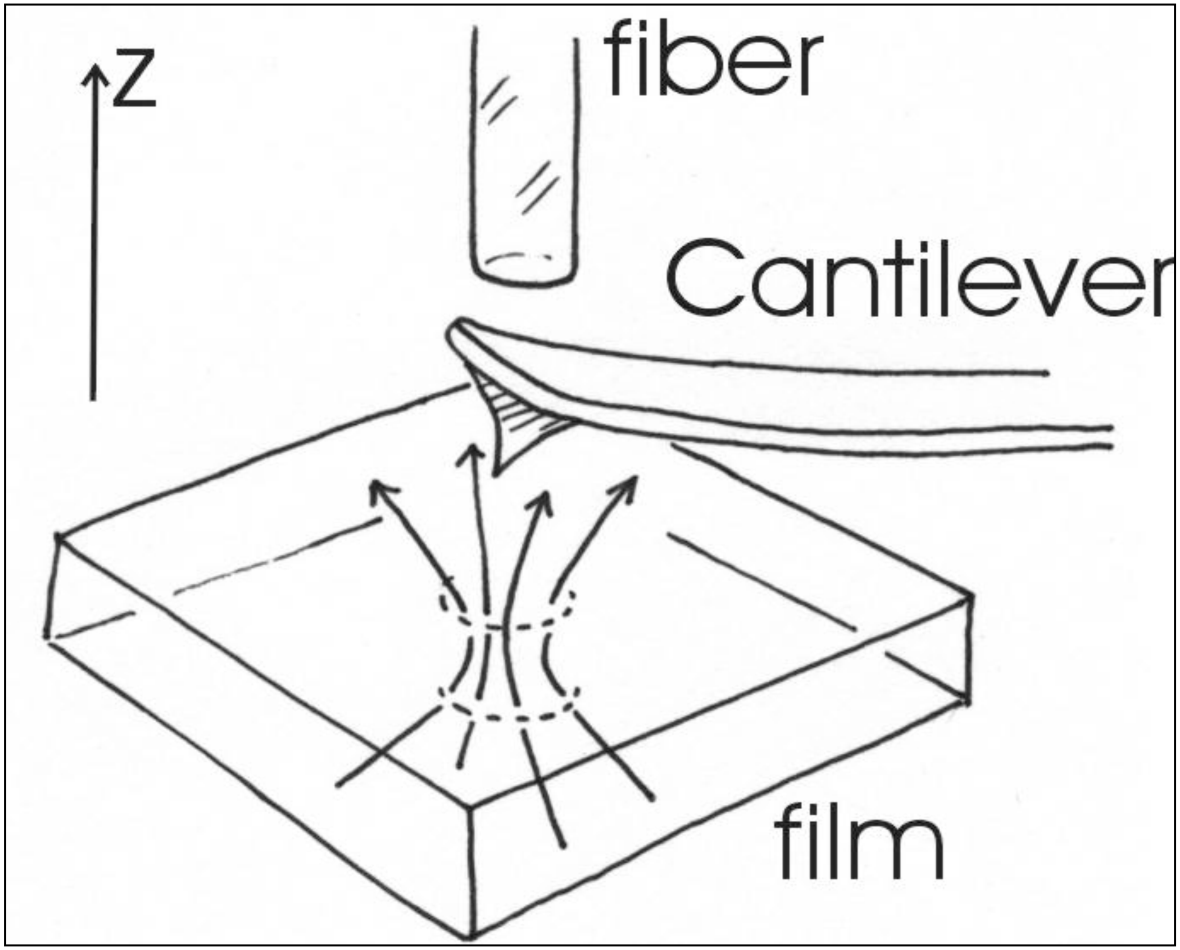
This leads to the quantization of magnetic flux:

$$\Phi = \int \vec{B} \cdot d\vec{a} = n\Phi_0$$

Where n is an integer
and the superconducting flux quantum

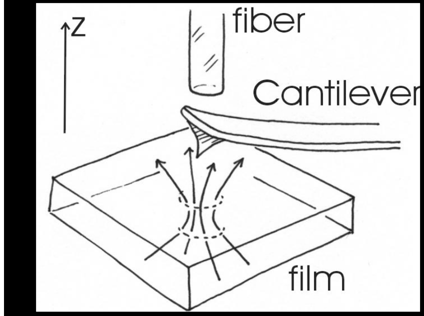
$$\Phi_0 = hc/2e = 20.7 \text{ Gauss } \mu m^2$$

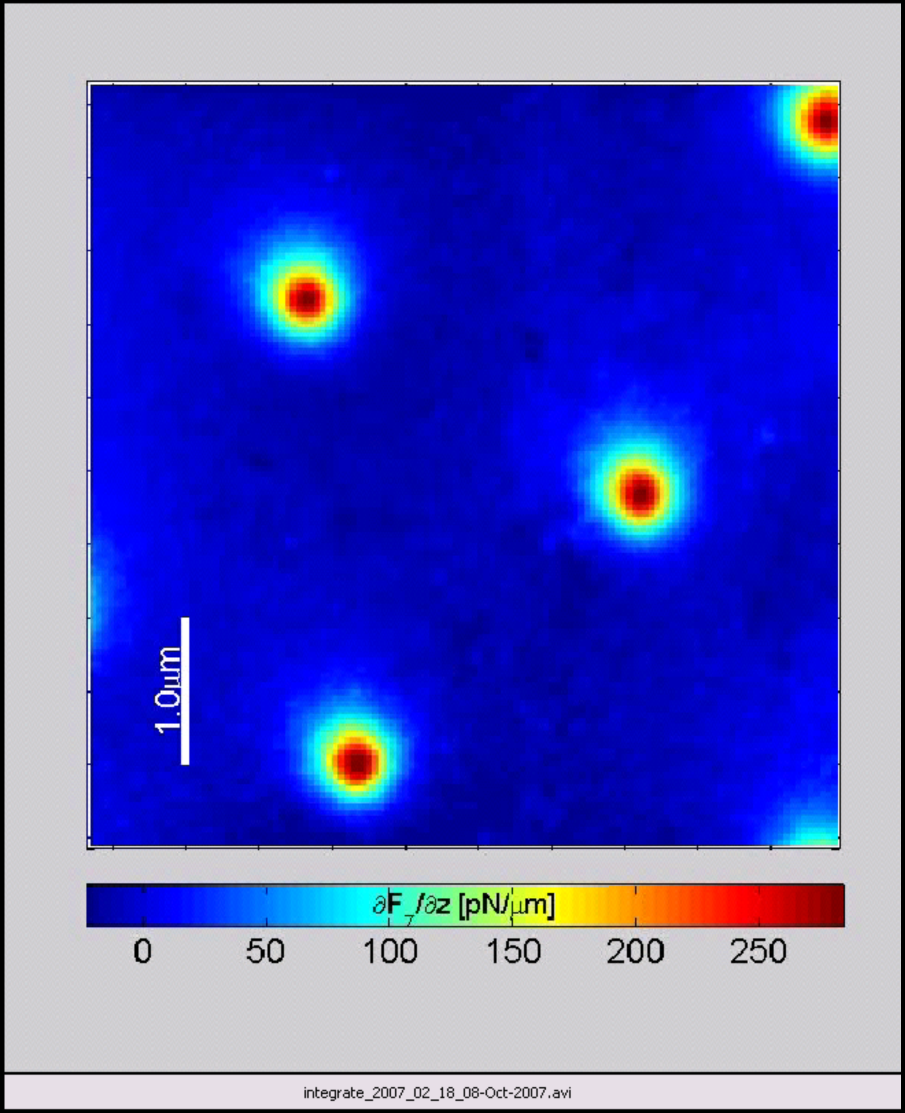
“Seeing” vortices with Magnetic Force Microscopy



Other ways to see vortices: Bitter decoration, scanning tunneling microscopy, magneto-optics, Hall probe microscopy, SQUID microscopy.

Experimental Data:
Images of Vortices in Superconducting $YBa_2Cu_3O_{6.99}$





Why do we care about vortices in superconductors?

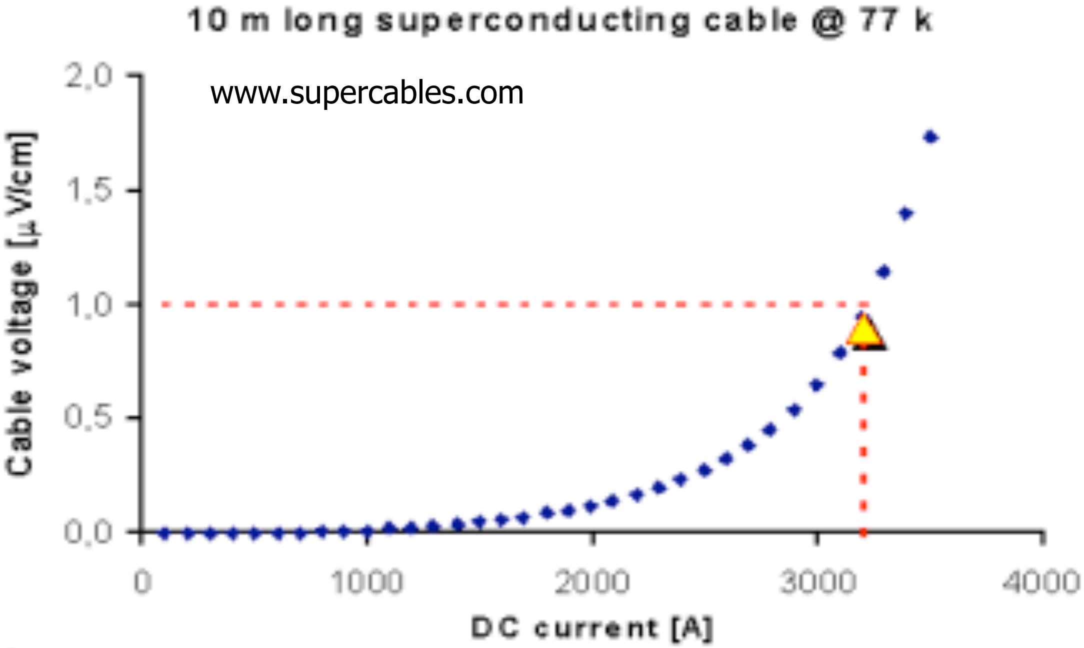
1) Fundamental interest

2) Superconducting technology

Large classical vortices in air cause undesirable dissipation.

Nanoscale quantum vortices in superconductors cause undesirable dissipation too.

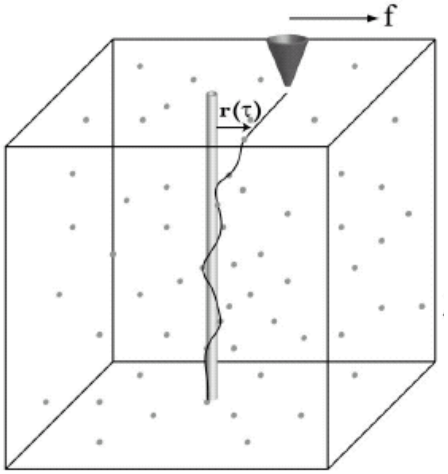
Currents make the vortices flow and destroy the perfect conductivity that makes superconductors so useful.

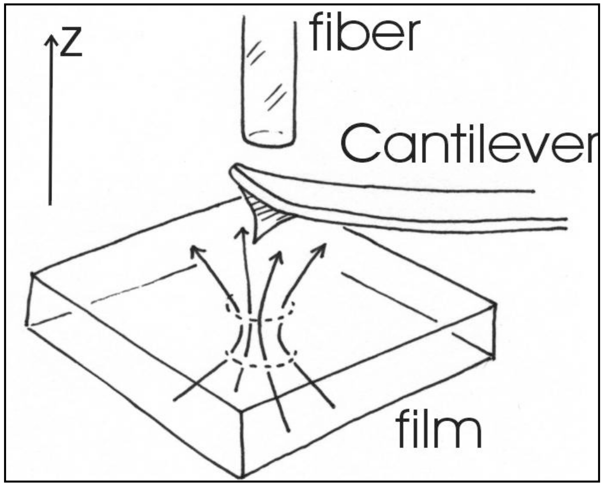


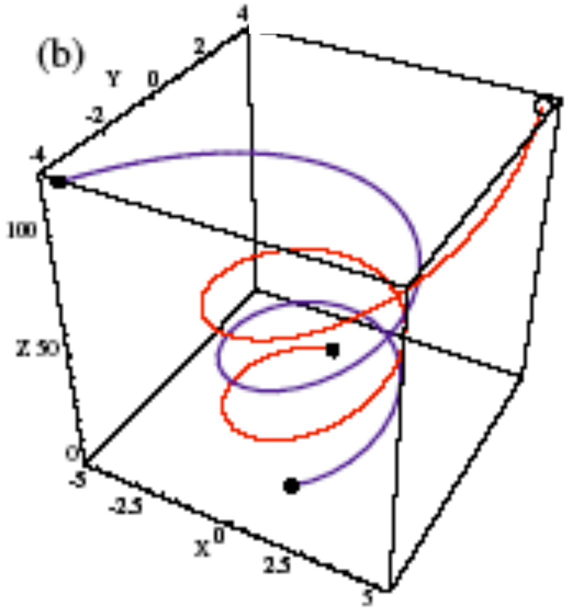
Single-vortex manipulation

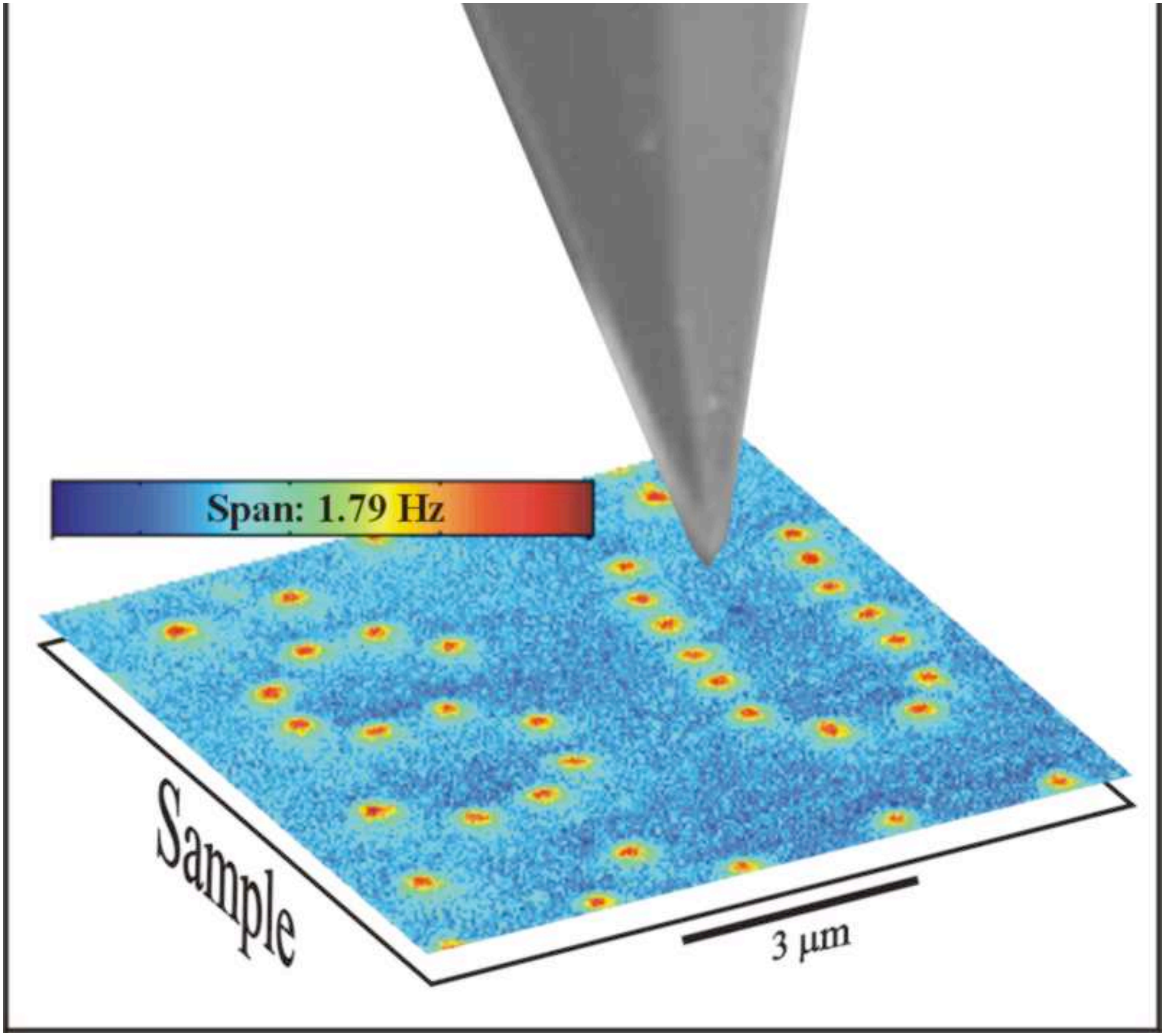
To address questions such as:

- How do vortices interact with the crystal lattice and its defects?
- How do vortices tilt?
- Do vortices entangle?



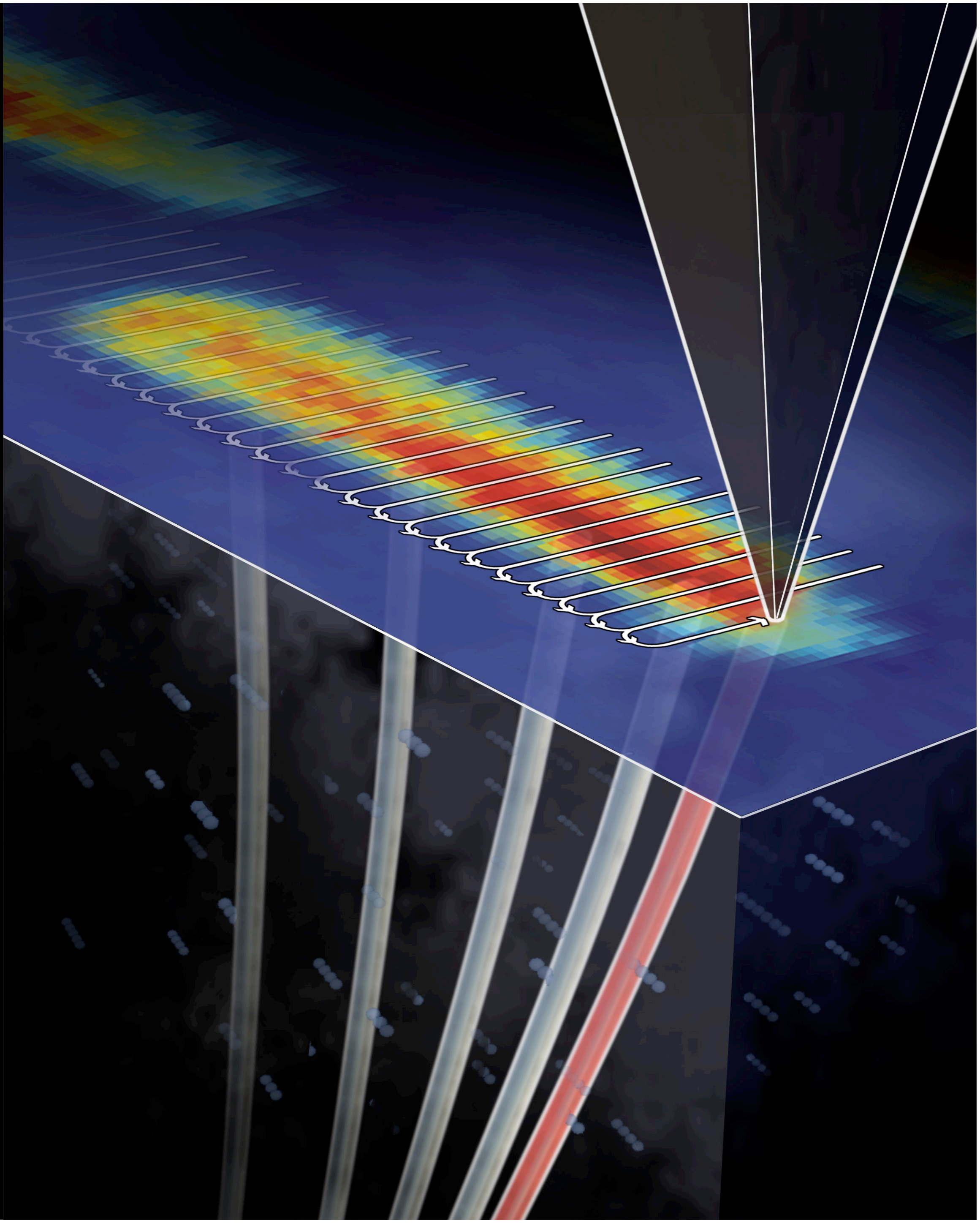






Dragging quantum vortices in niobium thin films:
Motion detected/controlled to better than 10 nm

Dragging quantum vortices in superconducting YBCO:
The vortex acts like a string moving through a landscape of defects that pin it.



Credits

Images

Todd's Quantum Intro Web Page
IBM (Dr. Don Eigler)
Scottish Canoe Association
Oak Ridge National Laboratory
Edubuzz.org
Clifford Hicks
David Pritchard
Zlatko Tesanovic
Superconductor Lab Oslo

Vortex Coworkers

Ophir Auslaener
Lan Luan
Jenny Hoffman
Eric Straver
Ruixiang Liang
Walter Hardy
Doug Bonn
John Kirtley
Martin Huber

Funding

DOE BES
AFOSR
NSF
IBSF

K-12 Nano Education

Download Hands-on Nano Activities from the Stanford Center for Probing the Nanoscale:

- http://teachers.stanford.edu/activities/

Summer Institute for Middle School Teachers at the Stanford CPN:

- http://www.stanford.edu/group/cpn/education/

Explore Nano further at http://teachers.stanford.edu/links/

- Nano Games (Activities from University at Albany)
- NanoSense (Activities)
- NISEnetwork (Activities, media)
- nanoHUB (Presentations, media)
- NanoKids (Activites, presentations from RICE University)
- Resource Area For Teachers (hands-on activities and supplies)

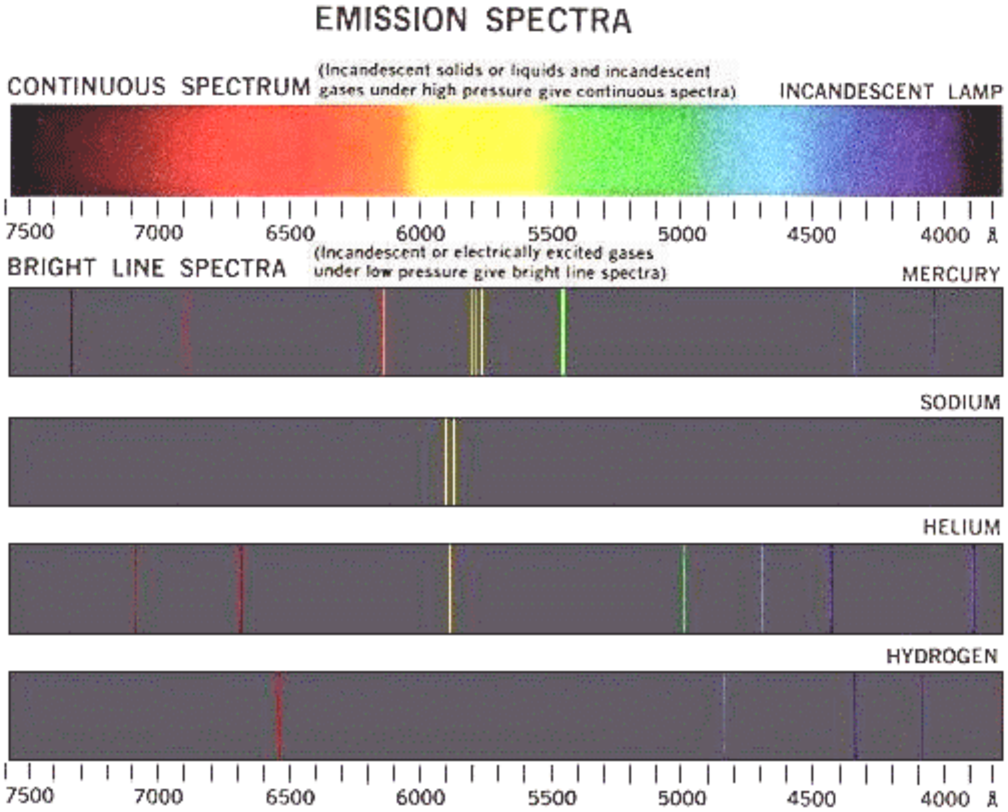
for more info, contact

kmoler@stanford.edu or Tobi Beetz, tobi@stanford.edu

CPN

Extra Slides

Quantized atomic orbitals



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continuous spectrum
of visible light

mercury (quantized)

sodium (quantized)

helium (quantized)

hydrogen (quantized)

Quantum mechanics: wave-particle duality

Quantum mechanical view of the atom

Classical view of the atom

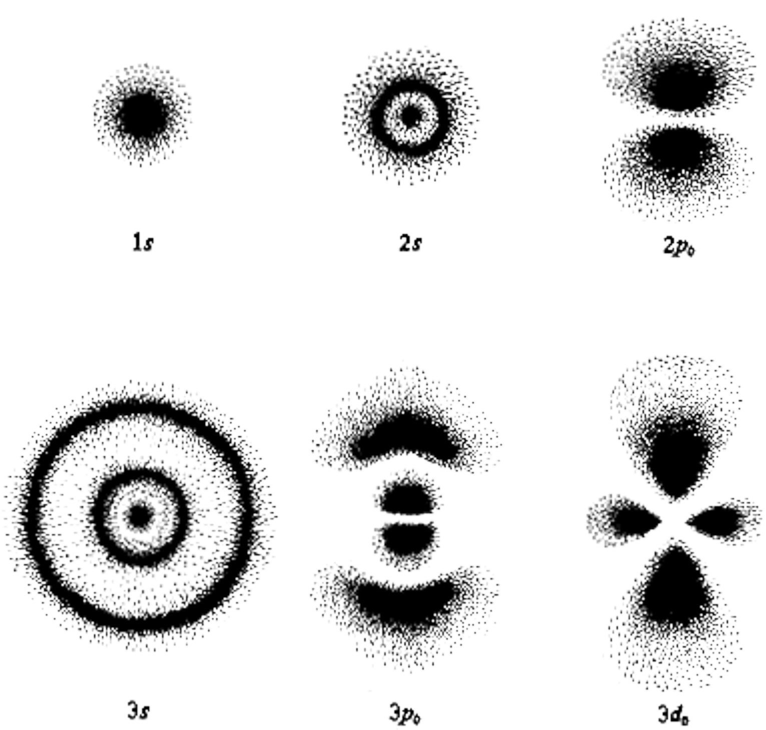

Figure 6-12. Probability density plots of some hydrogen atomic orbitals. The density of the dots represents the probability of finding the electron in that region.

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Quantum mechanics: wave-particle duality

Quantum mechanical view of the atom

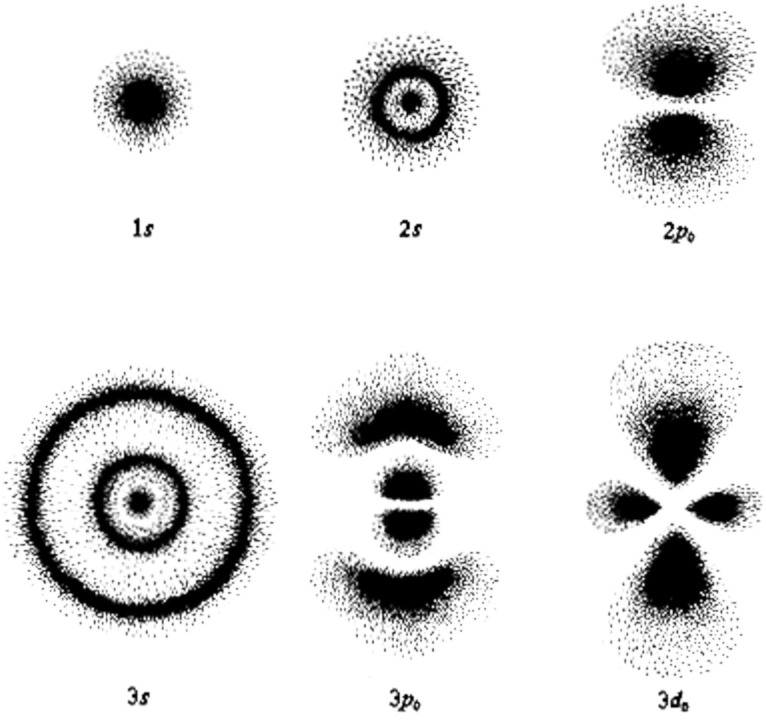

Figure 6-12. Probability density plots of some hydrogen atomic orbitals. The density of the dots represents the probability of finding the electron in that region.

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Schrödinger's Equation

$$i\hbar\frac{\partial}{\partial t}\psi\left(\vec{r},t\right)=\frac{\hbar^2}{2m}\nabla^2\psi\left(\vec{r},t\right)+V\left(\vec{r},t\right)\psi\left(\vec{r},t\right)$$

i is the imaginary number, $\sqrt{-1}$
$\hbar$ is Planck's constant (divided by 2π)
m is the mass of the particle
∇^2 is the Laplacian operator,

$$\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$$

$V\left(\vec{r},t\right)$ is the external potential

$\psi\left(\vec{r},t\right)$ is the wave function

Quantum mechanics: wave-particle duality

The wave function

$$\psi(r,t)$$

$$\boxed{|\psi|^2 \sim probability}$$

Quantum mechanical view of the atom

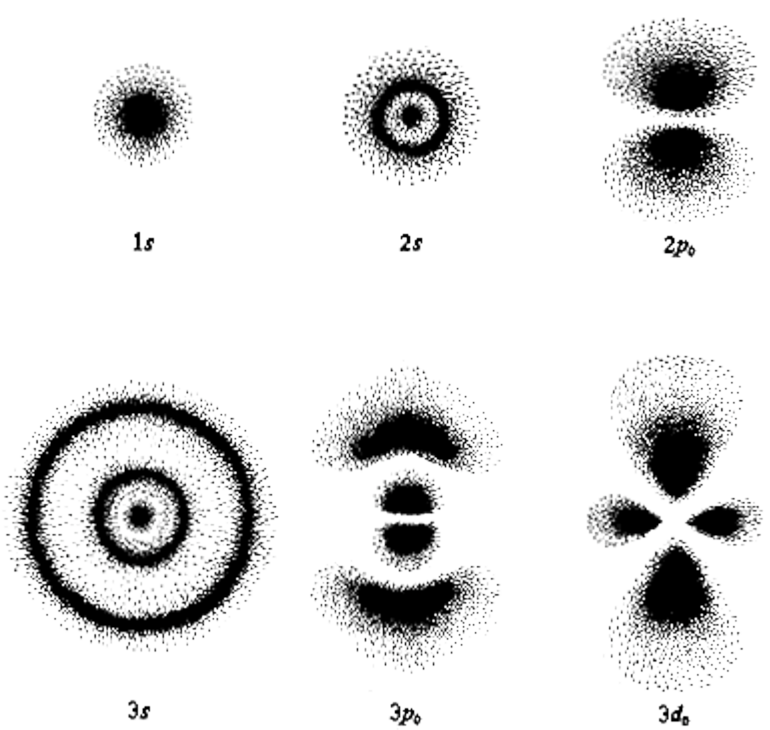

Figure 6-12. Probability density plots of some hydrogen atomic orbitals. The density of the dots represents the probability of finding the electron in that region.

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Macroscopic Metaphor: “Drafting”

BCS Theory of Superconductivity 1957

phonon-mediated electron-electron interaction

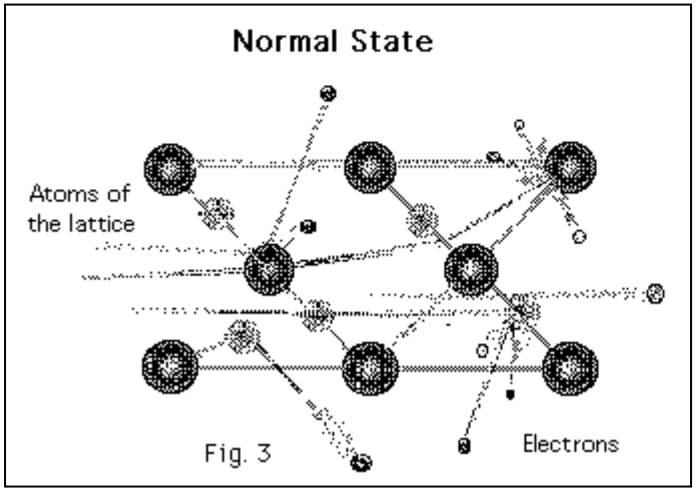
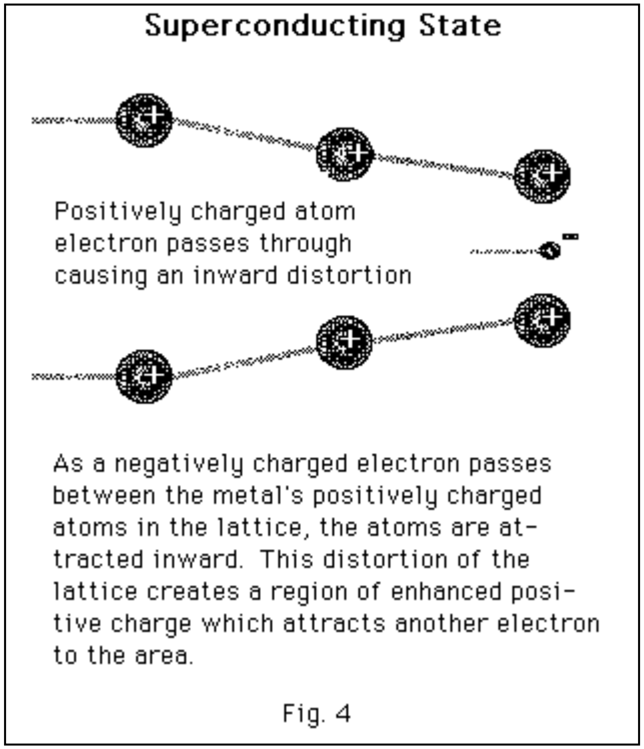


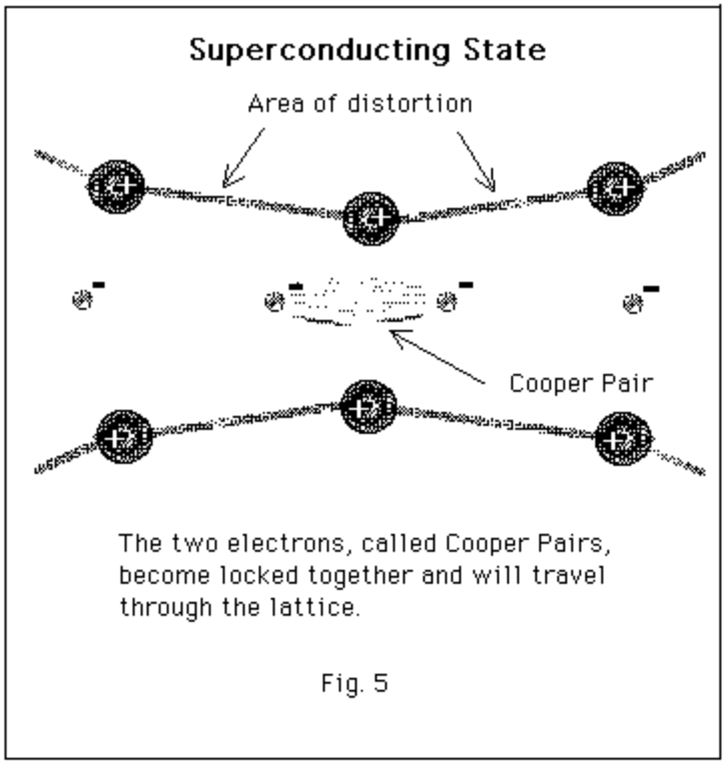
Fig. 3



Positively charged atom electron passes through causing an inward distortion

As a negatively charged electron passes between the metal's positively charged atoms in the lattice, the atoms are attracted inward. This distortion of the lattice creates a region of enhanced positive charge which attracts another electron to the area.

Fig. 4



The two electrons, called Cooper Pairs, become locked together and will travel through the lattice.

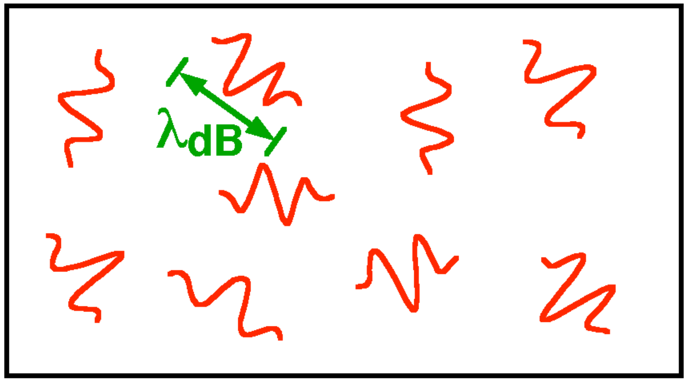
Fig. 5

Image credit: Oak Ridge National Lab

Like toddlers pair on the Galilee,
Electrons pair on a Fermi sea,
Superconductivity.

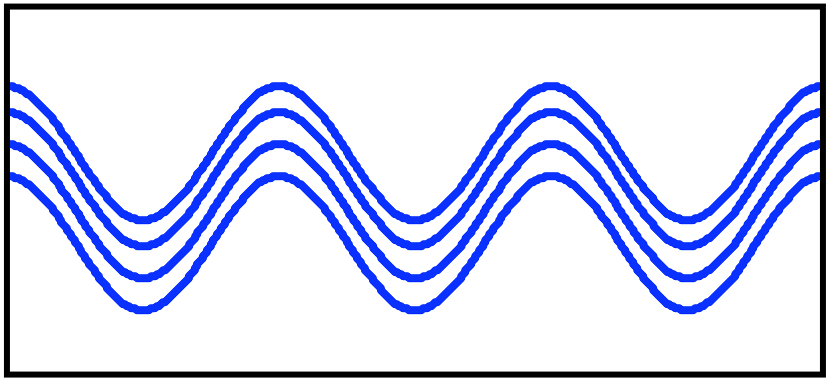
Macroscopic Quantum Fluids

Ordinary Gas or Fluid



particles move somewhat independently
many small waves
doesn’t look wavelike over large distances

Quantum “Superfluid”



particles “march in lockstep”
one big wave made of many particles
coherent, wavelike behavior over large distances

Superconductors are superfluids made of *charged* particles.

Aside: the phrase “macroscopic quantum” has multiple uses.
A “macroscopic quantum state” has long-range (macroscopic) coherence.
However, the phrase “macroscopic quantum coherence” is usually reserved for Schrödinger cat states.

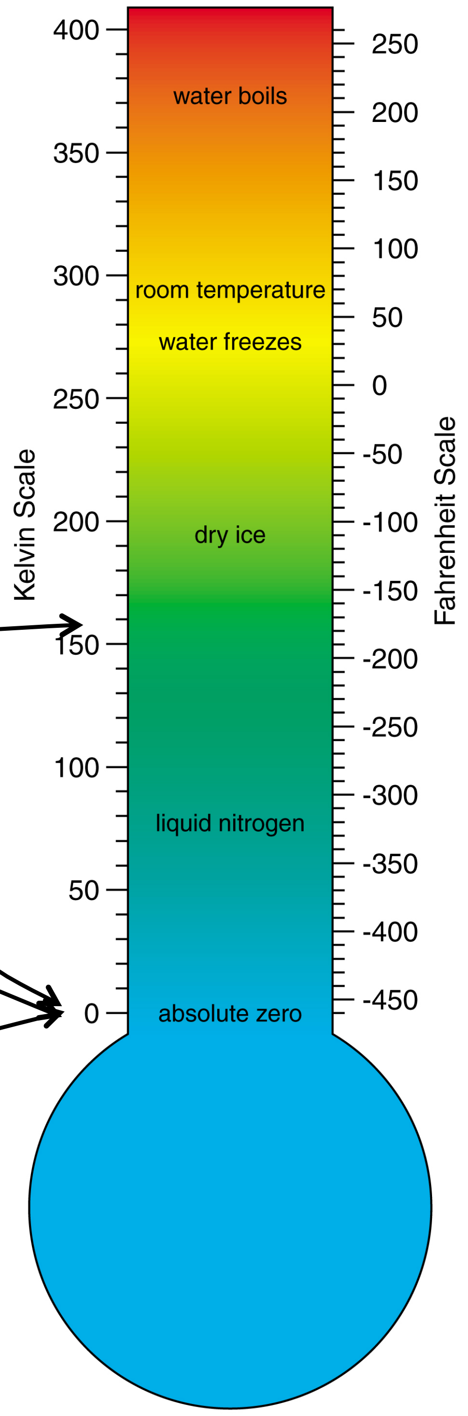
Temperature

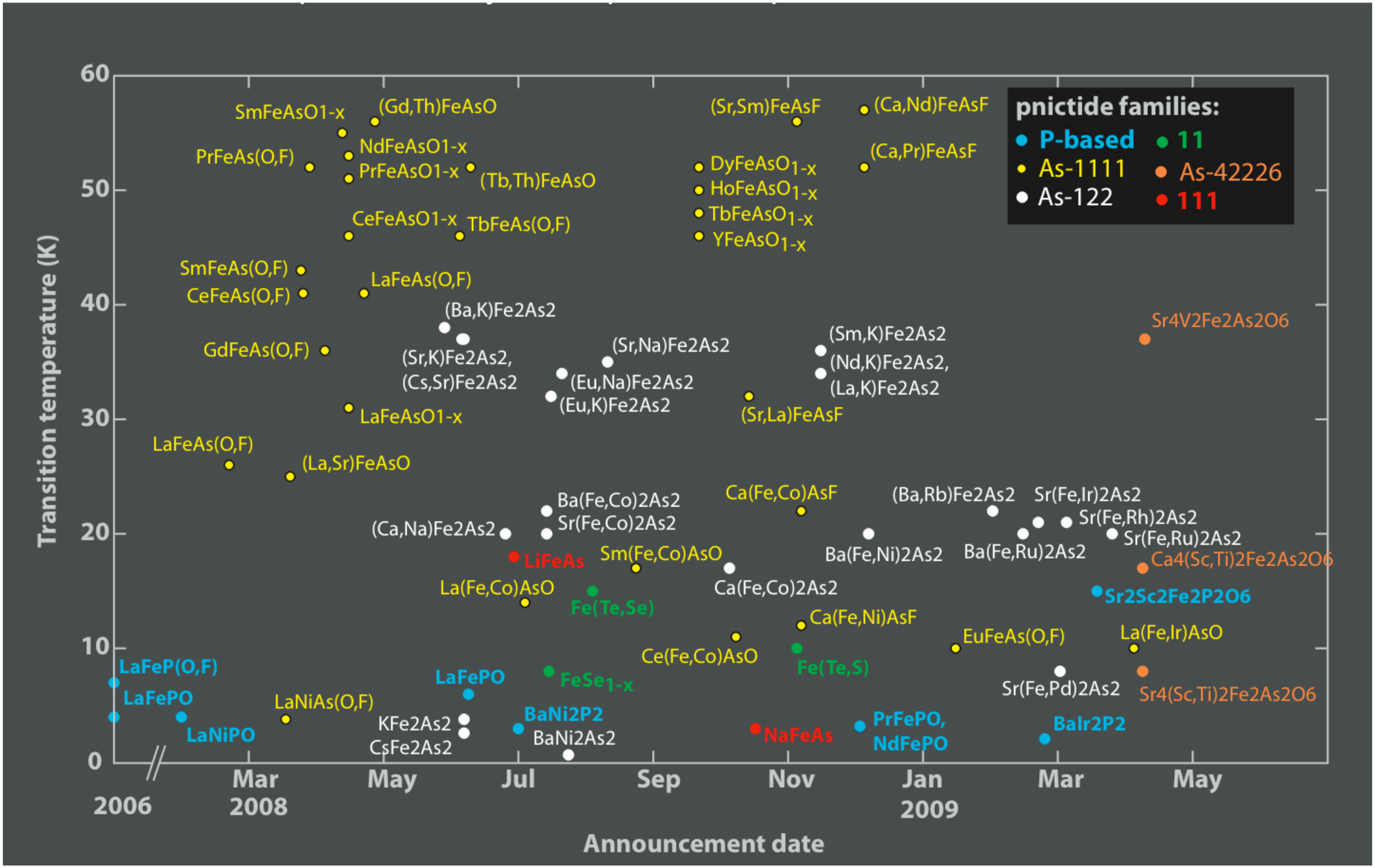
160 Kelvin
highest (known) temperature
superconductors
(excluding USO's)

2.2 Kelvin
superfluid He-4

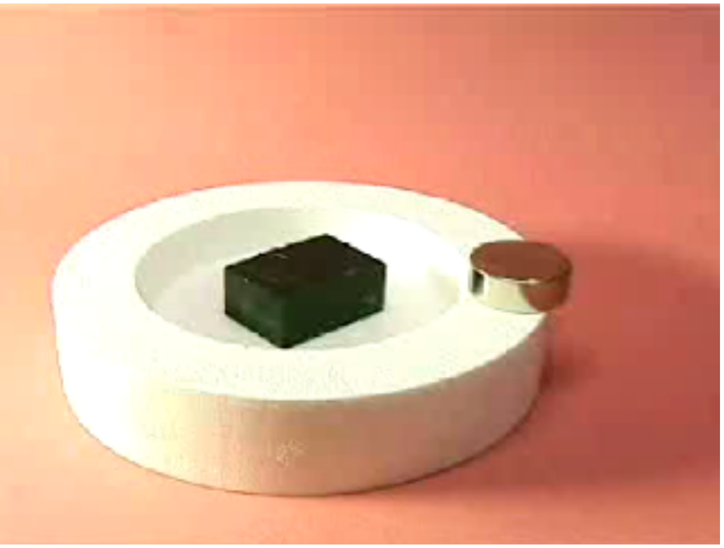
2 milliKelvin
superfluid He-3

sub-microKelvin
atomic Bose-Einstein
condensates



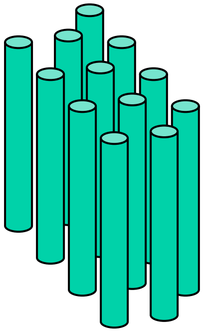

pnictide families:
● P-based
● 11
● As-1111
● As-42226
● As-122
● 111
Transition temperature (K)
60
50
40
30
20
10
0
Announcement date
2006
Mar
2008
May
Jul
Sep
Nov
Jan
2009
Mar
May
SmFeAsO1-x
(Gd,Th)FeAsO
PrFeAs(O,F)
NdFeAsO1-x
PrFeAsO1-x
(Tb,Th)FeAsO
CeFeAsO1-x
TbFeAs(O,F)
SmFeAs(O,F)
CeFeAs(O,F)
LaFeAs(O,F)
GdFeAs(O,F)
(Ba,K)Fe2As2
(Sr,K)Fe2As2,
(Cs,Sr)Fe2As2
LaFeAsO1-x
LaFeAs(O,F)
(La,Sr)FeAsO
(Sr,Sm)FeAsF
(Ca,Nd)FeAsF
DyFeAsO1-x
HoFeAsO1-x
TbFeAsO1-x
YFeAsO1-x
(Ca,Pr)FeAsF
(Sr,Na)Fe2As2
(Eu,Na)Fe2As2
(Eu,K)Fe2As2
(Sm,K)Fe2As2
(Nd,K)Fe2As2,
(La,K)Fe2As2
(Sr,La)FeAsF
Sr4V2Fe2As2O6
(Ca,Na)Fe2As2
Ba(Fe,Co)2As2
Sr(Fe,Co)2As2
Ca(Fe,Co)AsF
(Ba,Rb)Fe2As2
Sr(Fe,Ir)2As2
Sr(Fe,Rh)2As2
Sr(Fe,Ru)2As2
Ba(Fe,Ni)2As2
Ba(Fe,Ru)2As2
Ca4(Sc,Ti)2Fe2As2O6
LiFeAs
Sm(Fe,Co)AsO
Ca(Fe,Co)2As2
La(Fe,Co)AsO
Fe(Te,Se)
Sr2Sc2Fe2P2O6
Ca(Fe,Ni)AsF
EuFeAs(O,F)
La(Fe,Ir)AsO
Ce(Fe,Co)AsO
Fe(Te,S)
LaFeP(O,F)
LaFePO
LaFePO
FeSe1-x
Sr(Fe,Pd)2As2
Sr4(Sc,Ti)2Fe2As2O6
LaNiAs(O,F)
KFe2As2
CsFe2As2
BaNi2P2
BaNi2As2
NaFeAs
PrFePO,
NdFePO
BaIr2P2
LaNiPO

Levitation

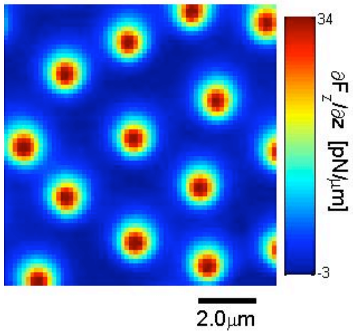


Visualization

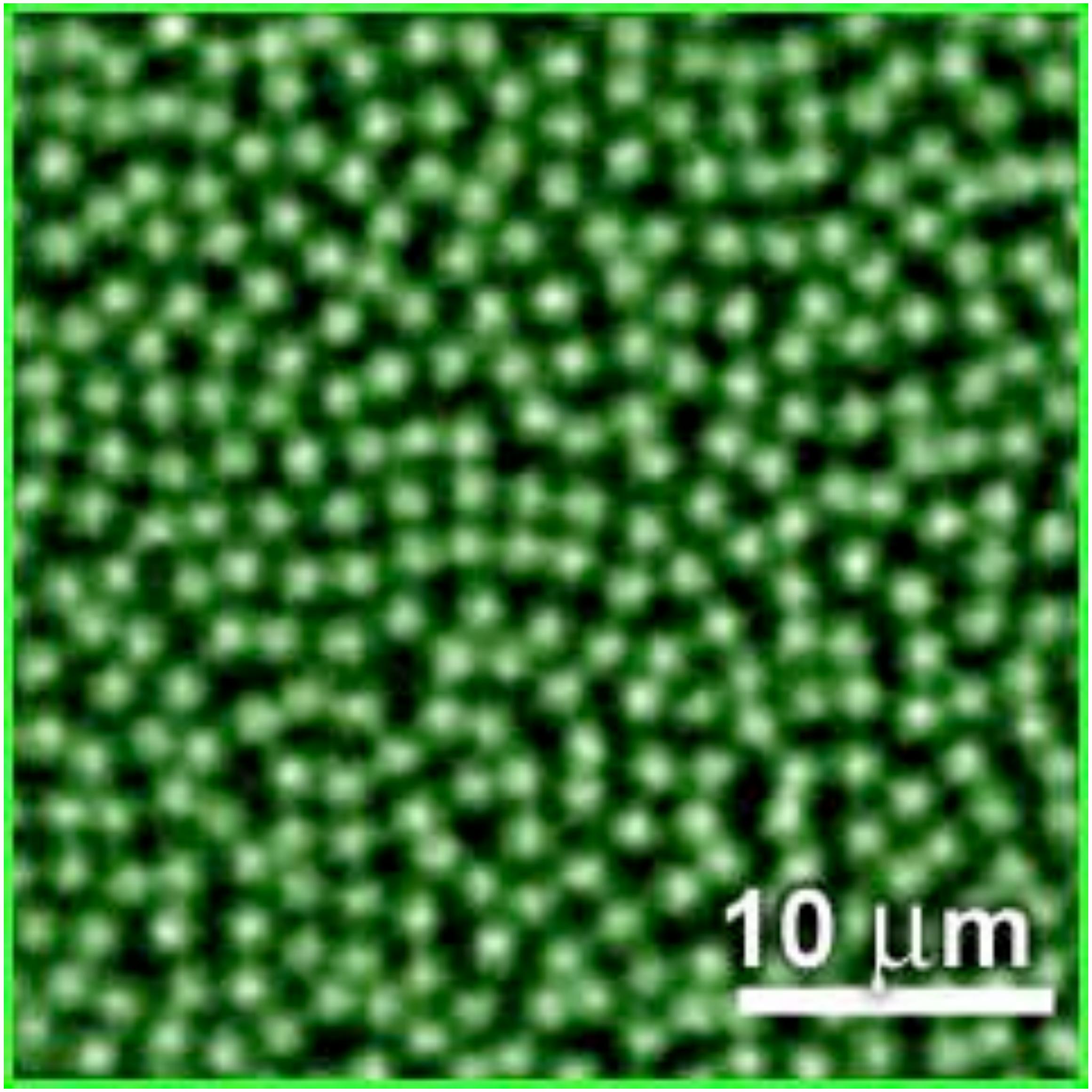
Vortices, each carrying 1 magnetic flux quantum, penetrate the superconductor.

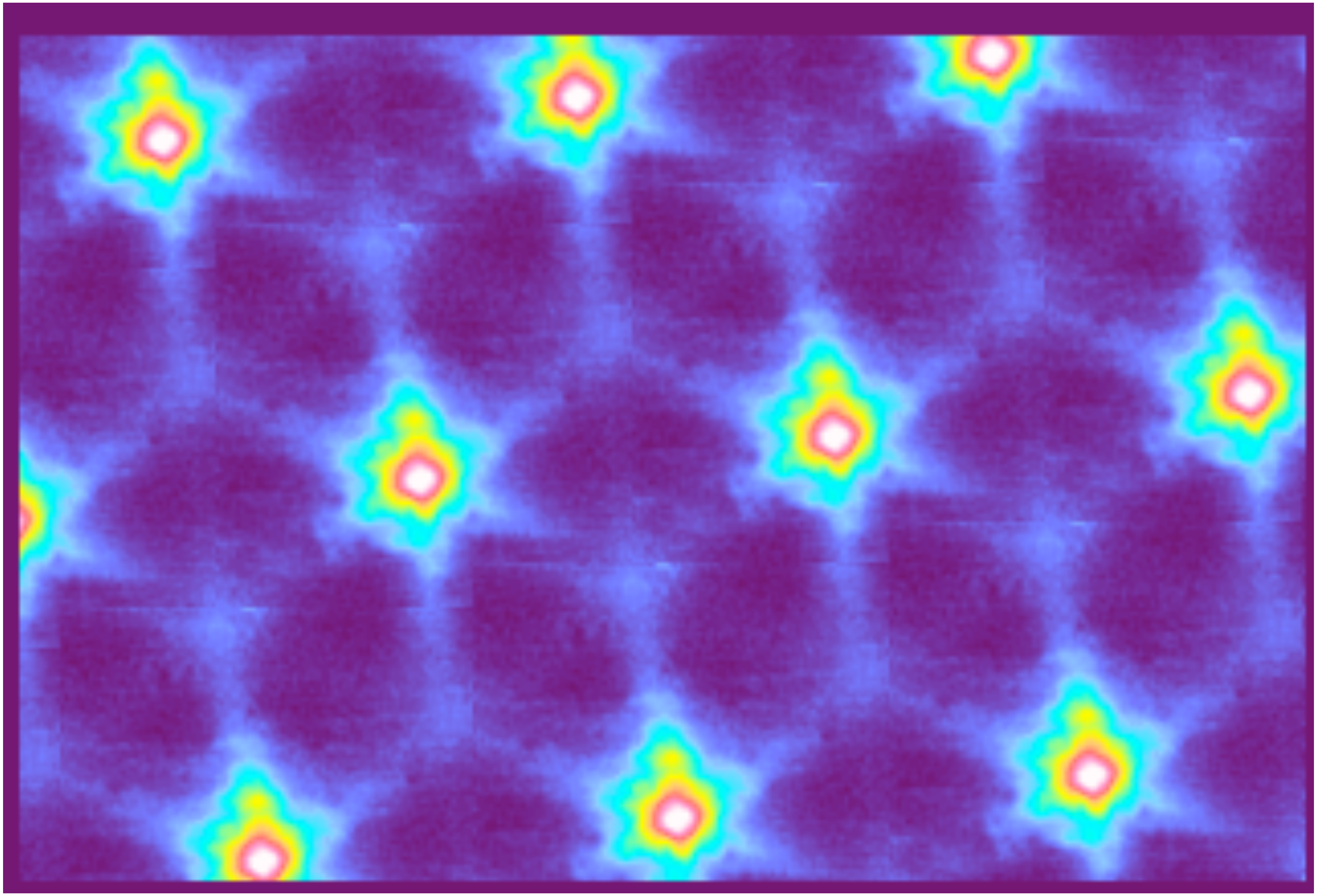


Sketch of vortices



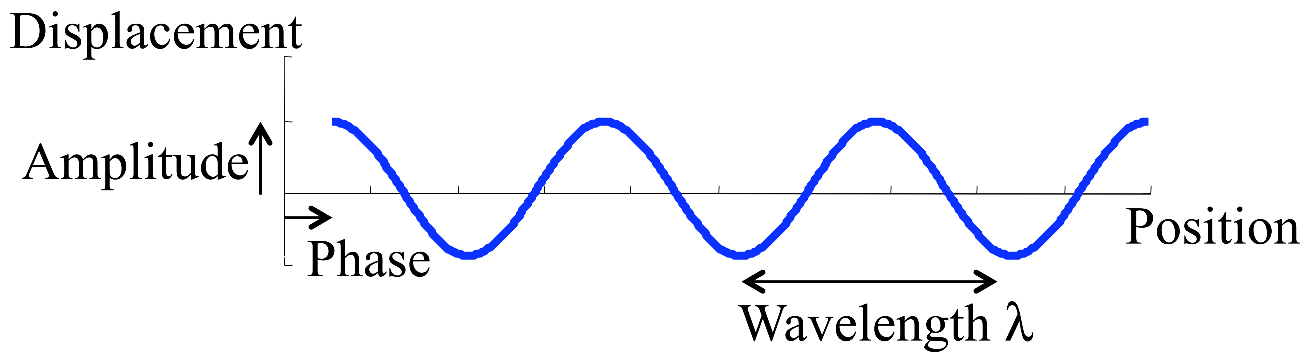
Actual magnetic image of YBCO surface


10 μm

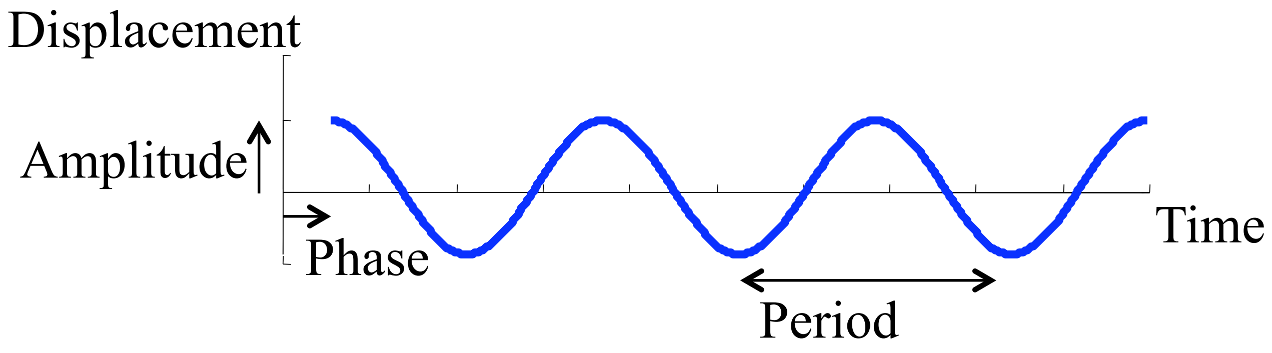


Mathematical example of a wave

At a fixed time:



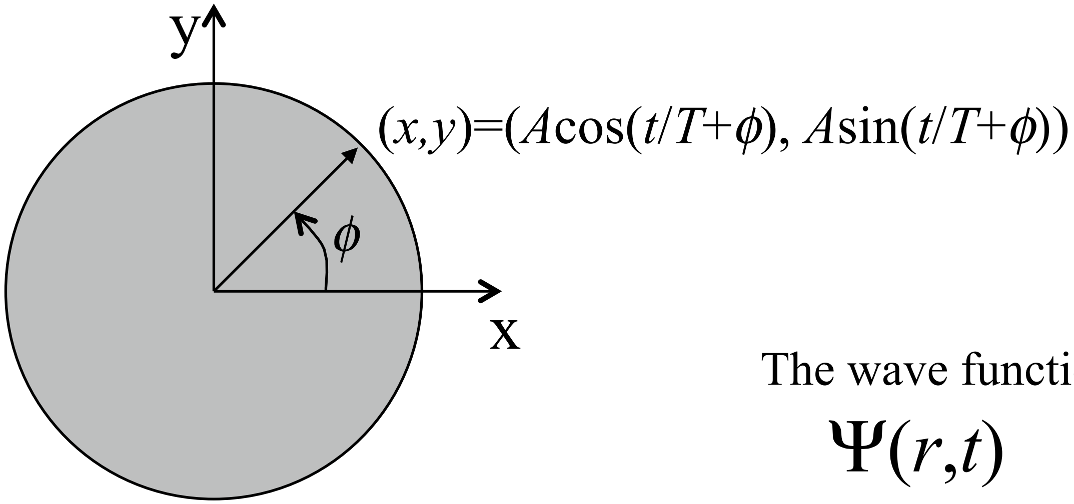
At a fixed position:



wavelength = velocity x period

Aside: *internal* phase

Internal *phase: think of a hand on a clock, or an oven timer*



$$(x,y)=(A\cos(t/T+\phi),\ A\sin(t/T+\phi))$$

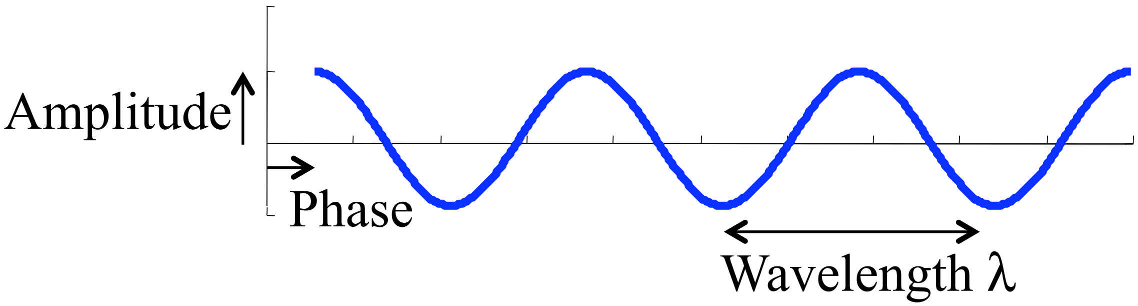
The wave function

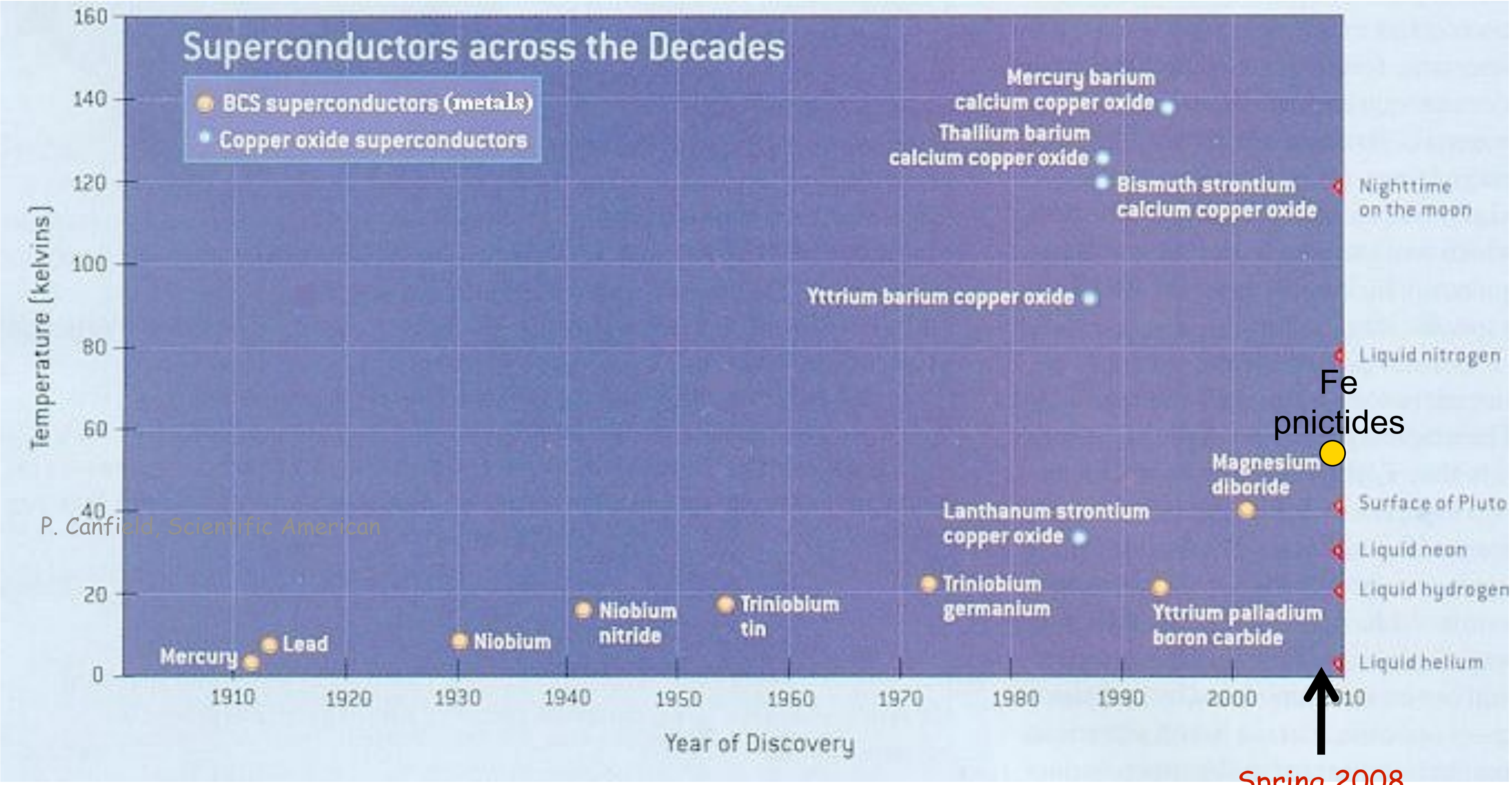
$$\Psi(r,t)$$

has an internal phase

$$\Psi = \underset{\textit{amplitude}}{\psi}\, e^{i\underset{\textit{phase}}{\varphi}}$$

Mathematical example of a wave





Fe pnictides

P. Canfield, Scientific American

Spring 2008

What is superconductivity good for ?

Big magnets

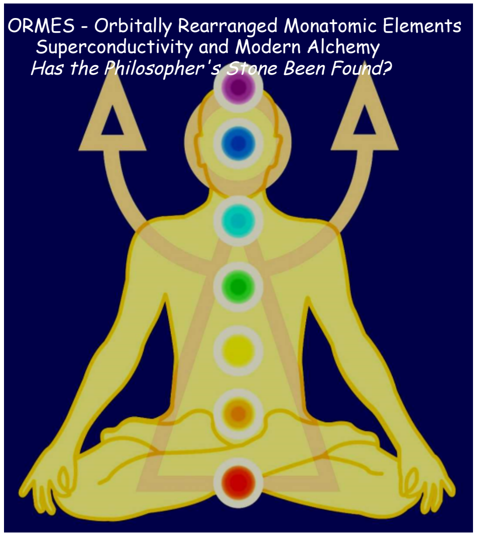
Power transmission

Maglev trains

Cell phone base stations

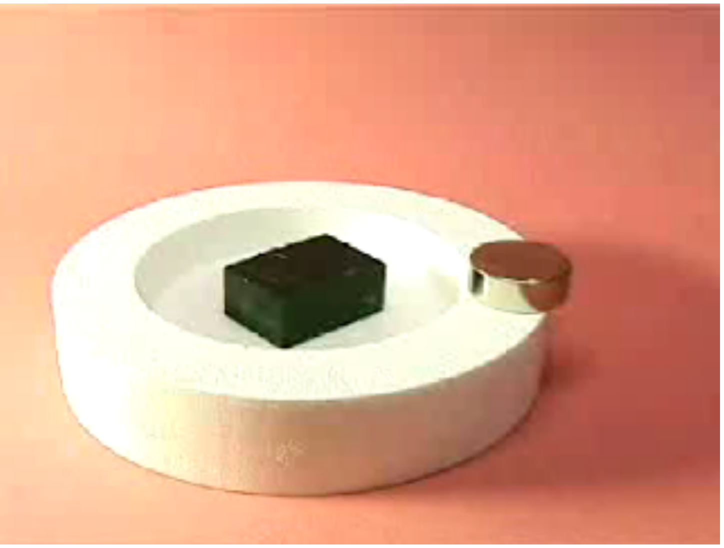
Magnets in MRI systems
Compact superquiet EM motors
Fast information processing
Directed energy devices
...

Pursuit of happiness

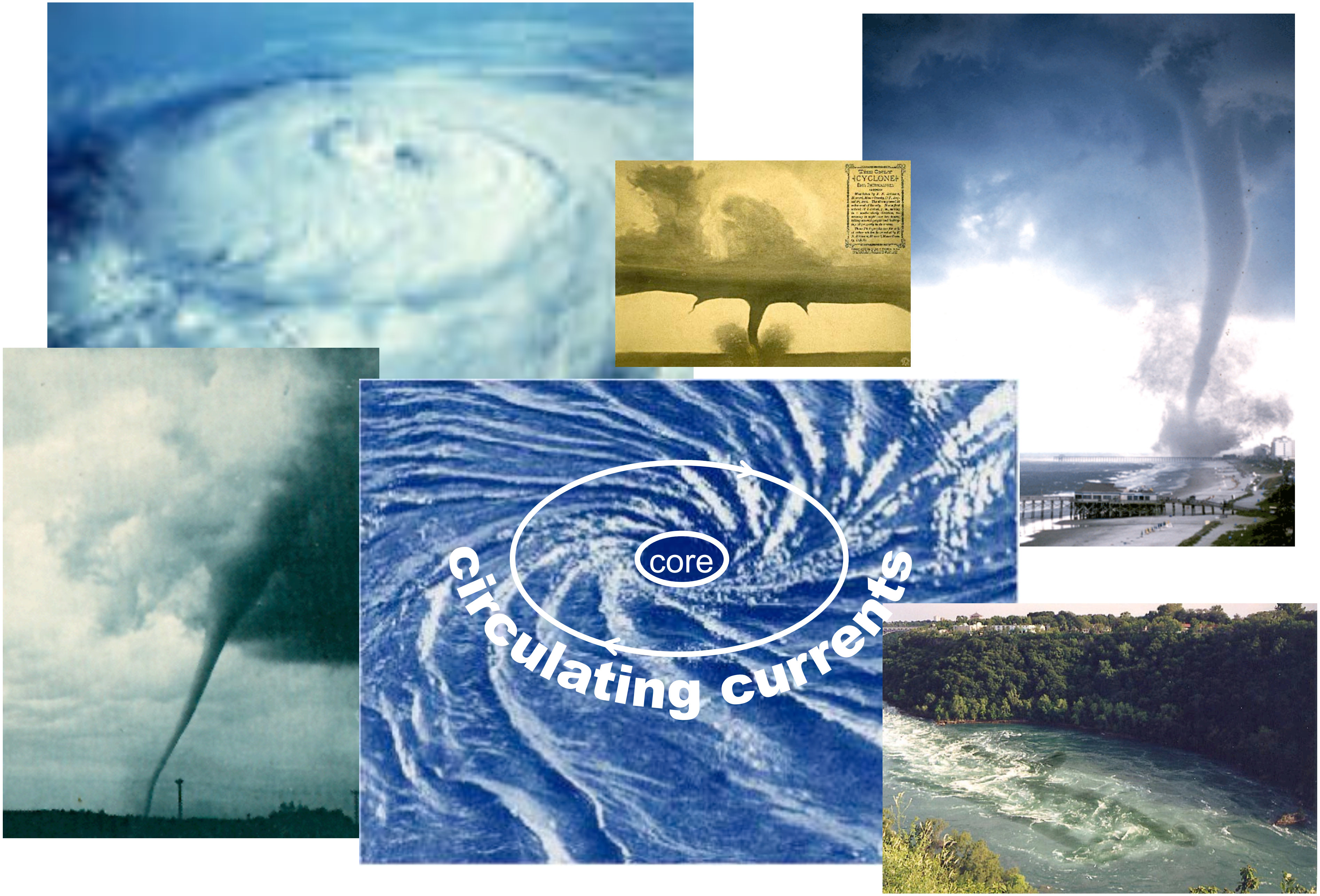


ORMES - Orbitally Rearranged Monatomic Elements
Superconductivity and Modern Alchemy
Has the Philosopher's Stone Been Found?

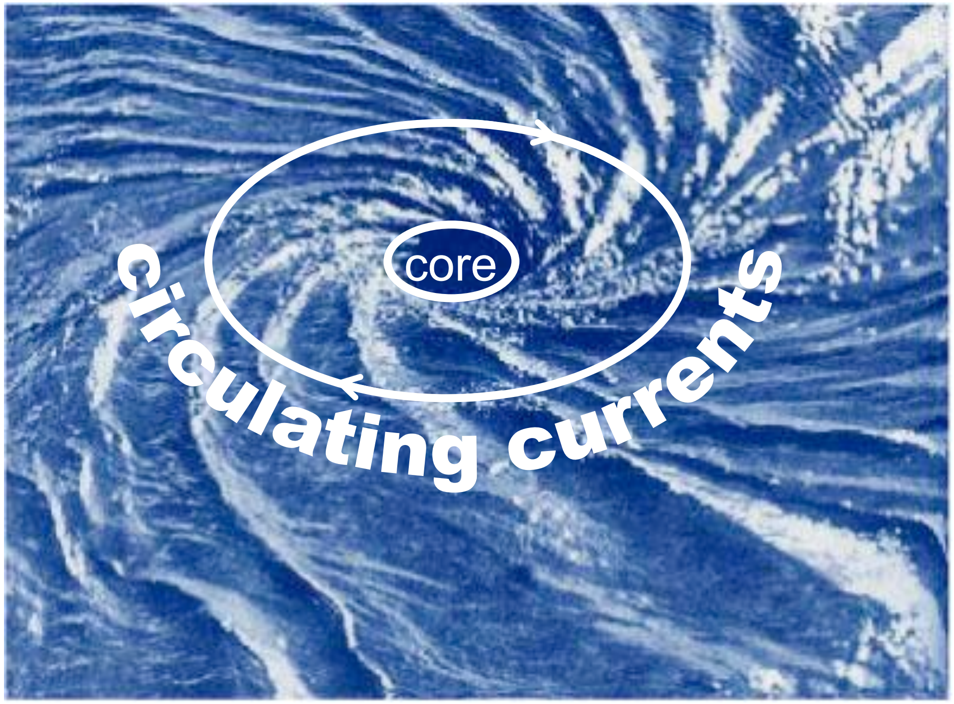
Physics Fairs



Vortices in Classical Systems



Vortices in Superconductors



Vortices in Normal and Quantum Fluids

- Have cylindrical symmetry
- Consist of fluid swirling around a core, with the fluid's velocity getting faster and faster near the core

Vortices in Quantum Fluids

- Are persistent
- Are quantized

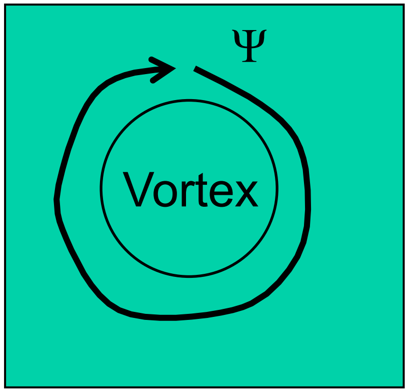
Vortices in Superconductors (which are charged quantum fluids)

- Carry their own magnetic field
- Cause dissipation when they move
- Are the major limitation to the practical applications of superconductors

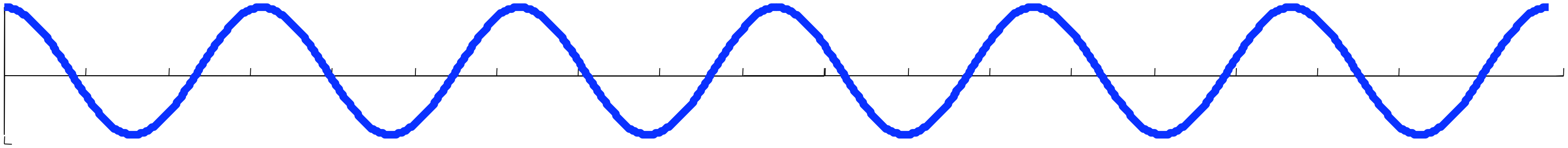
Each Vortex Carries *Quantized* Flux

The "pseudowavefunction" has a phase

$$\Psi = |\Psi| e^{i\phi}$$

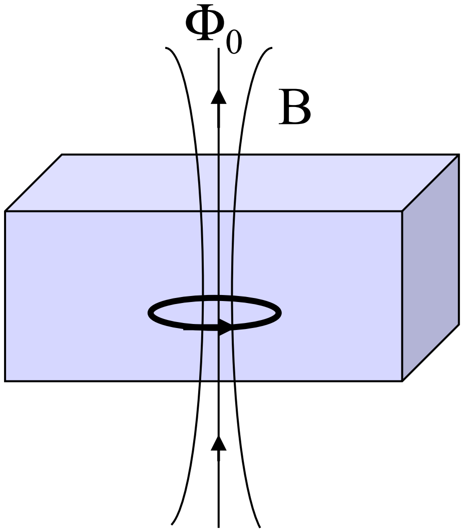


For the superfluid swirling around the vortex core, the phase can only change by multiples of 2π



This leads to the quantization of magnetic flux:

$$\boxed{\Phi = \int \vec{B} \cdot d\vec{a} = n\Phi_0}$$



Superconducting flux quantum

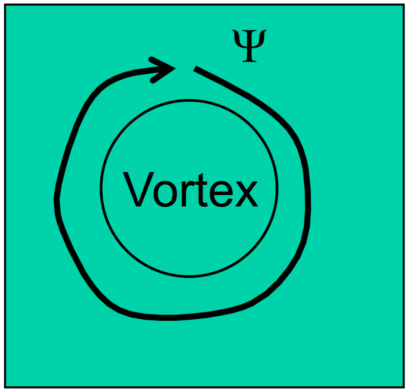
Φ_0 = hc/2e = 20.7 Gauss μm^2

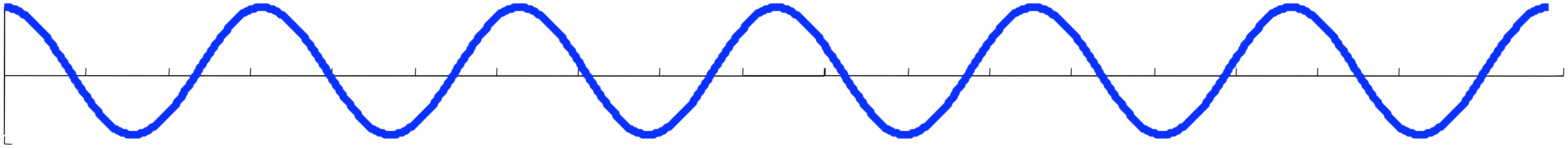
Why do we care about vortices in superconductors?

1) Fundamental interest

The vortex only exists because of the quantum "pseudowavefunction"

$$\Psi = |\Psi| e^{i\phi}$$





So studying the vortices often gives us clues about the nature of the underlying quantum state.