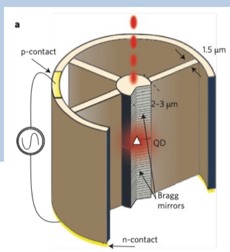
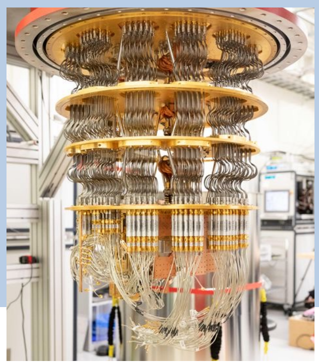
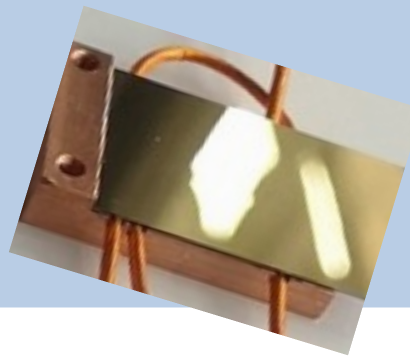
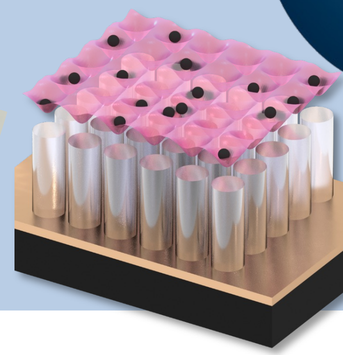
Lecture : Quantum Technology introduction
Talence

Quantum technologies : Applications and hardware









Simon BERNON
Laboratoire de photonique, numérique et nanosciences
Bordeaux

Outline

	Quantum technology Context and Physical Hardware SB	3x1h30 Lecture
	Magnetometry and Magnetically induced optical birefringence in an atomic vapor (Brahim Lounis)	1h30 Lecture – 2h Experimental Demonstration
	Quantum gravimeter : matterwave interference in zero gravity… in the lab (Baptiste Battelier / Clement Metayer)	1h30 Lecture – 2h Experimental Demonstration

Quantum Flagship

10 years -> 1 billion euros

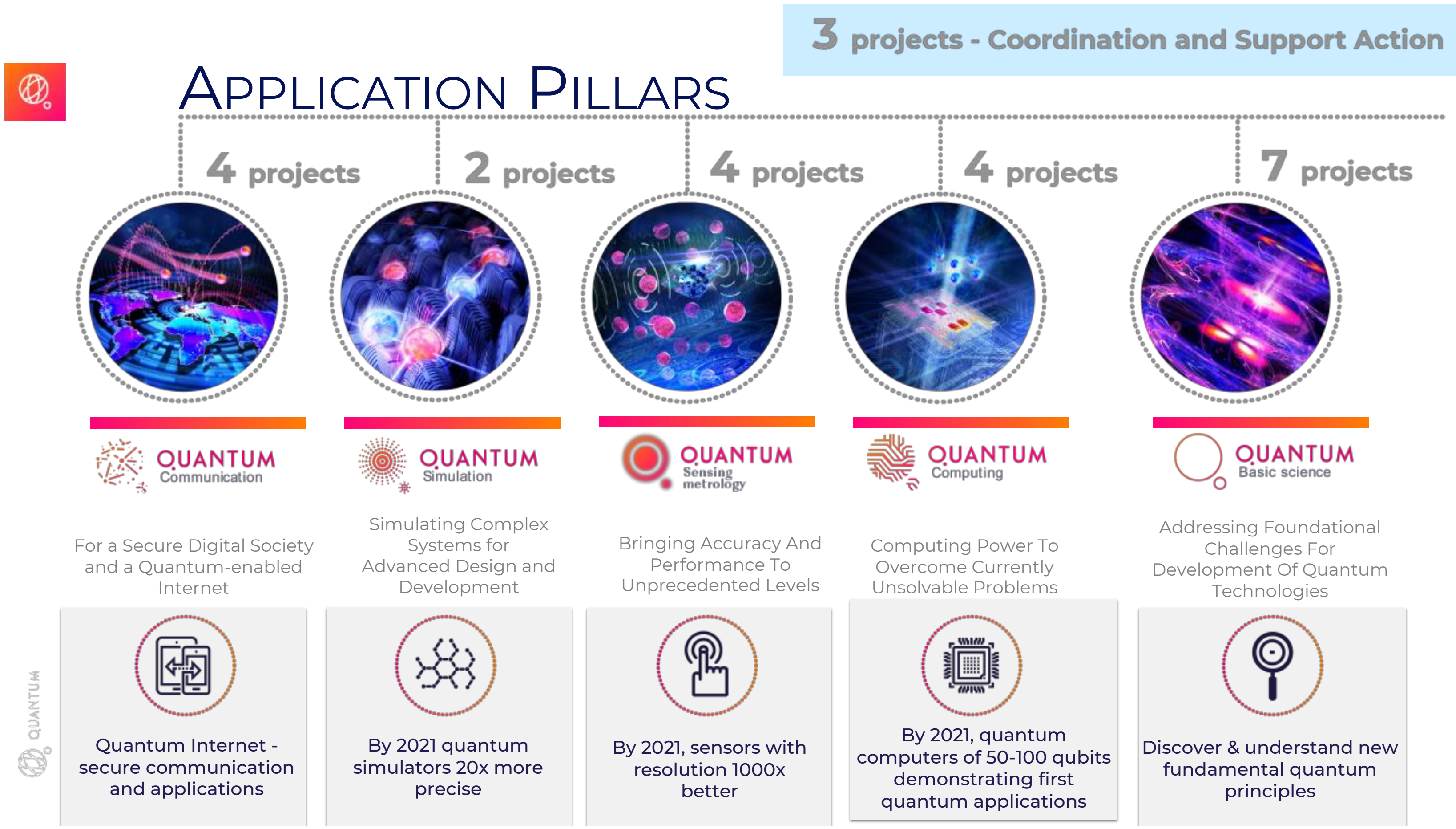


Figure 1: An overview of the ramp-up phase of the Quantum Technologies Flagship and the areas of the 21 scientific projects it finances.

Ramp-up phase : report

Key performance Indicators: Quantum Communication[15]	
Performance[16]	World record 20 ms quantum memory; low-cost large-scale production ready QRNG; modular and miniaturized integration of various quantum communication systems
European Technical Leadership[17]	World first proof of principle entanglement-based quantum network consisting of three quantum nodes 1.3 km apart
Deployment[18]	2 subsystems ready; EuroQCI roadmap published; national deployment of testbeds; OpenQKD[19] testbed and use case driven sites established
Adoption[20]	5 new EuroQCI services; see also OpenQKD in Action[21] for a list of early testbeds and use cases

Ramp-up phase : report

Key Performance Indicators: Quantum Computation[26]	
Performance[27]	Developed platform independent theoretical and experimental tools to verify quantum advantage
European Technical Leadership[28]	25 qubits (superconducting); 50 qubits (trapped ions)
European Impact Leadership[29]	Quantum error correction with 17 qubits implemented. 70 use-cases elaborated with industrial partners ranging from chemistry to machine learning and optimization through to symbolic AI and graph algorithmics[30]
Accessibility[31]	Forschungszentrum Jülich (DE) aims to provide access to a 100-qubit quantum computer building on the OPENSUPERQ results; Forschungszentrum Jülich and GENCI (FR) will also host and provide access to a 100-qubit analogue simulator

Ramp-up phase : report

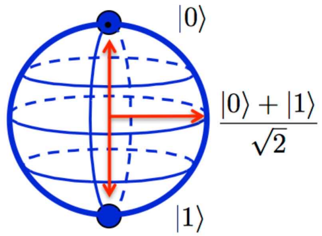
Key Performance Indicators: Quantum Simulation[35]	
Performance[36]	Optical lattices reached practical quantum advantage in scientific problems involving dynamics of phase transitions and quantum transport in strongly interacting systems
Market readiness[37]	Two 100-qubit analogue quantum simulators (PAQUANS/PASQAL) to be installed in Forschungszentrum Jülich (DE) and GENCI (FR)
European Technical Leadership[38]	Number of individually addressable atoms/ions: >50 (ions); >300 (tweezer array); >1500 (optical lattices)

Key Performance Indicators: Quantum Sensing and Metrology[43]	
Market readiness[44]	3 (clocks; cold-atom gravitometers; NV-centre magnetometers) TRL advancements in all quantum sensors studied: NV-centres in ultrapure diamonds, atomic vapor cells, quantum clocks
Next generation technologies[45]	Increased sensitivity in NMR and MRI; miniaturized atomic clocks, atomic gyroscopes, atomic spectrometers; molecule detectors; THz imaging

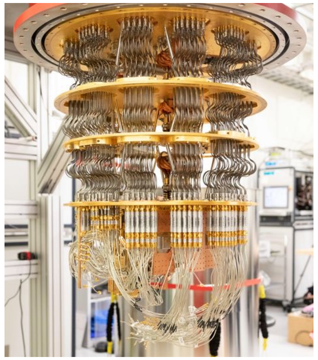
https://qt.eu/news/2024/2024-02-14_new-roadmap-to-position-europe-as-the-quantum-valley-of-the-world

Technology oriented

Quantum computing



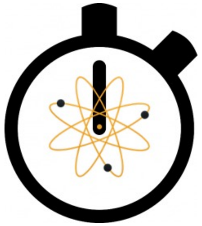
Qubit

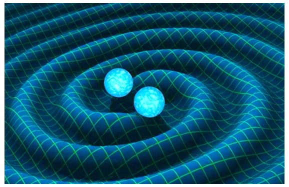


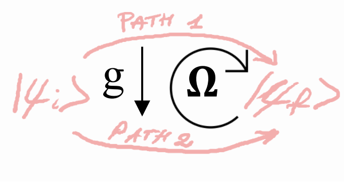
<u>Transmon</u>

Superconducting circuits

Quantum metrology, sensing







Clocks

Redshift

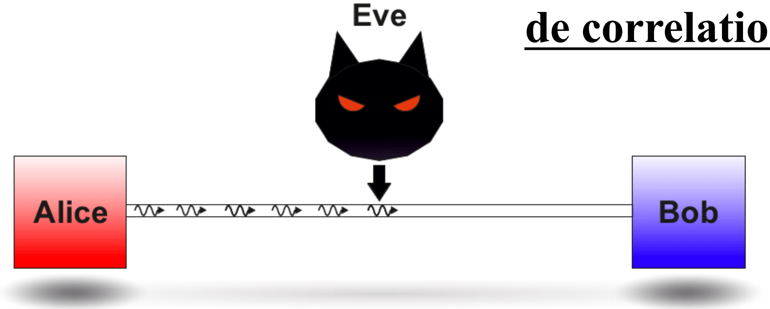
Gravitational waves

Inertial sensors

<u>Interferometers and NV centers</u>

Quantum communication

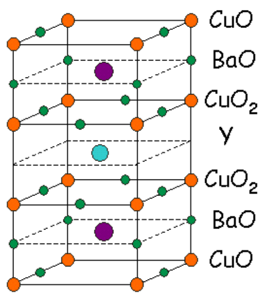
<u>Quantum Dot : photon unique et fonction de correlation</u>

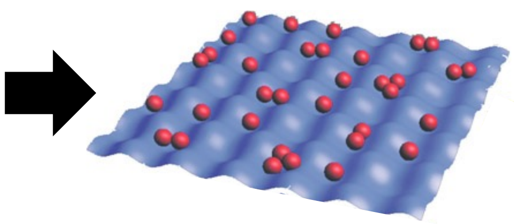


Cryptography

Quantum simulations

<u>Optical lattices and beyond</u>





Complex molecules
Strongly correlated materials

Controllable individual elements

The Promise of a Quantum Computer

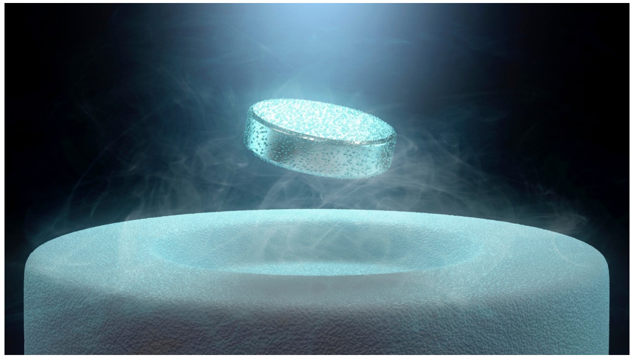
A Quantum Computer …

- Offers exponential improvement in ***speed*** and ***memory*** over existing computers
- Capable of ***reversible computation***
- e.g. Can factorize a 250-digit number in seconds while an ordinary computer will take 800 000 years!

ARDA Quantum Information Science and Technology Roadmapping Project

1. **Quantum Computing Roadmap Overview**
2. **Nuclear Magnetic Resonance Approaches**
3. **Ion Trap Approaches**
4. **Neutral Atom Approaches**
5. **Optical Approaches**
6. **Solid State Approaches**
7. **Superconducting Approaches**
8. **"Unique" Qubit Approaches**
9. **The Theory Component of the Quantum Information Processing and Quantum Computing Roadmap**

http://qist.lanl.gov



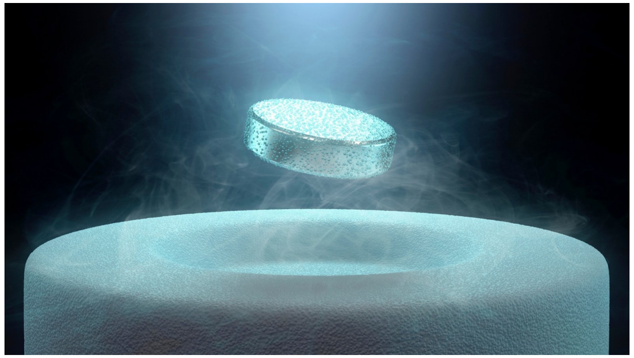
Superconductors

1 – Zero Resistance

3 – Perfect diamagnetism

2 – Persistent currents

4 – Energy gap



Superconductors

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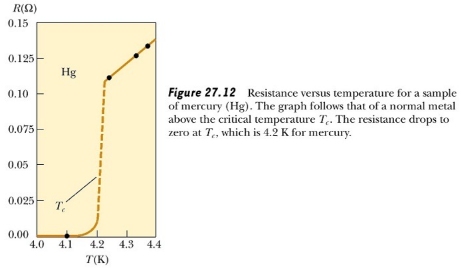
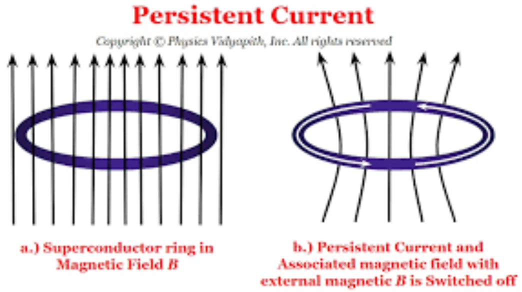
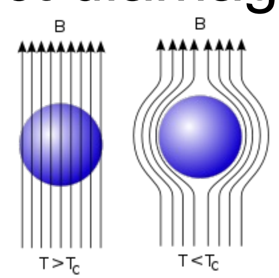


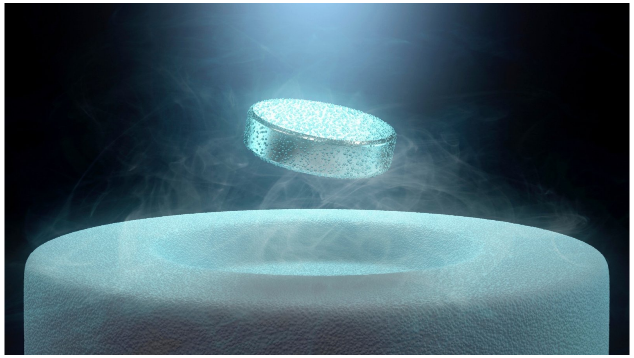
2 – Persistent currents



3 – Perfect diamagnetism



4 – Energy gap



Superconductors

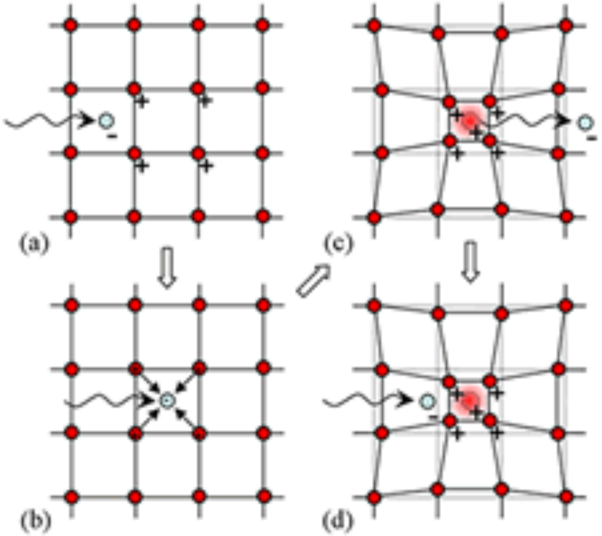


Fig.11 Electron-phonon interaction

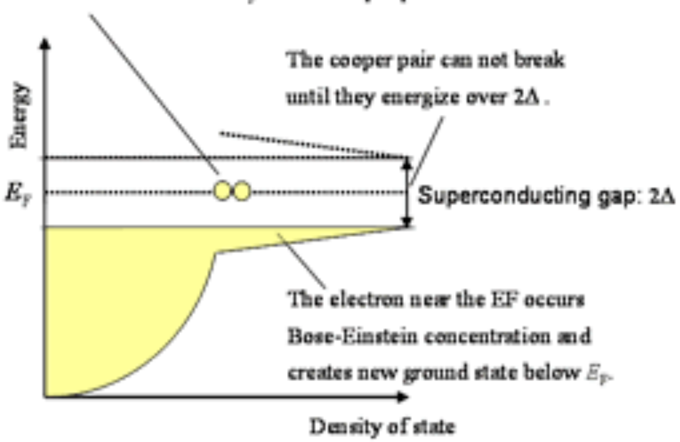


Fig.12 Electron state in superconductivity

4 – Energy gap

From quantum tunneling to the Josephson effect

"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"

"for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"

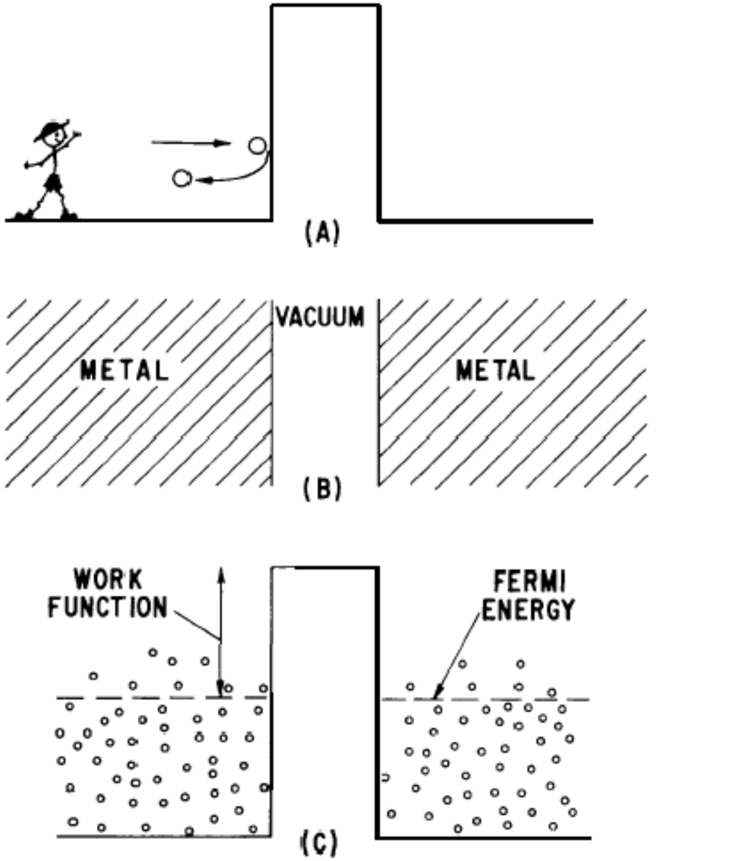


Fig. 1.

Leo Esaki

1/4 of the prize

Japan

IBM Thomas J. Watson Research Center Yorktown Heights,

Ivar Giaever

1/4 of the prize

USA

General Electric Company Schenectady, NY, USA

Brian David Josephson

1/2 of the prize

United Kingdom

University of Cambridge Cambridge, United Kingdom

http://www.nobel.se/physics/laureates/1973/giaever-lecture.pdf

From quantum tunneling to the Josephson effect

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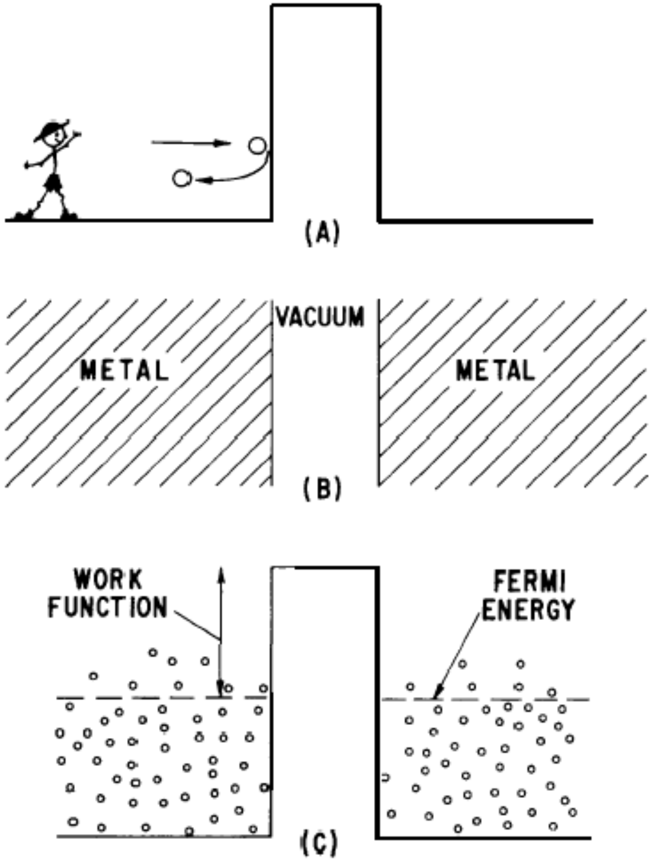


Fig. 1.

http://www.nobel.se/physics/laureates/1973/giaever-lecture.pdf

Following slides inspired from :

https://ocw.mit.edu/courses/6-763-applied-superconductivity-fall-2005/pages/lecture-notes/

Normal-Insulator-Normal junction (N-I-N)

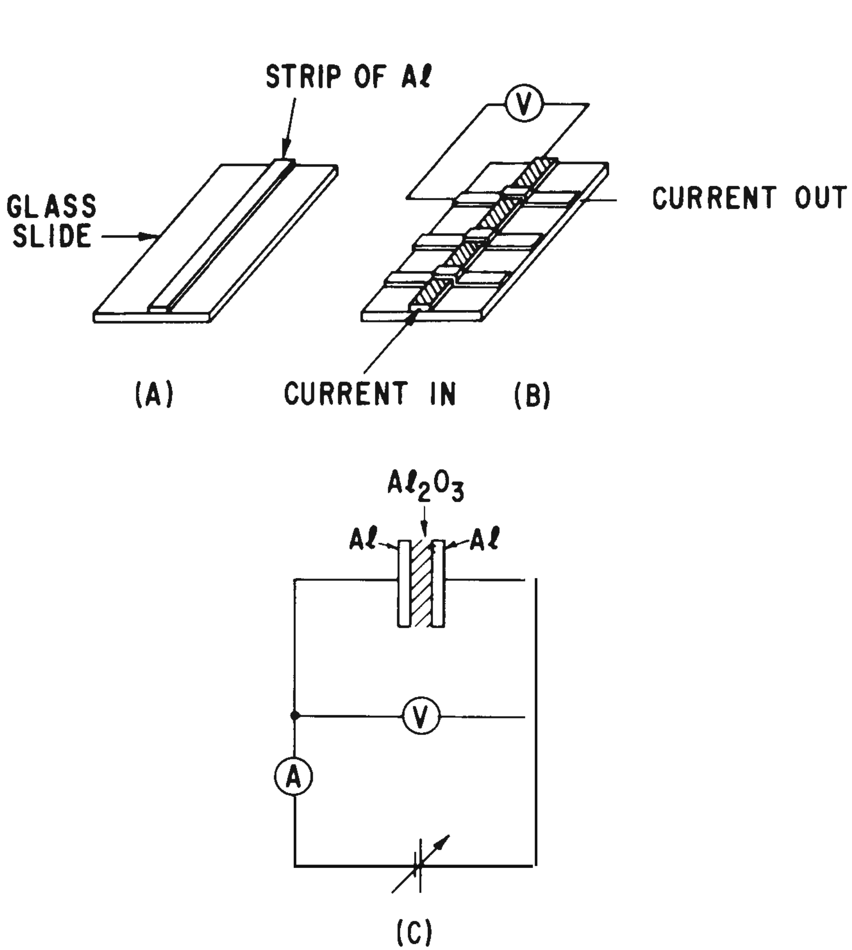
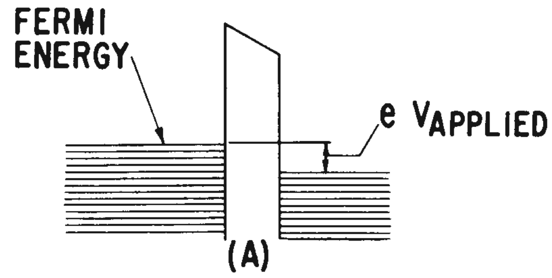


Fig. 3.



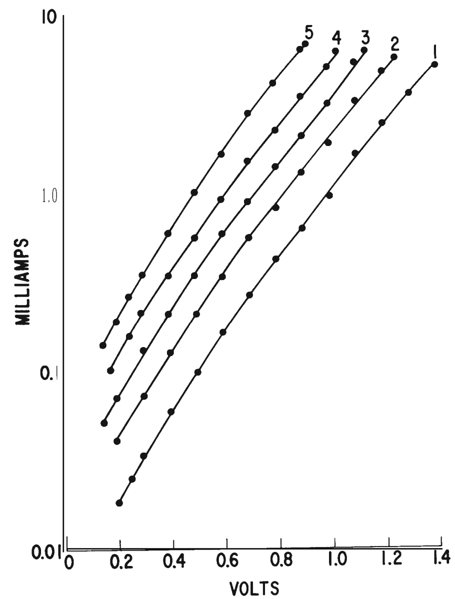


Fig. 4.
Current-voltage characteristics of five different tunnel junctions all with the same thickness, but with five different areas. The current is proportional to the area of the junction. This was one of the first clues that we were dealing with tunneling rather than shorts. In the early experiments we used a relatively thick oxide, thus very little current would flow at low voltages.

Normal-Insulator-Superconductor junction (N-I-S)

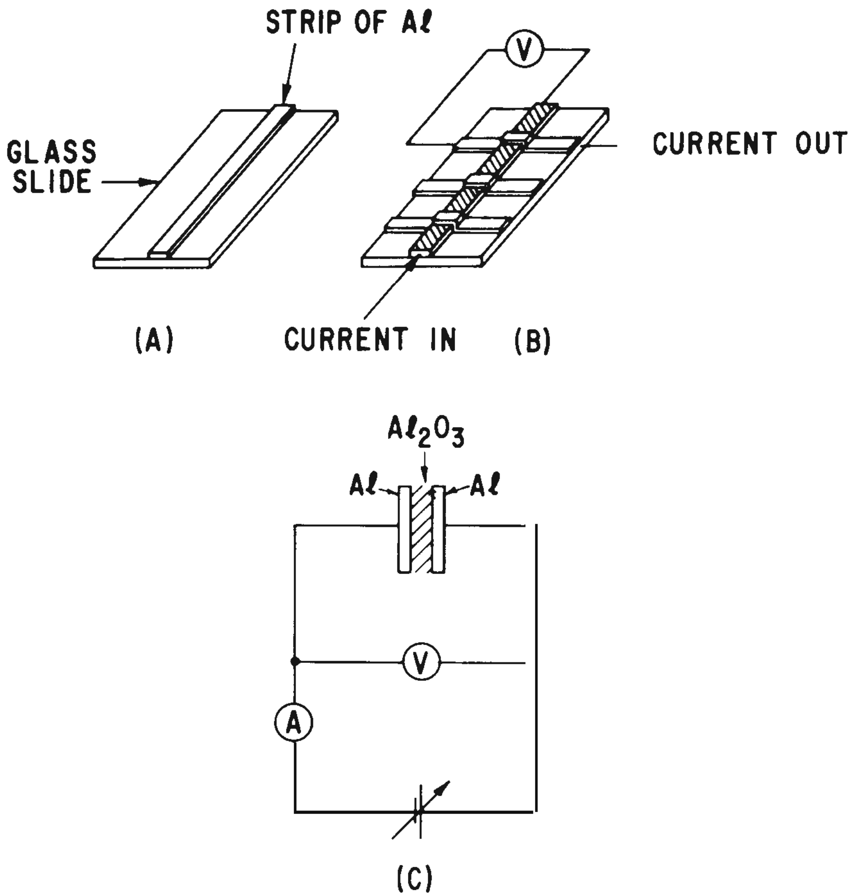
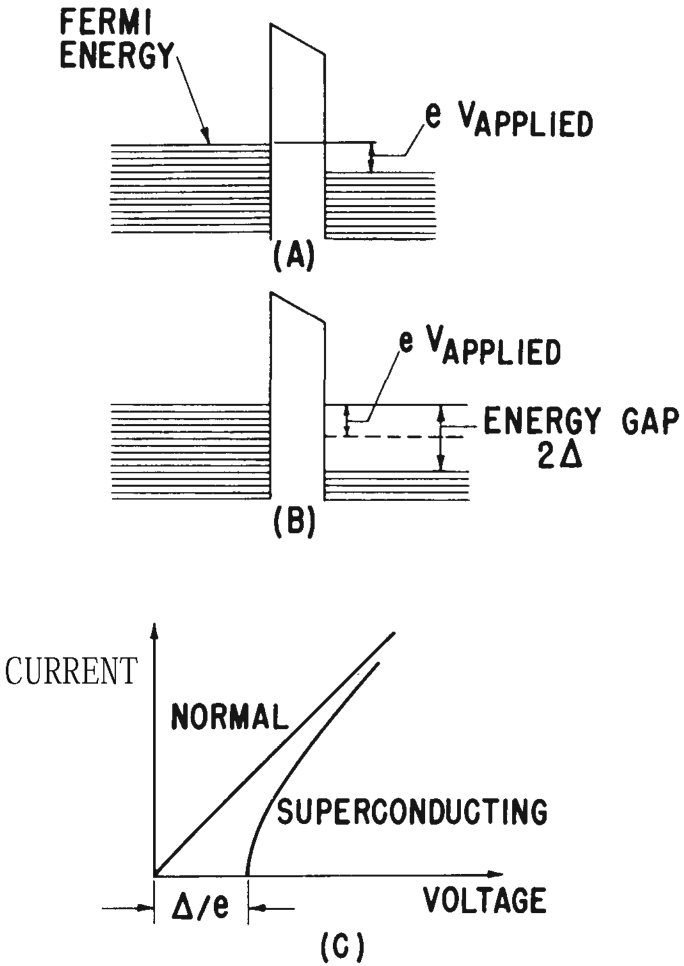
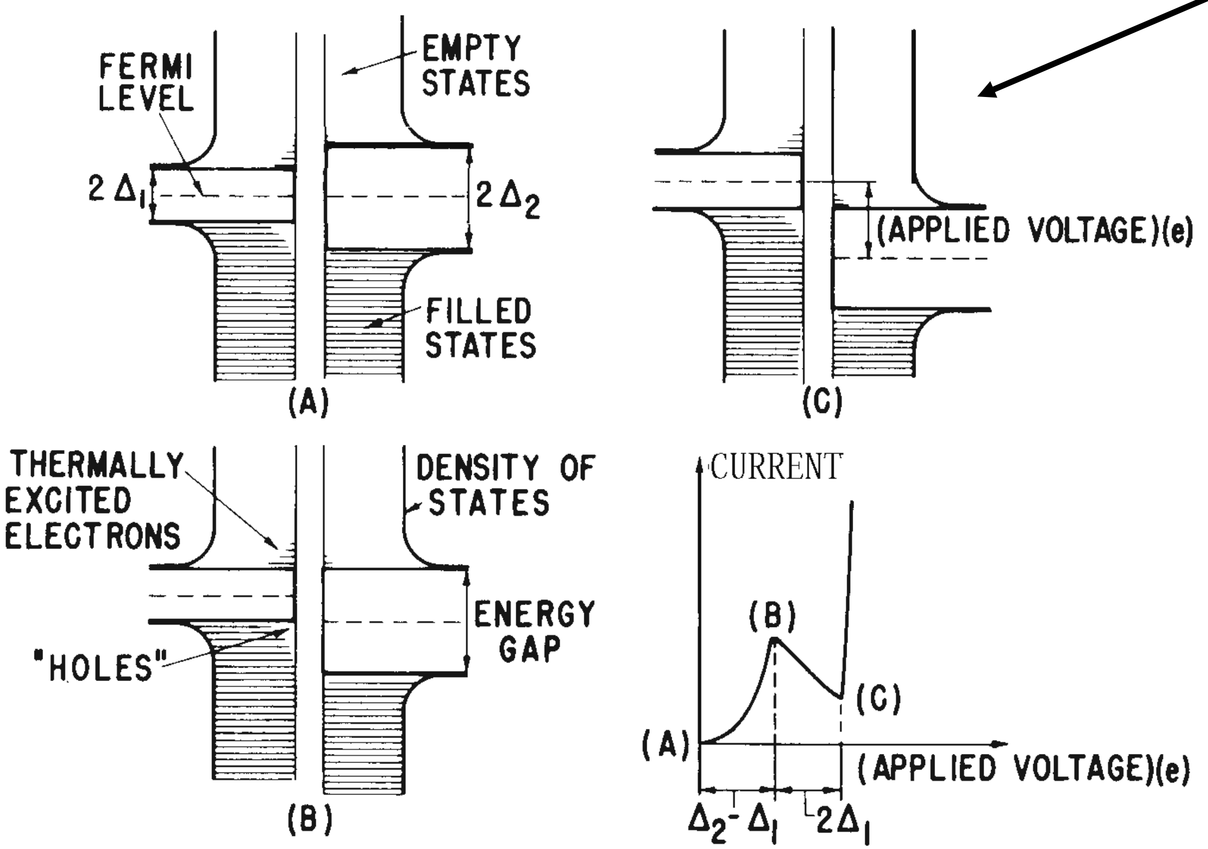
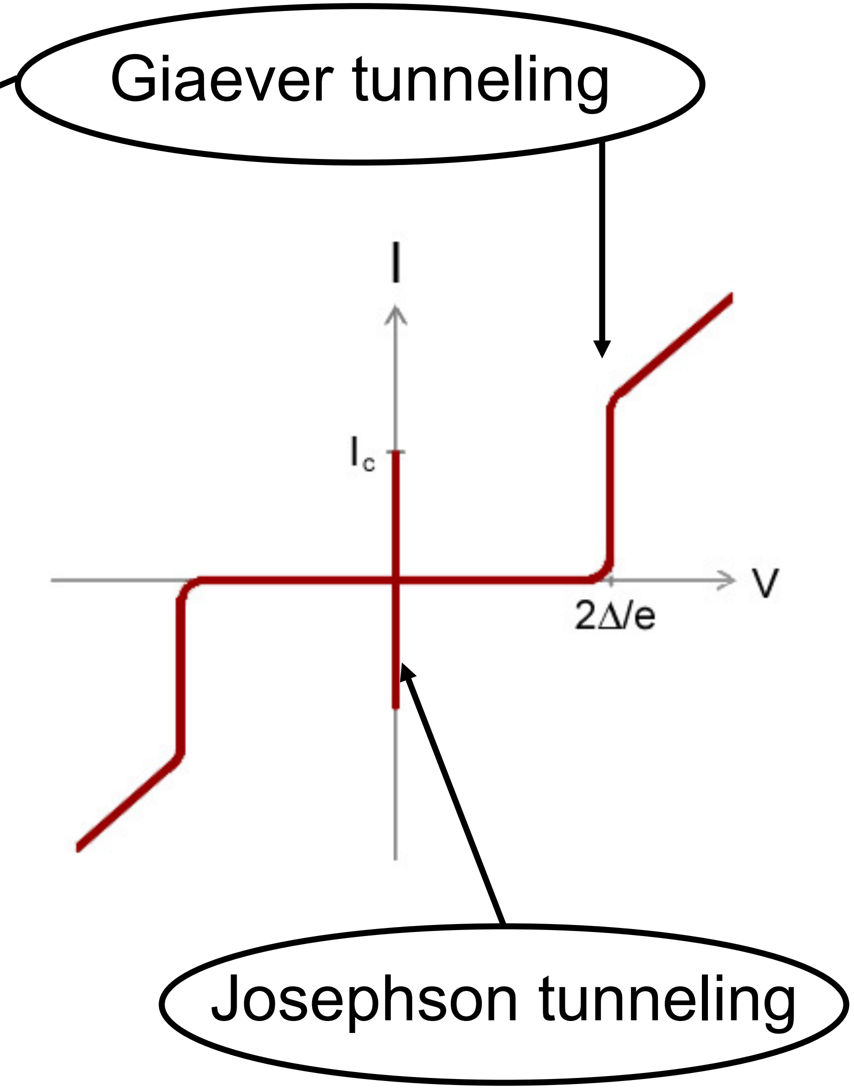


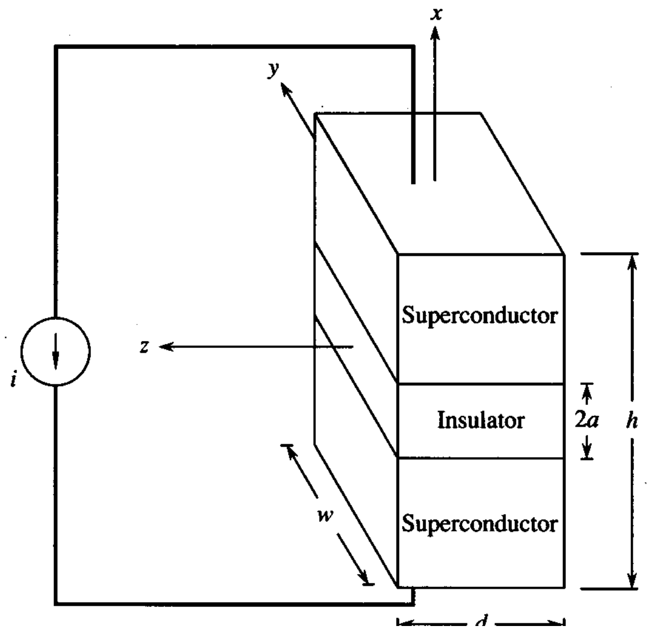
Fig. 3.



Superconductor-Insulator-Superconductor junction (S-I-S)







1. The wavefunction describes the whole ensemble of superelectrons such that

$$\Psi^*(\mathbf{r},t)\Psi(\mathbf{r},t) = n^\star(\mathbf{r},t) \longrightarrow \text{density}$$

and $$\int d\mathbf{r}\,\Psi^*(\mathbf{r},t)\Psi(\mathbf{r},t) = \mathsf{N}^\star \longrightarrow \text{Total number}$$

$$\Psi(\mathbf{r},t) = \sqrt{n^\star(\mathbf{r},t)}\, e^{i\theta(\mathbf{r},t)} = \sqrt{n^\star}\, e^{i\theta(\mathbf{r},t)}$$

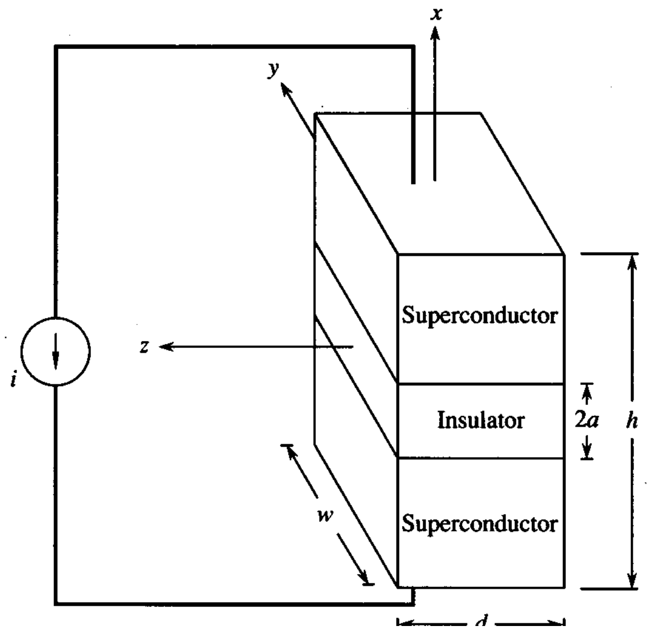
2. The flow of probability becomes the flow of particles, with the physical current density given by

$$\mathbf{J}_\mathsf{S} = q^\star \,\mathrm{Re}\left\{\Psi^*\left(\frac{\hbar}{im^\star}\nabla - \frac{q^\star}{m^\star}\mathbf{A}\right)\Psi\right\}$$

3. This macroscopic quantum wavefunction follows

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \frac{1}{2m^\star}\left(\frac{\hbar}{i}\nabla - q^\star\mathbf{A}(\mathbf{r},t)\right)^2\Psi(\mathbf{r},t) + q^\star\phi(\mathbf{r},t)\,\Psi(\mathbf{r},t)$$

Equation super-courants



Courant — Potentiel vecteur — Phase fonction d'onde

$$\mathbf{J}_s(\mathbf{r},t) = -\frac{1}{\Lambda}\left(\mathbf{A}(\mathbf{r},t) + \frac{\Phi_o}{2\pi}\nabla\theta(\mathbf{r},t)\right)$$

$$\frac{\partial}{\partial t}\theta(\mathbf{r},t) = -\frac{1}{\hbar}\left(\frac{\Lambda \mathbf{J}_S^2}{2n^\star} + q^\star\phi(\mathbf{r},t)\right)$$

$$\Lambda \equiv \frac{m^\star}{n^\star (q^\star)^2}$$

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$$\Phi_o \equiv \frac{2\pi\hbar}{|q^\star|} = \frac{h}{|q^\star|}$$

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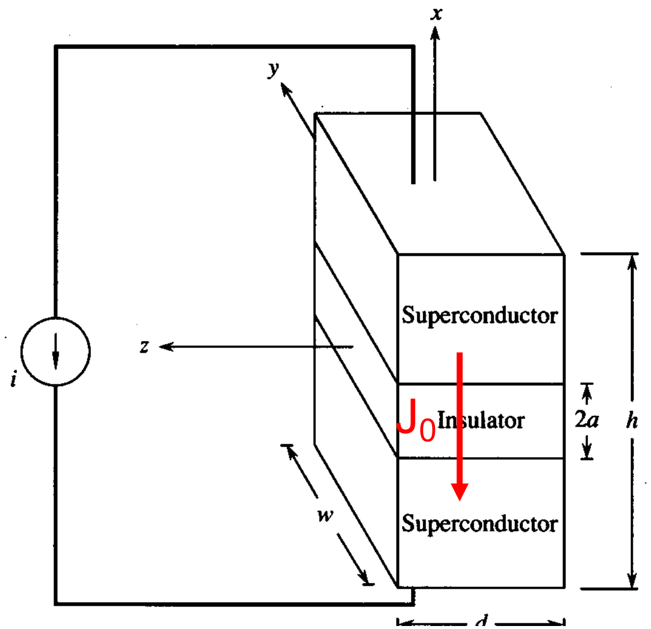
Equation super-courants



Courant

Potentiel vecteur

Phase fonction d'onde

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$$\Lambda \equiv \frac{m^\star}{n^\star(q^\star)^2}$$

Conservation du flux en l'absence de champ EM

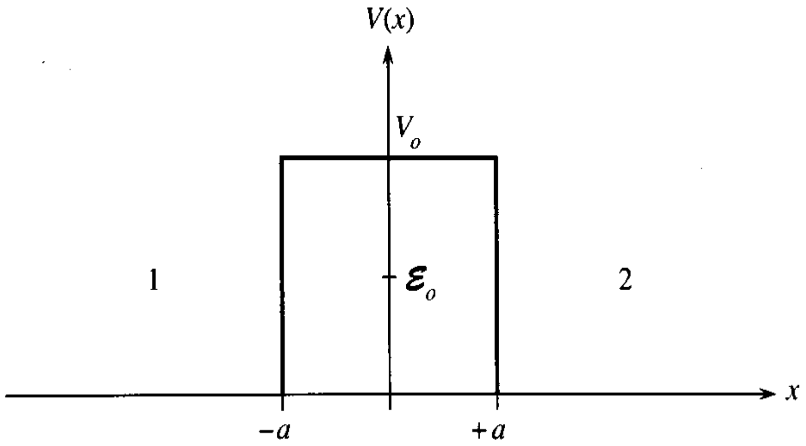
$$\mathbf{J}_S(\pm a,t) = -\frac{\Phi_o}{2\pi\Lambda}\nabla\theta(\pm a,t) = \mathbf{J}_O \quad \& \quad \frac{\partial}{\partial t}\theta(\pm a,t) = -\frac{1}{\hbar}\left(\frac{\Lambda \mathbf{J}_O^2}{2n^\star}\right) = -\frac{\mathcal{E}_o}{\hbar}$$

$$\Phi_o \equiv \frac{2\pi\hbar}{|q^\star|} = \frac{h}{|q^\star|}$$

3. This macroscopic quantum wavefunction in the insulator

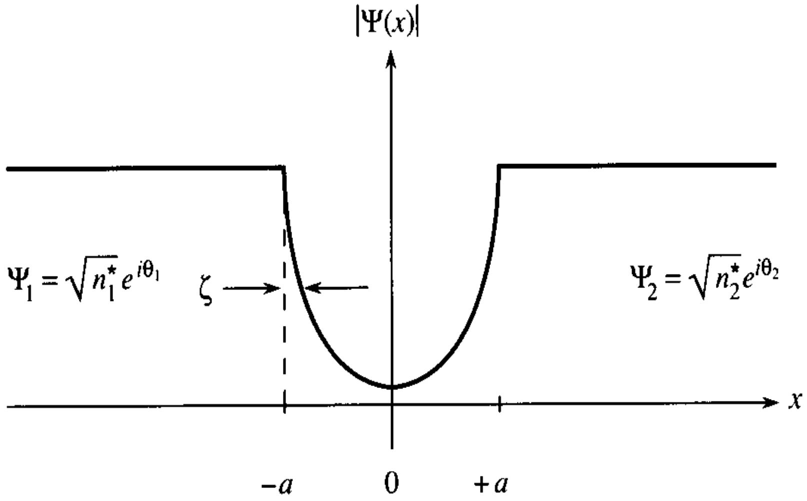
$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \frac{1}{2m^\star}\left(\frac{\hbar}{i}\nabla - q^\star\mathbf{A}(\mathbf{r},t)\right)^2\Psi(\mathbf{r},t) + q^\star\phi(\mathbf{r},t)\,\Psi(\mathbf{r},t) + \underbrace{V(x)}_{\text{Tunneling Potential Barrier}}\Psi(\mathbf{r},t)$$

Tunneling through the barrier



The energy of the superelectron is less than the barrier height, so that no classical particles flow.

$$-\frac{\hbar^2}{2m^\star}\nabla^2\Psi(\mathbf{r}) = \underbrace{(\mathcal{E}_o - V_o)}_{\text{constant}}\Psi(\mathbf{r}) \qquad \text{for } |x| \leq a$$



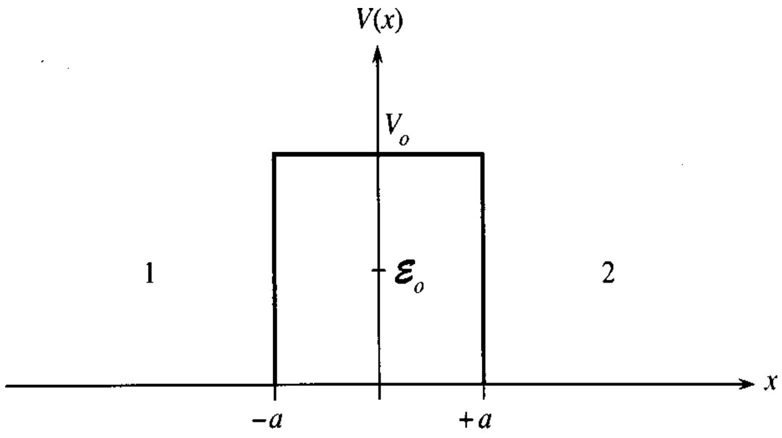
Therefore, in the insulating region

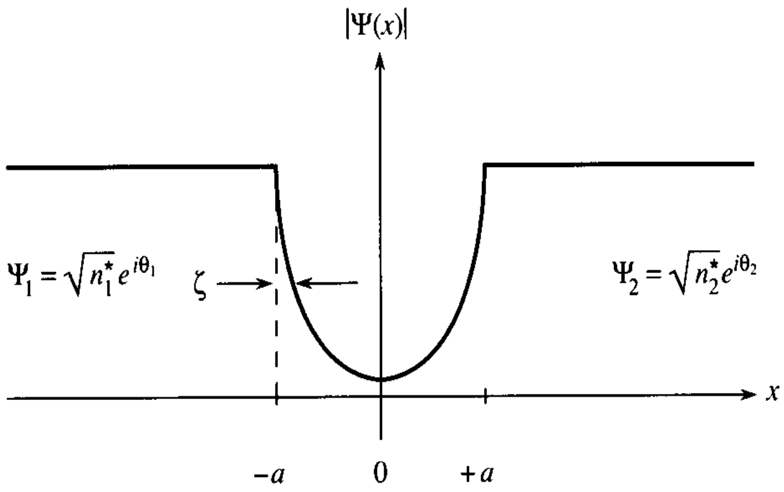
$$\Psi(x) = C_1 \cosh x/\zeta + C_2 \sinh x/\zeta$$

Where $\zeta \equiv \sqrt{\dfrac{\hbar^2}{2m^\star(V_o - \mathcal{E}_o)}}$ so that

$$\mathbf{J}_\mathrm{S} = \frac{2q^\star}{m^\star}\mathrm{Re}\left\{\Psi^* \frac{\hbar}{i}\nabla\Psi\right\} = \frac{q^\star\hbar}{m^\star\zeta}\mathrm{Im}\left\{{C_1}^* C_2\right\}$$

Tunneling through the barrier





$$\mathsf{J_S} = \frac{2q^\star}{m^\star} \mathrm{Re}\left\{\Psi^* \frac{\hbar}{i} \nabla\Psi\right\} = \frac{q^\star \hbar}{m^\star \zeta} \mathrm{Im}\left\{C_1{}^* C_2\right\}$$

At the boundaries.

$$\Psi(-a) = \sqrt{n_1^\star}\, e^{i\theta_1} \quad \& \quad \Psi(+a) = \sqrt{n_2^\star}\, e^{i\theta_2}$$

So that

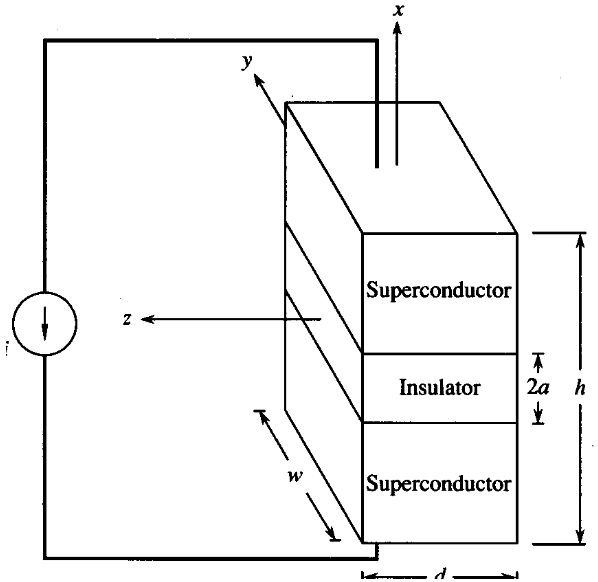
$$C_1 = \frac{\sqrt{n_1^\star}\, e^{i\theta_1} + \sqrt{n_2^\star}\, e^{i\theta_2}}{2\cosh(a/\zeta)} \quad \& C_2 = -\frac{\sqrt{n_1^\star}\, e^{i\theta_1} - \sqrt{n_2^\star}\, e^{i\theta_2}}{2\sinh(a/\zeta)}$$

Therefore,

$$\mathsf{J_S} = \mathsf{J_C} \sin(\theta_1 - \theta_2)$$

with
$$\mathsf{J_C} = \frac{e\hbar\sqrt{n_1 n_2}}{m\zeta \sinh(2a/\zeta)}$$

Josephson current-phase relation

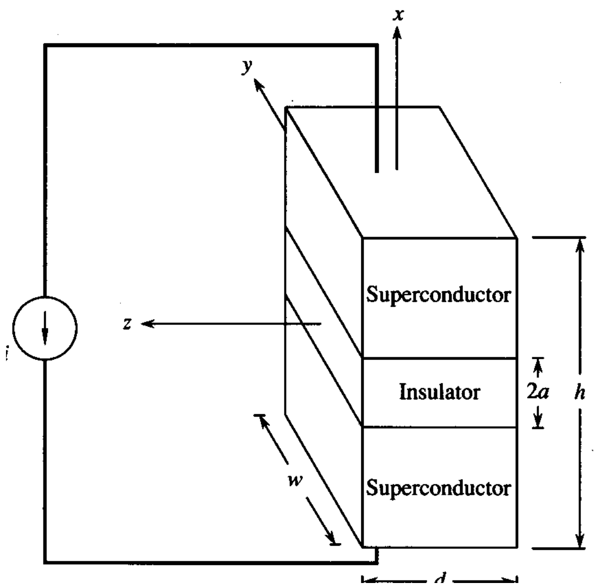


$$\mathbf{J}_\mathrm{S} = \mathbf{J}_\mathrm{C} \sin\left(\theta_1 - \theta_2\right)$$

Généralisation en présence of an EM field ?

$$\mathbf{J}_\mathrm{S} = q^\star\,\mathrm{Re}\left\{\Psi^*\left(\frac{\hbar}{im^\star}\nabla - \frac{q^\star}{m^\star}\mathbf{A}\right)\Psi\right\}$$ ET $$\theta_1 - \theta_2 = -\int_1^2 \nabla\theta dl$$

Josephson current-phase relation



$$\mathbf{J}_\mathsf{S} = \mathbf{J}_\mathsf{C} \sin(\theta_1 - \theta_2)$$

Généralisation in presence of an EM field ?

$$\mathbf{J}_\mathsf{S} = q^\star \,\mathrm{Re}\left\{\Psi^*\left(\frac{\hbar}{im^\star}\nabla - \frac{q^\star}{m^\star}\mathbf{A}\right)\Psi\right\}$$ AND $$\theta_1 - \theta_2 = -\int_1^2 \nabla\theta dl$$

$$\boxed{\mathbf{J}_\mathsf{S}(\mathbf{r},t) = \mathbf{J}_\mathsf{C}(y,z,t)\sin\varphi(y,z,t)}$$

where the *gauge-invariant phase* is defined as

$$\varphi(y,z,t) = \theta_1(y,z,t) - \theta_2(y,z,t) - \frac{2\pi}{\Phi_o}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

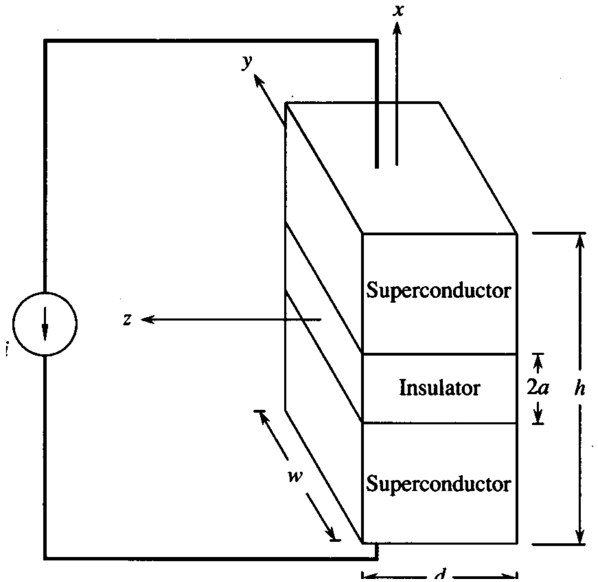
Gauge transformation

$$A' = A + \nabla\chi$$

$$\theta' = \theta + \frac{q^\star}{\hbar}\chi$$

$$\phi' = \phi - \frac{\partial\chi}{\partial t}$$

Josephson current-phase relation



$$\mathbf{J}_\mathrm{S} = \mathbf{J}_\mathrm{C} \sin(\theta_1 - \theta_2)$$

Généralisation en présence of an EM field ?

$$\mathbf{J}_\mathrm{S} = q^\star \,\mathrm{Re}\left\{\Psi^* \left(\frac{\hbar}{im^\star}\nabla - \frac{q^\star}{m^\star}\mathbf{A}\right)\Psi\right\}$$

ET

$$\theta_1 - \theta_2 = -\int_1^2 \nabla\theta dl$$

$$\boxed{\mathbf{J}_\mathrm{S}(\mathbf{r},t) = \mathbf{J}_\mathrm{C}(y,z,t)\sin\varphi(y,z,t)}$$

where the *gauge-invariant phase* is defined as

$$\varphi(y,z,t) = \theta_1(y,z,t) - \theta_2(y,z,t) - \frac{2\pi}{\Phi_o}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

The rate of change of the *gauge-invariant phase* is

$$\frac{\partial\varphi}{\partial t} = \frac{\partial\theta_1}{\partial t} - \frac{\partial\theta_2}{\partial t} - \frac{2\pi}{\Phi_o}\frac{\partial}{\partial t}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

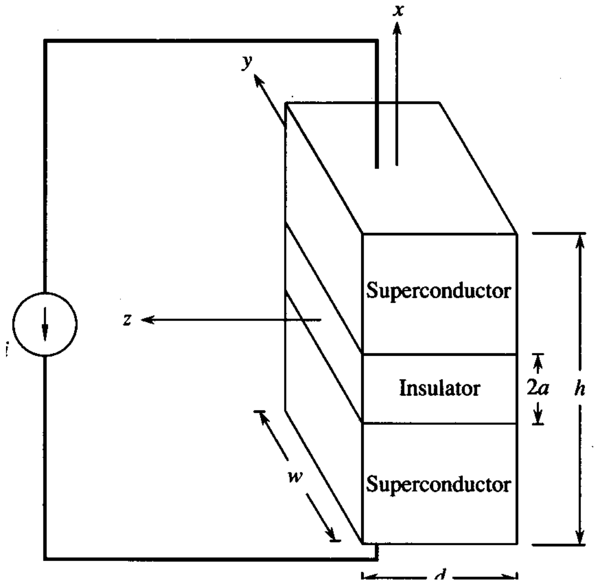
Gauge transformation

$$A' = A + \nabla\chi$$

$$\theta' = \theta + \frac{q^\star}{\hbar}\chi$$

$$\phi' = \phi - \frac{\partial\chi}{\partial t}$$

Josephson voltage-phase relation



The rate of change of the *gauge-invariant phase* is

$$\frac{\partial\varphi}{\partial t} = \frac{\partial\theta_1}{\partial t} - \frac{\partial\theta_2}{\partial t} - \frac{2\pi}{\Phi_o}\frac{\partial}{\partial t}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

At the boundary in the electrodes,

$$\frac{\partial}{\partial t}\theta(\mathbf{r},t) = -\frac{1}{\hbar}\left(\frac{\Lambda \mathbf{J}_S^2}{2n^\star} + q^\star\phi(\mathbf{r},t)\right) \quad \text{so that}$$

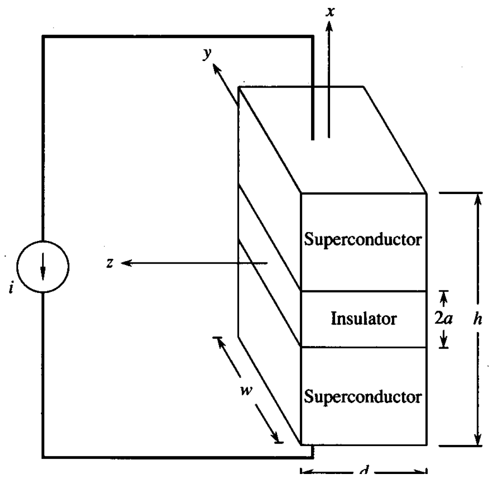
$$\frac{\partial\varphi}{\partial t} = -\frac{1}{\hbar}\left(\frac{\Lambda}{2n^\star}\underbrace{\left[\mathbf{J}_S^2(-a) - \mathbf{J}_S^2(a)\right]}_{0} + q^\star\underbrace{\left[\phi(-a) - \phi(a)\right]}_{\int_1^2 -\nabla\phi\cdot d\mathbf{l}}\right) - \frac{2\pi}{\Phi_o}\frac{\partial}{\partial t}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

Therefore, $\dfrac{\partial\varphi}{\partial t} = \dfrac{2\pi}{\Phi_o}\displaystyle\int_1^2\left(-\nabla\phi - \frac{\partial\mathbf{A}}{\partial t}\right)\cdot d\mathbf{l}$ or $\boxed{\dfrac{\partial\varphi(y,z,t)}{\partial t} = \dfrac{2\pi}{\Phi_o}\displaystyle\int_1^2 \mathbf{E}(\mathbf{r},t)\cdot d\mathbf{l}}$

Voltage

Josephson voltage-phase relation

Distributed element

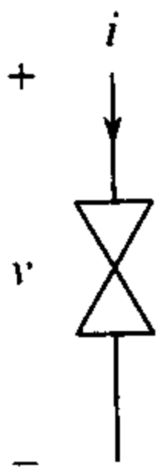


$$\mathbf{J}_S(\mathbf{r}, t) = \mathbf{J}_C(y, z, t) \sin \varphi(y, z, t)$$

$$\varphi(y,z,t) = \theta_1(y,z,t) - \theta_2(y,z,t) - \frac{2\pi}{\Phi_o} \int_1^2 \mathbf{A}(\mathbf{r}, t) \cdot d\mathbf{l}$$

$$\frac{\partial \varphi(y,z,t)}{\partial t} = \frac{2\pi}{\Phi_o} \int_1^2 \mathbf{E}(\mathbf{r}, t) \cdot d\mathbf{l}$$

Lumped element



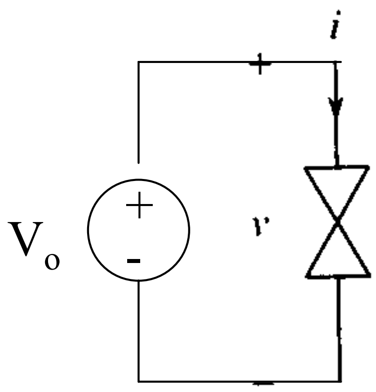
$$i = I_c \sin \varphi$$

$$v = \frac{\Phi_o}{2\pi} \frac{d\varphi}{dt}$$

$$\varphi(t) = \theta_1(t) - \theta_2(t) - \frac{2\pi}{\Phi_o} \int_1^2 \mathbf{A}(\mathbf{r}, t) \cdot d\mathbf{l}$$

I_c is the *critical current*

AC Josephson effect



$i = I_c \sin\varphi$

$v = \frac{\Phi_o}{2\pi}\frac{d\varphi}{dt}$

The voltage source is DC with v=V_0, so that

$$\varphi(t) = \varphi(0) + \frac{2\pi}{\Phi_o} V_o t$$

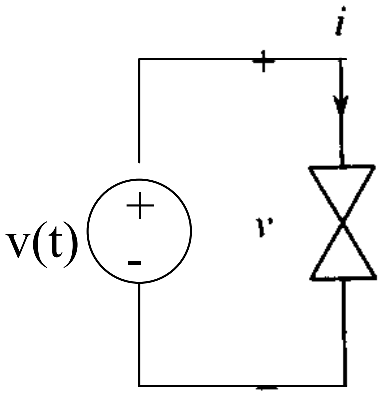
The resulting current is ac!

$$\begin{aligned} i &= I_c \sin\left(\frac{2\pi}{\Phi_o} V_o t + \varphi(0)\right) \\ &= I_c \sin\left(2\pi f_J t + \varphi(0)\right) \end{aligned}$$

The *Josephson frequency* is $f_J = \frac{V_o}{\Phi_o} = \frac{2e}{h} V_o = 483.6 \times 10^{12}\, V_o\ (\mathrm{Hz})$

A dc voltage of 10 µV causes an oscillation frequency of about 5 GHz, a Josephson microwave oscillator. But with a typical I_c of 1 mA, this oscillator delivers a very small power of the order of 10 nW. Therefore need many synchronous oscillators.

AC and DC voltage drives



$i = I_c \sin \varphi$

$v = \frac{\Phi_o}{2\pi} \frac{d\varphi}{dt}$

Let $v(t) = V_o + V_s \cos \omega_s t$

Then the guage-invariant phase is

$$\varphi(t) = \varphi(0) + \frac{2\pi}{\Phi_o} V_o t + \frac{2\pi V_s}{\Phi_o \omega_s} \sin \omega_s t$$

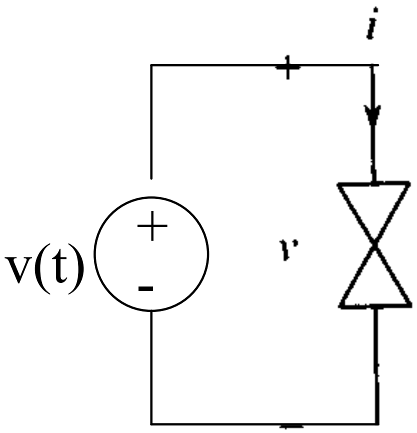
The current is FM-like: $i = I_c \sin\left(\varphi(0) + \frac{2\pi}{\Phi_o} V_o t + \frac{2\pi V_s}{\Phi_o \omega_s} \sin \omega_s t\right)$

Use the Fourier-Bessel series to express the current as a Fourier series

$$i = I_c \sum_{n=-\infty}^{\infty} (-1)^n \left[J_n\left(\frac{2\pi V_s}{\Phi_o \omega_s}\right)\right] \sin\left[(2\pi f_J - n\omega_s)t + \varphi(0)\right]$$

A dc current will occur when $2\pi f_J = n\, \omega_s$, that is, $V_o = n\left(\frac{\Phi_o}{2\pi}\right)\omega_s$

DC voltage standard



$$i = I_c \sin\varphi$$

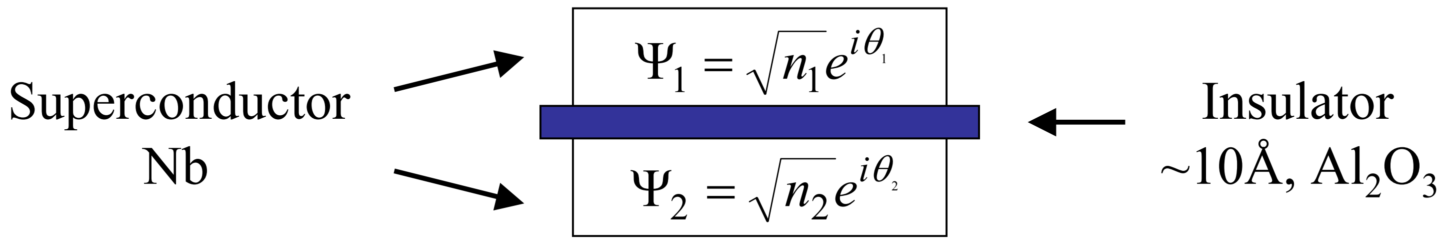
$$v = \frac{\Phi_o}{2\pi}\frac{d\varphi}{dt}$$

$$V_o = n\left(\frac{\Phi_o}{2\pi}\right)\omega_s$$

An ac voltage of 1 GHz applied across the junction will give a dc current, at $V_0 = 0$ and at dc voltages of integral multiples of 2μV.

The principle of the dc Volt: Put 5000 Josephson junctions in series, and apply a fixed frequency, which can be done very accurately, and measure the interval of the resulting dc voltages that occur at precise voltage intervals.

Josephson Junction = non linear inductor



- Josephson relations:

$$I = I_c \sin\varphi$$

$$V = \frac{\Phi_0}{2\pi}\frac{d\varphi}{dt}$$

$$\varphi = \theta_1 - \theta_2 - \frac{2\pi}{\Phi_0}\int_1^2 A(r,t)dl$$

- Behaves as a nonlinear inductor:

$$V = L_J \frac{dI}{dt},$$

where $L_J = \dfrac{\Phi_0}{2\pi\, I_c \cos\varphi}$

Φ_0 = flux quantum

483.6 GHz / mV