MACROSCOPIC QUANTUM TUNNELLING AND COHERENCE: THE EARLY DAYS

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Quantum Superconducting Circuits and Beyond

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Some 60's pre-history: Is there a quantum measurement problem?

"In our opinion, our theory [of the measurement process] constitutes an indispensable completion and a natural crowning of the basic structure of present-day quantum mechanics. We are firmly convinced that further progress in this field of research will consist essentially in refinements of our approach." (Daneri et al., 1966)

"The current interest in [questions concerning the quantum measurement problem] is small. The typical physicist feels that they have long been answered and that he will fully understand just how if ever he can spare twenty minutes to think about it." (Bell and Nauenberg, 1966)

"Is "decoherence" the answer?" (Ludwig, Feyerabend, Jauch, Daneri et al…)

NO!

Then, can we get any experimental input to the problem? i.e.

Can we build Schrödinger's cat in the lab?

Some early reactions:

1) Unnecessary, because “we already knew that QM works on the macroscopic scale” (superfluid He, superconductivity, lasers)

2) Ridiculous, because “decoherence will always prevent macroscopic superpositions” (“electron-on-Sirius” argument)

What kind of system could constitute a “Schrödinger’s cat”?

1) Must have macroscopically distinct states, with transitions between them mediated by intrinsically QM processes

2) For QM processes to be non-negligible, need relevant values of S (classical action) to be not too large in units of $\hbar$

3) To avoid decoherence, coupling to “environment” should be small

4) To avoid decoherence, intrinsic dissipation should be small

Promising candidate: Josephson devices

1) At least in rf SQUID ring ("flux qubit") states of opposite circulating current (may be) "macroscopically distinct"

2) Back-of-envelope estimates ⟹ with attainably small capacitance, $S/\hbar \lesssim 20$

3) Techniques for shielding and isolation well devloped in context of metrology

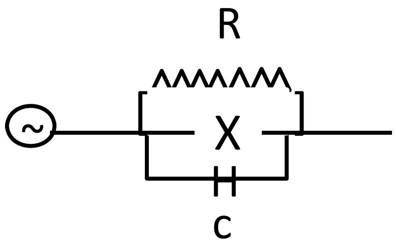
4) Most obvious source of intrinsic dissipation, normal electrons, vanishes exponentially at low T: for 1 cm^2 block of Nb at T = 50mK, $n_n \sim 10^{-100}$!

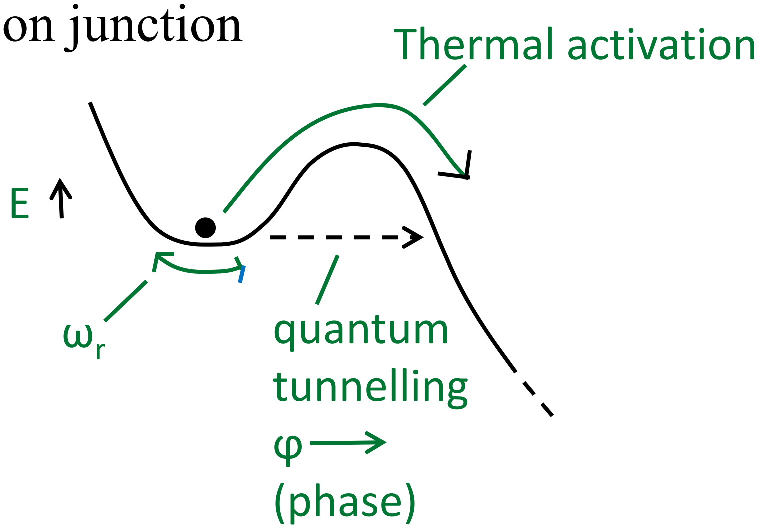
↑

number (not fraction!) of normal electrons

Two principal experimental setups:

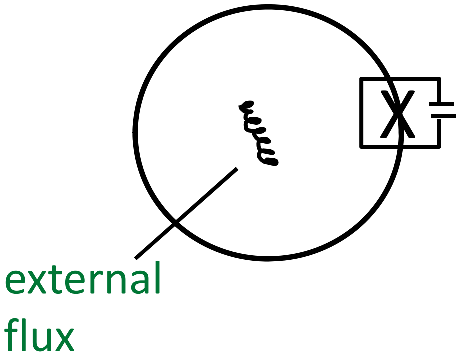
A. Current-biased Josephson junction

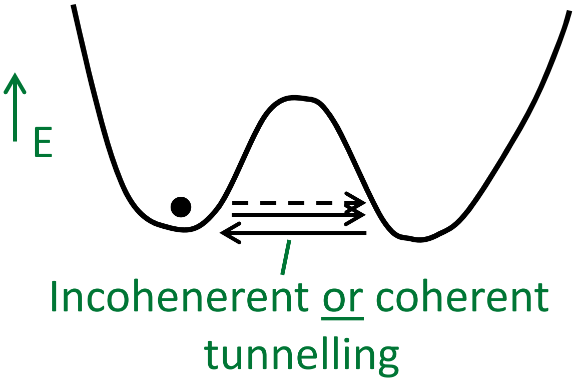




“macroscopic quantum tunnelling”
(MQT)

B. Rf SQUID ring (“flux qubit”)





“macroscopic quantum coherence”
(MQC)

Ivanchenko and Zilberman (1968): back-of-envelope estimate of onset of MQT when $k_B T \sim \hbar\omega_\rho$.

Fulton and Dunkleberger (1974): experiments on Kramers activated escape of JJ from zero-voltage state down to $k_B T \sim 4\hbar\omega_\rho$, no evidence for MQT

De Bruyn Ouboter (1980): observation of incoherent tunnelling of rf SQUID between flux states

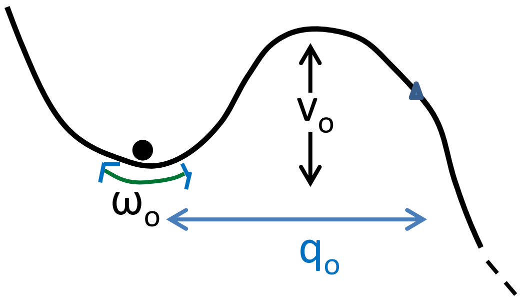
Clark et al., (1980): claim evidence for MQC-type behavior in rf SQUID.

The \$64 K question, c. 1980:

What does damping/decoherence do to the “naïve” predictions?

((classical) damping $\rightleftarrows$ (quantum) decoherence)

The simplest case (MQT with “ohmic” damping):



If classical equation of motion is

$$M\ddot{q} + \frac{\partial V}{\partial q} = 0$$

quantum tunnelling

Then (plausibly!) escape rate by QT is

$$\Gamma_{QT} = A_o \exp - B_o/\hbar \qquad B_o \equiv WKB \text{ exponent}$$

$$= \frac{36}{5}\left(\frac{V_o}{\hbar\omega_o}\right),$$

$$A_o \equiv \omega_o (60 B_o / 2\pi\hbar)^{1/2}$$

But: what if classical equation of notion is

$$M\ddot{q} + \underset{\substack{\uparrow \\ \text{Friction coefficient}}}{\eta}\dot{q} + \frac{\partial V}{\partial q} = 0$$

Must find a way to treat dissipative term in language of QM

Solution (Feynman & Vernon, Ullersma ...):

model environment by bath of harmonic oscillators

(Why does this work? – cf. 19th century atomic physics!)

How to combine this with WKB technique?

Solution: use instanton method (Stone, Callan & Coleman …)

But must include “counterterm” to offset reactive effects of coupling (suppression of barrier height)

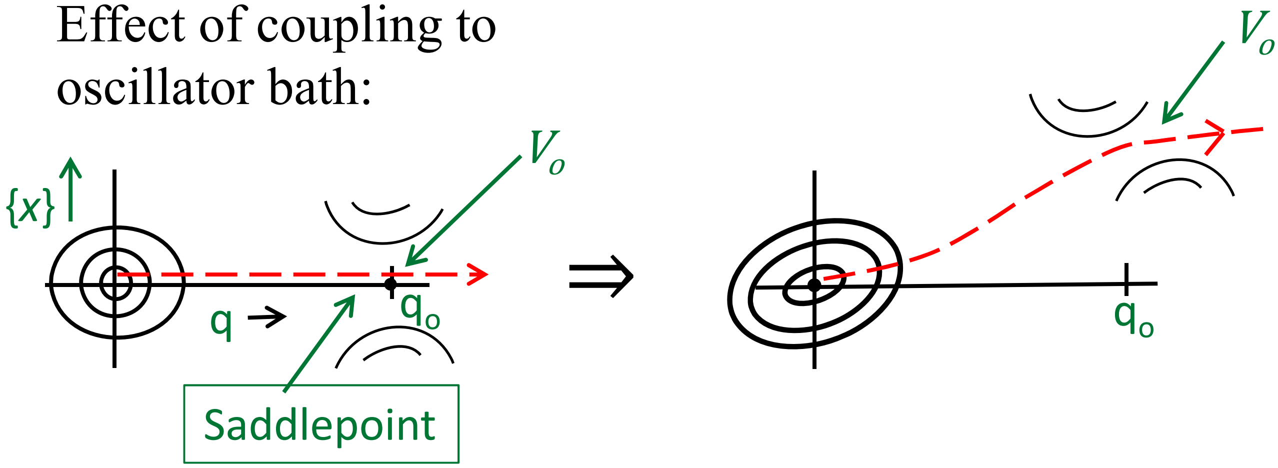
Final result for escape rate by QT in presence of ohmic dissipation:

$$\Gamma_{QT} = A \exp - B/\hbar \qquad \left(\mathrm{A},\ \alpha \text{ calculable as } f(\eta)\right)$$

$$B = B_o + \eta q_o^2 \alpha/\hbar$$

Why does (ohmic) dissipation suppress QT rate but not classical (Arrhenius – Kramers) rate?

Effect of coupling to oscillator bath:



Height of saddlepoint unaffected by coupling (provided counterterm included)

Arrhenius – Kramers exponent is V_o, no reference to path length; WKB exponent is

$$\int \{(2mV)^{1/2}/\hbar\} ds \sim V_o^{1/2} s$$

↑
Path length

⇒ (exponent of) Γ_{AK} unaffected, Γ_{QT} suppressed.

Objections:

1) Misunderstanding of question (without counterterm, barrier always lowered ⇒ Γ_{QT} increased)
2) "can we quantize the equations of mathematical economics?"

Ambegaokar, Eckern, Schön: fully microscopic model of Josephson tunnel junction, confirms predictions of phenomenological approach in appropriate limit.

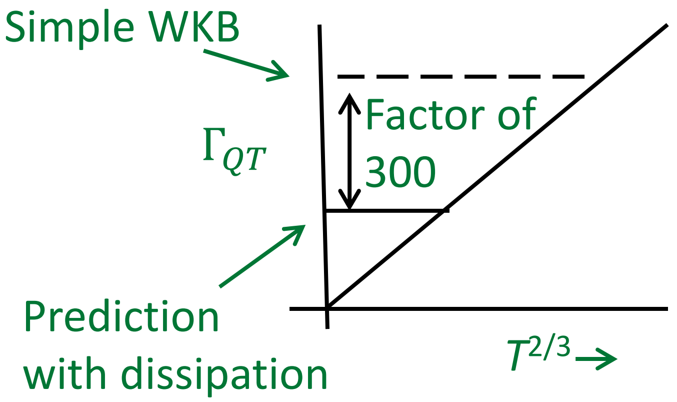
Voss & Webb, Jackel et al. (1981): qualitative confirmation of existence of MQT phenomenon, but parameters not independently measured.

Some quantitative tests of QM of macrovariable (RSJ)

Devoret et al. (1984): resonant activation (⇒ quantized energy levels)

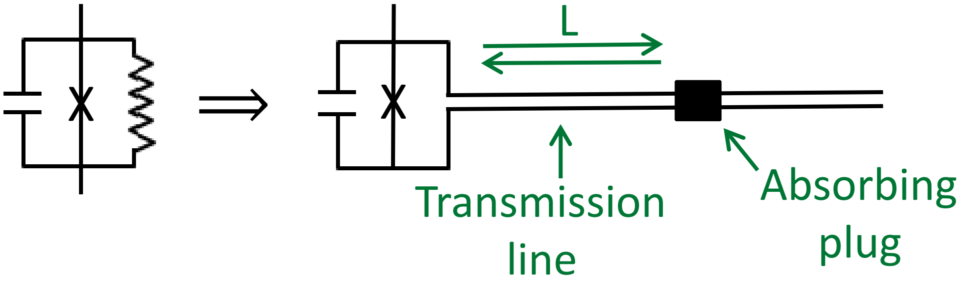
Martinis et al. (1985): MQT with light dissipation (no fitting parameters)

Cleland et al.; (1987) Suppression of MQT by dissipation



With no fitted parameters, agreement with theory incorporating dissipation within factor ~2

Urbina et al. (1989) “latency” of tunnelling:



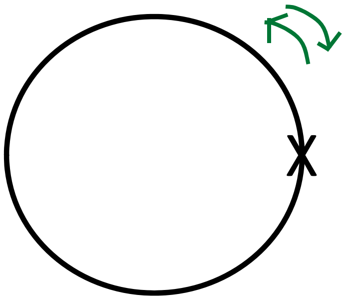
Absorption by plug affects tunnelling rate only when $2L/c \lesssim$ bounce time” ($\sim\omega_o^{-1}$)!

So: everything seems consistent with QM working for macrovariable at level of Josephson devices. But can we exclude alternative views? (cf. EPR-Bell).

For this, need MQC:

AJL & Garg (1985): temporal correlations in (eg) flux qubit predicted by macrorealism violate predictions of any macrorealistic theory ("temporal Bell inequalities")

Where Do We Stand To-Day?



flux qubit

Prediction of QM:
States like
$\frac{1}{\sqrt{2}}\left(\circlearrowleft| > \; + |\circlearrowright >\right)$ possible!

↖ ↗

different in behavior of
10^5-10^9 electrons

Many experiments. (e.g. Ramsey-fringe) consistent with QM predictions including effects of dissipation (e.g. Chiorescu et al. 2003, Plantenberg et al. 2007)

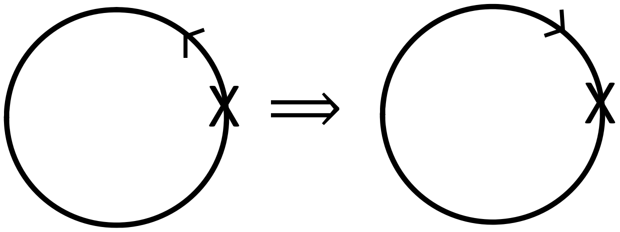
But: to date no real analog of Freedman – Clauser – Aspect experiment in EPR-Bell case, ie.

Alternative theories of the macroworld not definitively excluded

(Palacios – Laloy et al. 2010: transmon, weak-measurement technique)

How "macroscopically distinct" are putatively superposed states of flux qubit?

Korsbakken et al. (2010):



define W ≡ no. of electrons whose state we need to change.

For flux qubit (because of indistinguishability of electrons),

$$W_{FQ} \sim N(v/v_F \lesssim 5{,}000$$

"not macro- or even mesoscopic"

total number of electrons in penetration depth

mean velocity of circulating electrons

However: if we compare stationary and moving states of smallest visible dust particle,

$$W_{DP} \sim 1{,}500 \text{ !}$$

So: are we already at the level of "everyday life"?

Happy birthday, Michel!