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# Observation of the Temporal Decoupling Effect on the Macroscopic Quantum Tunneling of a Josephson Junction

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## Abstract

We have measured the Macroscopic Quantum Tunneling (M.Q.T.) rate out of the zero voltage state of a Josephson junction shunted by a delay line terminated by a resistor. As the length of the line is increased *in situ*, thereby increasing the delay with which the resistor damps the junction, the M.Q.T. rate increases until it almost recovers its value in the absence of damping: this constitutes the temporal decoupling effect. We compare our results to the theoretical predictions.

## 1. Tunneling in presence of friction and the temporal decoupling effect

Although tunneling has been known since the early developments of quantum mechanics, the way in which the coupling of a quantum variable to the environment affects its tunneling has been questioned only recently. This problem has been raised for the quantum tunneling of a macroscopic variable, which is unavoidably coupled to the external world. Indeed, Caldeira and Leggett [1] predicted that such a coupling can drastically reduce the rate of quantum tunneling out of a metastable state. They showed that this reduction depends only on the damping experienced by the tunneling variable and on no other feature of the environment. They also computed this reduction at zero temperature for instantaneous friction. This effect has since been observed on the Macroscopic Quantum Tunneling (M.Q.T.) of shunted Josephson junctions [2, 3].

Another fundamental prediction [4–6] is that this reduction does not take place if the response time of the environment to the motion of the variable that tunnels is too long. The characteristic response time for this temporal decoupling effect to occur is an environment independent time scale of the tunneling phenomenon itself. It is much shorter then the lifetime of the metastable state and can be interpreted as the average time the variable "spends" under the barrier while tunneling.

We present here measurements of this temporal decoupling effect on the M.Q.T. rate of a current biased Josephson junction in a new setup. In our experiment, the response time of the biasing circuit which constitutes the environment can be adjusted *in situ*, while all other parameters are kept constant. These other experimental parameters having been measured independently, we can compare our results to the theoretical predictions unambiguously.

## 2. M.Q.T. of a Josephson junction

A Josephson junction consists of two layers of superconductor separated by a thin insulating barrier. It has a single macroscopic degree of freedom, the superconducting phase difference $\delta$ between both layers. When a junction is connected to a measuring circuit, $\delta$ couples to the electromagnetic degrees of freedom of the circuit, just as an atom placed in a cavity couples to the modes of the cavity. This circuit constitutes the environment of the junction. The current biasing and voltage sensing circuit we have used in our experiments is completely described, as far as the junction is concerned, by an ideal dc current source in parallel with a frequency dependent impedance $Z(\omega)$, as shown in Fig. 1. Connected to this circuit, the junction can be modeled as a particle of coordinate $\delta$ moving in a one-dimensional tilted washboard potential $U(\delta) = U_0(-s\delta - \cos\delta)$, where $U_0 = I_0\Phi_0/2\pi$ and $s = I/I_0$. $I_0$ is the junction critical current, $I$ the bias current and $\Phi_0 = h/2e$ the flux quantum. This particle is also subject to a damping force and to a fluctuating force which arise from the coupling of the junction variable $\delta$ with the degrees of freedom of the impedance $Z(\omega)$, assumed in thermal equilibrium at a temperature $T$.

The velocity of the particle represents the voltage across the junction. When the particle is trapped in a potential well, the junction is in its metastable zero voltage state. For $s \lesssim 1$, the well (see Fig. 2) is characterized by (*i*) the barrier height $\Delta U = U_0'(1-s)^{3/2}$, where $U_0' = (4\sqrt{2}/3)U_0$ and (*ii*) the frequency of the small oscillations at the bottom of the well $\omega_p = (2\pi I_0/\Phi_0 C)^{1/2}(1-s^2)^{1/4}$, where $C$ is the junction capacitance. In the thermal regime defined by $k_B T \gg \hbar\omega_p$, where $k_B$ is the Boltzmann constant, the fluctuating force causes the escape out of the well. When $k_B T \ll \hbar\omega_p$ quantum tunneling from the ground state in the well through the potential barrier is the dominant escape process [7].

After an escape event, the particle accelerates down the washboard potential and quickly reaches a limit velocity. This represents the switching of the junction to its voltage state. One can then reset the junction to the zero voltage state by momentarily reducing to zero the bias current. We measure the lifetime of the metastable zero voltage state by recording a series of switching events.

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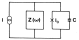

*Fig. 1.* Josephson junction biases by a current source and shunted by an impedance representing its electrical environment. The Josephson junction is the combination of an ideal Josephson element (cross) and of a capacitor.

## 3. Realisation of delayed friction

The adjustable impedance $Z(\omega)$ was constructed by biasing the junction through a coplanar transmission line partially covered by a microwave absorbing block, as shown in Fig. 3. The portion of transmission line left uncovered defines a delay line, of length $l$, characteristic impedance $Z_c$ and propagation velocity $c_l$. The covered portion behaves in the microwave range as a terminating resistor $Z_t$ for the delay line. The impedance of this circuit is

$$Z(\omega) = Z_c \frac{(1 - a\,e^{-2i\omega t_d})}{(1 + a\,e^{-2i\omega t_d})} \qquad (1)$$

where $t_d = l/c_l$ is the delay and $a = (Z_t - Z_c)/(Z_t + Z_c)$ is the reflection coefficient of the terminating resistor.

If one applies a voltage step to such a circuit, the current response $F(t)$, which is the Fourier transform of $[i\omega Z(\omega)]^{-1}$, consists of a series of steps separated by $2t_d$, as shown in Fig. 4(a). Thus, by changing in situ the length $l$ one changes the rise time of the response function $F(t)$.

## 4. Effect of friction on M.Q.T. of a Josephson junction

Leggett [4] has calculated the effect on M.Q.T. at zero temperature of a circuit with arbitrary response function $F(t)$. His result can be cast in the form

$$\Gamma = (\omega_p/2\pi)\cdot(120\pi B)^{1/2}\exp(-B) \qquad (2)$$

with

$$B = B_0\left[1 + \int_0^\infty F(t)G(t)\,dt\right] + \mathcal{O}[F(t)] \qquad (3)$$

where $B_0 = 7.2\Delta U/\hbar\omega_p$ is the tunneling exponent in absence of environment and where function $G(t)$ is, for $x \lesssim 1$, given by

$$G(t) = \frac{45}{\pi^4 C}\sum_{n=1}^{\infty}\frac{n}{[n + (\omega_p t/2\pi)]^5}. \qquad (4)$$

As can be seen in Fig. 4(b), $G(t)$ is a monotonic decaying function. We define the passage time $t_p$ by

$$t_p = \frac{\int_0^\infty tG(t)\,dt}{\int_0^\infty G(t)\,dt}. \qquad (5)$$

For $G(t)$ given by expression (4), the value of the passage time is $t_p = 0.46(2\pi/\omega_p)$. The structure of expression (3) implies that the environment does not affect the escape rate if the rise time of $F(t)$ is much longer than the passage time: this constitutes the temporal decoupling effect.

Grabert *et al.* [8] have extended Leggett's theory at finite temperature and arbitrary damping strengths. They found that the effect of friction on the escape rate decreases strongly as soon as the temperature reaches the cross-over temperature defined by $k_B T_{co} = \hbar\omega_p/(2\pi)$ and that quantitative deviations from the above expression arise when one takes into account the response function $F(t)$ at all orders. We have numerically computed the predictions of this theory for the response function $F(t)$ corresponding to our experiment.

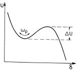

*Fig. 2.* Potential well from which the junction phase difference escapes.

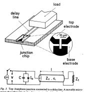

*Fig. 3.* Top: Josephson junction connected to a delay line. A movable microwave absorbing block (load) terminates the delay line. Bottom: schematics of the equivalent circuit at microwave frequencies (narrow lines). We have also schematically added the current biasing and voltage measurement circuit (thick lines).

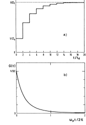

*Fig. 4.* (a) Current response function $F(t)$ of the delayed friction circuit of Fig. 3 to a voltage step. (b) Function $G(t)$ for tunneling out of the cubic potential [expression (4)].

## 5. Experimental procedure and determination of the parameters

The Josephson junction, the delay line and the last stage of a series of low pass filters were cooled down in a dilution refrigerator. These filters were designed to prevent any spurious thermal or external noise to reach the junction. The total excess noise was estimated to correspond to less than 1 mK of thermal noise at the lowest temperature (18 mK) in the bandwidth 0.1–15 GHz. The escape events were recorded and analysed as described in reference [7].

The parameters of the circuit $Z_c$, $c_1$, and $Z_t$ were measured with a network analyser. The parameters of the junction, $I_0$ and $C$ were determined in the thermal activation regime [7]. The values of all these experimental parameters are listed in Table I.

Table I. *Experimental parameters*

$Z_c = 72 \pm 5\,\Omega$
$c_1 = 2.3 \pm 0.1 \times 10^8\ \mathrm{m\,s^{-1}}$
$Z_t = 20 \pm 5\,\Omega$
$C = 2.7 \pm 0.15\,\mathrm{pF}$
$I_0 = 7040 \pm 20\,\mathrm{nA}$

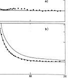

*Fig. 5.* Lifetime $\tau$ of the zero voltage state versus delay $t_d$ at two temperatures (a) $T = 65\,\mathrm{mK}$ and (b) $T = 18\,\mathrm{mK}$. Dashed line corresponds to the zero temperature perturbative expression (2). Full line is the prediction of a numerical calculation using theory developed in Ref. [8].

## 6. Measurements of the temporal decoupling effect

We have measured the lifetime $\tau = \Gamma^{-1}$ of the metastable state for lengths $l$ ranging between 2 and 40 mm and for temperatures between 18 and 150 mK. We focus here on the behaviour of the lifetime when the length $l$, and hence the delay $t_d$, is increased.

Fig. 5 displays this behaviour at two temperatures for the same bias current. These two temperatures of 18 mK and 65 mK are respectively below and above the crossover temperature $T_{co} = 47\,\mathrm{mK}$ of that experiment.

At 18 mK, the lifetime is three times longer at the shortest delay $t_d = 10\,\mathrm{ps}$ than at the longest ones. The temporal decoupling effect is almost complete at a delay of 100 ps. The dashed line shows the prediction of eq. (2). There is only a qualitative agreement with the data, as expected in view of the finiteness of temperature and friction. The continuous line is a best fit obtained from our full numerical theory using the parameter values listed in Table I and for $s = 0.9855$, the estimated value being $s = 0.9858 \pm 0.0005$. The corresponding passage time is $t_p = 78\,\mathrm{ps}$.

At 65 mK, in the thermal regime, we do not observe any important change of the lifetime with the delay, as predicted by theory. Similar data taken at 31 mK and 45 mK show that the decrease of the temporal decoupling effect is gradual when the temperature is raised.

## 7. Temporal decoupling in other tunneling systems

The concept of temporal decoupling is not restricted to systems of macroscopic nature, and appears to be relevant to understand tunneling of microscopic particles like electrons in the Scanning Tunneling Microscope (S.T.M.) or in heterostructures.

In both cases the potential only consists of a barrier and has no minimum, and the environment consists of the electromagnetic plasma modes in the conducting electrodes. These modes screen the field created by the tunneling electron and can therefore react on it. Persson and Baratoff [9] have shown that this dynamical screening affects the tunneling rate only if it is effective on a time scale shorter than a characteristic time of tunneling, the traversal time introduced by Büttiker and Landauer [10]. These authors interpret the traversal time as the average time spent by the particle while it tunnels through the barrier. Tunneling rate measurements of Gueret *et al.* [11] on heterostructures with barriers of various barrier heights have shown that the dynamical screening is indeed effective only when the electronic plasma period in the electrodes is shorter than the traversal time of the electrons through the barrier.

Thus, the passage time we have introduced plays for the decay of a metastable state the same role as the traversal time for tunneling through a barrier.

## 8. Conclusion

We have found that the lifetime of a current biased Josephson junction placed in the quantum regime and experiencing delayed friction decreases with increasing delay until it saturates. This temporal decoupling effect is in qualitative agreement with Leggett's predictions and in quantitative agreement with the complete theory developped by Grabert *et al.* Saturation occurs when the delay is a few times longer than the passage time. This time is a second time scale for the quantum decay of a metastable state, related to the traversal time originally introduced for the tunneling of particles impinging on a potential barrier.

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