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Autor: Devoret, M.H. / Martinis, J.M. / Esteve, D.

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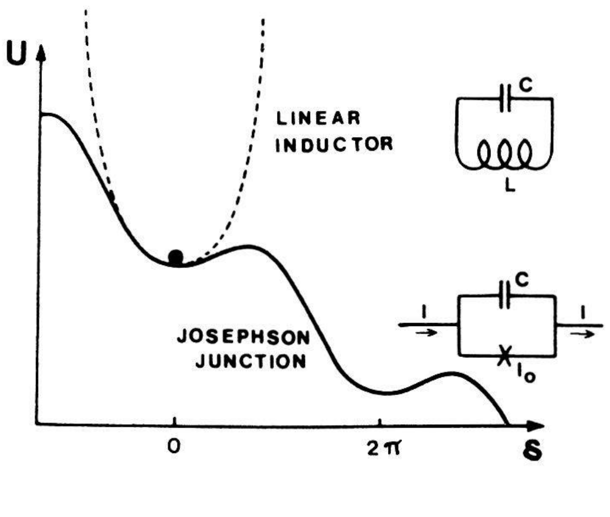
MACROSCOPIC QUANTUM PHENOMENA IN THE CURRRENT BIASED JOSEPHSON JUNCTION.

M. H. DEVORET, J.M. MARTINIS, D. ESTEVE AND J. CLARKE*
Service de Physique du Solide, CEN Saclay, 91191 GIF Cedex, France
* Permanent address : Physics Department, U.C.B., Berkeley, CA 94720, USA.

This brief communication presents the results of an experiment [1] adressing the question : do macroscopic degrees of freedom obey quantum mechanics? Although the answer may seem obvious to many cynicists ("Of course they do! What do you expect ?"), a direct test of the postulates of quantum mechanics at the macroscopic level has been until recently beyond the reach of experimentalists. Quantum mechanics usually sneaks into our macroscopic world through collective phenomena such as superfluidity, superconductivity or the Josephson effect. Although these phenomena are conventionnally described as being macroscopic, they are in fact macroscopic manifestations of the coherent addition of microscopic variables each governed by quantum mechanics. Leggett has emphasized the distinction between these collective quantum effects and the "genuine" macroscopic quantum phenomena in which a macroscopic degree of freedom behaves quantum mechanically [2].

In our experiment, the macroscopic degree of freedom is the phase difference across a current biased Josephson tunnel junction. The underlying microscopic physics of the Josephson effect plays no role in our experiment and for all purposes our junction can be thought of simply as a non-linear inductor in parallel with a capacitor (see Fig. 1). The inductor is

Fig. 1

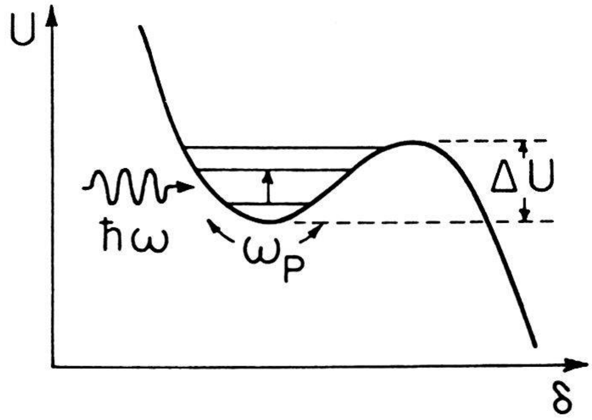


determined by the critical current I_0 of the junction and the bias current I. The capacitor is the self-capacitance of the junction. The phase difference δ is equivalent to the flux ϕ through the inductor : $\delta \Longleftrightarrow 2\pi\phi/\phi_0$ (ϕ_0 is the flux quantum). The non-linearity of the inductor is such that the classical equation of motion obeyed by the phase is analogous to the equation of motion of a particle in a tilted cosine potential U (see Fig. 1). The anharmonicity of this potential is essential to the observation of the quantum behavior of the macroscopic variable δ.

To see this, consider instead of a current biased Josephson junction a simple LC harmonic oscillator. The unavoidable coupling to the environnement will damp the oscillator. This damping can be represented by a resistor R in parallel with the circuit. Two conditions have to be met in order for the flux ϕ through the inductor to behave quantum mechanically. First, the thermal fluctuations must be reduced well under the level of quantum fluctuations. This amounts to $\hbar\omega_{LC} >> kT$, where ω_{LC} is the oscillator frequency given by $(1/LC)^{1/2}$. Second, the damping must be low enough that the lifetime of the quantum energy levels is much greater than the period of oscillation. This is equivalent to $R >> (L/C)^{1/2}$. These conditions can now be routinely obtained in the laboratory. A working example is L = 0.1 nH, C = 10 pF, R = 50 Ω and T = 20 mK. However, the harmonic oscillator is a special case : the quantum mechanical average value $\langle\phi(t)\rangle$ will behave exactly like its classical counterpart $\phi(t)$, a property which is often expressed by saying that the harmonic oscillator is always in the correspondence limit. Only higher moments such as $\langle\phi(0)\phi(t)\rangle$, which seem hard to measure, will reveal the quantum nature of this macroscopic system. On the contrary, for the anharmonic oscillator, the average $\langle\phi(t)\rangle$ directly shows quantum effects.

We bias the junction so that its phase difference is initially in a relative minimum of the tilted cosine potential shown in Fig. 1. In the vicinity of a minimum, the potential can be very well approximated by a cubic potential (see Fig. 2). Because of the anharmonicity of the potential, the energy levels will not be equidistant like in the harmonic oscillator. Furthermore the levels will now be metastable because they can decay by quantum tunneling through the potential barrier. For the metastable bound states in the well the phase difference is stationnary and the junction is in its zero-voltage state. However, for the continuum of propagative states

Fig. 2



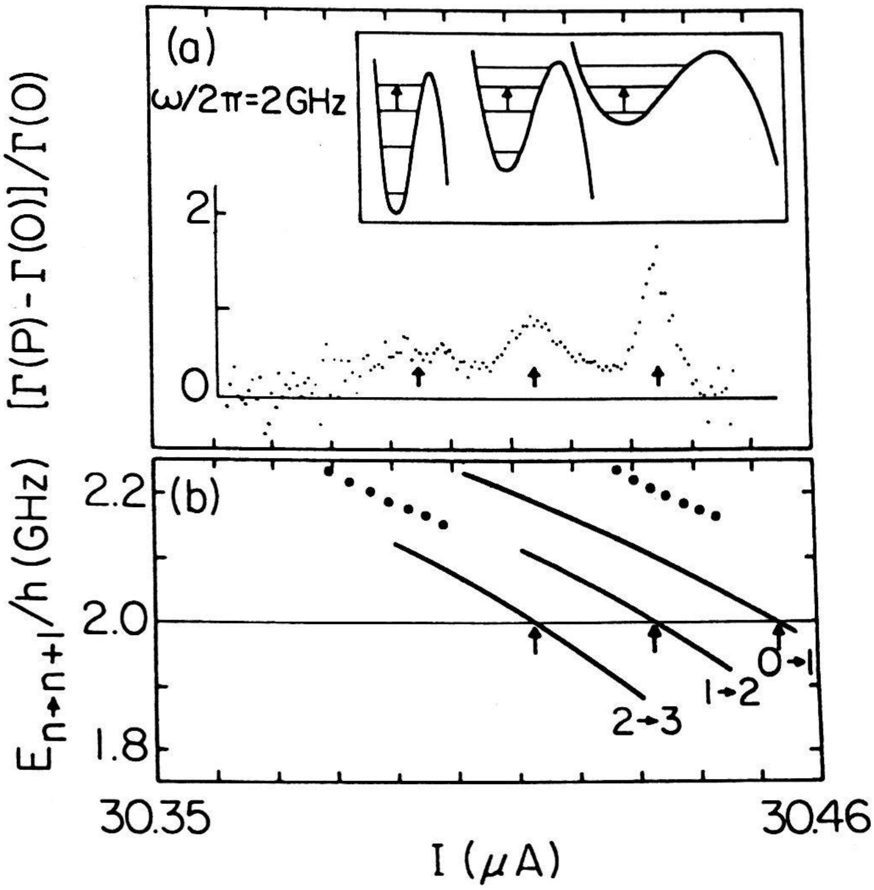
outside the well, the phase evolves with time and the junction is in its non-zero voltage state. The onset of the non-zero voltage state can easily be detected by measuring the voltage across the junction.

We have observed both the quantized energy levels and the quantum tunneling by measuring the escape rate to the non-zero voltage state. Our experiment differs from others [3] mainly in that the escape rate measurement is done in the presence and absence of microwave irradiation. The microwave irradiation is a powerful "knob" on the system with which we can extract all the junction parameters relevant to the escape.

Quantized energy levels

Under suitable conditions at low temperatures there are only several levels in the well. For temperatures T greater than $\hbar\omega_p/2\pi$, the escape in the absence of microwaves will occur via thermal activation above the potential barrier at a rate $\Gamma(0)$. In the presence of microwave power P however, the population of the excited states at the top of the well increases. The particle then escapes with a rate $\Gamma(P)$ which is much faster than $\Gamma(0)$. One thus expects a resonant enhancement of the escape rate when the irradiation frequency matches a transition frequency $(E_{n+1}-E_n)/h$. In practice, we keep the frequency fixed and vary the bias current I, with the effect of changing continuously all the level spacings. One can in this way determine spectroscopically the position of the energy levels in the well. Our results for a C = 47 pF junction are plotted in figure 3a.

Fig. 3



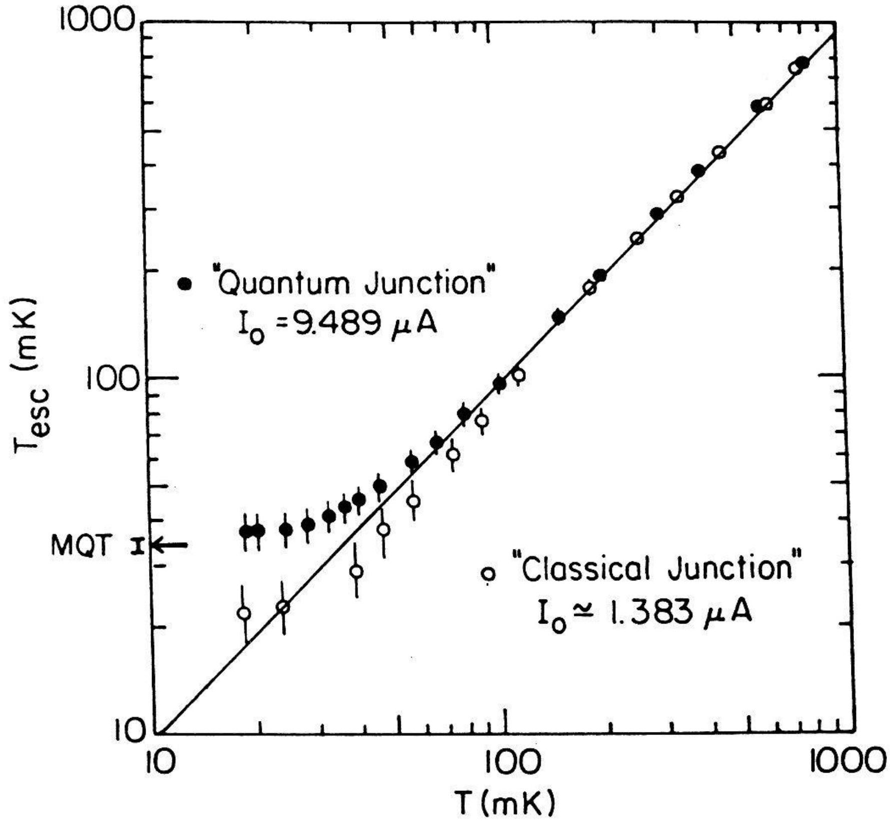
These results can be compared with a quantum calculation based on the Schrödinger equation of the particle in the well. There is no adjustable parameters since ΔU and ω_p are measured <u>in situ</u> in the classical regime where the escape takes place through thermal activation [4]. An unambiguous agreement between the experimental value of the relative positions of the resonances and their theoretical prediction is found (see Fig. 3b). The relatively small shift in the absolute value of the position of the resonances is likely to be due to the uncertainty in the determination of the critical current (the resulting uncertainty in the 0 → 1 transition frequency is shown by the dotted line).

In this experiment, the junction is only slightly damped, the dissipation being due to the last filtering stages of the current bias and voltage measurement circuitry. The Q factor for the oscillations in the well, around 80, was measured also <u>in situ</u> in the classical regime. The relative width of the resonance in the quantum regime is approximatively equal to 1/Q, as predicted by theory [5].

Quantum tunneling

This relatively small amount of dissipation in the experiment should have a negligible effect on the absolute value of the quantum tunneling rate in absence of microwaves [6]. Indeed, we have found good quantitative agreement between this rate and the theoretical WKB predictions. Fig. 4 shows the escape rate plotted as an escape temperature T_{esc} defined through the relation $\Gamma = (\omega_p/2\pi)\exp(-\Delta U/kT_{esc})$ versus temperature. This measurement was done for a C = 6 pF junction which could be placed more firmly in the quantum regime (at the expense of a somewhat greater damping : $Q \approx 30$; however the damping was not strong enough to affect significantly the escape rate). The white dots correspond to a measurement done with a magnetic field on the junction which has the effect of reducing its critical current. With a reduced critical current, the potential barrier width is larger and the junction should behave classically down to the lowest temperatures. Indeed the escape rate followed the classical prediction (solid line) showing that no significant amount of external noise was reaching the junction. When the

Fig. 4



critical current is restored to its original value, we measure a higher value of the escape rate (solid dots). The escape rate becomes temperature independent at low temperatures which is expected if the escape mechanism is dominated by quantum fluctuations. This interpretation is supported by the quantitative agreement between this limit value of the measured escape rate and its theoretical prediction (arrow).

In conclusion, our results of the measurement of the escape rate out of the zero-voltage state for a current biased Josephson junction agree quantitatively with predictions based on quantum theory, all the relevant parameters being measured in situ. This agreement provides very strong evidence for the quantum nature of the macroscopic variable δ.

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