The Enigmatic Electron

-tiptoeing through 120 years of physics history-

by

Professor Kristian Fossheim

Department of physics

NTNU

Invited lecture in the series

«Forum for matematiske perler»

Department of Mathematics, NTNU

March 9, 2018

Sorry folks, no math today, only physics.

But take comfort and remember what Marilyn (almost) said:

«Math is a physicist`s best friend»

My path today will be «littered» with Nobel prizes in physics

Evaluating my topic

- Don’t we really know everything we want to know about this tiny particle, the electron?
  - The electron was the first fundamental particle discoverd.

Evaluating my topic

- Don’t we know all we need to know about this tiny particle?
  - The electron was the first fundamental particle we discovered.
  - The electron has a negative charge *e* = - 1.602 x 10^{-19} C

Evaluating my topic

- Don’t we know all we need to know about this tiny particle?
  - The electron was the first fundamentalparticle we discoverd.
  - The electron posesses a negative charge e = -1.602 x 10^{-19} C
  - The electron mass is $m_e =$ 9.109 x 10^{-31} kg

μ_e

Evaluating my topic

- Don’t we know all we need to know about this tiny particle?
  - The electron was the first fundamentalparticle we discoverd.
  - The electron posesses a negative charge e = - 1.602 x 10^{-19} C
  - The electron mass is $m_e = \ 9.109$ x 10^{-31} kg
  - The electron has a magnetic moment μ_e=928.476 4620(57) x 10^{-26} J T^{-1}

Evaluating my topic

- Don’t we know all we need to know about this tiny particle?
  - The electron was the first fundamentalparticle we discoverd.
  - The electron posesses a negative charge e =1.602 x 10^{-19} C
  - The electron mass is $m_e = 9.109$ x 10^{-31} kg
  - The electron has a magnetisk moment μ_e=928.476 4620(57) x 10^{-26} J T^{-1}
  - Anything else we need to know?

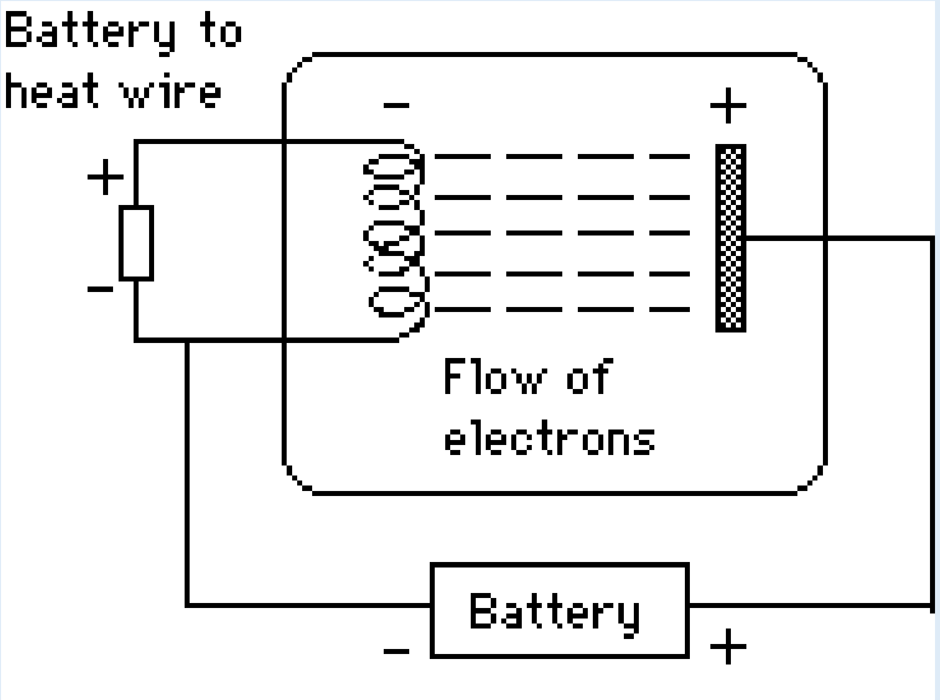
Maybe some history?

- «Elektron» is greek for *amber,* well known for attracting small objects

- In the 1880`s one concluded that a *smallest electric charge* exsists
- In 1891 Johnstone Stoney suggested naming this charge electron
- In 1897 J J Thomson found a particle of very small mass which carried this smallest charge, and called the particle «electron».
- The instrument used was the cathod ray tube
- Thomas Alva Edison is give credit for discovery of electric current in vacuum.

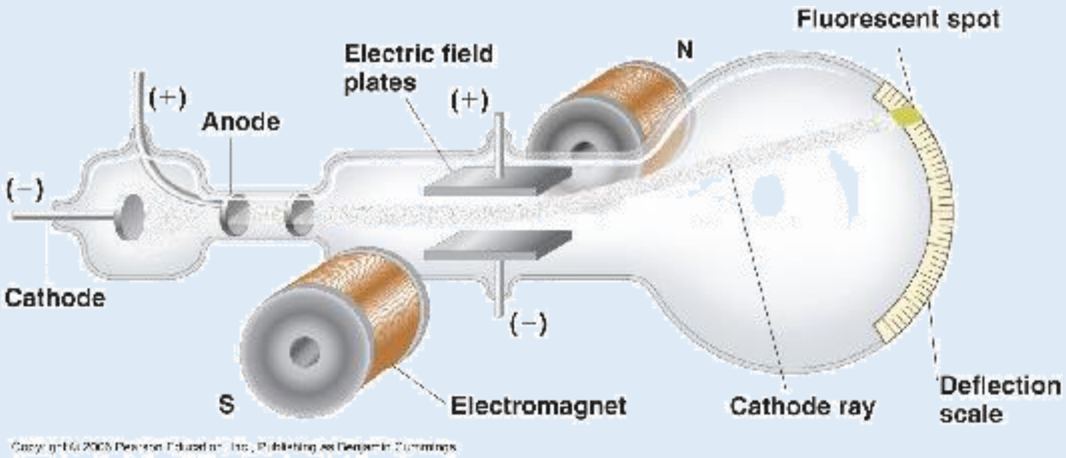
A little more history?

- The Edison-effect
  - Negative current through vacuum



J J Thomson: Discoverer of the electron, officially. The first elementary particle

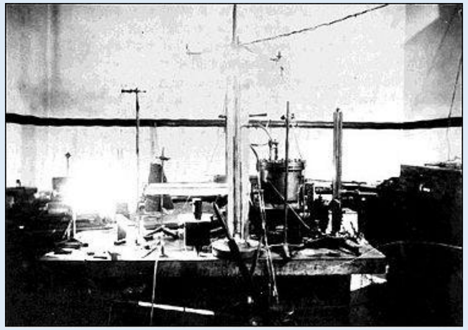
- Thomson cathode ray tube 1897,
  sketch



Balancing the vertical magnetic and electric forces allows the ratio e/m to be calculated. The experiment demonstrated the existence of an elementary charge, but only e/m could be determined, not the charge e.

Determining the electron charge e

First measurement of charge e: Millikan`s oil drop-experiment 1909



- Oil drops are blown in between two horisontal metal plates at different electic potential, then charged by use of X-rays.
- Adjusting the potential V across distance *l* to balance gravitation Mg against vertical electric force for n particles attached to one oil drop of mass M:
  - $e = nMgl/V$
- Charge was found in multiples of elementary value

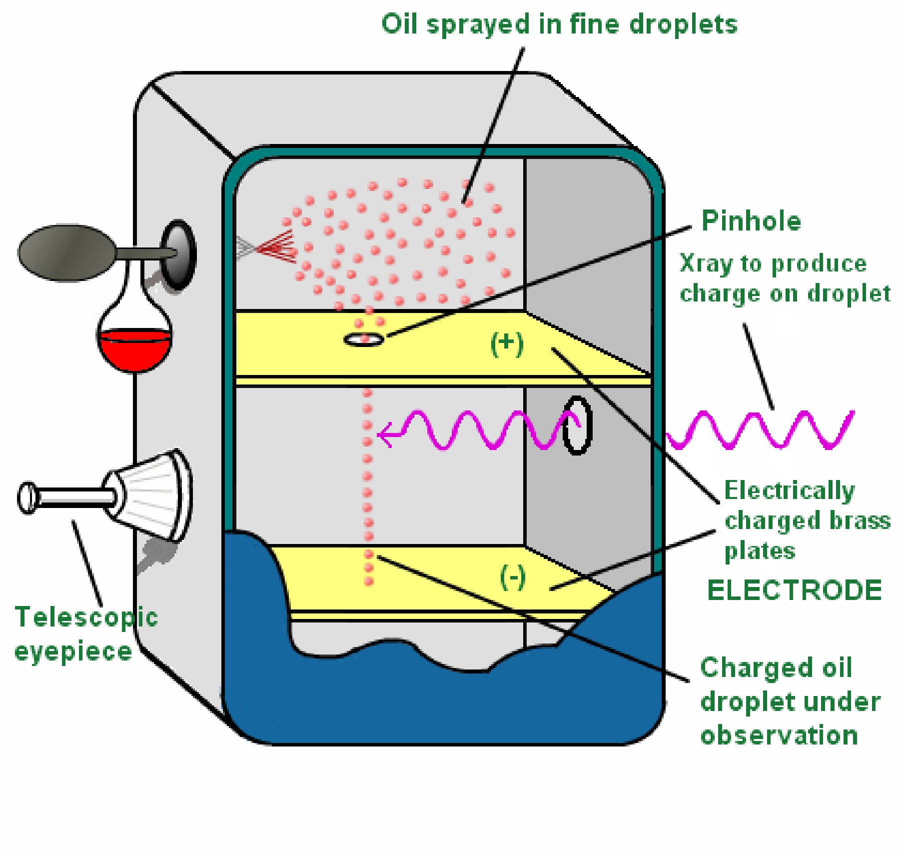
  e = $1.5924(17)\times10^{-19}$ C

  The electron is always charged -1e

  Smallest quantum of charge still is - (1/3)e

  Quarks have charge $-\frac{1}{3}e$ or $\frac{2}{3}e$

  But these are not free particles



Best value of e today?

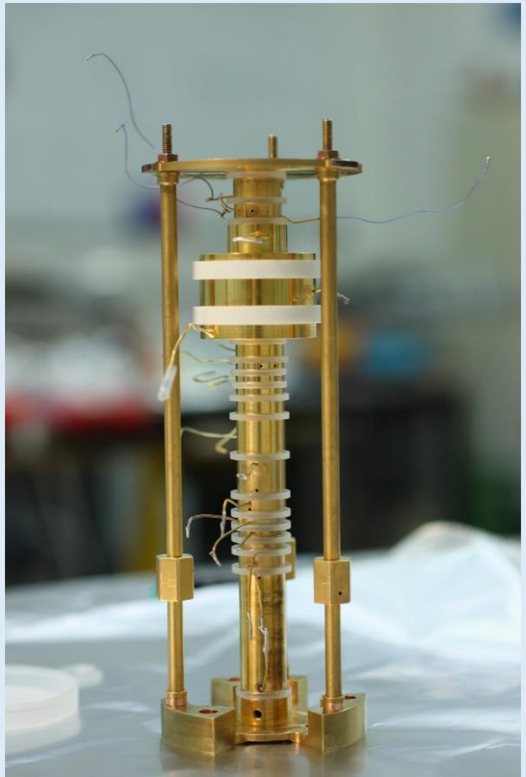
- Official best values:
  $e = 1.6021765314 \times 10 -19$ C
- 10 decimal accuracy!

Electron mass:

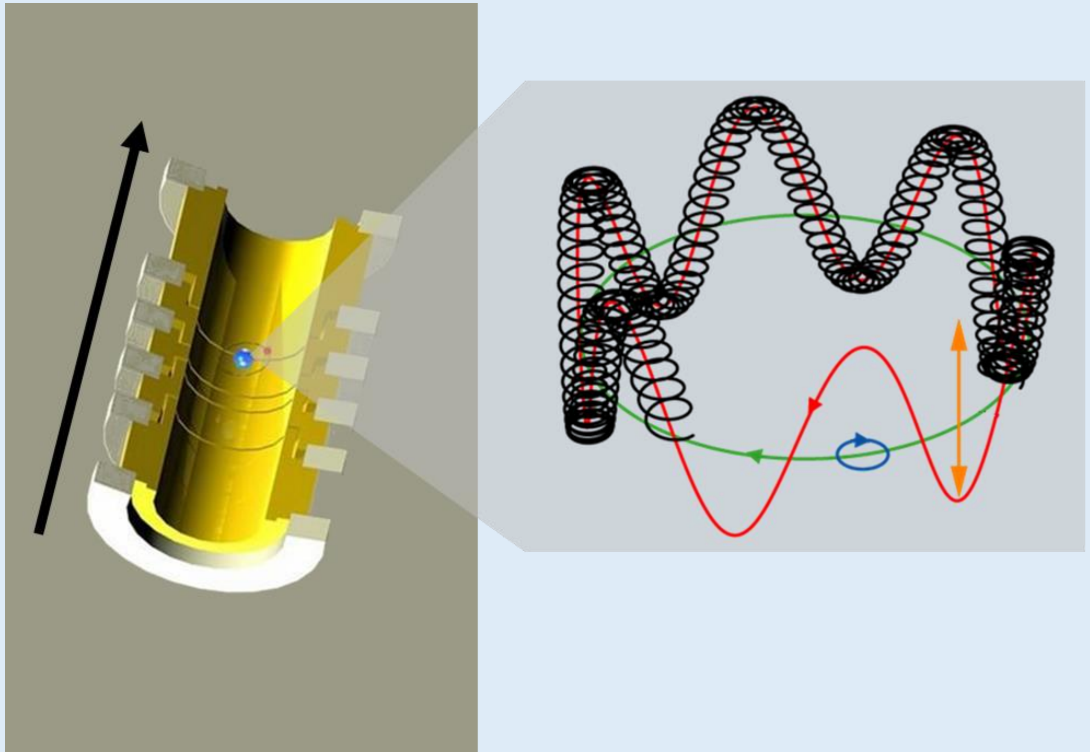
With this instrument scientists at the Max Planck institute in 2014 determined the electron mass with a precision 13 times (!) better than previously known value.

"A scale for absolute lightweights: Physicists used this Penning trap to determine the mass of an electron by forcing it, together with a carbon 12 nucleus, to follow a helical trajectory. The revolution frequency of the carbon ion is an input for a calculation which ultimately provides an extremely precise value for electron mass."

Penning trap



The key is that the revolution frequency of the carbon ion in the trap and the wobble frequency of electron precession are in an exact ratio to one another

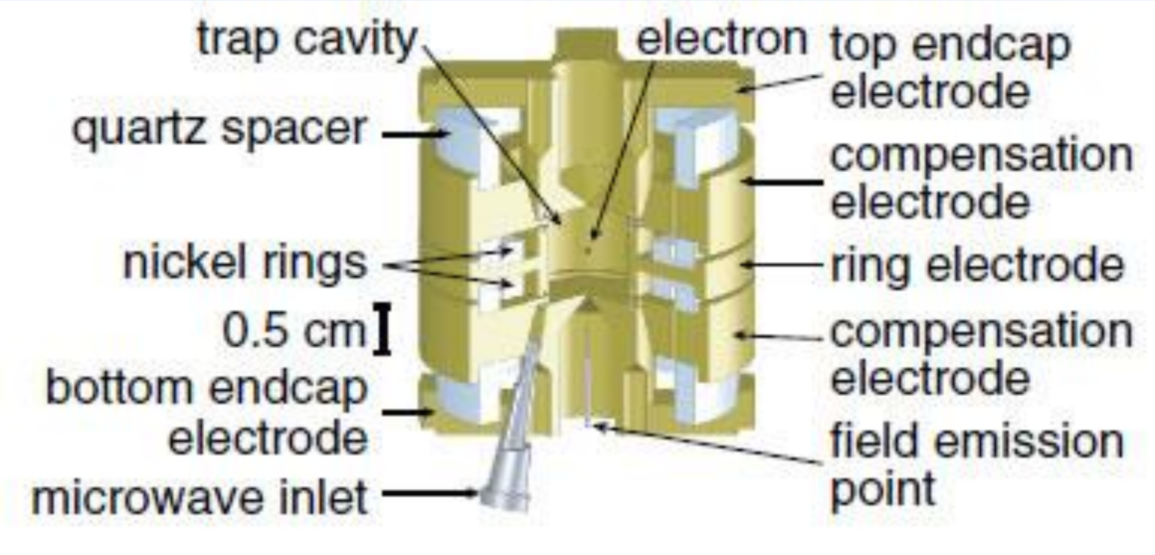


The magnetic moment $\boldsymbol{\mu}$

Harvard 2014: Measurements in a *Penning trap:*

One electron (!) circulating in a magnetic field at 100 mK

Penning trap, again

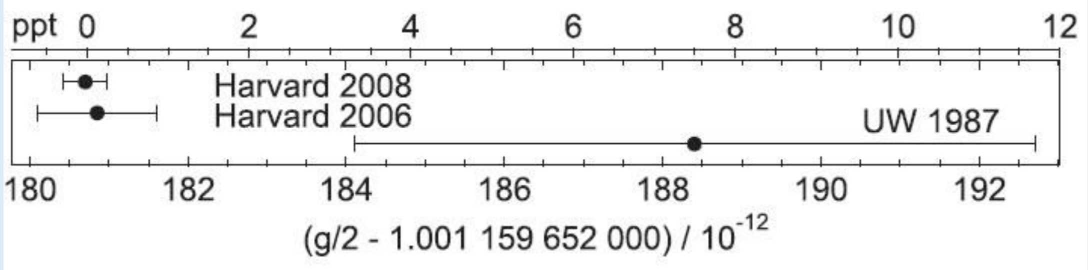


(Bohr magneton $\boldsymbol{\mu_B} = \frac{\boldsymbol{eh}}{\boldsymbol{2m}} = 927.4\text{x}10^{-26}$ J T^{-1}

Measuring the energy difference between when one electron spin is pointing up or down (!)

12 times more precise value for magnetic moment than previously obtained. It took 12 PhD theses to reach that point. The result:

μ_e **=928.476 4620(57) x 10^{-26} J T^{-1}**



Why are these values of natural constants so important? Examples: In relation to energy, you *have* to know them

Mass m: mgl is energy.

Charge e : eE*l* is energy…

Magnetic moment $\boldsymbol{\mu}$: $\boldsymbol{\mu B}$ is energy…..

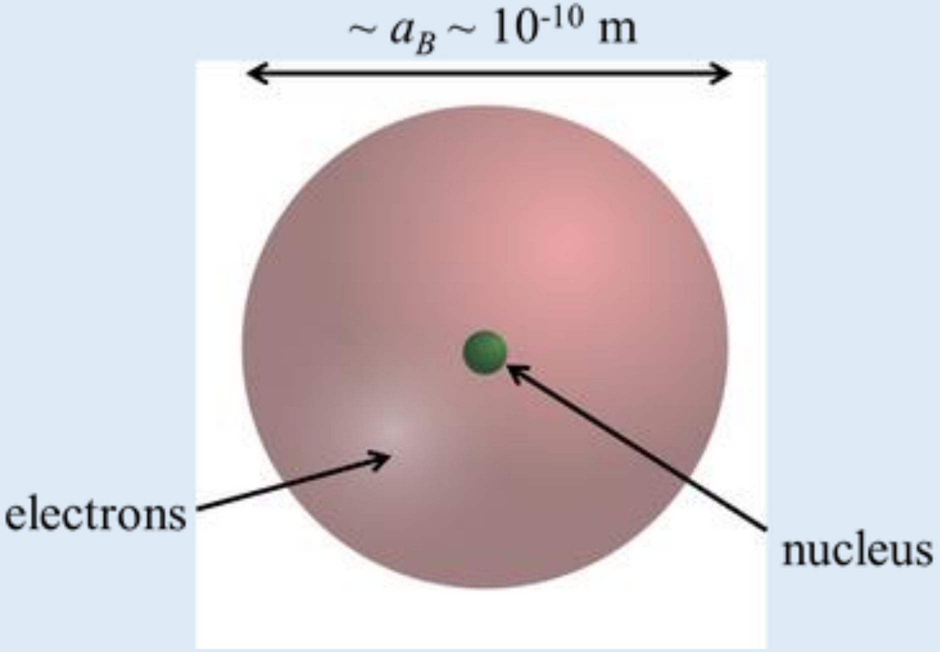
What about electron size?

The size r of the electron?

- First approach: (Virial theorem) By equating potential and 2x(kinetic energy) one finds an estimate for r:

$$\approx\ 10^{-10}\mathrm{m}$$

- This could best be interpreted as the space the electron occupies when moving around in the simplest atom, hydrogen



Size of the electron?

Second approach: Energy required to pack all charge e into one sphere of radius r, by equating this energy to Einstein`s E=mc2

Leads to the classical electron-radius r

$$E = e^2/4\pi\epsilon_0 r = mc^2$$

$$r_c = e^2/(4\pi\epsilon_0 mc^2) \sim 10^{-15}\ \text{m}$$

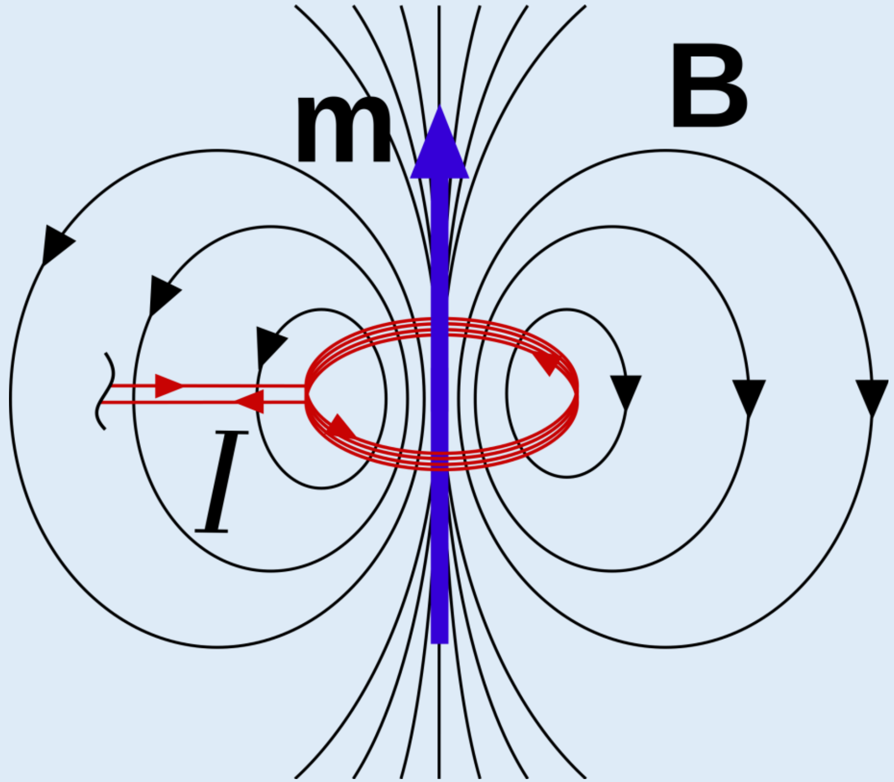
Size of the electron?

Third approach

The electron has «spin». Is it a circulating charge at radius r?

- The rotation speed at equator must surely be lower than the speed of light
- This gives us the Compton-length for the radius

  $\lambda_c \sim \hbar/(mc) \approx 10^{-12}$ m
- At least 1000 times too large according to lower limit from observational data
- Magnetisme does not come from circulating charge



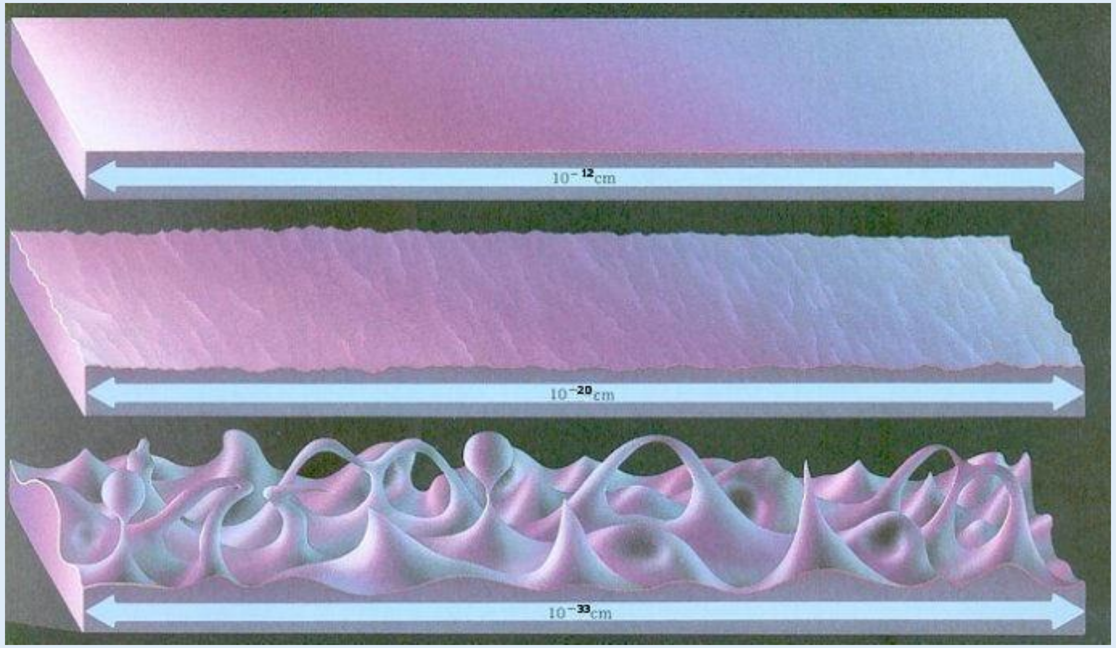
Space on different scales. Relevant for electron size?

1.Scale of $10^{-12}\ m$:
Flat space

2.Scale of $10^{-20}\ m$:
Small ripples appear

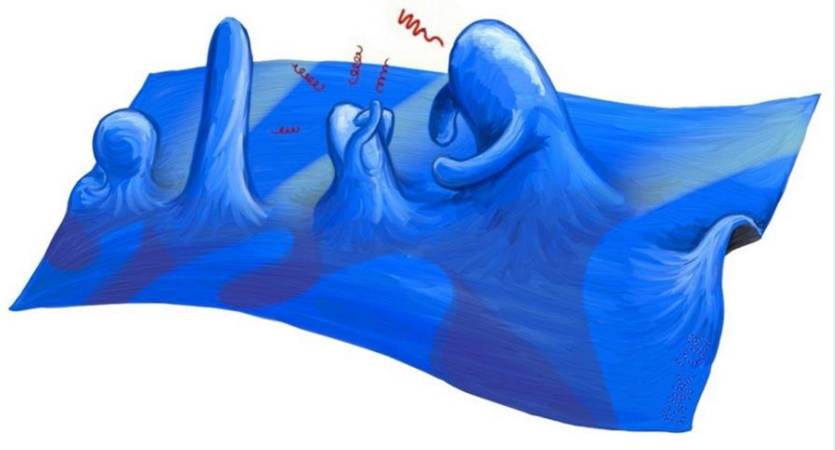
3.Scale of Planck length
$\ell_p = \sqrt{\hbar G / c^3} \approx 10^{-35}$ m

Strong fluctuations



At smaller length we have no clue except for string theory

Concensus: According to modern understanding, **the electron is a** point particle with a point charge **and no spatial extent**



- Experiments give no hint of electron size larger
- than 10^{-18} m

- **Quantum field theory tells us the electron is an excitation in the electron field**, «like a ripple on water»
- Quantum field theory says ALL particles are «ripples», excitations, on each particle`s quantum field! Strange?
- Well, take comfort: The **photon** is an -admittedly, massless- particle which we are all familiar with as **indeed an excitation on the electromagnetic field.**
- Generalizing this: **Such is quantum physics for ALL particles, including the electron**
- Enigma? YES, for most of us it is.

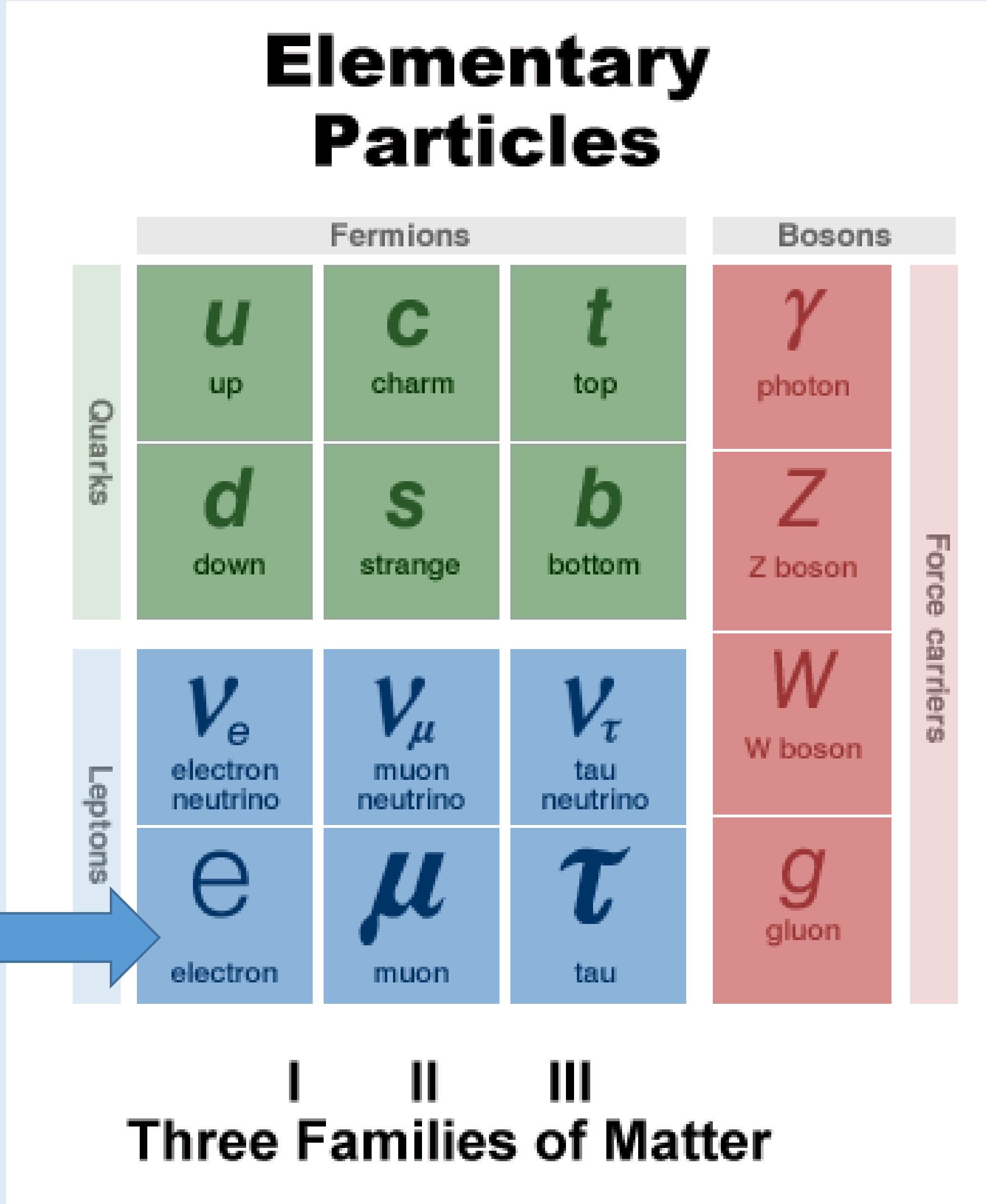
God news:
The electron enjoys family life!

Lepton-family, spin $\pm 1/2\hbar$

Quark-family, spin $\pm 1/2\hbar$

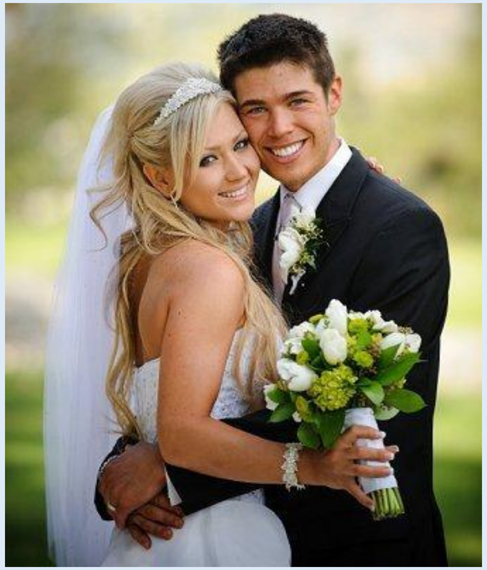
Boson-family, spin $\pm 1\hbar$

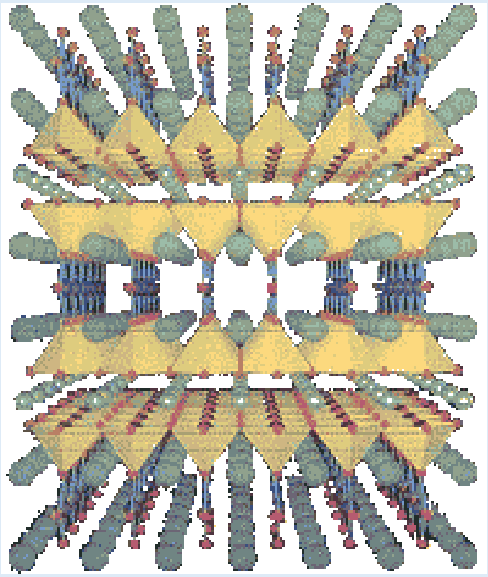
Our small friend



Paradox:

In spite of point like electron size, everything we see, yes *everything*, are structures built by electrons, including you and me!

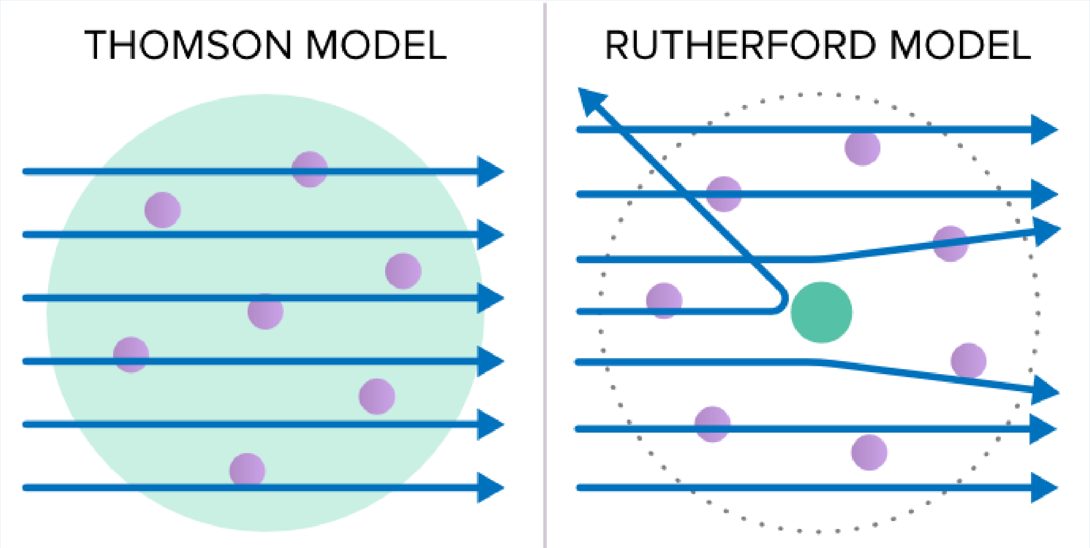


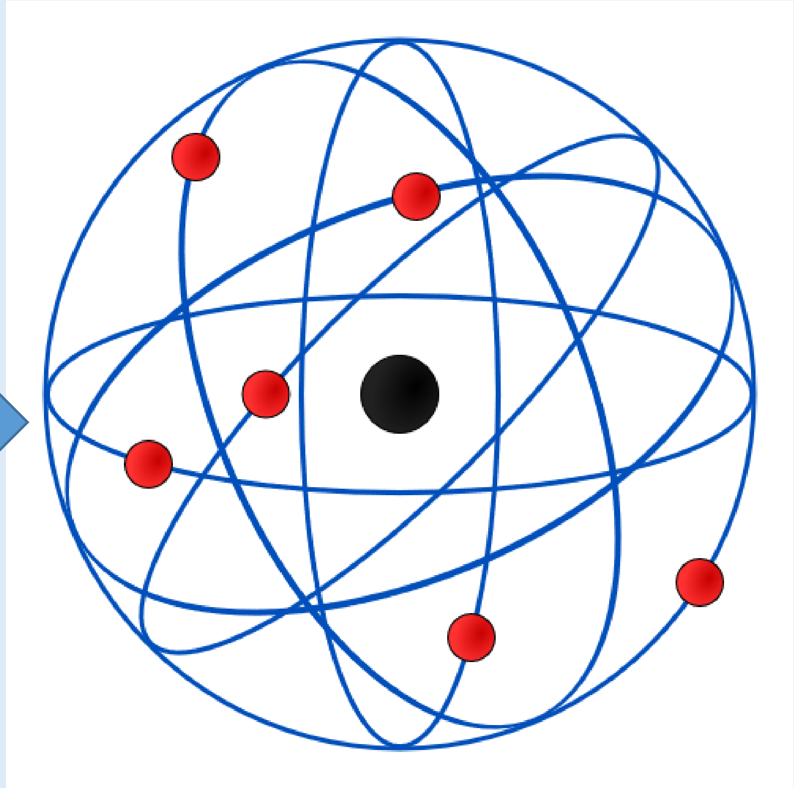


To grasp this we shall need to go to quantum physics

Thomson vs Rutherford
What is an atom?

Model of atom ~ 1910



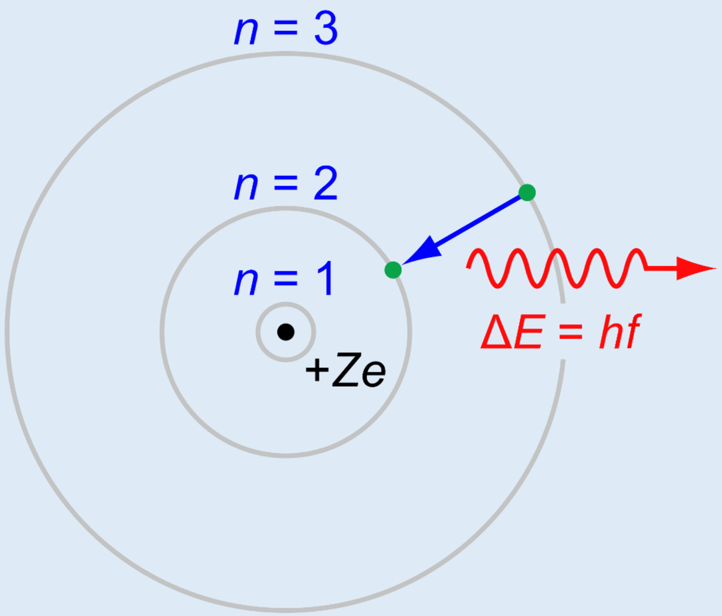


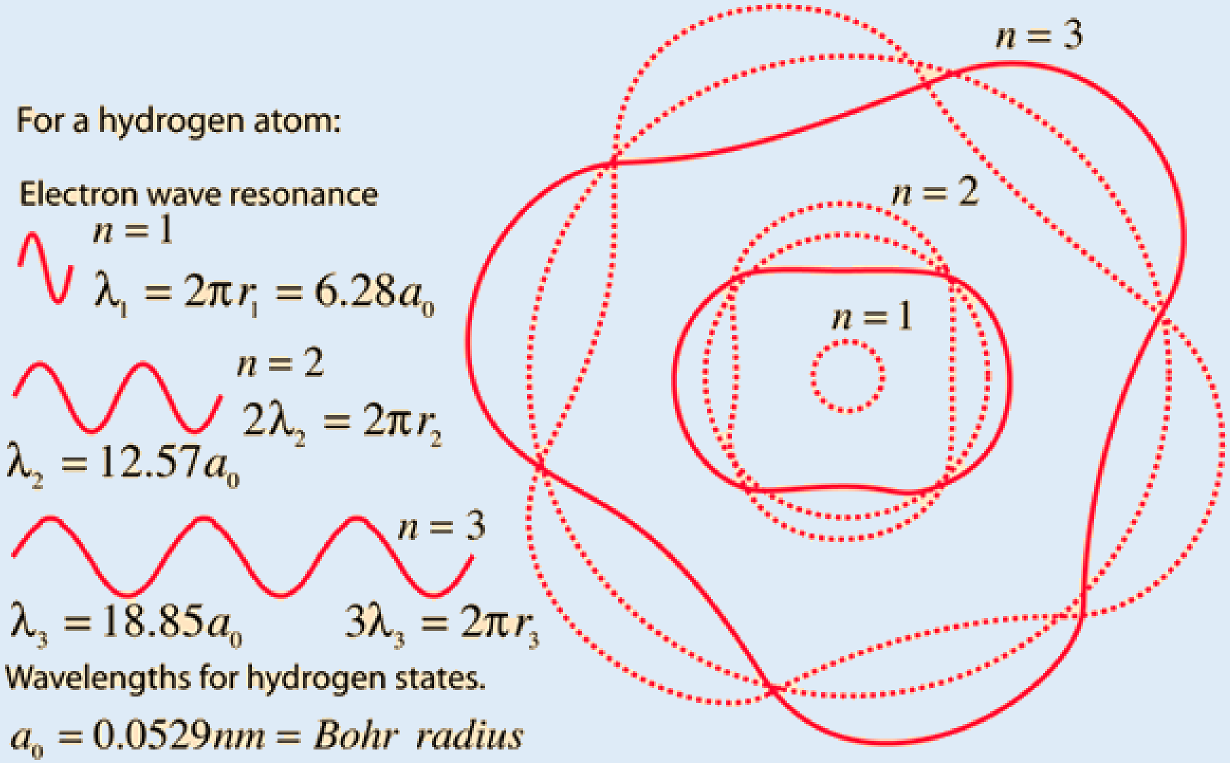
Bohr model 1913

explained the spectral lines of hydrogen etc

Einstein had explained photoemisson

Quantum physics developing: Energy levels using quantum numbers n





Bohr introduced concepts like stationary states, and quantization of angular momentum L=$\mu v r = n\hbar$

Quantum physics, waves of matter

French physicist de Broglie suggested in 1924 that the electron has wave properties.

Erwin Schrødinger in Zurich gave a talk to Peter Debye and colleagues on that subject.

Debye said: «If there are waves, there has to be a wave equation. Go and find it!»

That`s exactly what Schrødinger did!

Reminder: Classical wave equation:

$$\frac{\partial^2 u}{\partial t^2} = a^2 \frac{\partial^2 u}{\partial x^2}$$

Inspired by Einstein, de Broglie postulated a wavelength:

$$\lambda = \frac{h}{p} = \frac{h}{mv}\sqrt{1 - \frac{v^2}{c^2}}$$

Erwin Schrødinger found an equation for material particles of mass m (1926)

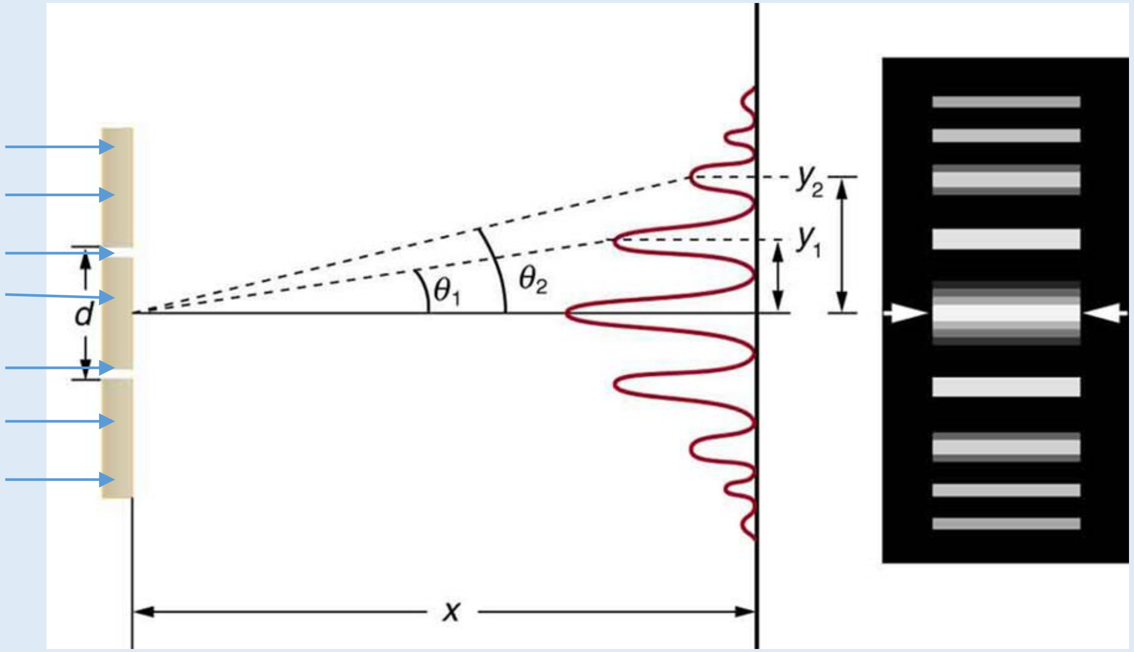
(Here the time independent version)

$$\frac{-\hbar^2}{2m}\frac{\partial^2 u(x)}{\partial x^2} + V(x)u(x) = E\, u(x)$$

Wave characteristics

First: Study waves of light

Interference between waves from two sources, here two slits in a screen.



Will this work for electrons?

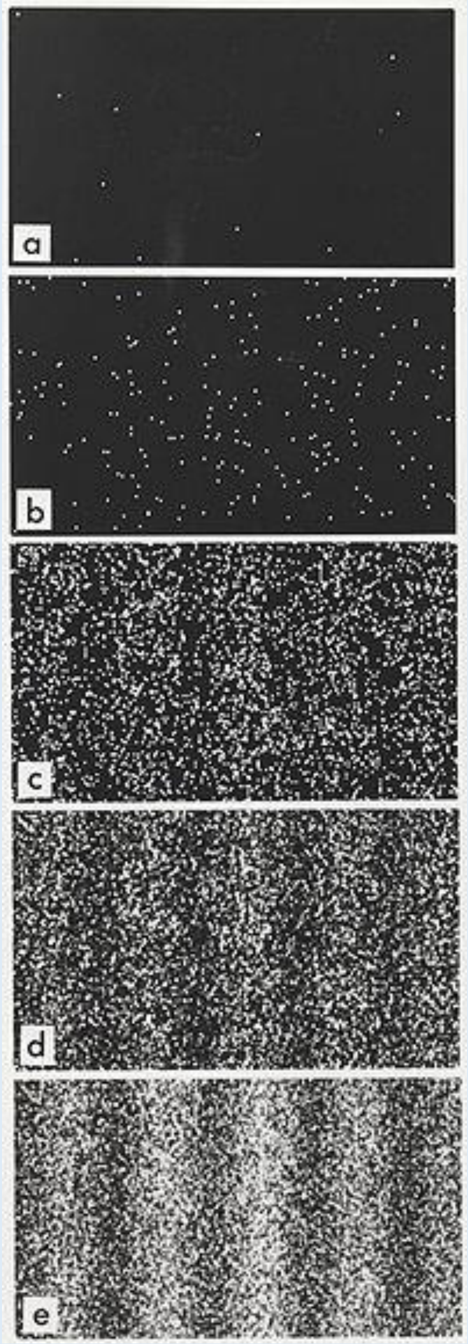
Electrons through a double slit, like we did with light. Real data

Top picture: very few particles, farther down a,b,c,d,e, more and more particles.

We have wave interference pattern for particles

First experiment: Davisson and Germer 1927

- This pattern can only arise when the particle waves in some sence go through both slits.
- This is quantum physics.
- But how can we undestand it?
- Note, fortunately: We do not claim that the particles are smeared out in space!



Interpretation of particle as wave?

Einstein said: «God does not play dice».

Max Born 1925: The waves are probability waves.

The wavefunction u(x) gives a probability distribution for where the particle can be.

Werner Heisenberg: we always have *limited simultaneous knowledge* about where the particle is and how fast it travels.

Heisenberg`s uncertainty relation is the bedrock of quantum mechanics, like a «first commandment» of quantum physics: You can only know this much, not more!

The Heisenberg-relation for particle with momentum p and position x with uncertainties Δp and Δx

$$\Delta p \cdot \Delta x \geq \tfrac{1}{2}\hbar \quad \text{or} \qquad \Delta v \cdot \Delta x \geq \tfrac{1}{2}\hbar/m$$

A similar relation applies to energy and time.

Experimentally confirmed

Similar relation in classical waves (Think about vibrating string)

Werner Heisenberg

Q: Why can matter be so hard when it is mostly «empty» space?

Ex: Just two tiny particles make up the hydrogen atom

A: The **strength of the coulomb force**, combined with the structure of quantum mechanics, expressed by the **Pauli principle**: *all electrons in an atom must be in different quantum states*

$$F = \frac{1}{4 \cdot \pi \cdot \epsilon_0} \cdot \frac{Q_1 \cdot Q_2}{r^2}$$

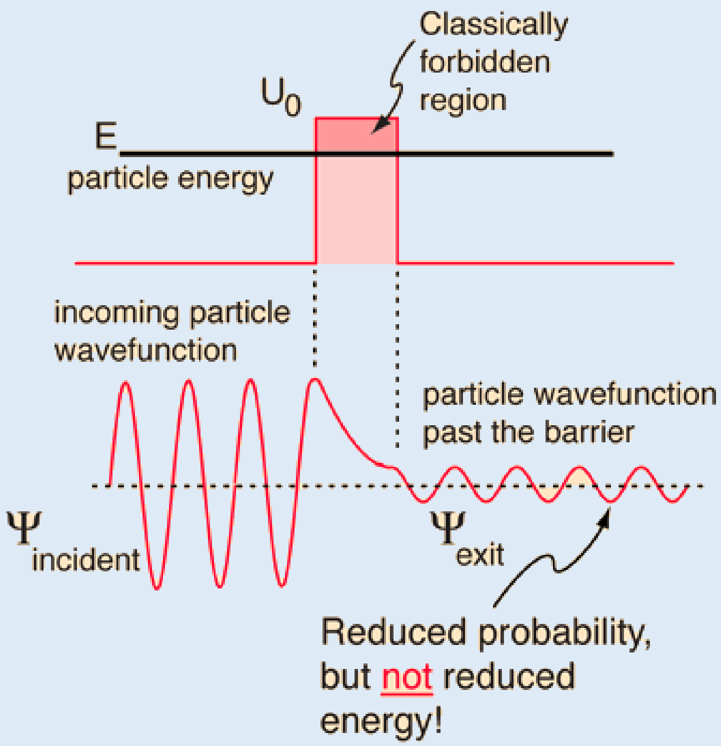
$$\epsilon_0 = 8,8542 \cdot 10^{-12} \frac{As}{Vm}$$

NB!The coulomb force between two electrons is about **42 orders of magnitude stronger than the gravitation force** between them. Compressing a multielectron atom is extremely tough to do!
On the other hand: Hydrogen «should» collaps, due to attraction between proton and electron **but does not due to the Heisenberg uncertainty principle.**

A new enigma: Quantum-tunneling:

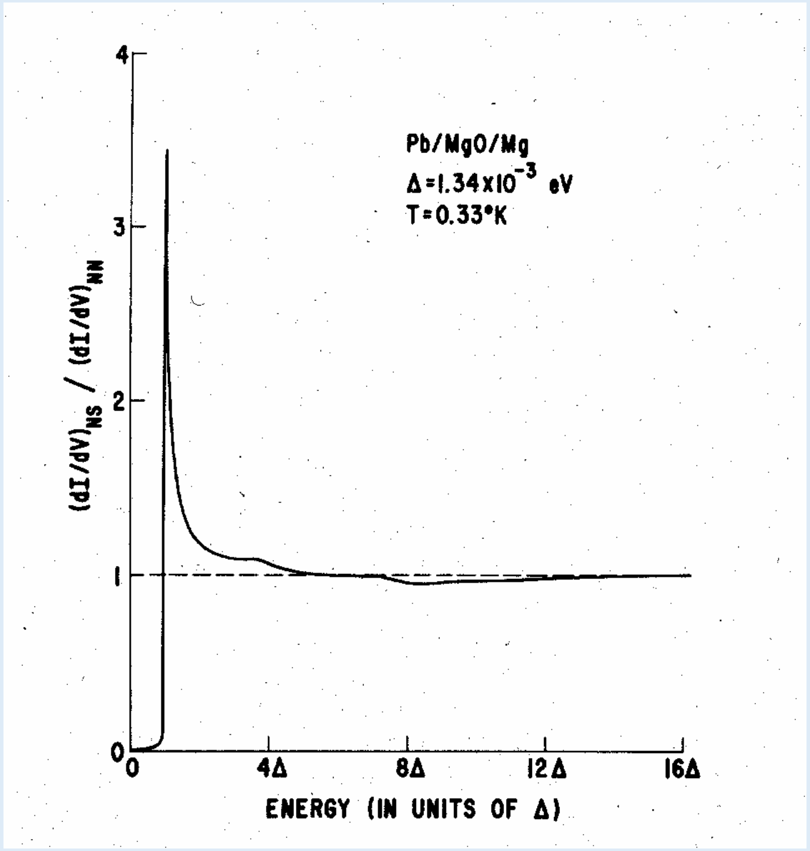
Electrons can penetrate barriers where they do not have enough (classical) energy to pass. Measurable tunneling current

But NB! There is no hole or «tunnel»! It leaves no trace



History`s most famous tunneling esperiment was performed by Norwegian physicist Ivar Giaever, graduate of our university (NTH) confirming the BCS theory of superconductivity, one of physics history`s greatest theories *(Biography by KF)*

Giaever receiving the DKNVS`s highest honour, the Gunnerus medal, at 250 years celebration of DKNVS in 2010

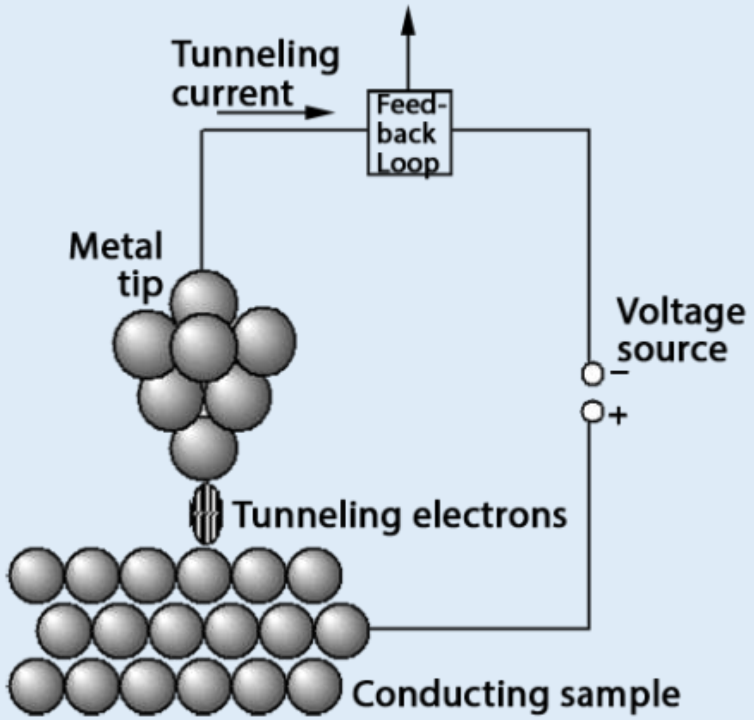


Important use of the tunnel effect

- One of the main foundations of today`s nanotechnology research
- Rohrer and Binnig,

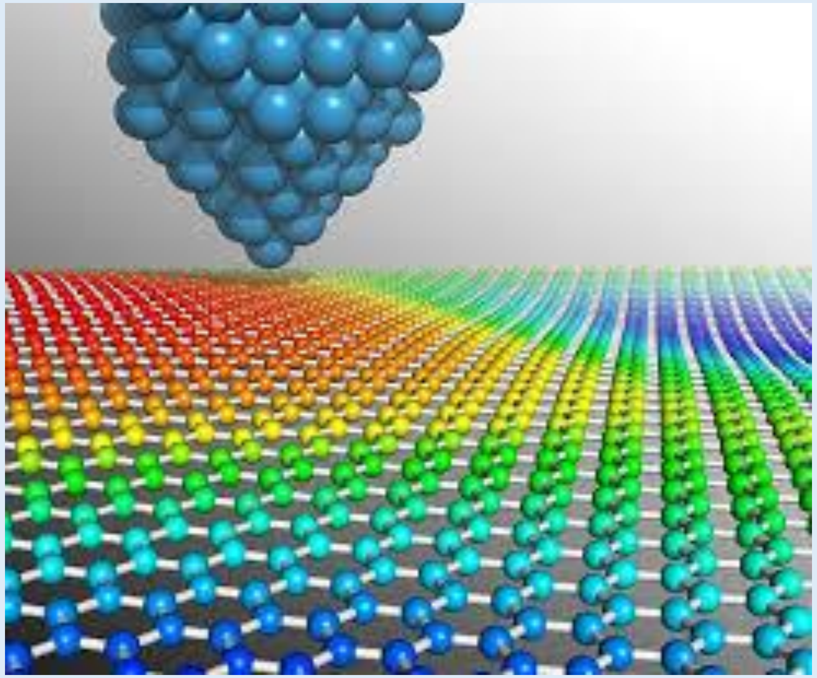
  IBM Zurich

Principle of STM: Scanning Tunneling Microscope

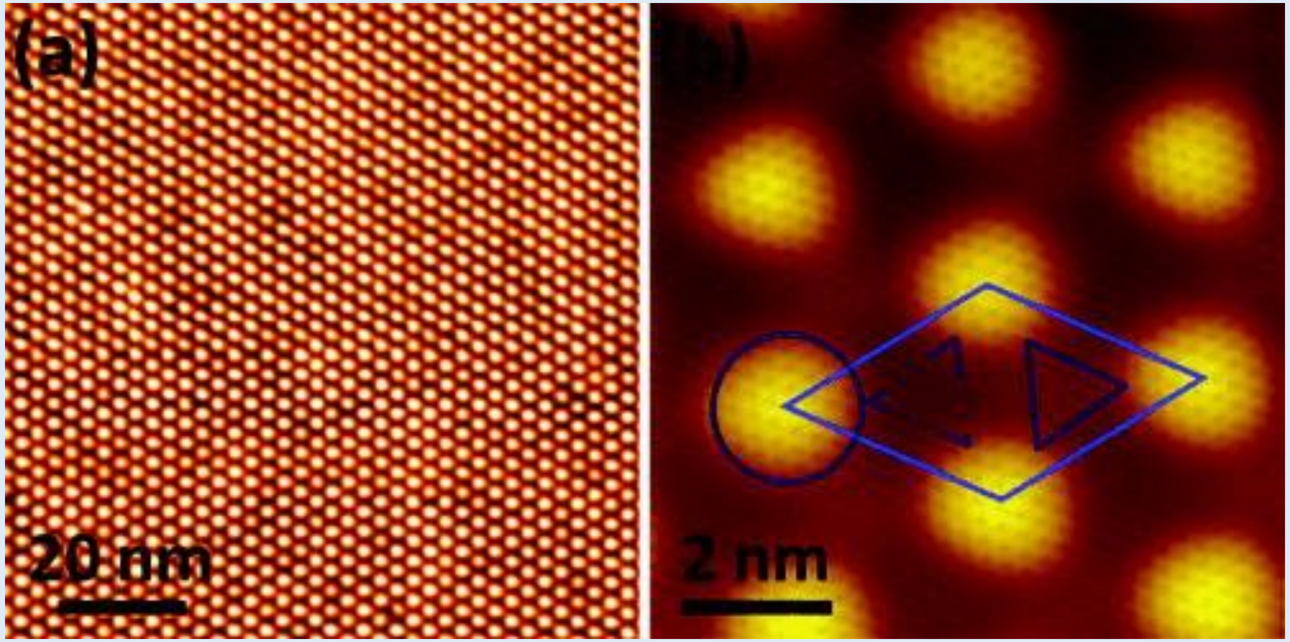


STM: Imaging solid surfaces at subatomic resolution

Sketch of STM-method at work



Real images, graphen, carbon in 2D



The transistor. The discovery that transformed how we live today

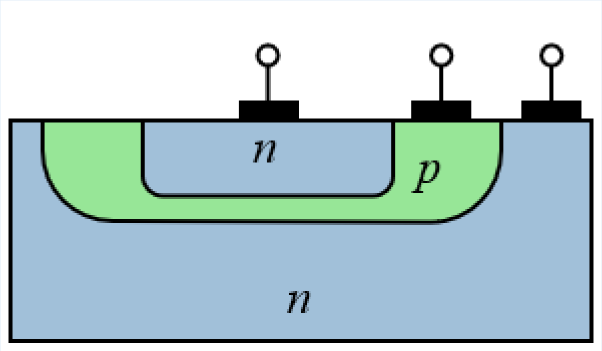
First transistor 1947

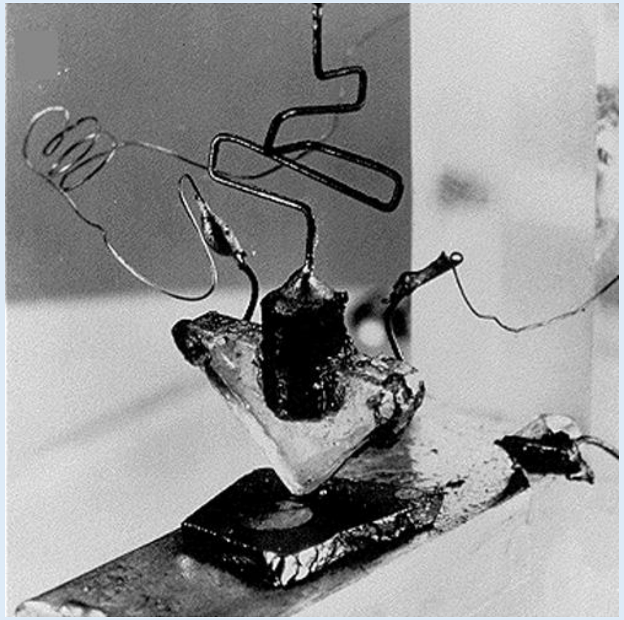
Shockley, Bardeen, Brattain,

Bell Labs

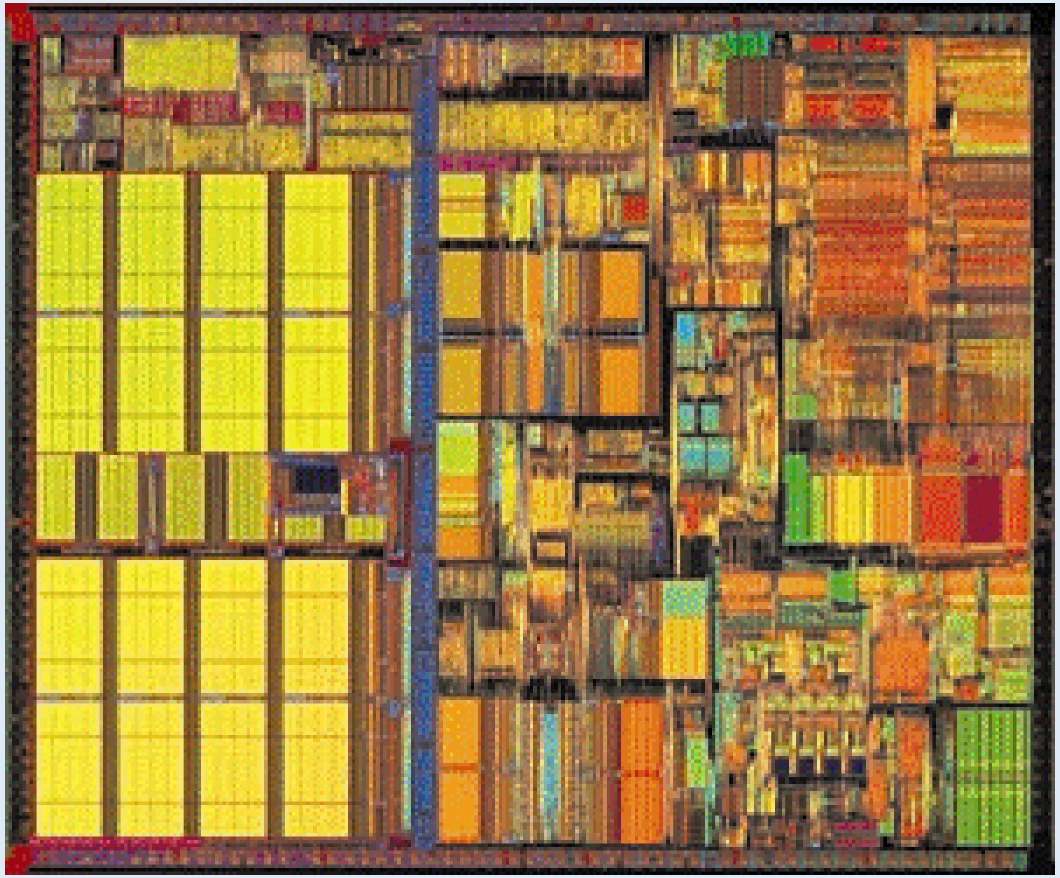
The basis of modern computer technology. Circuits built on semiconducting silicon, germanium. Signal switching, storage, valves, amplification etc

PC, mobil etc, invented 1947-48

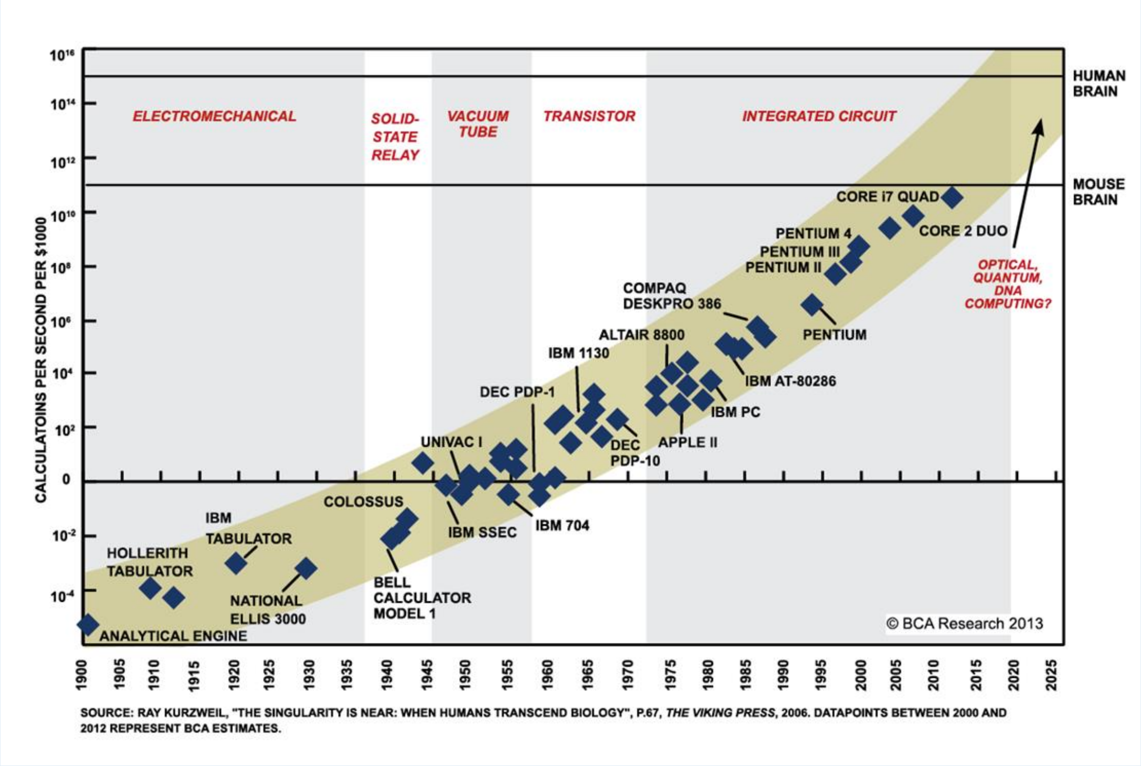




Integrated circuits allow tens of millions components on one chip (Pentium III)



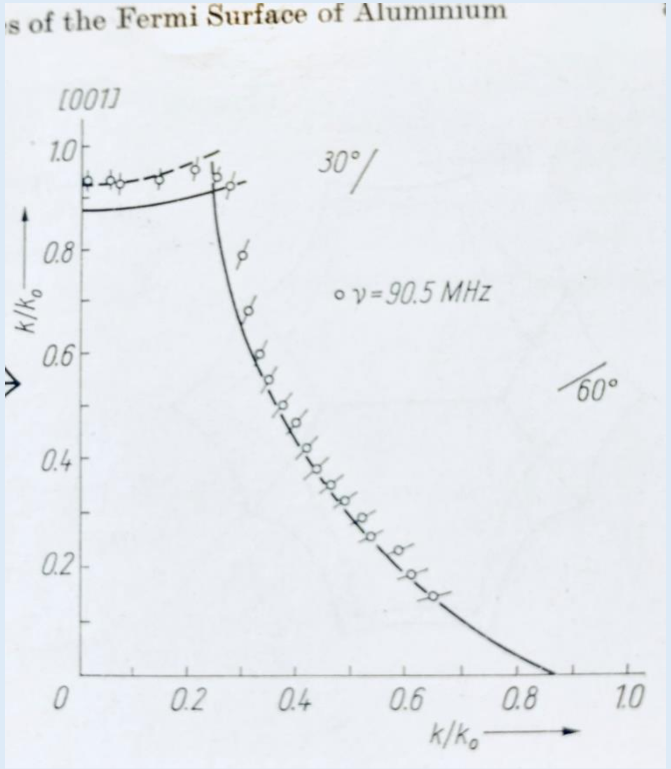
Moore`s law (1965) about increasing component density and data processing speed vs time, ~ doubling every second year



The electron manybody system: «electron gas» in metal

First measurements of electron impulse in varius directions in aluminium (Fermi surface)

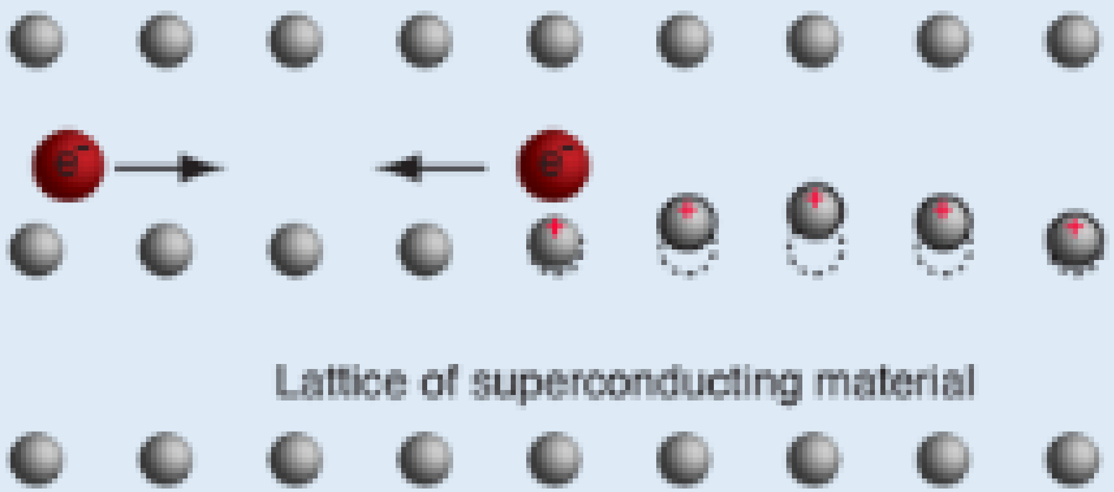
- Near ideal «gas»
- Segments of spheres. «electron gas» occupies all of momentum space inside observed figure



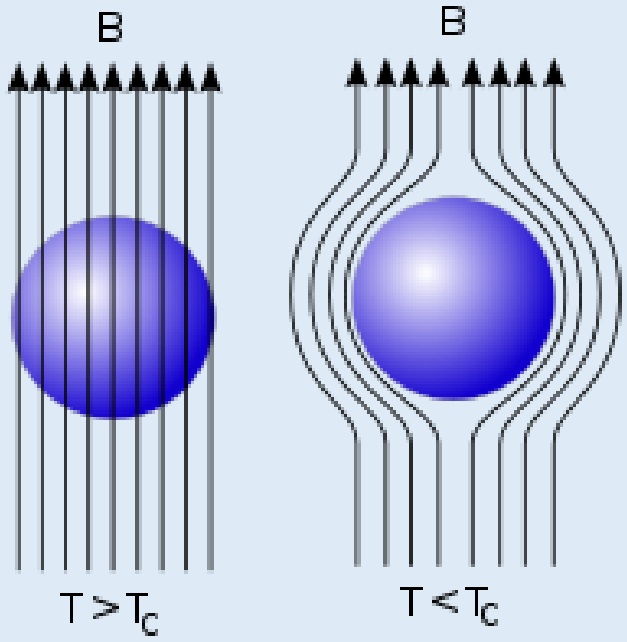
Low-Tc superconductor mechanism in metals

like aluminium, lead, mercury: «Cooper-pairs» of electrons created below Tc of (0- ca 25 K) through electron-electron interation via polarization of the positive ion lattice

- Two electrons of a Cooper-pair have lower energy than when totally free. This **energy gap** prevents electrons from experiencing individual **disturbance, resistance, by the therman motion of the surrounding ions.** So, electric current runs without resistance forever! First discovered 1911 at 4 K in frozen mercury.
- Most important application today: MR magnets in hospitals and clinics all over the world.



Superconductivity: The Meissner-effect: Metal sphere cooled through Tc loses all resistance and expels the magnetic field. Surface currents screen the inside from magnetic field. **Lossless current runs forever**

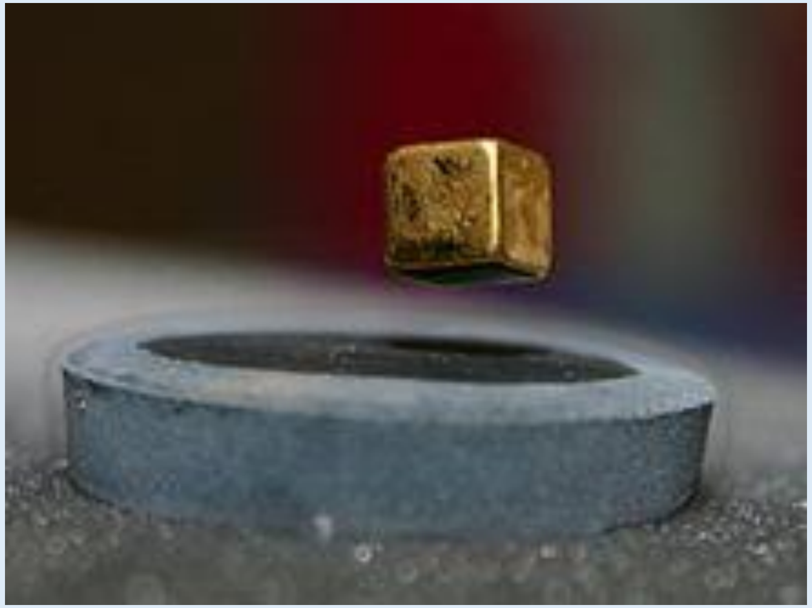


The enigma of superconductivity lasted for 45 years, from discovery in Leiden 1911 till Cooper and BCS theory 1956-57.

BCS (Bardeen- Cooper-Schrieffer theory) is a high point in all of theoretical physics

In 1986-87 came the discovery of «high-Tc superconductivity», up to 163 K.

(This type of experimental demonstration was performed live by me on the table of the NRK newsroom (Dagsrevyen) in connection with the award of the Nobel prize to Müller and Bednorz in 1987)



Phase transition from normal to superconducting metal
(indium) at 3.4 K

- Attenuation of ultrasound on passing from normal state above Tc to superconducting state

- Meissner effect causes screening of electromagnetic field and makes the transition observable with very high resolution

- Ref K Fossheim PRL 1967

Notice: Temperature scale in millikelvin

VOLUME 19, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JULY 1967

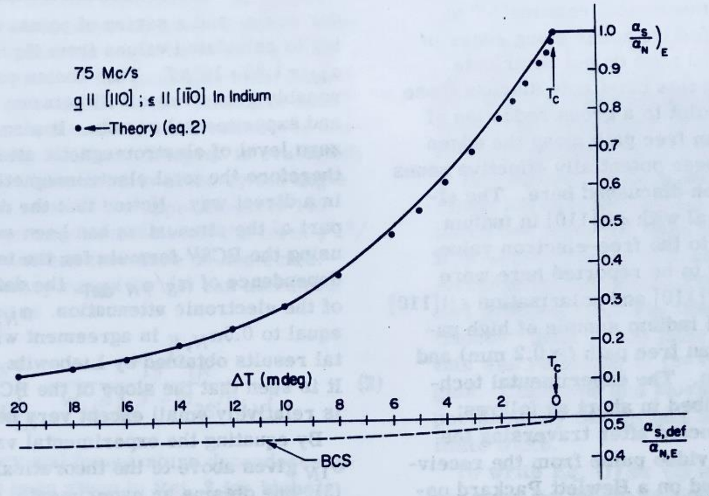


FIG. 2. The full line is a replot of the curve in Fig. 1 after the deformation attenuation has been subtracted, using the BCS function (bottom curve) for this part of the attenuation. The fit is then made by fixing the theoretical value of Eq. (2) to the curve at $\Delta T = 20$ mdeg. The ratio $\alpha_{S,\mathrm{def}}/\alpha_{N,E} = 0.50$ at T_c was taken from Ref. 15.

Discovery of high-Tc superconductor 1986-87
by Alex Müller and George Bednorz

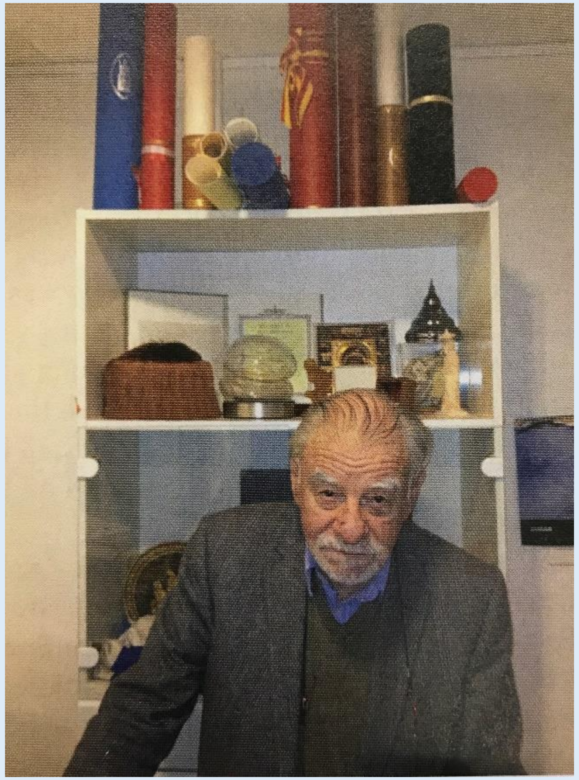
- Alex Müller has had very important impact on Norwegian physics. He worked at the IMB lab near Zurich
- He celebrated his 90th birthday in 1917.

  (I contributed a personal story of our collaboration, «Encounters with Alex», in the book to his honour)

- The discovery of high-Tc superconductivity has still not found its explanation, 30 years after the discovery
- Yet another Enigma!

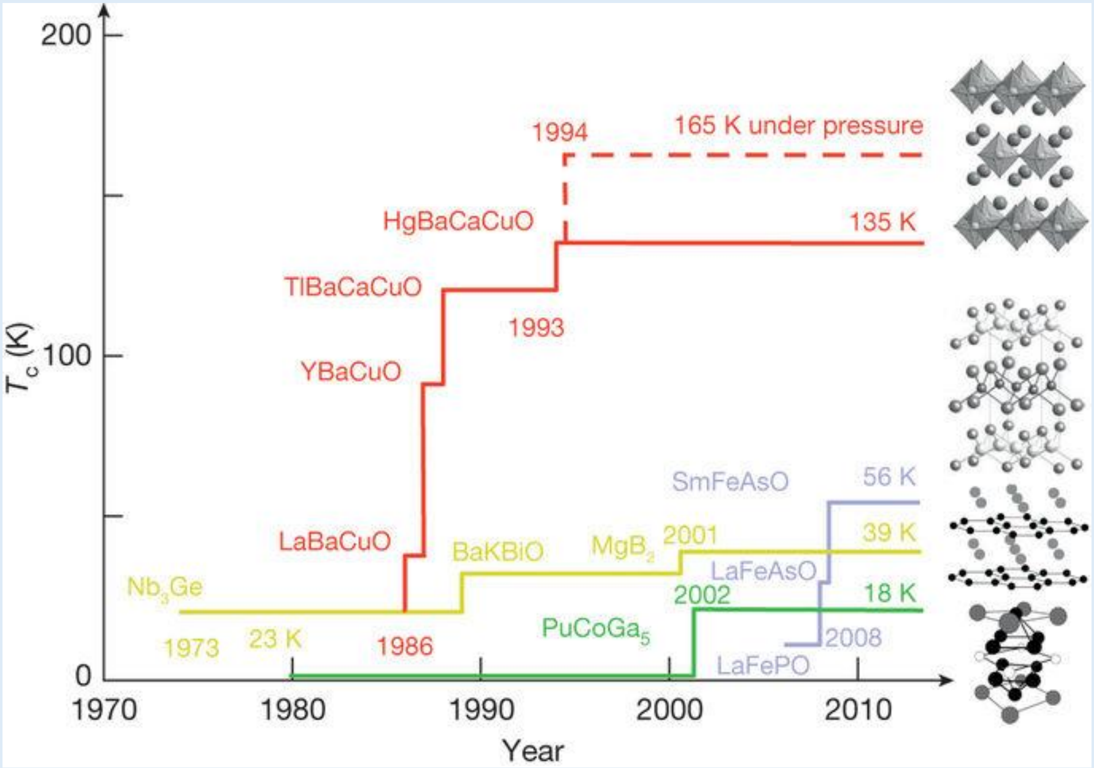
Alex Müller. Doctor Honoris Causa UNIT 1992. Nobel prize with Bednorz 1987

Here with the symbols of his 22 honorary degrees. (Photo KF)

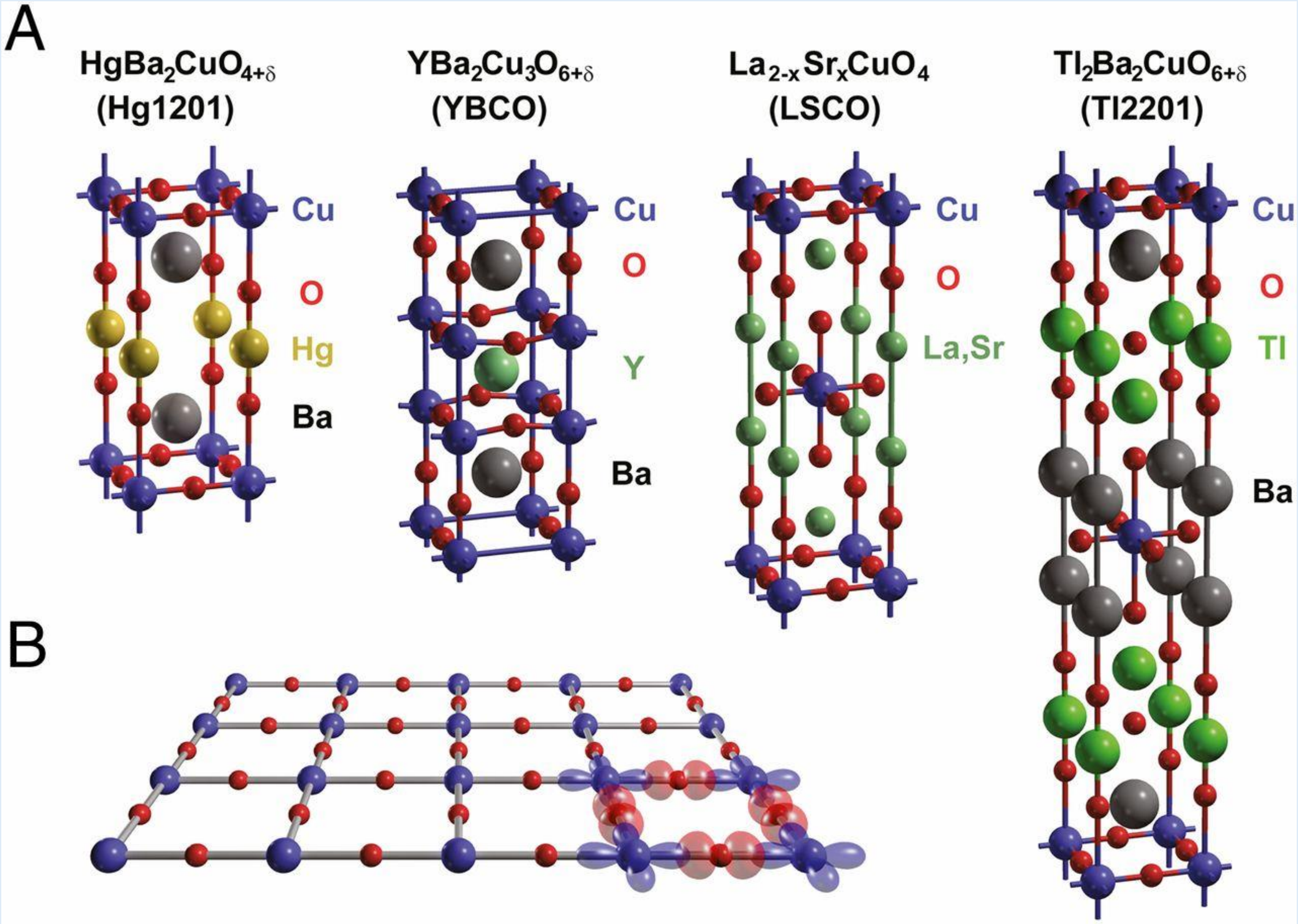


High-Tc cuprate superconductor progress

- Time development of observed Tc.



Some high-Tc superconductors discovered since 1986. There are now hundreds more



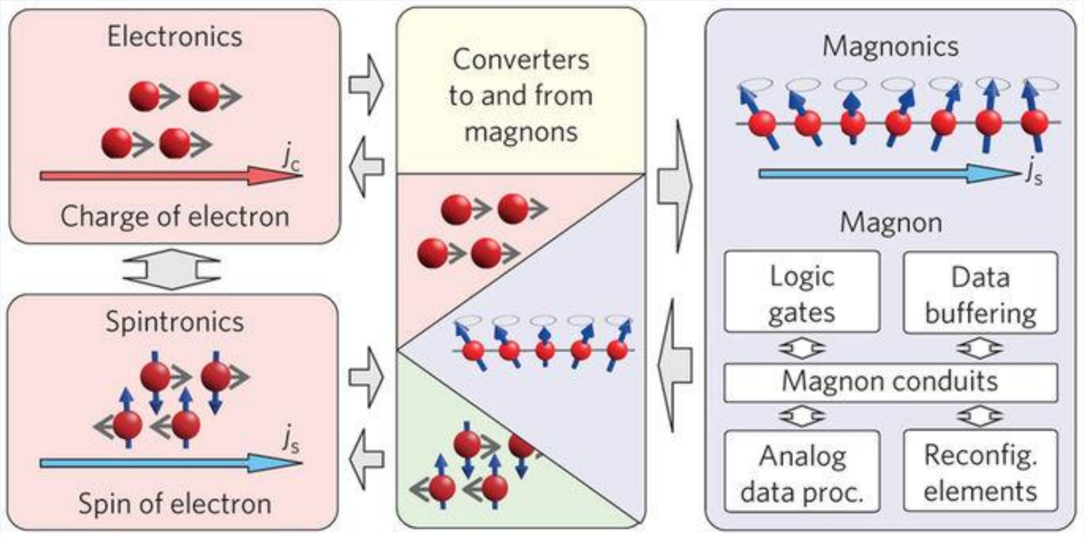
Spintronics, an alternative to the electronics we are used to, is coming our way in a very prestigeus project at Department of Physics:

«Senter For Fremragende Forskning (SFF): Spinntronikk (QuSpin)», just starting now, with near 50 people here and abroad

A major advantage is far less energy dissipation in spintronics curcuits +++

Signal storage and transport is not by electron charge but by the magnetic spin waves, magnons, hence does not require electron transport, allowing much lower dissipation and thereby continued increase of curcuit density and processing speed. Moore`s law may continue to persist.

Brataas, Sudbø, Linder, and several others are joining at our institute



Arne Brataas, Physics, NTNU

Head of SFF QuSpin, spintronics center

SUMMARY

The electron gave us quantum physics which revolutionized our understanding of nature

The electron gave us the transistor and the computer which revolutionized our lives

The Enigmatic Electron is still in for a bright future