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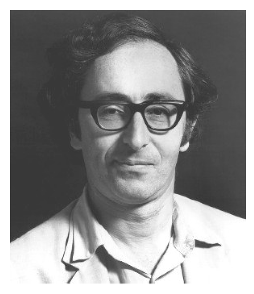
JOSEPHSON EFFECT

Abstract

In 1962, **Brian David Josephson** made the remarkable prediction, awarded by a Nobel prize in 1973, that a zero voltage supercurrent



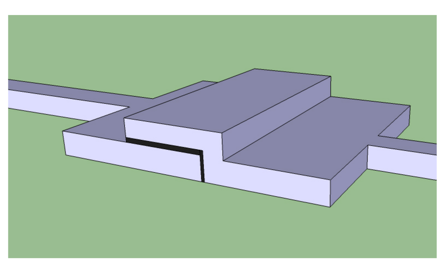
$$I_S = I_C \sin(\delta)$$

should flow between two **superconducting electrodes separated by a thin insulating barrier** (Superconductor/Insulator/Superconductor or SIS junction) [1-3]. Here δ is the difference in the phase of the Ginzburg-Landau wave function in the two electrodes, and the critical current I_C is the maximum supercurrent that the junction can support. He further predicted that if a voltage difference V were maintained across the junction, the phase difference δ would evolve according to the differential equation

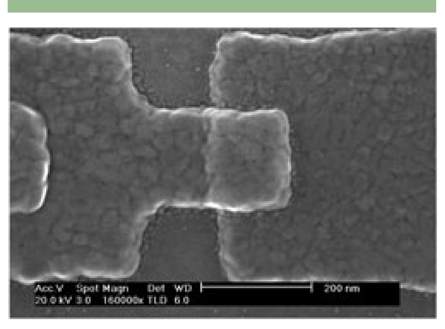
$$d\delta/dt = 2eV/\hbar$$

so that the current would be an alternating current of amplitude I_C and frequency ν=2eV/h. Thus, the quantum energy hν equals the energy change of a Cooper pair transferred accross the junction. These predicted effects, known as the **dc and ac Josephson effects**, respectively, have been fully confirmed by an immense body of experiments. Since then many works have extended the validity of this prediction to other kinds of weak links such as narrow constrictions of superconductor thin film (ScS) and Superconducting/Normal metal/Superconducting junctions (SNS). Researchers even continue nowadays to investigate it in more complex nanostructures such as carbon nanotubes or graphene nanoribbons.

In this experiment we propose the students to realize and manipulate macroscopic student-made Nb/NbOx/PbSn Josephson junctions in which the two predicted effects are observed.



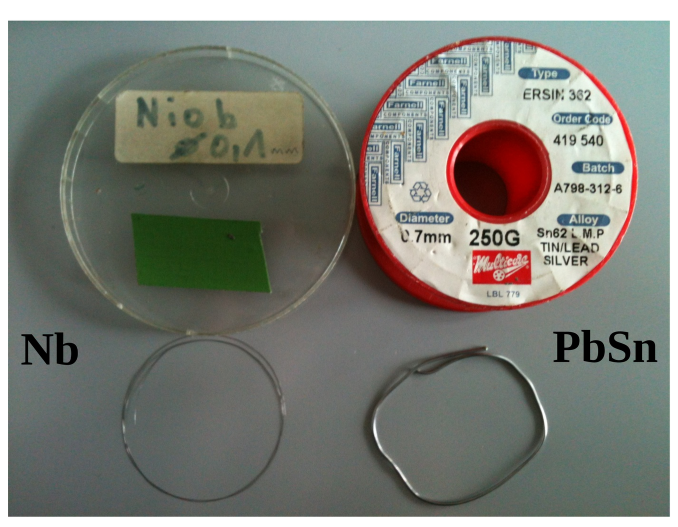
(a) Artist's view of a Josephson junction consisting of two superconducting materials separated by a thin insulating barrier (Creative commons).



*(b) Nanoscale Al/AlOx/Al Josephson junctions as used in the superconducting q-bits community (Supercond. Sci. Technol. **22,** 034009 (2009)).*

Experimental setup

(a)



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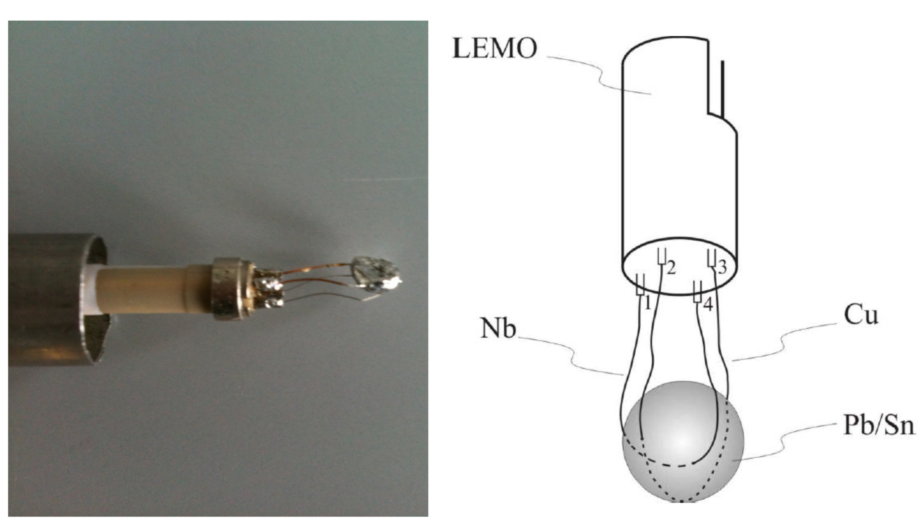

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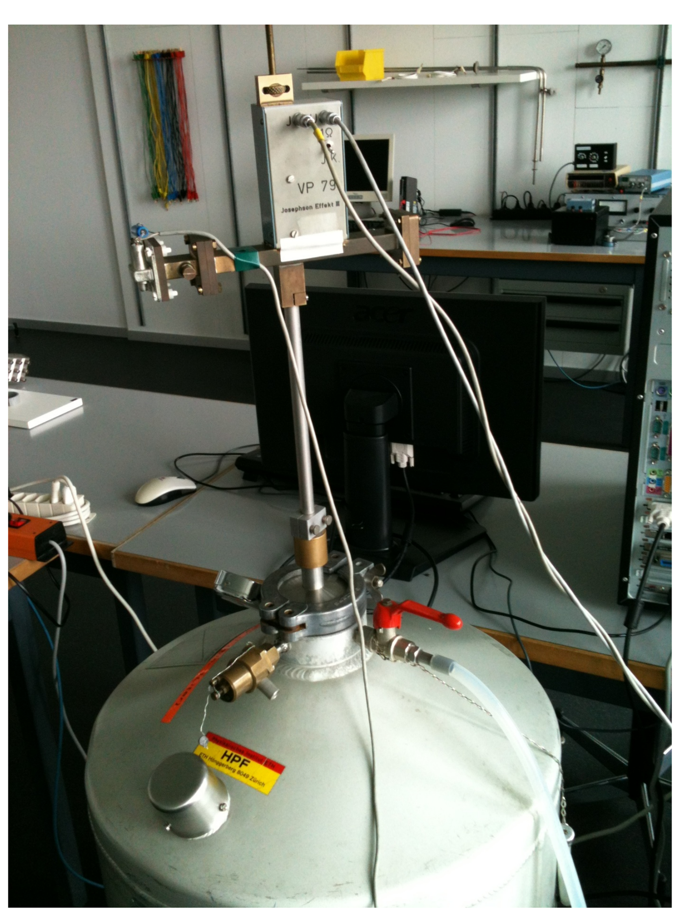

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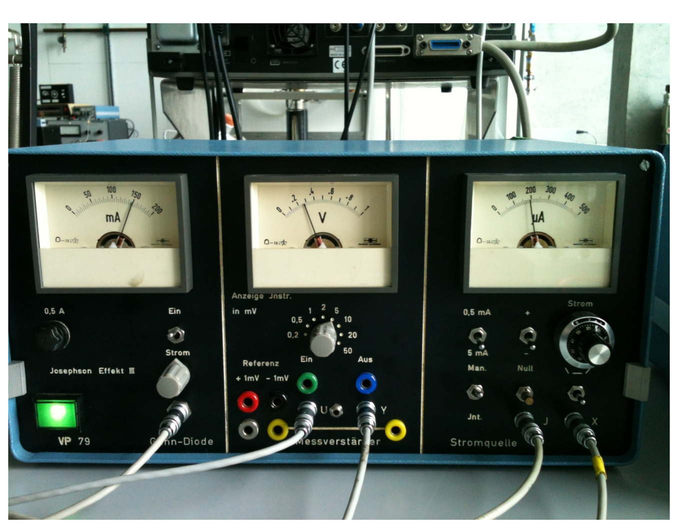
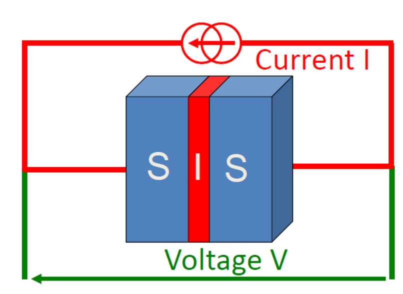


The students prepare their own Josephson junctions and measure them at low temperature. (a) Original Niobium and Plumb/Tin wires used to fabricate the Josephson junctions. (b) Picture and sketch of a realized macroscopic Josephson junction plugged in the measurement setup. (c) The sample is plugged into a stick containing a high frequency (10 GHz) antenna in close proximity to the sample. The stick is then immersed in a liquid Helium dewar at 4.2 K. (d) Left panel: Source of the gunn diode generating the radiofrequency signal. Center panel: voltmeter. Right panel: current source.

Results

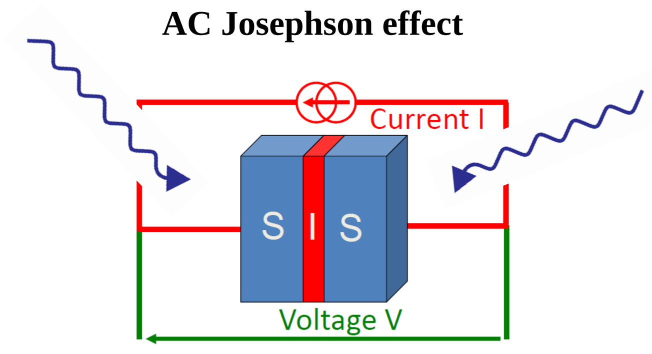
The students learn how to **fabricate Josephson junctions** as originally done in 1966 by J. Clarke [4]. The measurements are carried out in a liquid Helium dewar where a **temperature as low as 4.2K** (-269°C) is reached. Handling of cryogenic fluid is carefully introduced. Within this cold environment electrodes transit from the **normal state to the superconducting state** where the **dc and ac Josephson effects** can be observed. The measurement setup involves the use of basic **electronic tools** such as a current source, a voltage preamplifier and a voltmeter. The result of the experiment can be seen on a screen of a computer running a **Labview™ program**. Large freedom is given to the student to analyze their data. Whereas the dc Josephson effect can be seen very easily at low temperature through such junctions by simply measuring the V(I) trace, the ac Josephson effect implies the use of an additional **radiofrequency signal**. This signal, at a frequency ν_1 mixes with the oscillating current through the junction establishing voltage steps in the V(I) characteristics at multiple integers of $h\nu_1/2e$ where h is the Planck constant, e the charge of an electron and ν_1 is the irradiation frequency. The students are, as a result, able to **determine the superconducting flux quantum h/2e.**

DC Josephson effect



$$I_S = I_C sin(\delta)$$

AC Josephson effect



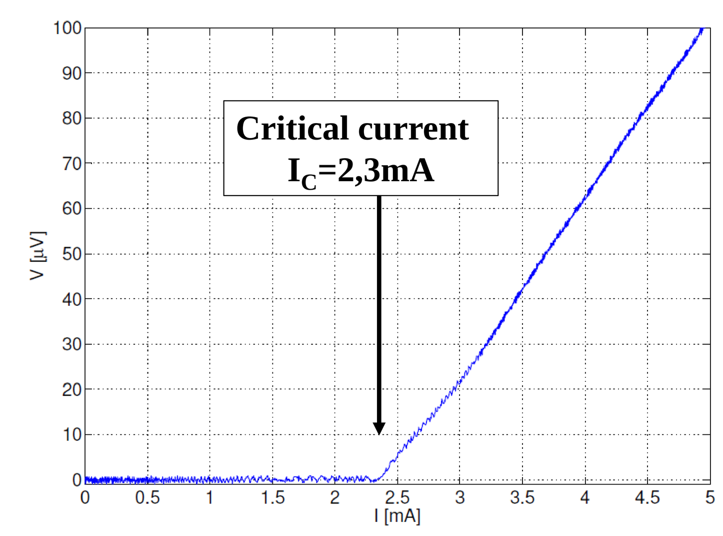
$$\frac{d\delta}{dt} = 2eV/\hbar \qquad V = V_0 + V_1 cos(2\pi\nu_1 t)$$

$$\delta(t) = \gamma_0 + 2\pi\nu_0 t + (2eV_1/h\nu_1) sin(2\pi\nu_1 t)$$

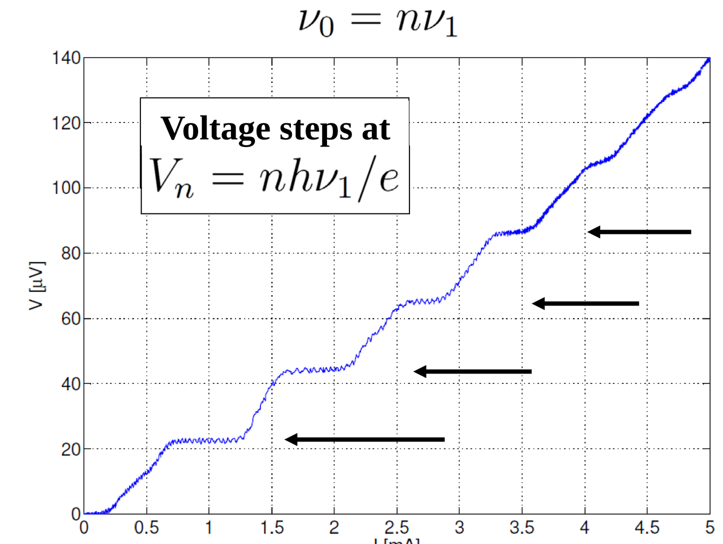
$$I_S = I_C \sum (-1)^n J_n(2eV_1/h\nu_1) sin(\gamma_0 + 2\pi\nu_0 t - n2\pi\nu_1 t)$$

$$\nu_0 = n\nu_1$$

(a)



(b)

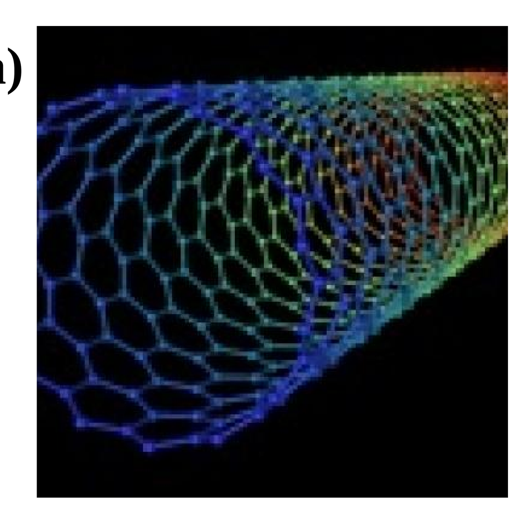


(a) V(I) trace of a Josephson junction made by a student without irradiation and at low temperature. One observes the dc Josephson effect with a critical current I_C=2,3 mA. (b) V(I) trace of the same junction submitted to high frequency irradiation (ν_1=10 GHz). Voltage steps, known as Shapiro steps, are a direct consequence of the ac Josephson effect. Their positions are given by the relation $\nu_0=n\nu_1$ where ν_0=2eV/h, ν_1 is the irradiation frequency and n is an integer number ($h\nu_1/e$~22 µeV).

Relation to current Research

The responsible of the experiment tells the students about the timeliness of the Josephson effects in current research and their applications. Students are encouraged to read recent research papers on the subject, such as the paper by J.P. Cleuziou *et al.,* Phys.Rev. Lett. 2007, about a Josephson junction based on a carbon nanotube.

(a)



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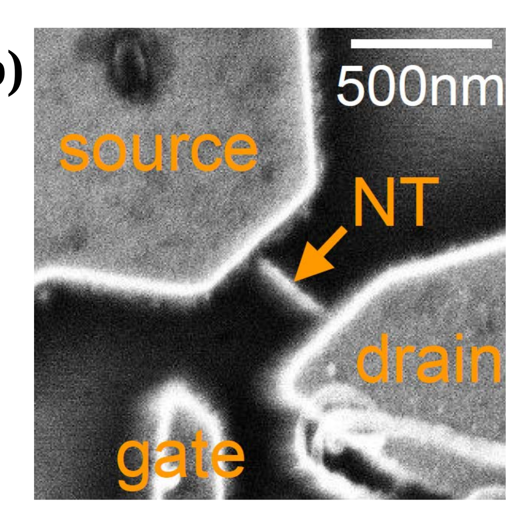

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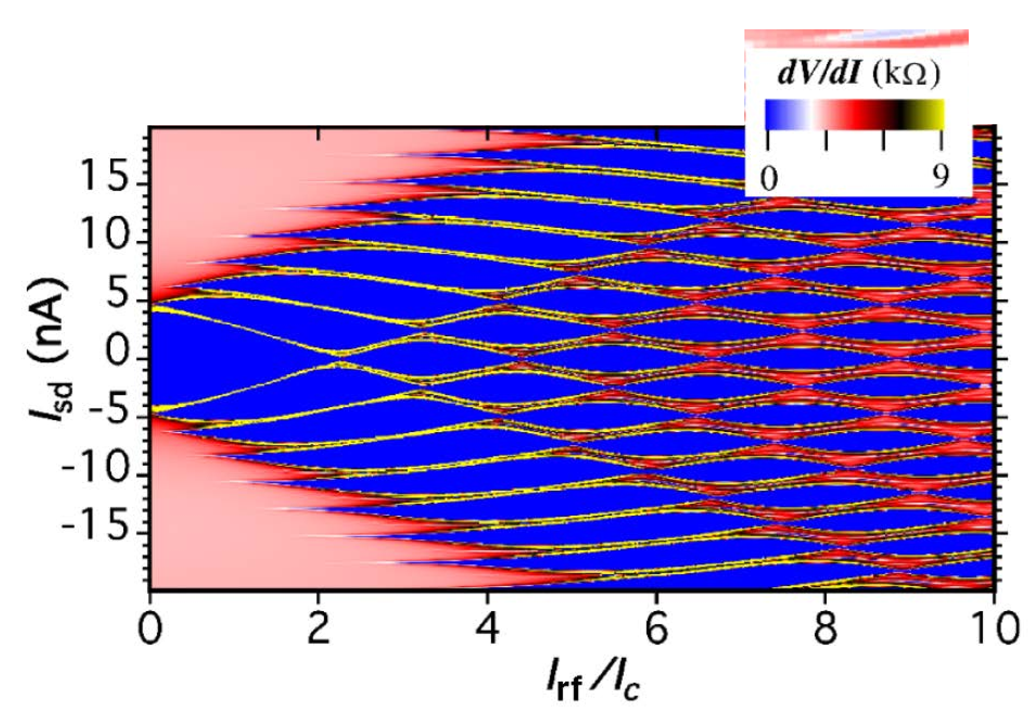

*(a) Artist's view of a carbon nanotube. The diameter is about 2-3 nm (Creative commons). (b) Scanning electron micrograph picture of a carbon nanotube connected between two Aluminum superconducting electrodes (J.Basset thesis Univ. Paris Sud 2011). (c) Dc current bias dependence of the resistance of a carbon nanotube Josephson junction submitted to a radio frequency signal (ν=3GHz) of varying amplitude I_{RF}. The power dependence clearly shows the Bessel function behaviour of the voltage steps positions that the students could measure (J.P.Cleuziou et al PRL **99**, 117001 (2007)).*

To learn more

[1] R.P.Feynman, R.B. Leighton and M.Sands, *The Feynman lectures on Physics, Vol. III, Quantum Mechanics, Chap. 21,* Addison Wesley
[2] M.Tinkham, *Introduction to superconductivity*, Mc Graw-Hill, 1975
[3] C. Kittel, *Introduction to solid state physics*, Wiley, ab 4. Auflage
[4] J. Clarke, *Phil. Mag.* **13**, 155 (1966)

Author : Julien Basset

23 April 2012