Quantised Single Electron Pumping
Electrons Go Surfing

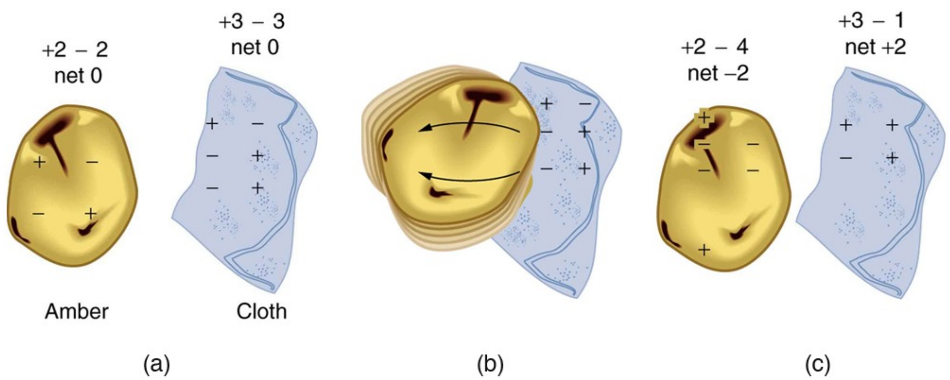
2025

Mark Blumenthal

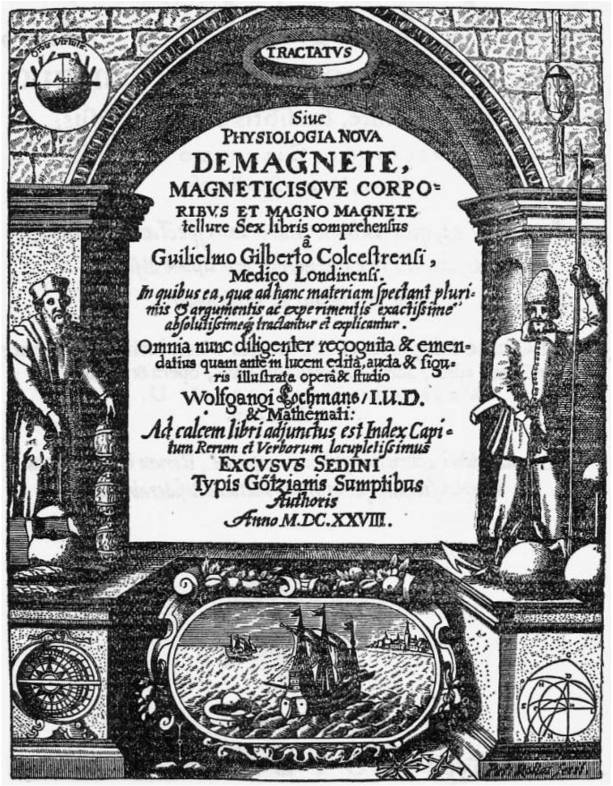
DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN

SA QuTI
South African Quantum Technology Initiative

Early Greeks
(12th BC - 600 AD)

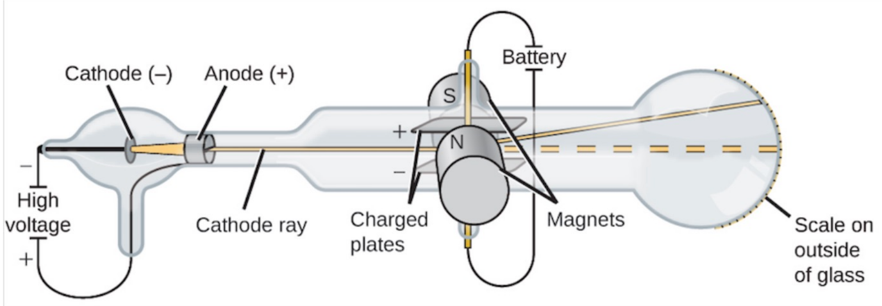


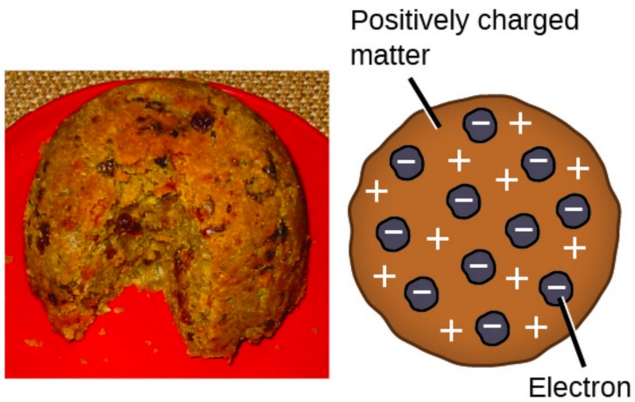
William Gilbert
(1600)



TRACTATVS
Siue
PHYSIOLOGIA NOVA
DE MAGNETE,
MAGNETICISQVE CORPO-
RIBVS ET MAGNO MAGNETE
tellure Sex libris comprehensus
à
Guilielmo Gilberto Colcestrensi,
Medico Londinensi.
*In quibus ea, quæ ad hanc materiam spectant pluri-
mis & argumentis ac experimentis exactissime
absolutissimeq; tractantur et explicantur.*
Omnia nunc diligenter recognita & emen-
datius quam antè in lucem edita, aucta & figu-
ris illustrata operâ & studio
Wolfgangi Lochmans / I.U.D.
& Mathemati:
*Ad calcem libri adjunctus est Index Capi-
tum Rerum et Verborum locupletissimus*
EXCVSVS SEDINI
Typis Götzianis Sumptibus
Authoris
Anno M.DC.XXVIII.

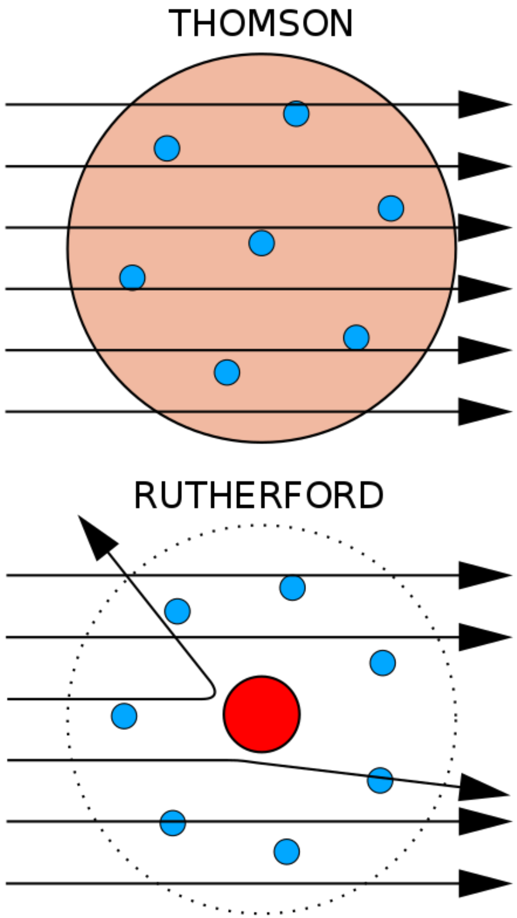
JJ Thompson (1897)

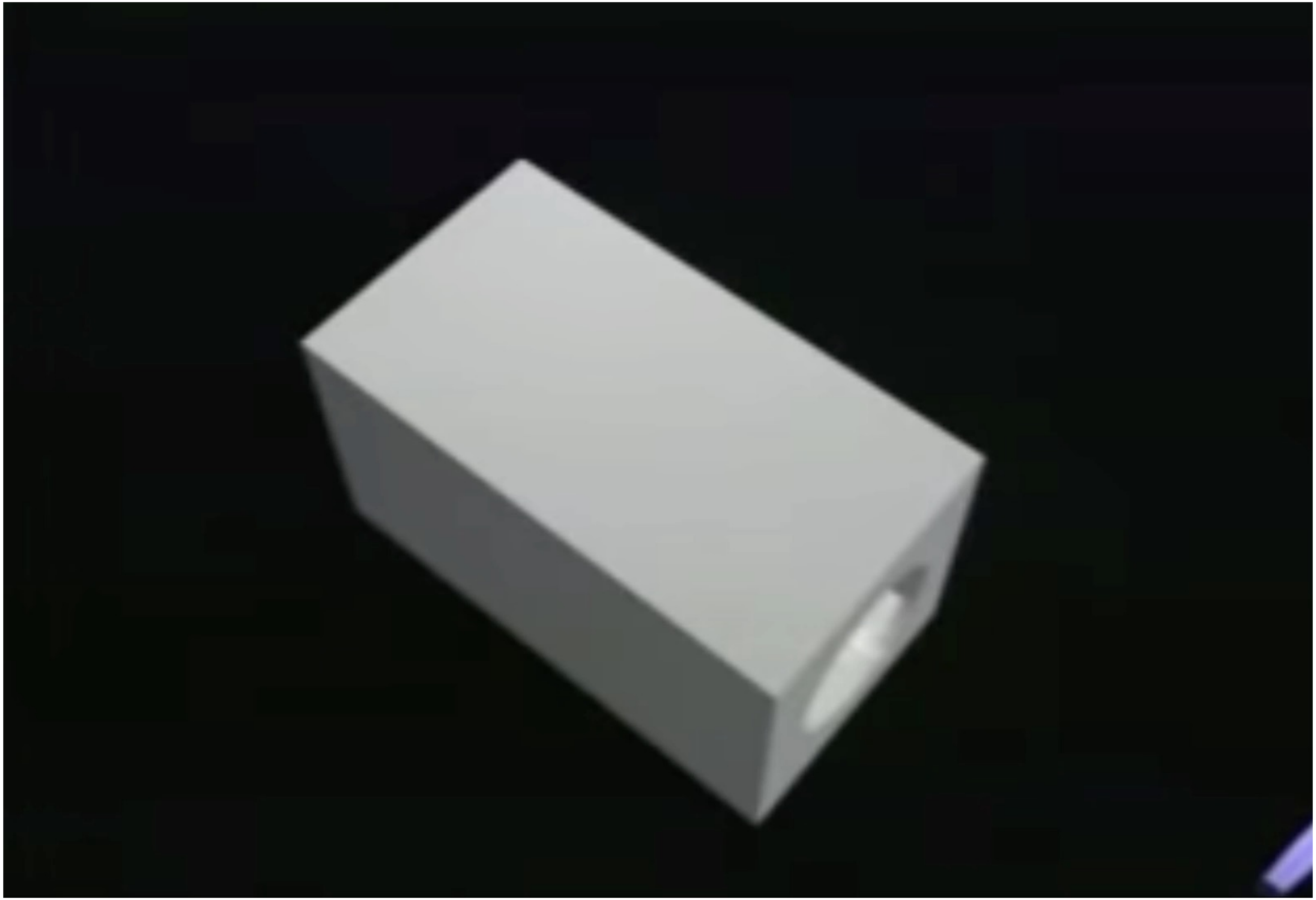




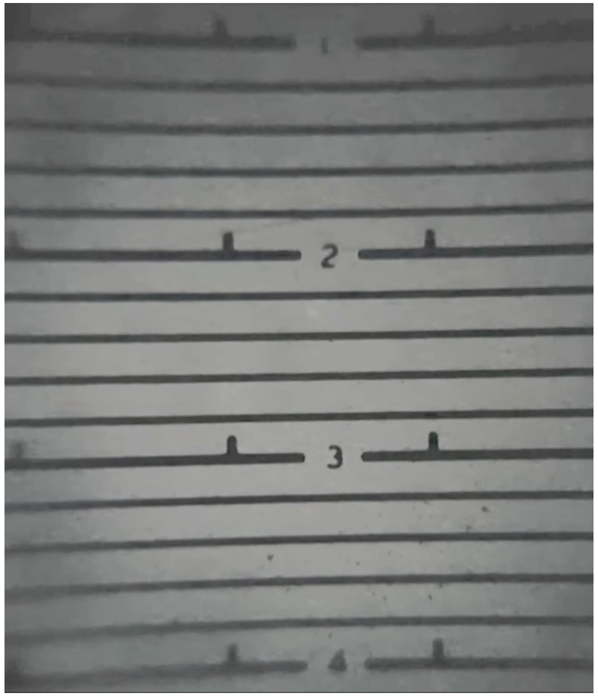
(a)

Ernest Rutherford (1909)

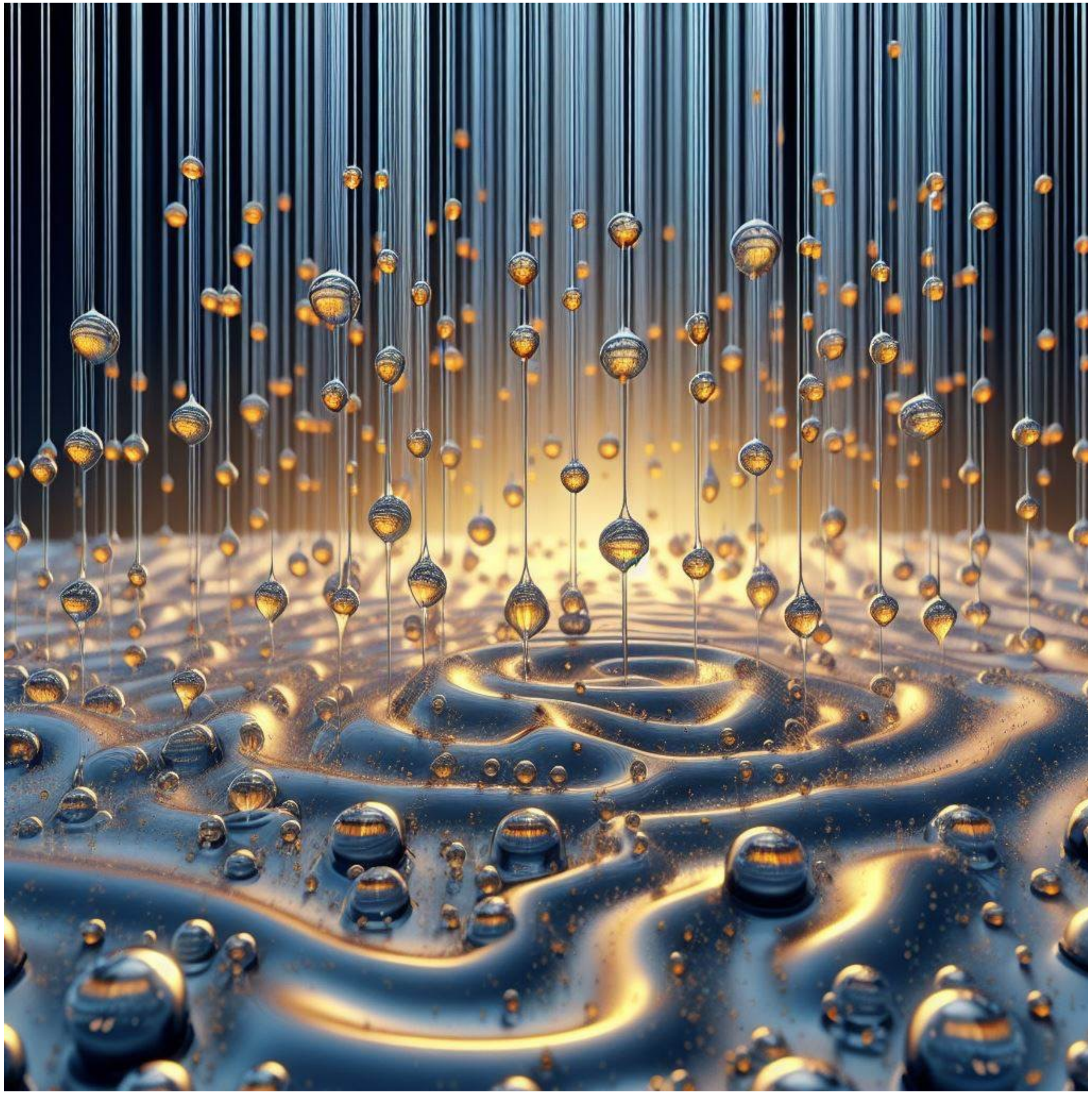




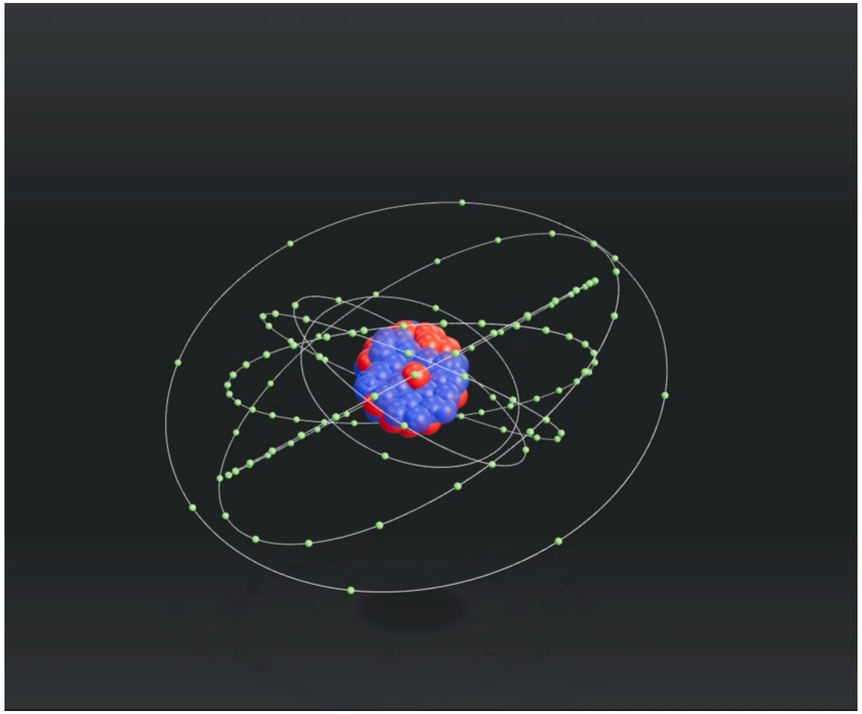
Millikan Oil Drop Experiment (1909)

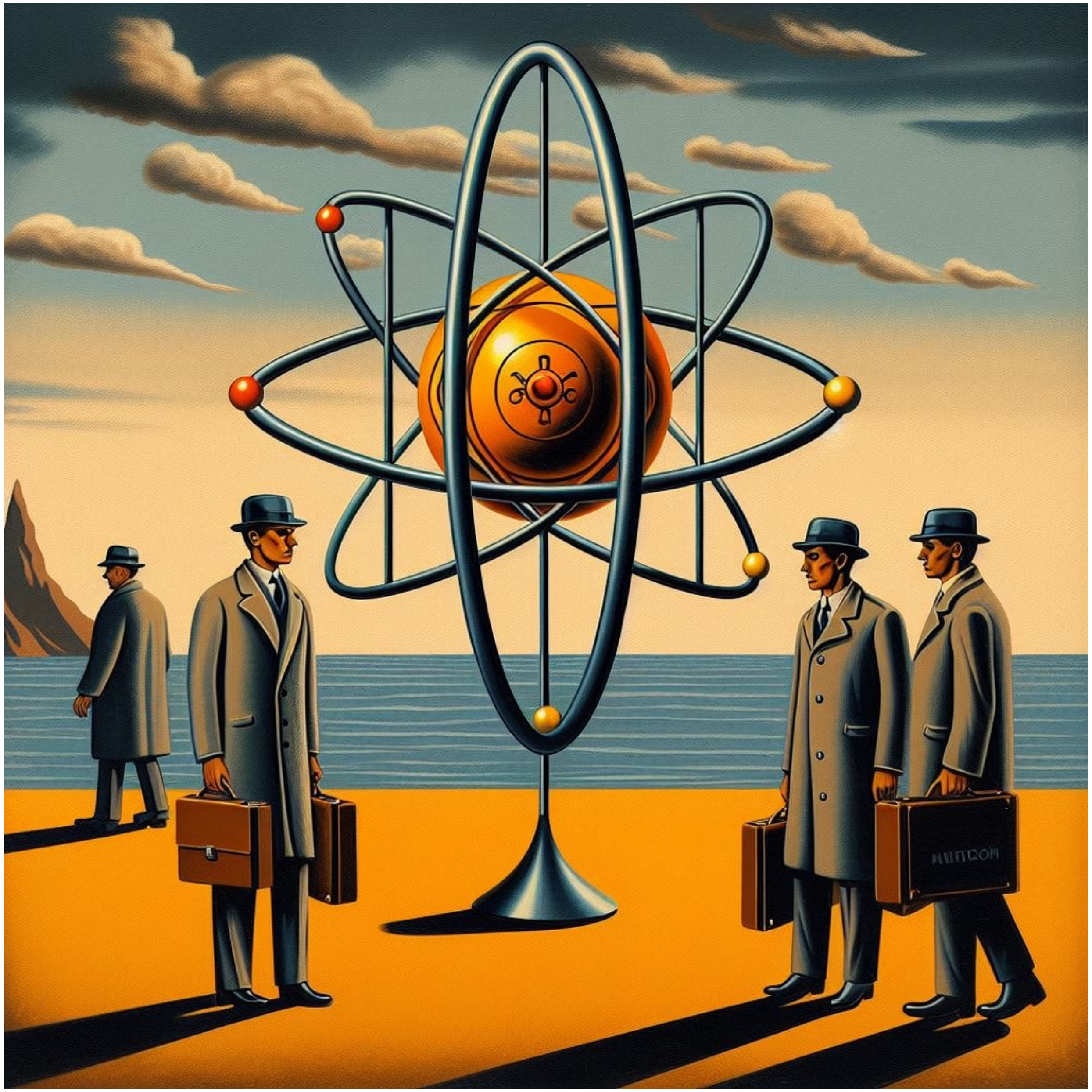


https://ophysics.com/em2.html



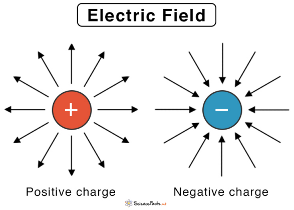
Bohr Model of the Atom (1913)

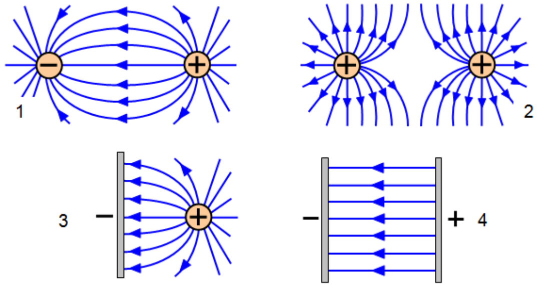




Electrons in Fields

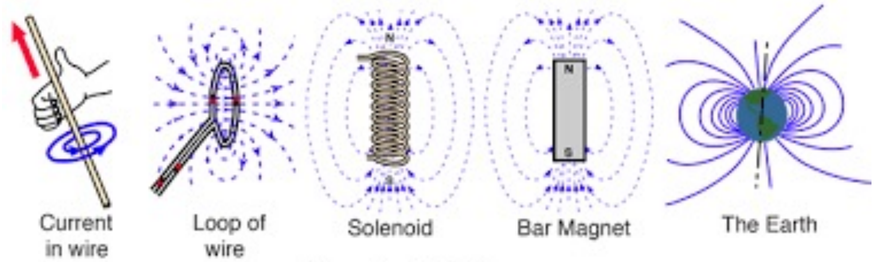
Electric





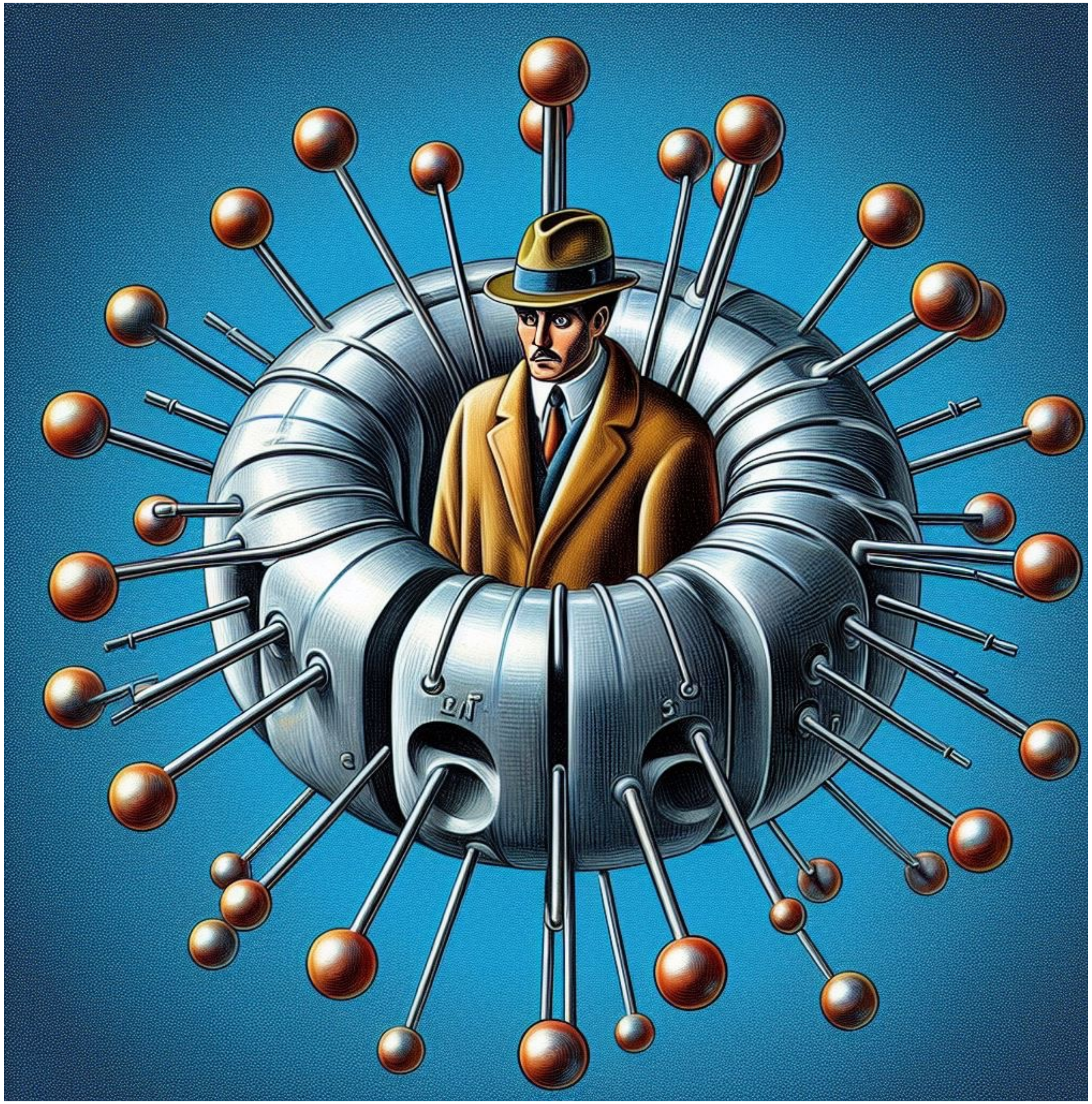
https://ophysics.com/em6.html

Magnetic

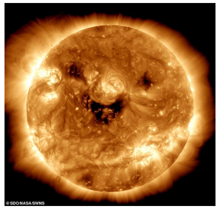


Magnetic Field Sources

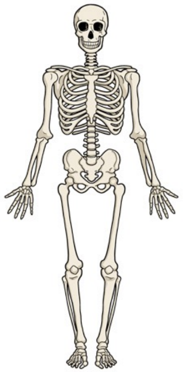
https://ophysics.com/em8.html



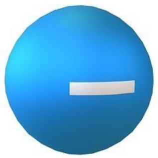
Electrons
Humans
and the Sun



1.39 Billion m



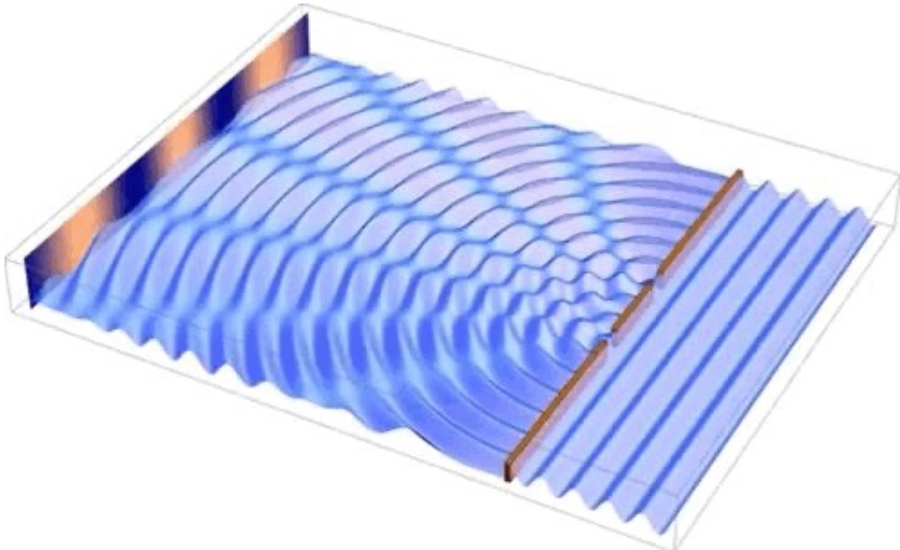
1.7 m

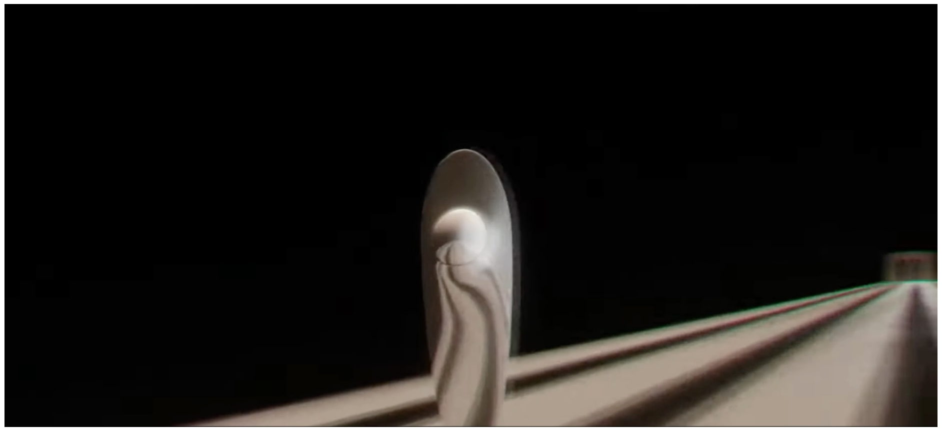


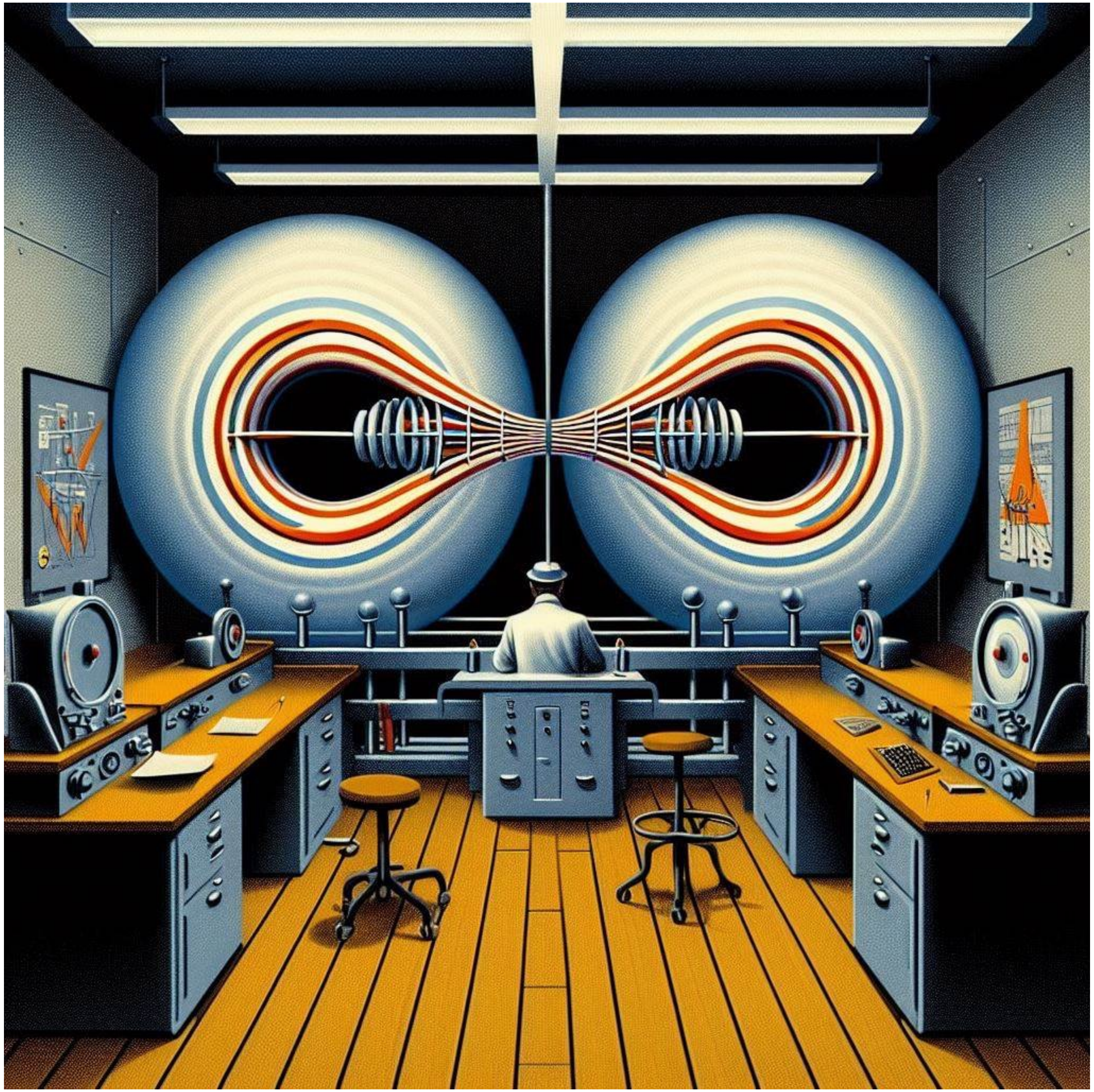
5.64 Femto m

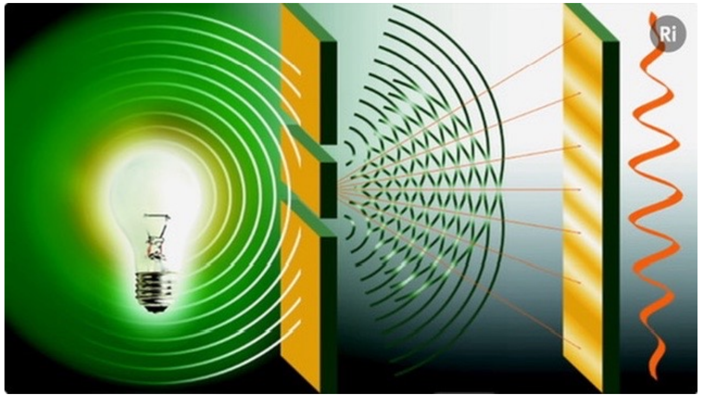
365 000

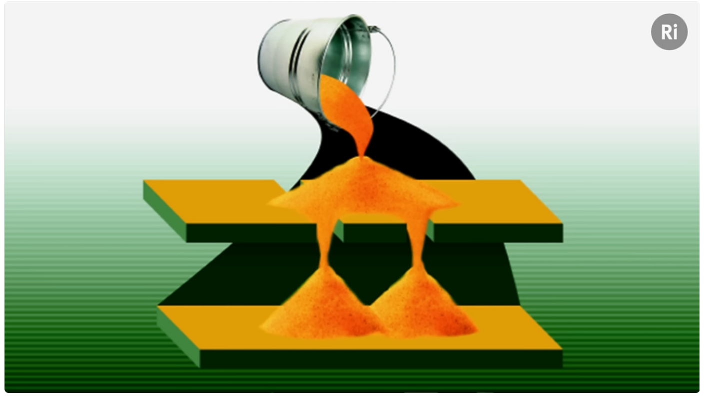
Davison and Germer (1927)

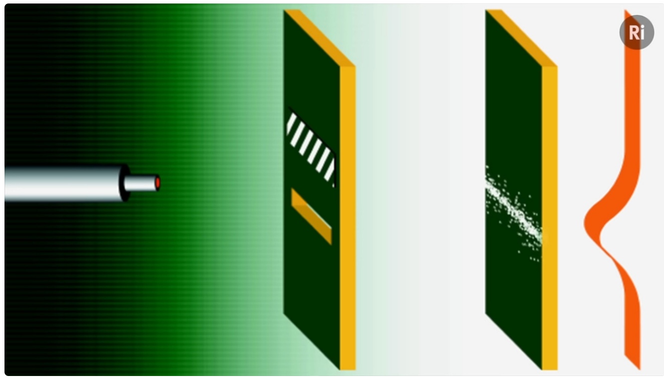


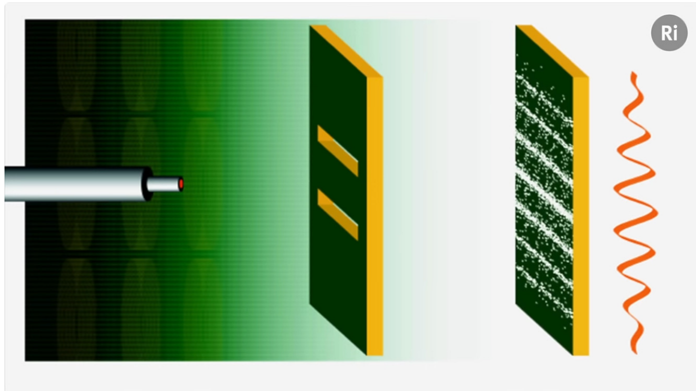


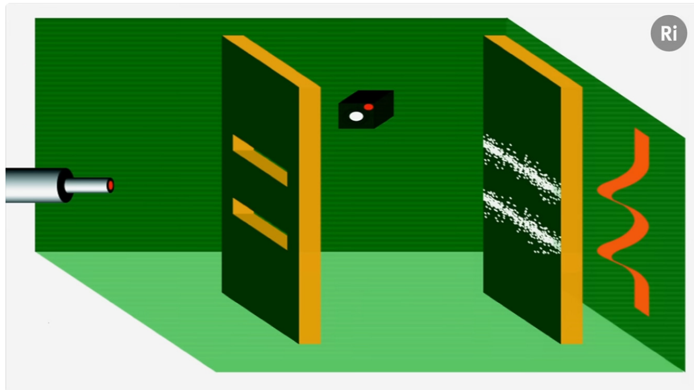




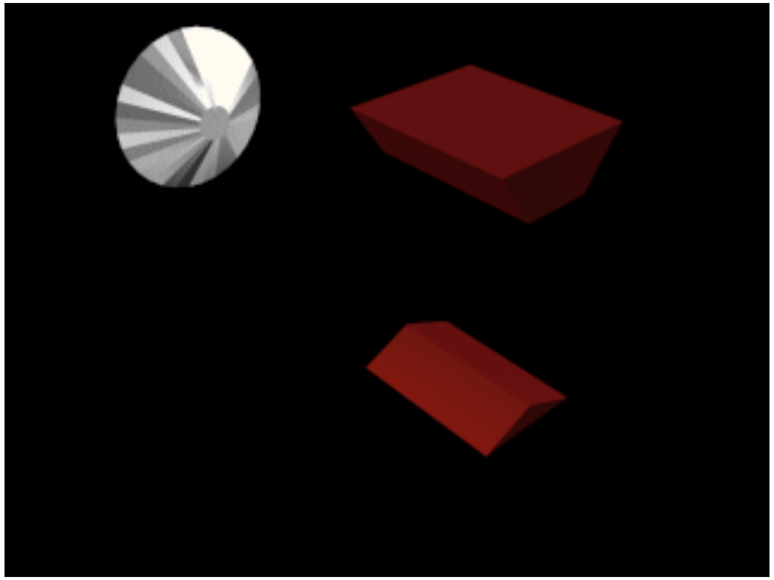


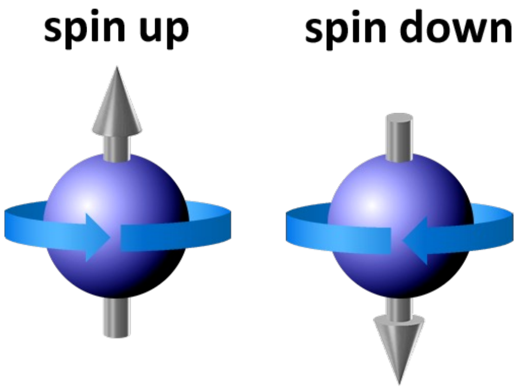


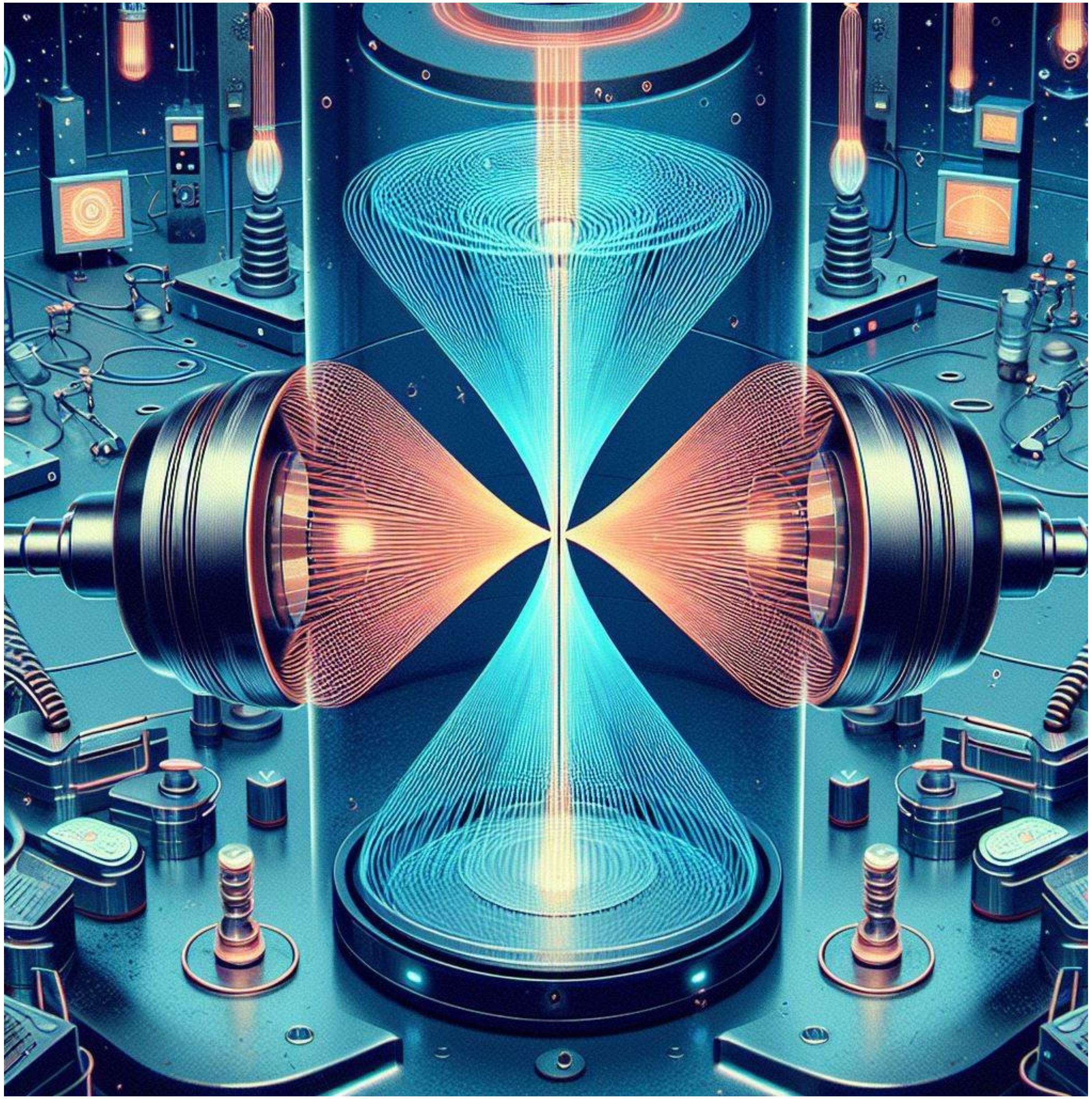


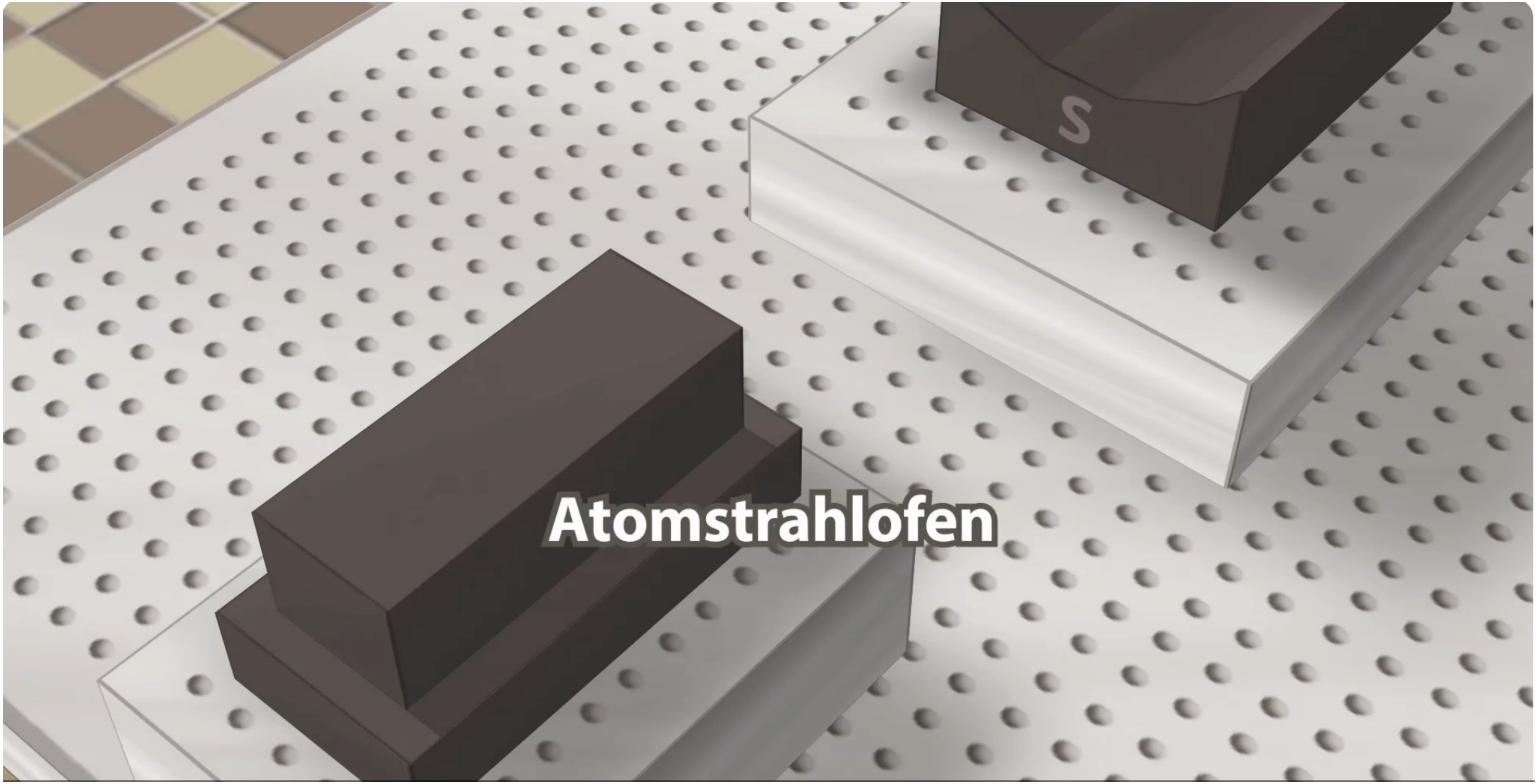


Stern-Girlach Experiment








S
Atomstrahlofen

Electron Spin

A tale of a blind man,
two tiles
and a desert!

Simple Harmonic Oscillator

- Particle in a **parabolic potential:**

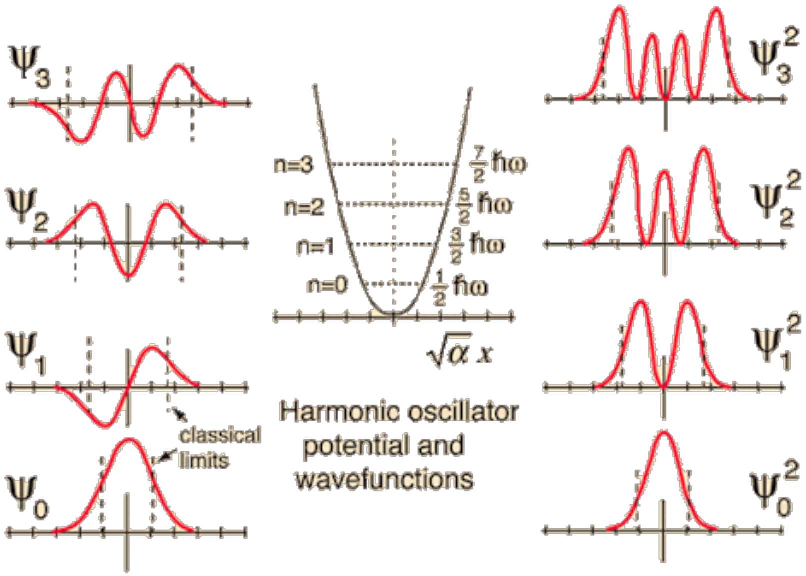
$$V(x) = \frac{1}{2}m\omega^2 x^2$$

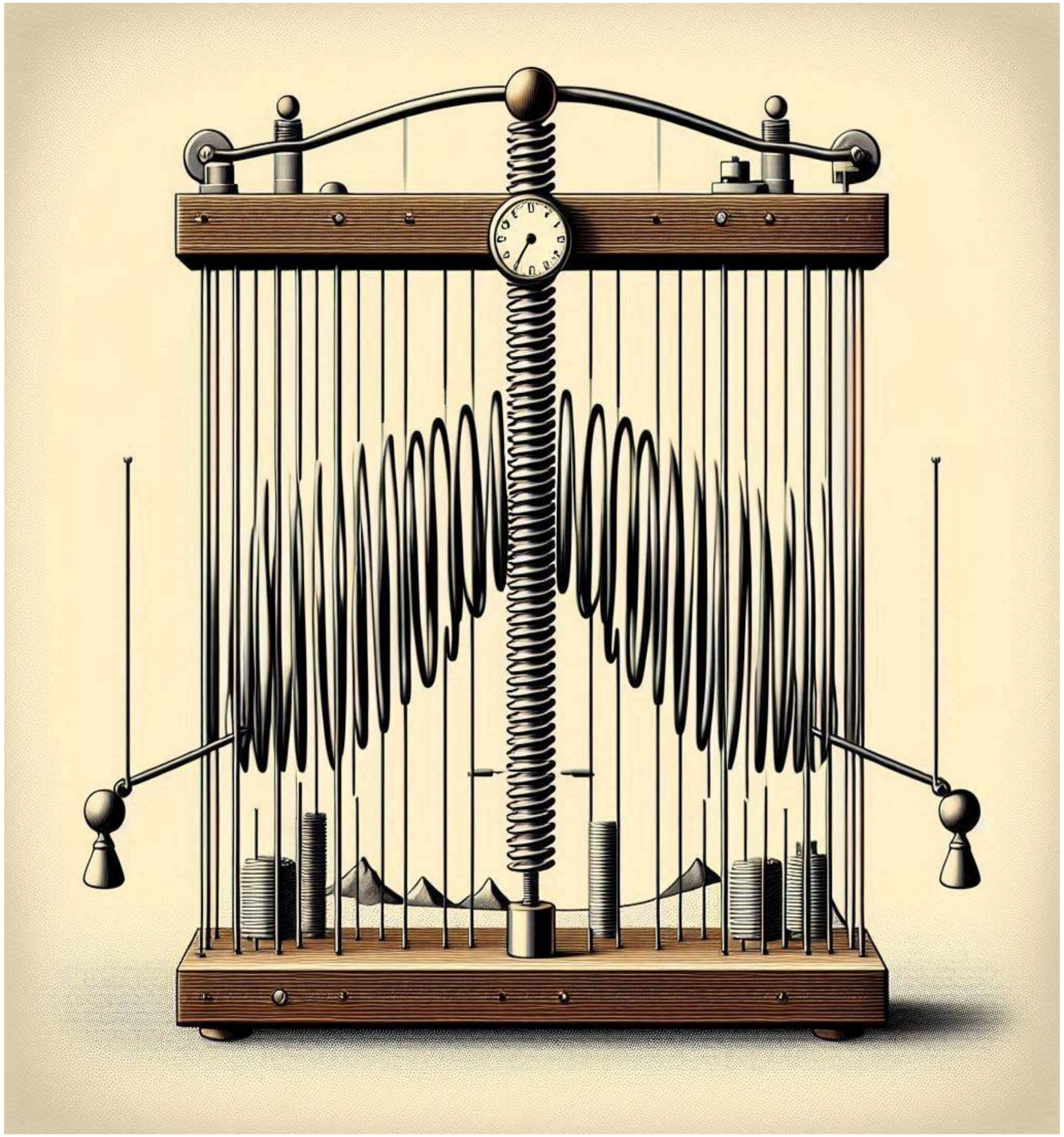
- Governed by Schrödinger equation:

$$\left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + \frac{1}{2}m\omega^2 x^2\right)\psi(x) = E\psi(x)$$

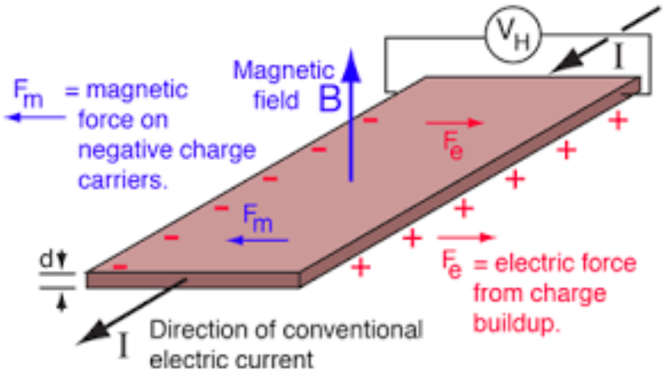
- Energy levels are **quantized**:

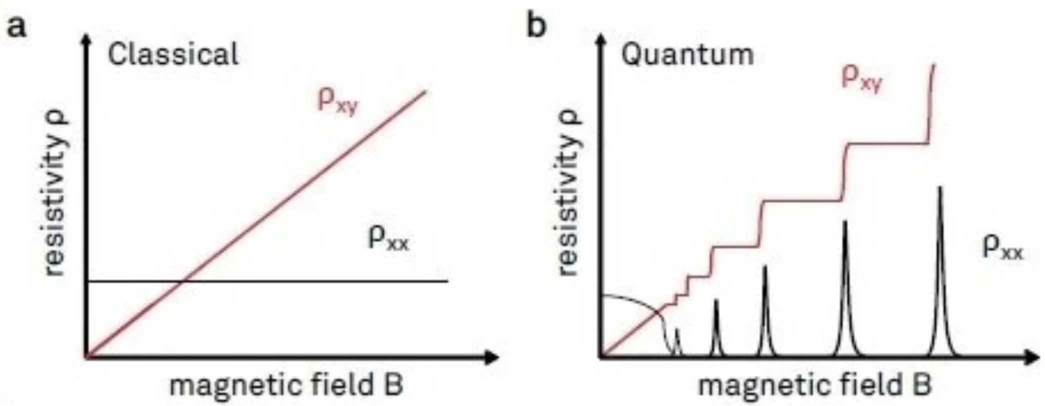
$$E_n = \hbar\omega\left(n + \frac{1}{2}\right), \quad n = 0, 1, 2, \ldots$$





Quantum Hall Effect





- Hamiltonian with B field resembles QHO:

$$H = \frac{1}{2m}(\mathbf{p} + e\mathbf{A})^2$$

- Energy levels are equally spaced:

$$E_n = \hbar\omega_c\left(n + \frac{1}{2}\right)$$

where $\omega_c = \frac{eB}{m}$ is the **cyclotron frequency**.

- Just like QHO: **discrete, equally spaced levels.**

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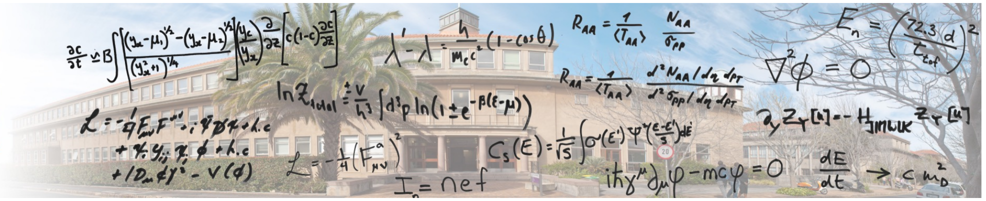
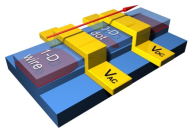
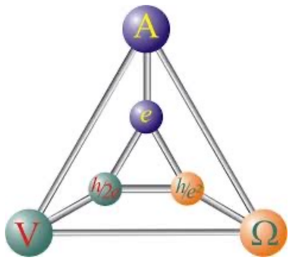
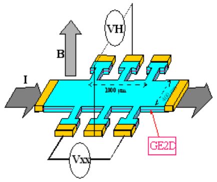
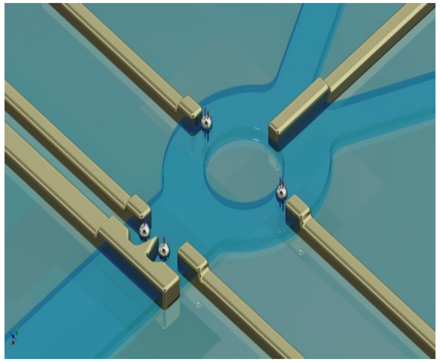


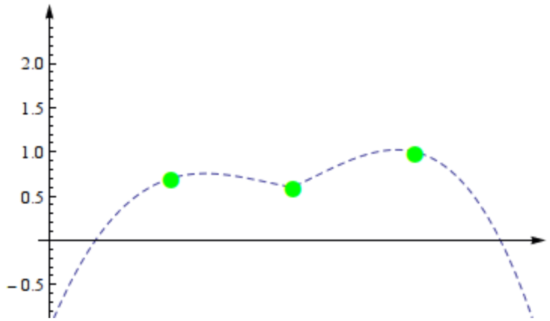
NanoElectronics Research Laboratory

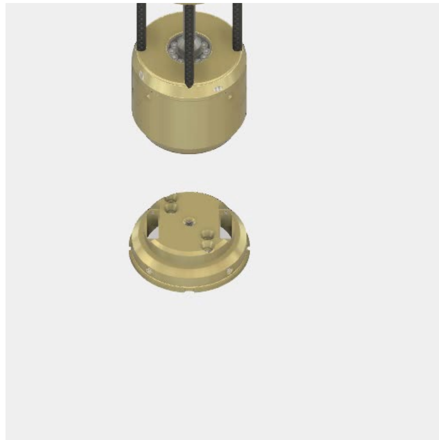


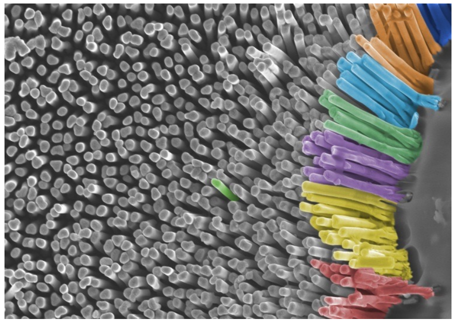


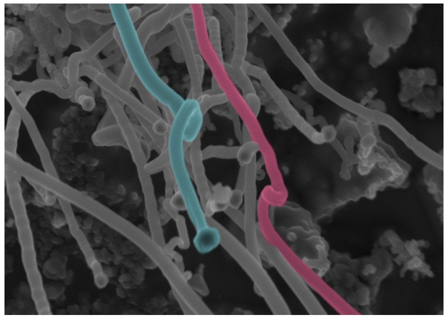




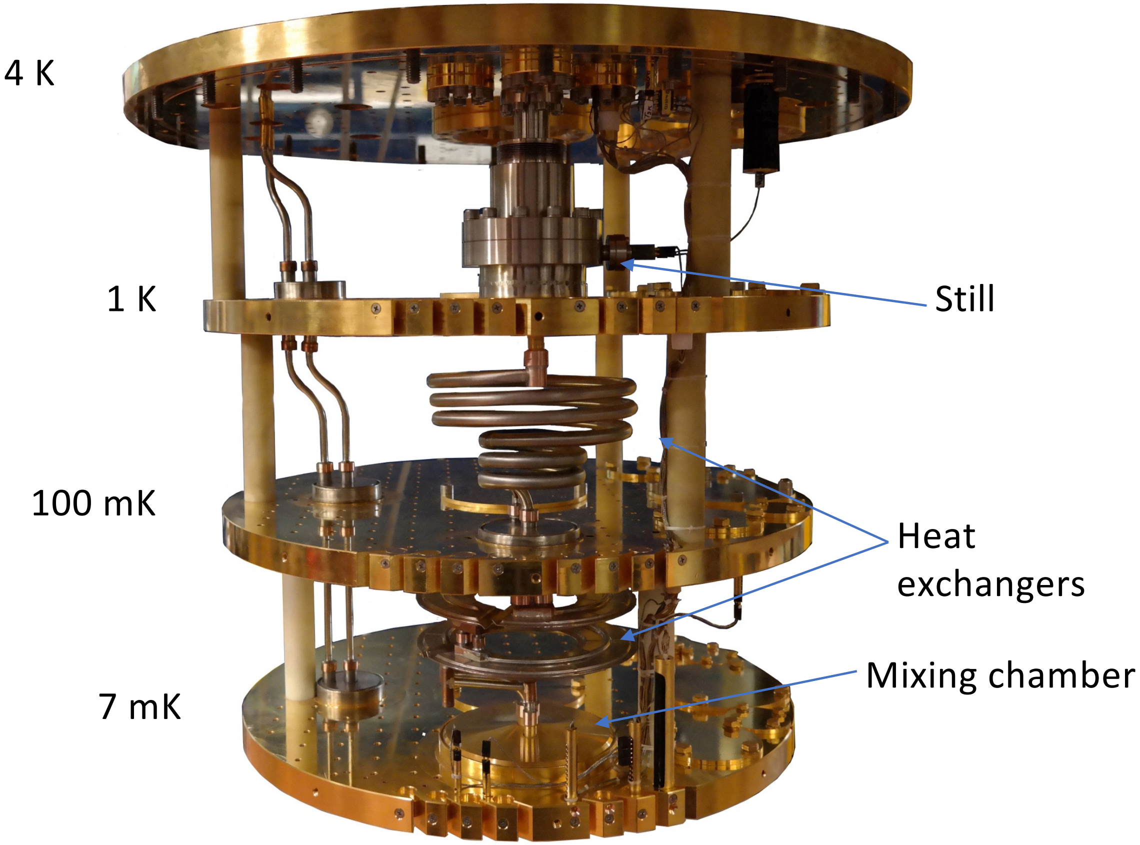






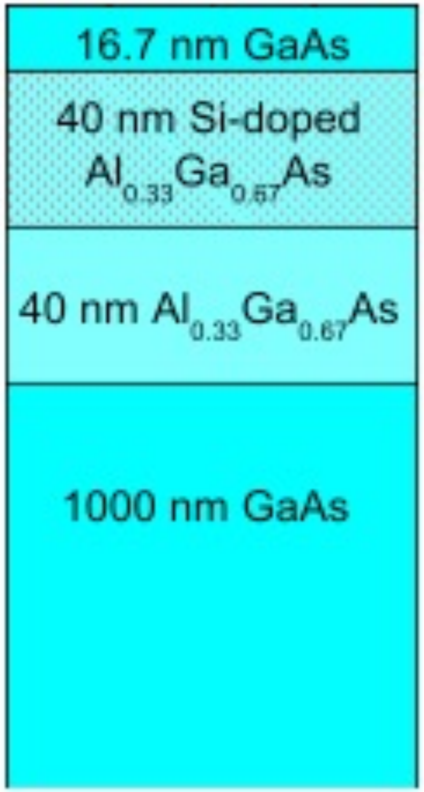


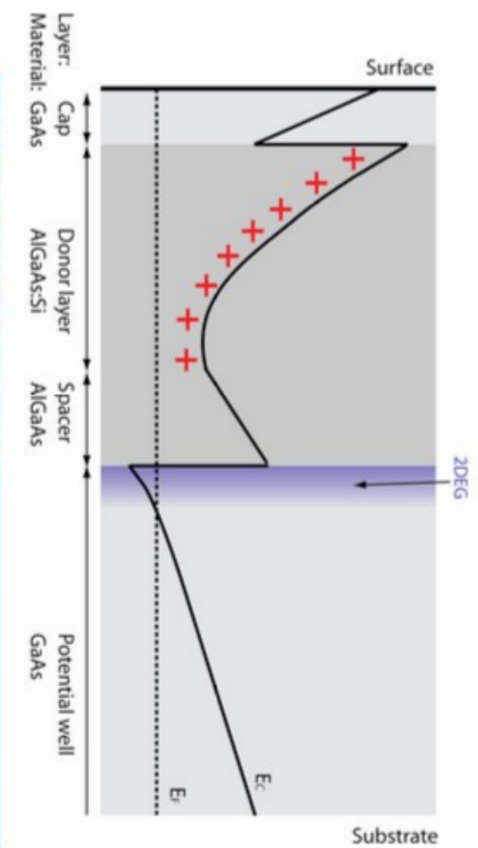
Coldest Place
in
Africa

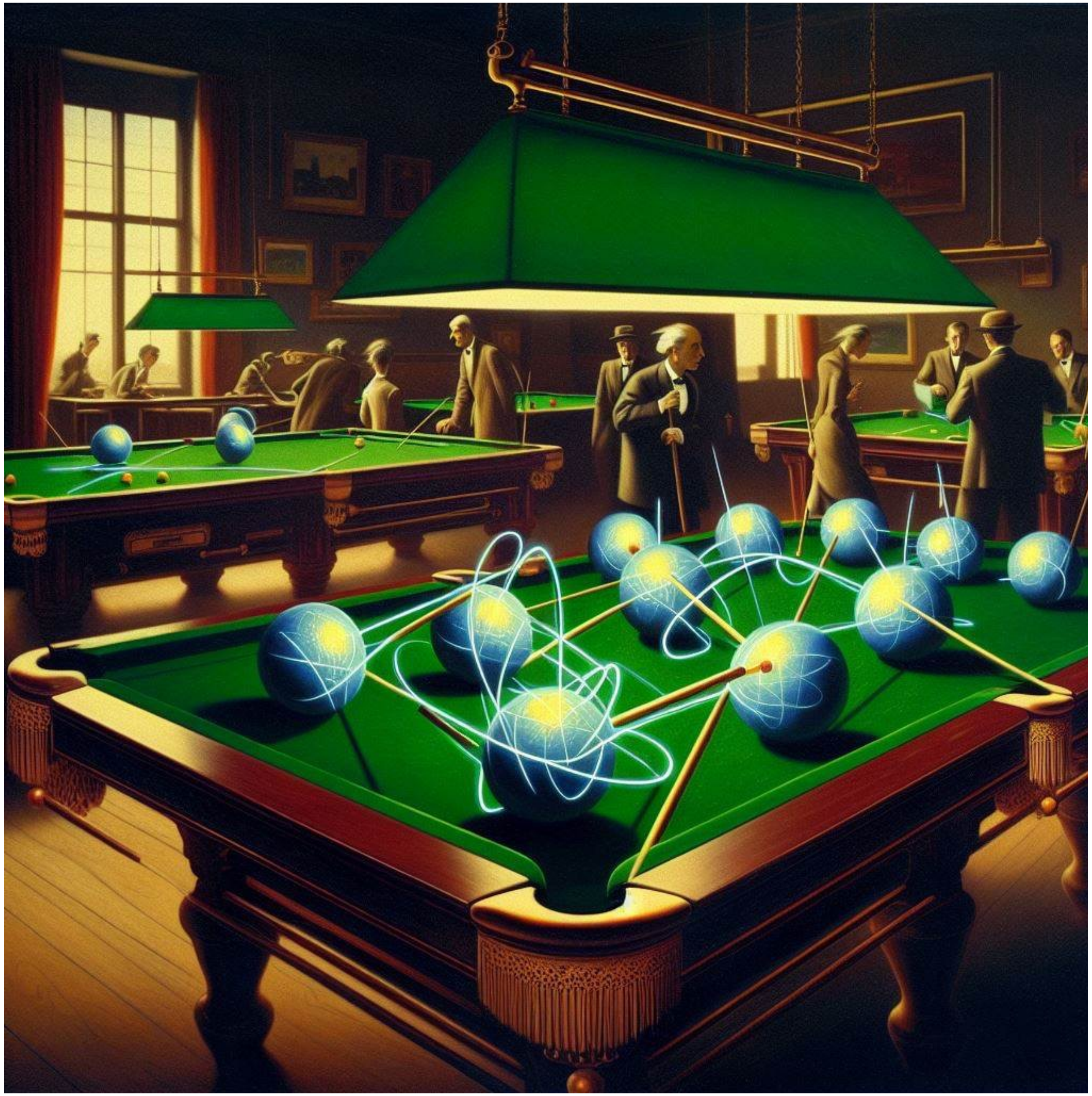

4 K
1 K
Still
100 mK
Heat
exchangers
Mixing chamber
7 mK


Boomerang Nebula

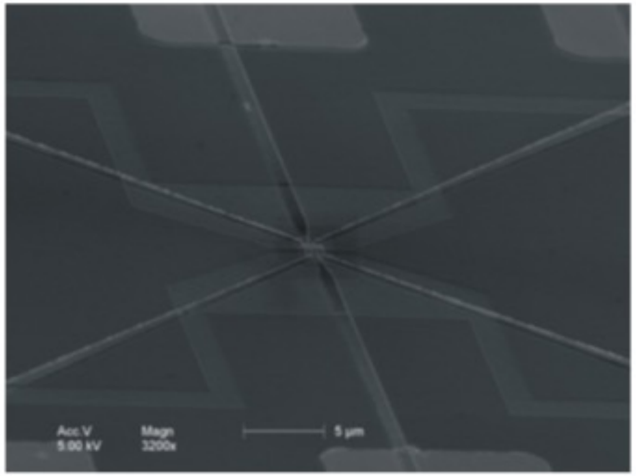
2D - Electron Gas

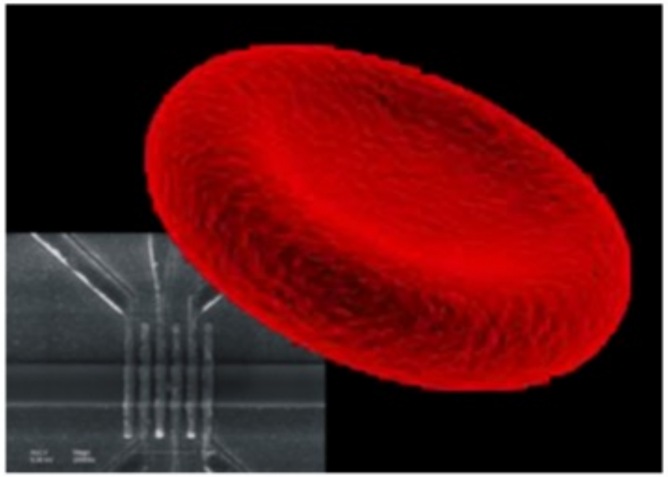


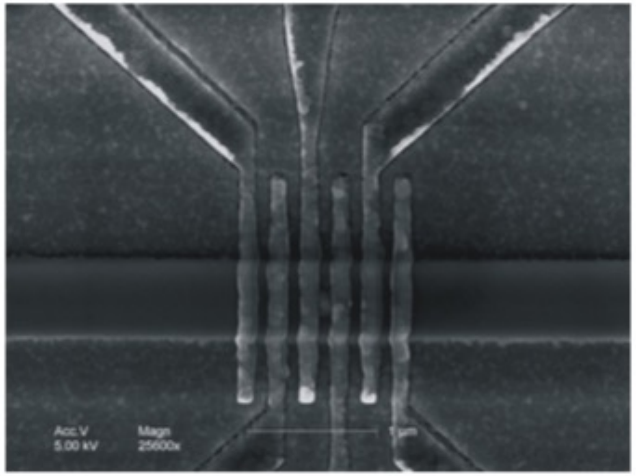


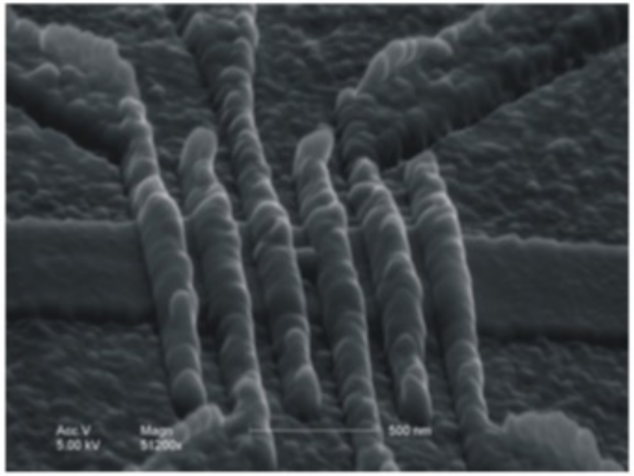


Electron Pumps

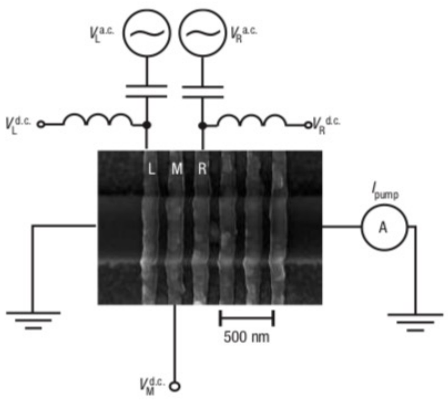


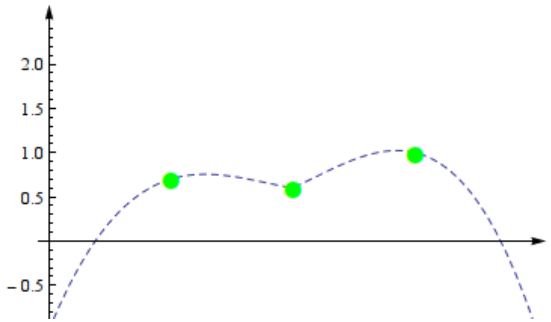




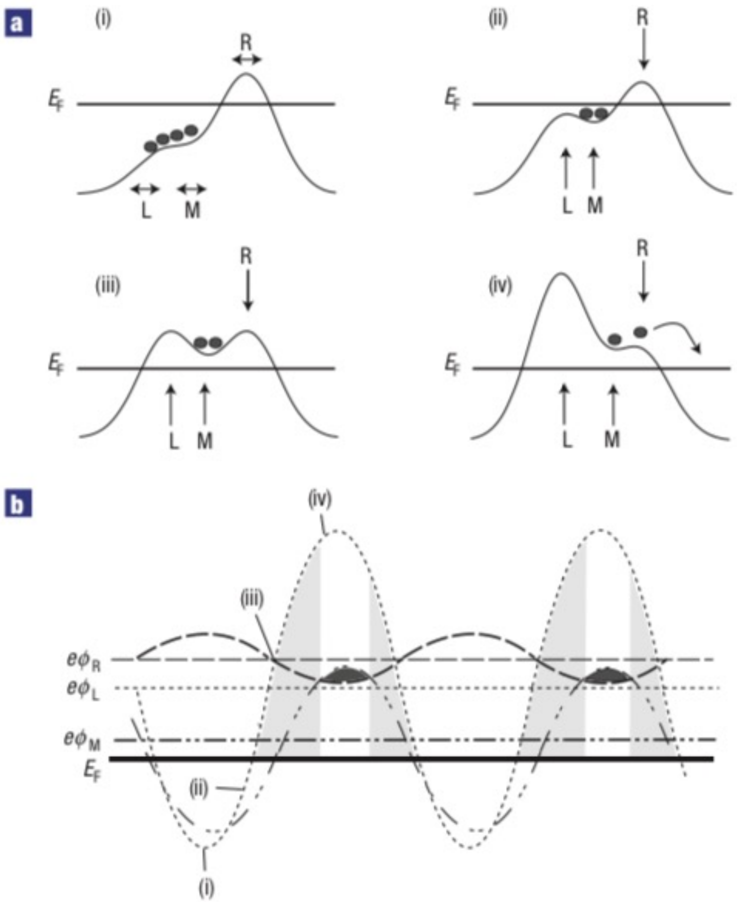


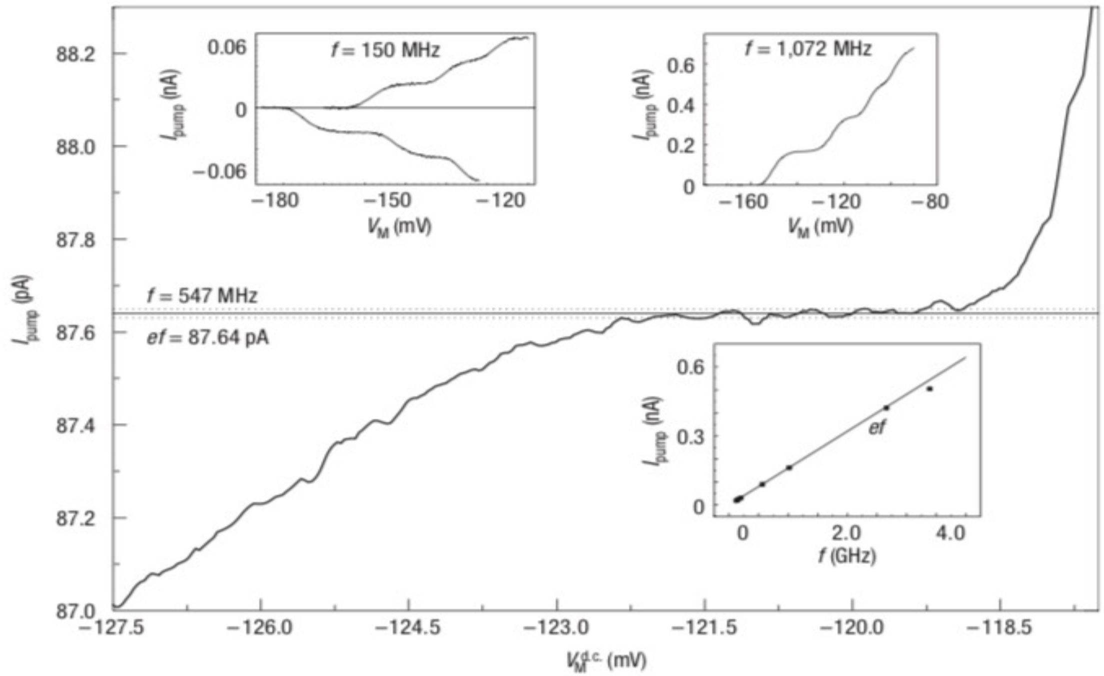
Electrons Go Surfing





High Frequency Single Electron Pumps

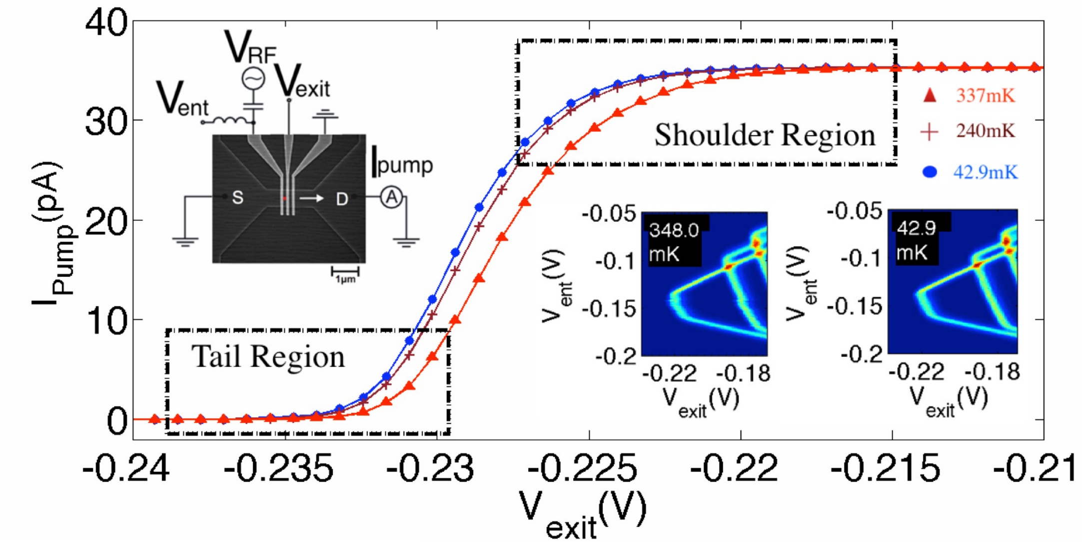


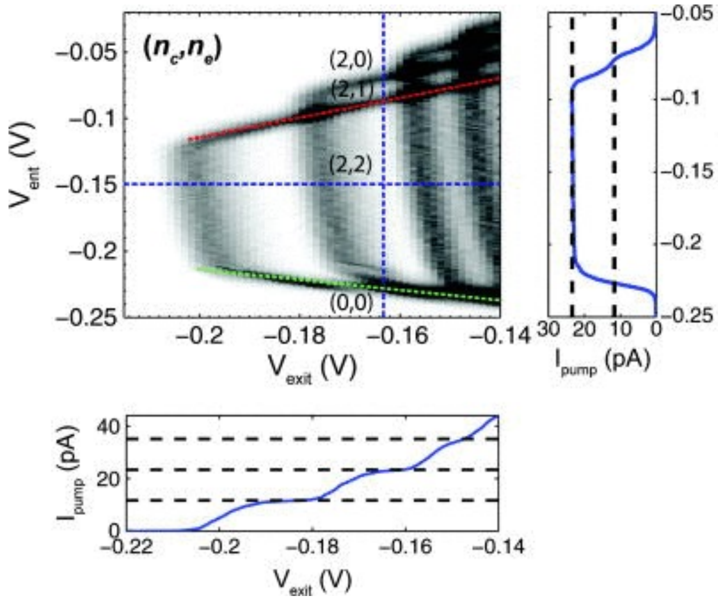


$$I = nef$$

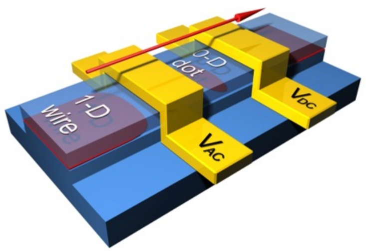
Blumenthal M.D et al. Gigahertz quantized charge pumping Nature Physics 3, 342 (2007)

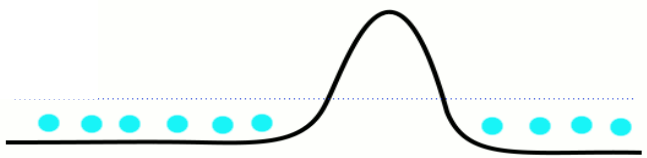
Pumping Mechanism and Temperature Effects

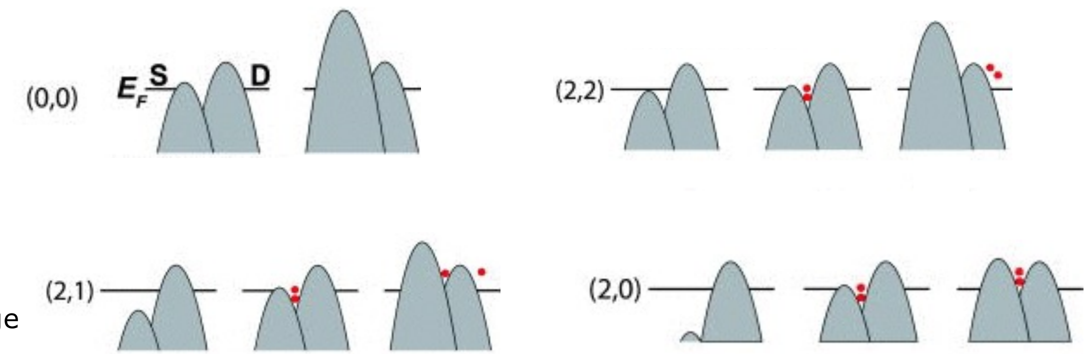




Wright, S. J. et al. Enhanced current quantization in high-frequency electron pumps in a perpendicular magnetic field. PhysRevB.78.(11) 3311 (2011)

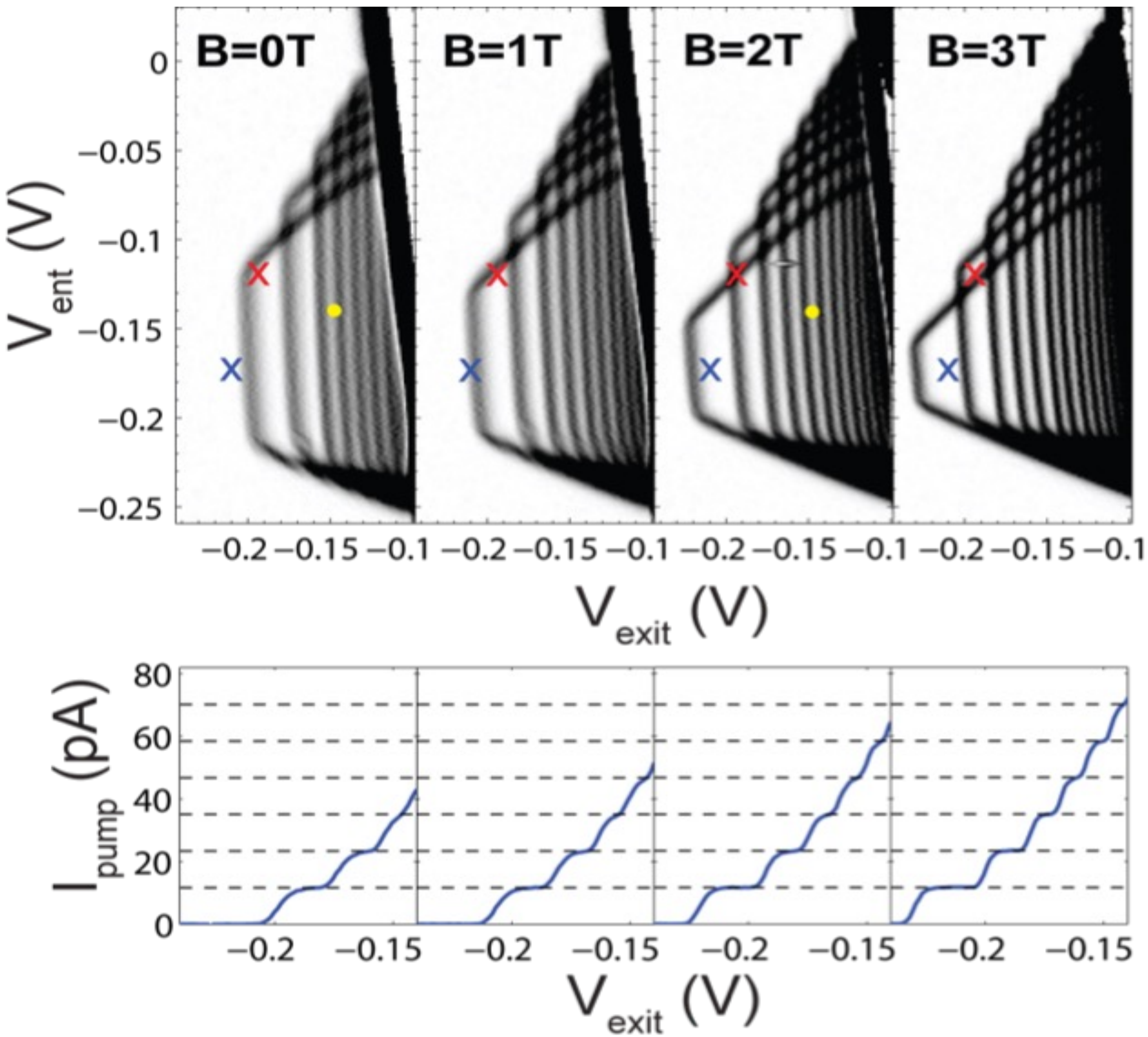




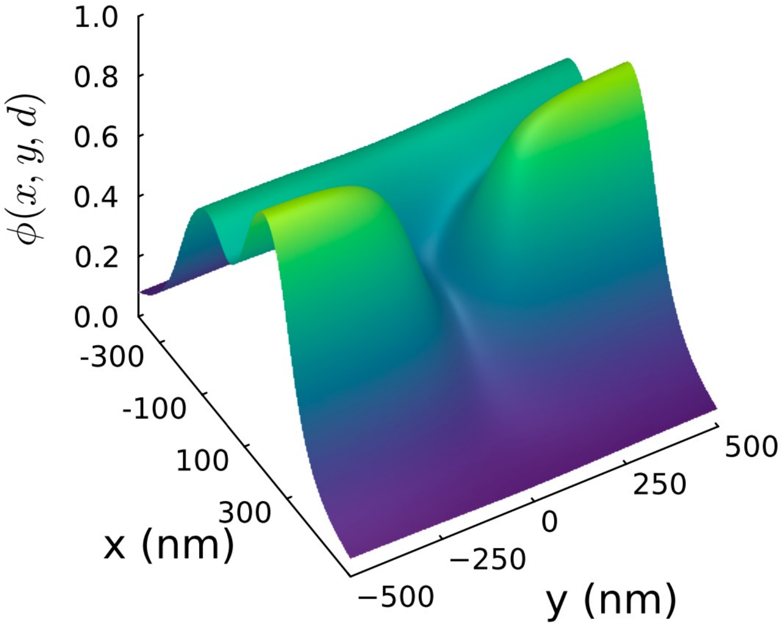


Kaestner, B et al. Single-parameter nonadiabatic quantized charge pumping. *Physical Review B - Condensed Matter and Materials Physics,* PhysRevB.77.(15) 3301

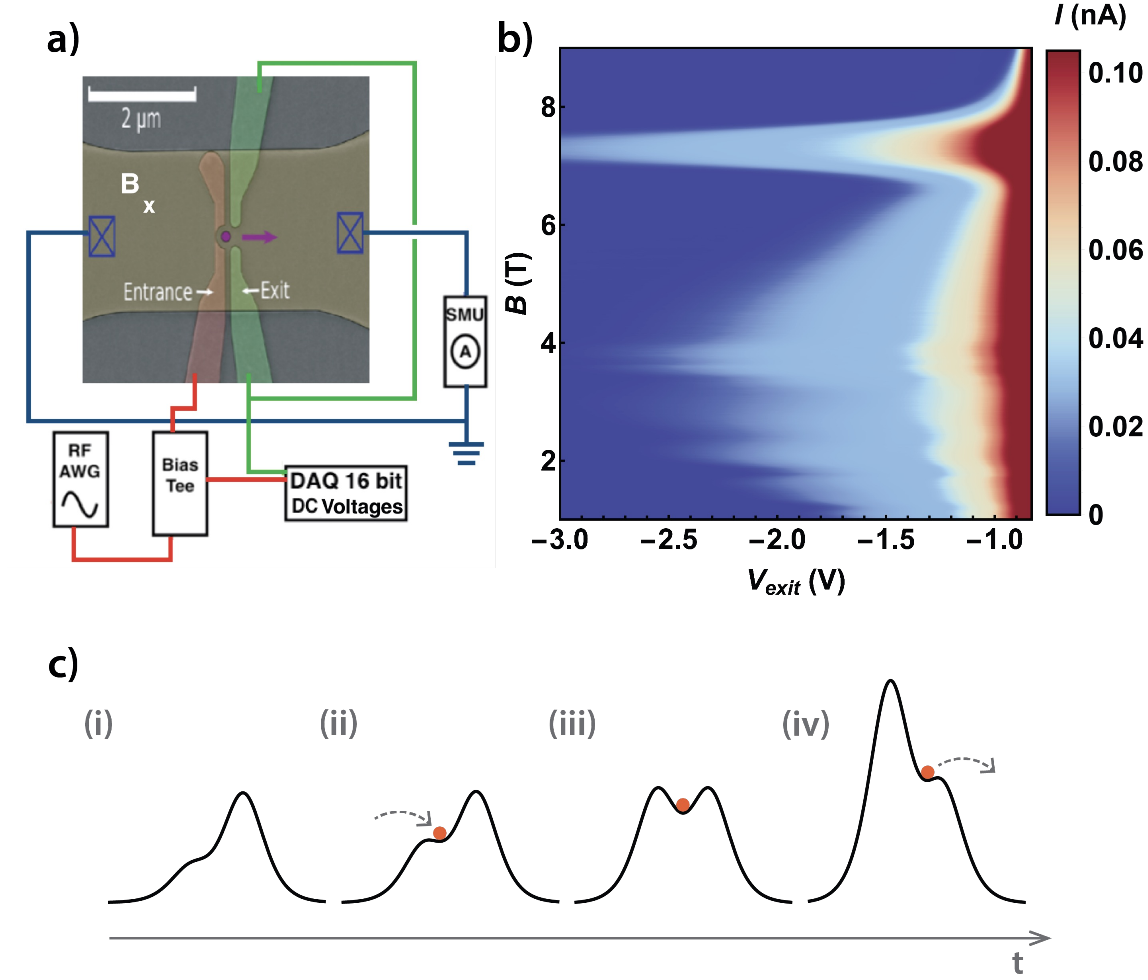
Magnetic Field Effects



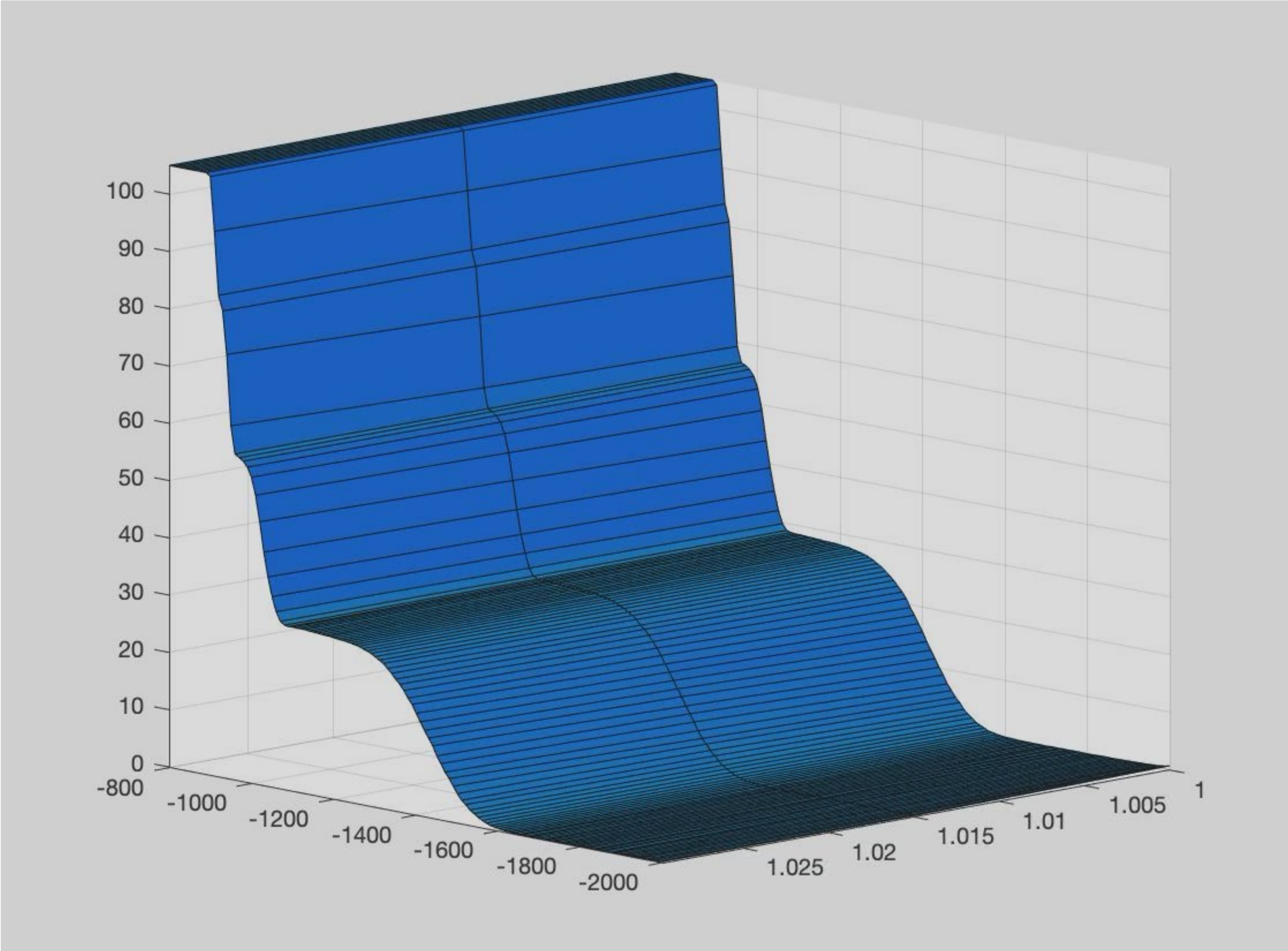
Wright, S. J et al. Enhanced current quantization in high-frequency electron pumps in a perpendicular magnetic field. PhysRevB.(78)23 3311 (2008)



1.0
0.8
0.6
0.4
0.2
0.0
$\phi(x, y, d)$
-300
-100
100
300
x (nm)
−500
−250
0
250
500
y (nm)



a)
2 μm
B x
Entrance
Exit
SMU
A
RF AWG
Bias Tee
DAQ 16 bit
DC Voltages
b)
I (nA)
0.10
0.08
0.06
0.04
0.02
0
B (T)
8
6
4
2
−3.0
−2.5
−2.0
−1.5
−1.0
V_{exit} (V)
c)
(i)
(ii)
(iii)
(iv)
t



100
90
80
70
60
50
40
30
20
10
0
-800
-1000
-1200
-1400
-1600
-1800
-2000
1.025
1.02
1.015
1.01
1.005
1

Ahronov Bohm Effect

In the paths the electrons are to take, we have:

$$\boldsymbol{B} = \nabla\times\boldsymbol{A} = 0$$

From Stokes theorem we have:

$$\oint_C \boldsymbol{A}.d\boldsymbol{r} = \int_S (\nabla\times\boldsymbol{A}).d\boldsymbol{S} = \int_S \boldsymbol{B}.d\boldsymbol{S} = \Phi_m$$

C is the contracted path of integration around the rings and Φ_m is the total magnetic flux through the ring. The vector potential then takes on the form:

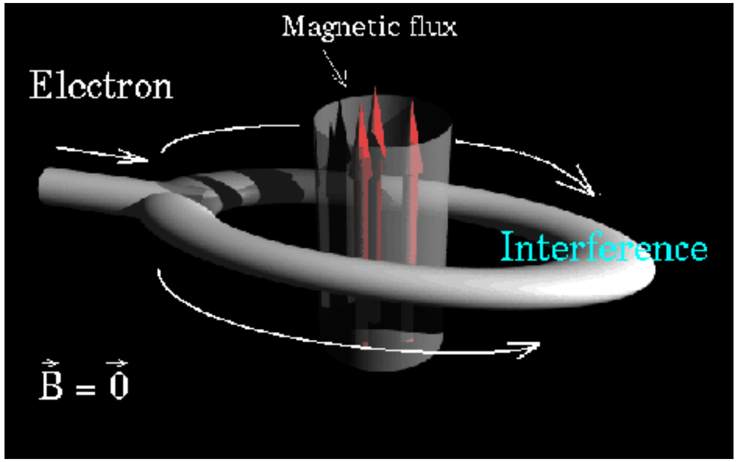
$$A = \frac{\Phi_m}{2\pi r}$$

r, is the distance from the centre axis through the ring.

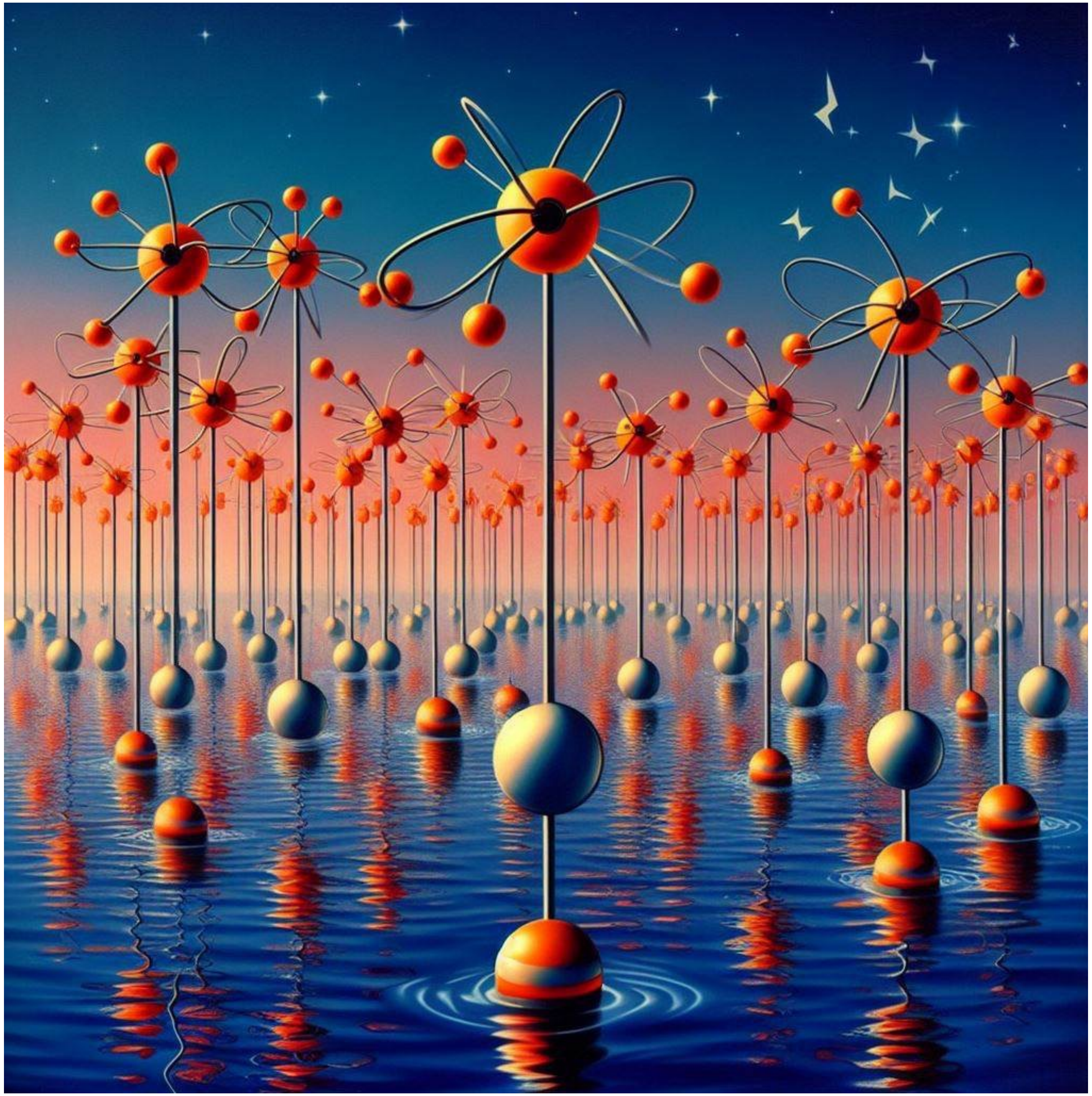
Classically we do not expect the electron motion to be affected by the enclosed magnetic field since the electrons are in fact not moving through the magnetic field. The particles wave function is however affected by the existence of the enclosed flux and a total phase difference between the two paths can be shown to be equal to:

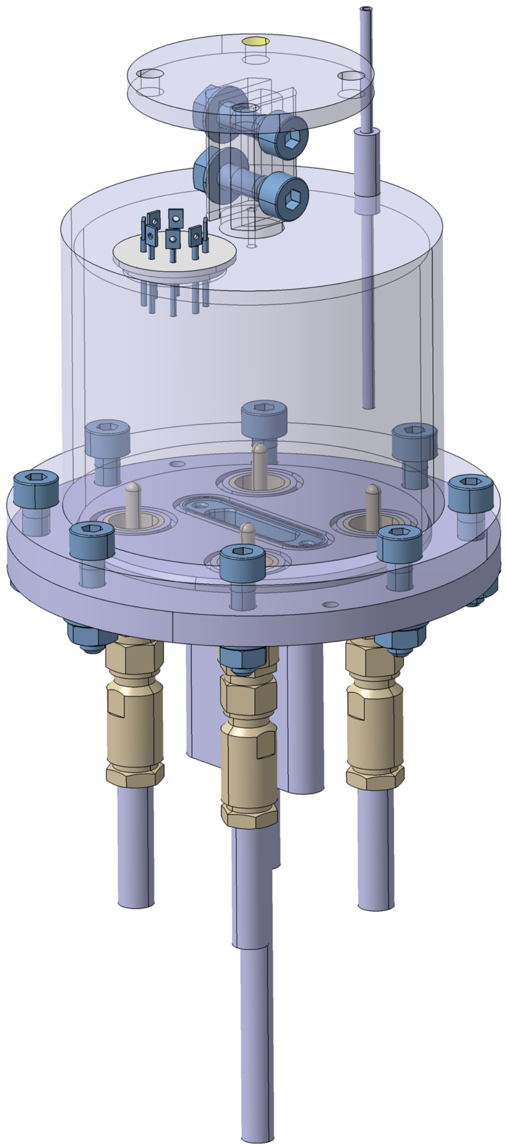
$\Delta\phi = \frac{e}{\hbar}\Phi_m = \pi\left(\frac{\Phi}{\Phi_0}\right)$ where, $\Phi_0 = \frac{h}{e}$ know as the quantum flux

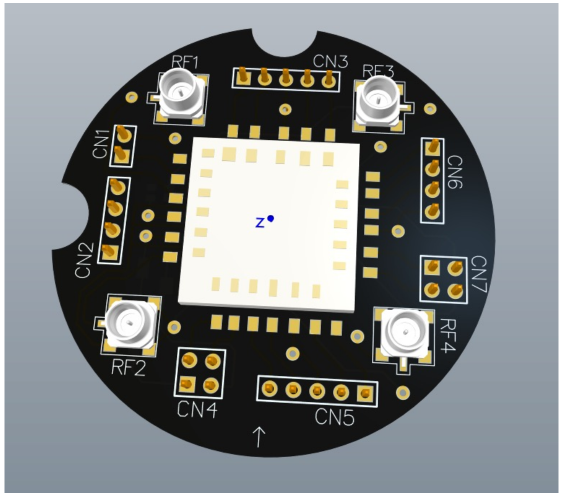
Interference is therefore periodic in the number of flux quanta passing through the loop. It is constructive when Φ is a multiple of Φ_0 and destructive halfway between.



Superfluid and Electrons






RF1
CN3
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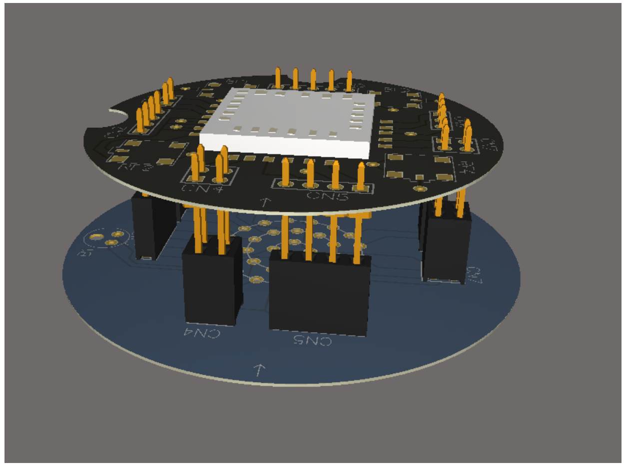
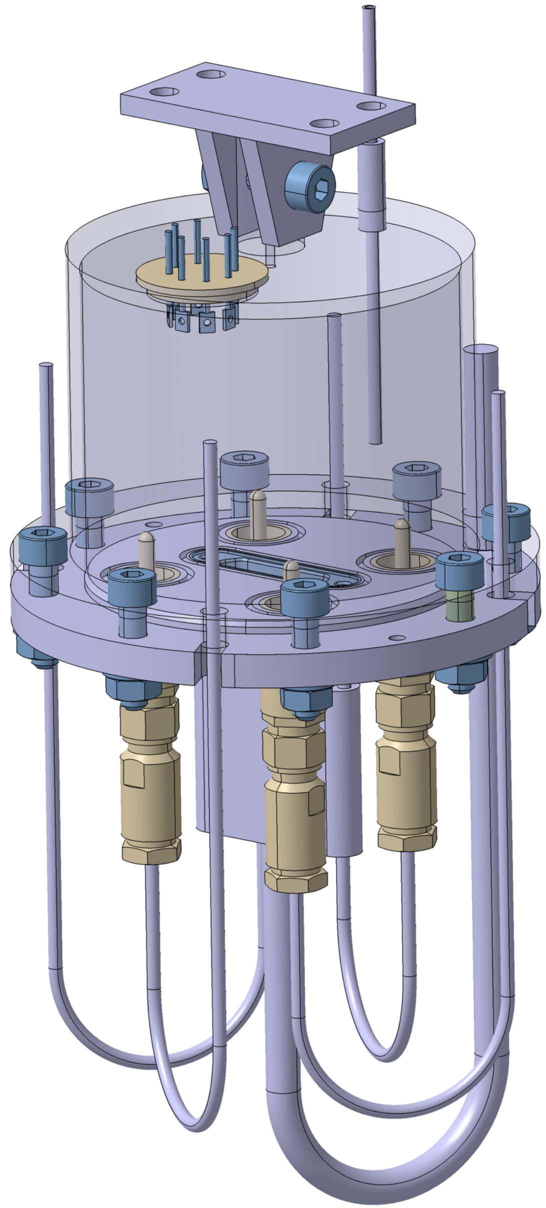
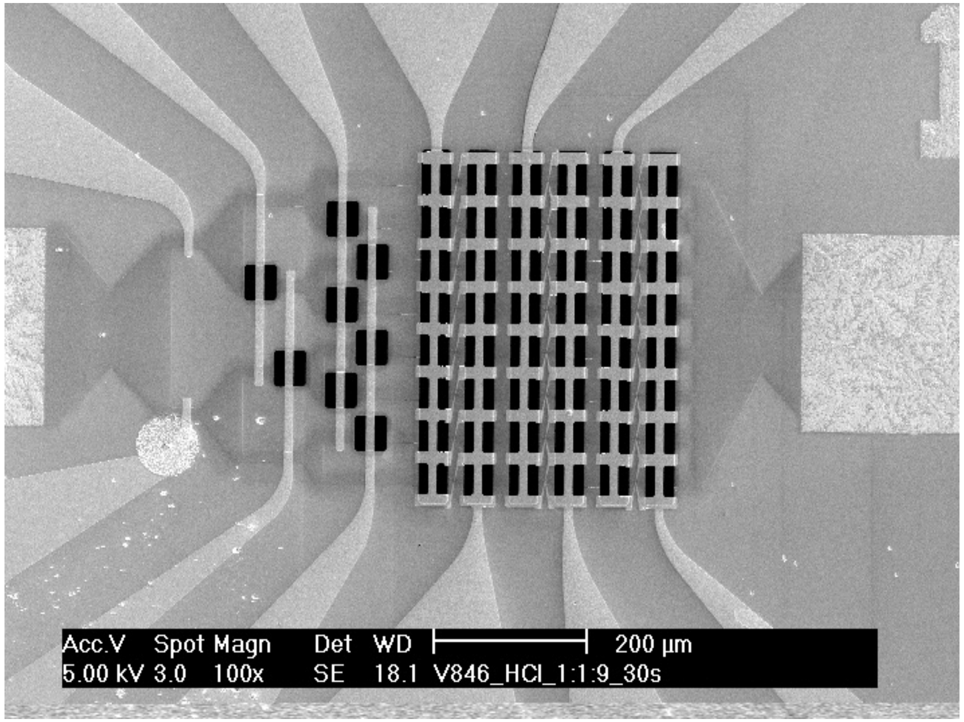
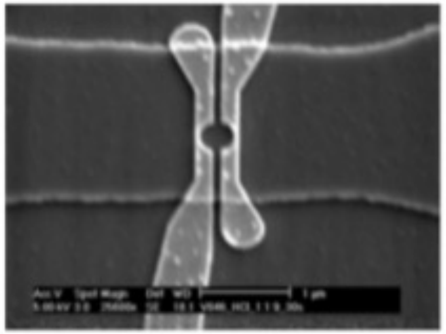
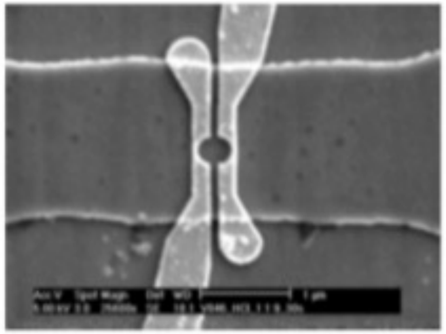


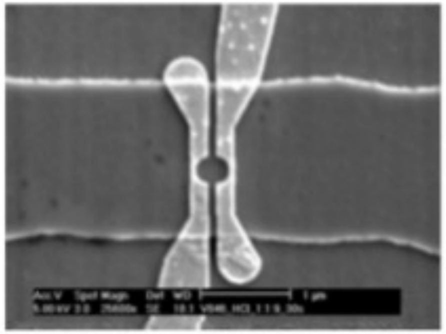


Multiplexor Devices



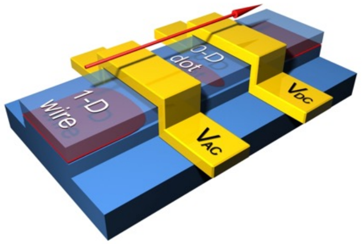


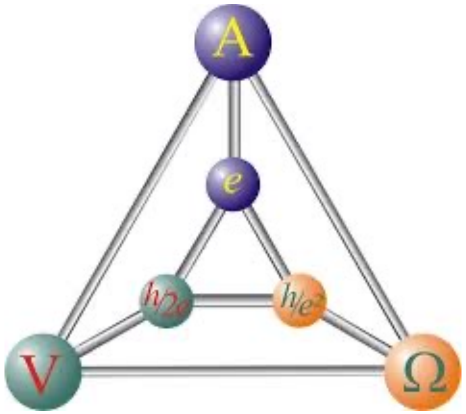


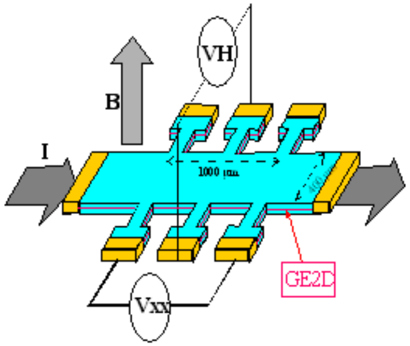


Applications

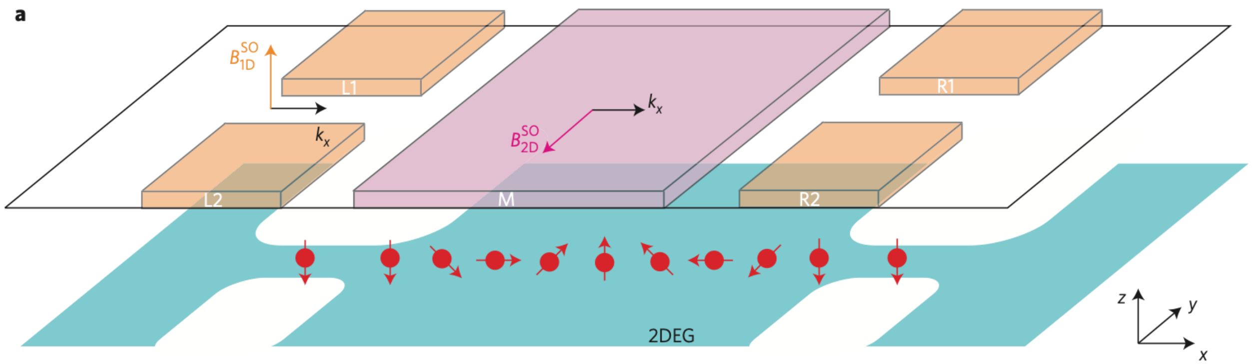
Quantum Metrology







Quantum Spin Selection



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Spin–Orbit Coupling (Summary)

- A relativistic effect where an electron's spin interacts with its orbital motion.
- The electron's spin magnetic moment feels the magnetic field created by its own motion around the nucleus.
- This interaction shifts atomic energy levels and affects the electron's spin behavior in electric fields.

Thank you

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