Testing Time Reversal Symmetry in Artificial Atoms

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Outline:

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Introduction

In many instances the fundamental laws of physics are invariant under time reversal transformations; time reversal symmetry (TRS)

$$t \to -t$$

Classical mechanics (CM)

$$m\ddot{\mathbf{r}}(t) = -\nabla V(\mathbf{r}(t)) \quad \longrightarrow \quad m\ddot{\mathbf{r}}(-t) = -\nabla V(\mathbf{r}(-t))$$

Quantum mechanics (QM)

$$i\hbar \frac{\partial \psi(\mathbf{r},t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2 \psi(\mathbf{r},t) + V(\mathbf{r})\psi(\mathbf{r},t)$$

$$\downarrow$$

$$i\hbar \frac{\partial \psi^*(\mathbf{r},-t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2 \psi^*(\mathbf{r},-t) + V(\mathbf{r})\psi^*(\mathbf{r},-t)$$

Introduction

If $V = V(\mathbf{r}(t), t)$ and

$V(\mathbf{r}(t), t) = V(\mathbf{r}(-t), -t)$ ⇒ TRS

Appropriate choice of an external potential (protocol).

Breakdown of TRS

i) Lorentz invariant local field theories; TR is not an exact symmetry. CPT theorem and tests in particle physics.

ii) Arrow of time and the second law of thermodynamics; Macroscopic systems.

Introduction

Microscopic (non – relativistic) systems : TRS
microreversibility

Macroscopic quantum (meso or nanoscopic) systems :
if decoherence and dissipation are properly controlled, TRS should be expected. Macroscopic quantum phenomena and foundations of quantum physics.

Macroscopic (thermal) systems : arrow of time
2nd law of thermodynamics

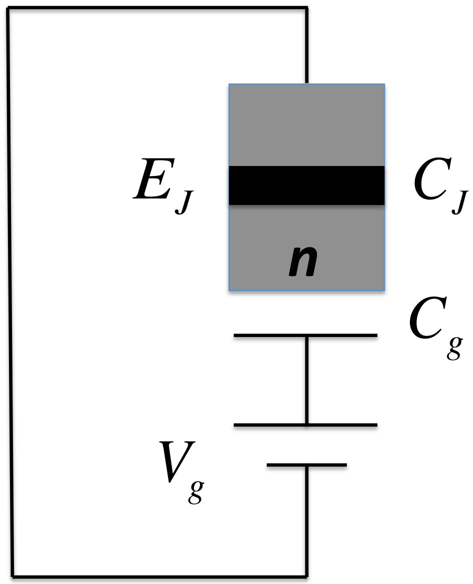
Introduction

Our main goal: direct measurement of microreversibility in properly chosen superconducting devices (artificial atoms).

In this presentation: theoretical proposal for a feasible experiment and possible spin – offs of its results.

Artificial atoms

The Cooper pair box (or charge qubit)



$$\mathcal{H}_{cqb} = 4E_C(n - n_g)^2 - E_J \cos\varphi$$

$$n = -i d/d\varphi \qquad n_g \equiv C_g V_g / 2e$$

$$E_C = \frac{e^2}{2(C_J + C_g)} \qquad E_J = \frac{\phi_0 i_0}{2\pi}$$

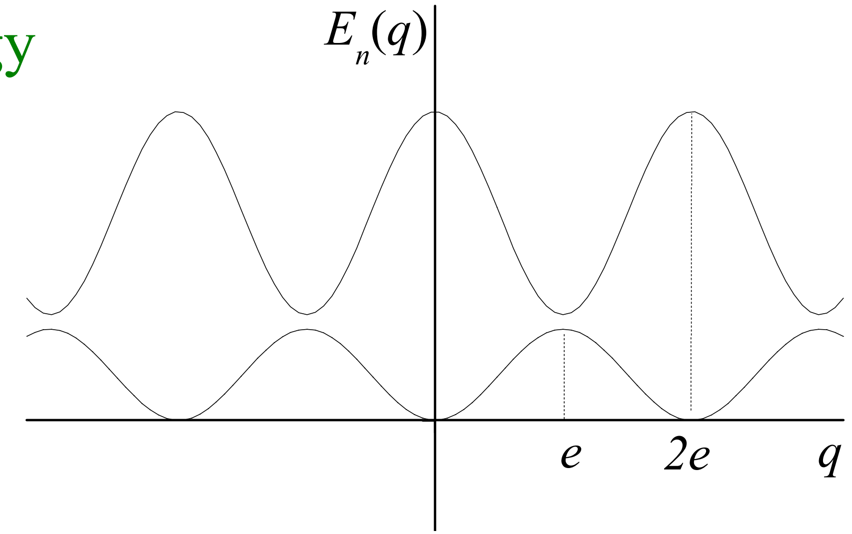
$$E_C \gg E_J$$

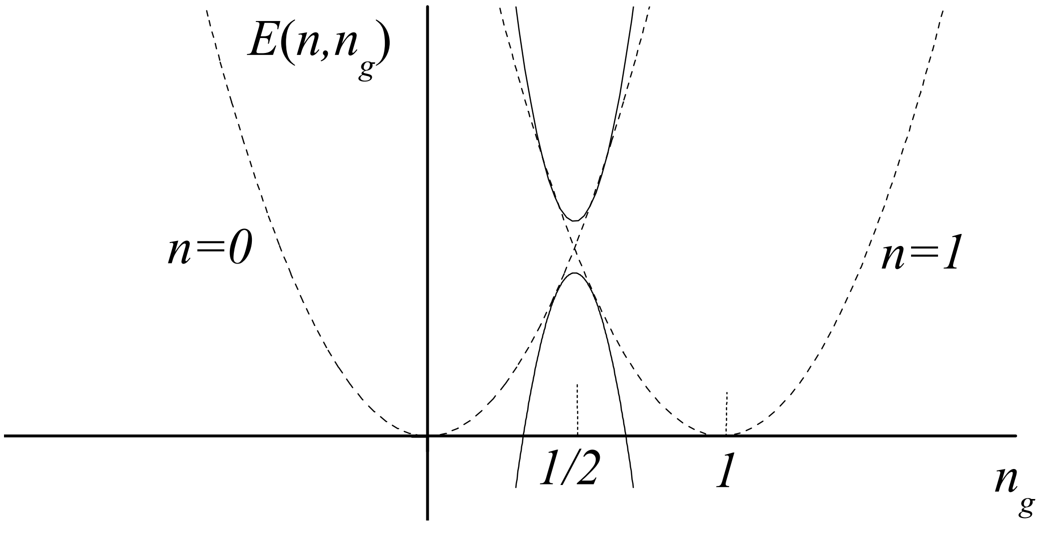
$$\mathcal{H}_{cqb} = \sum_n [4E_C(n - n_g)^2 |n\rangle\langle n| - \frac{1}{2} E_J (|n\rangle\langle n+1| + |n+1\rangle\langle n|)]$$

Artificial atoms

We can control the charging energy

$$q \equiv n_g(t) = \frac{C_g V_g(t)}{2e}$$





Qubit operation regime

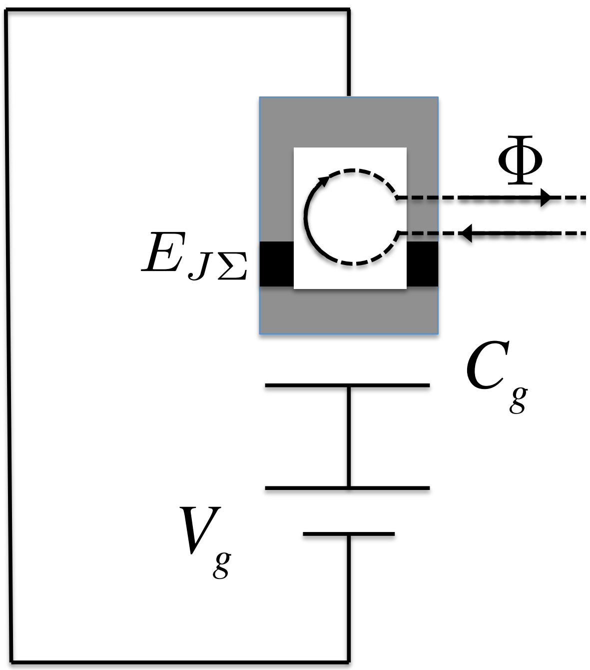
$$n_g \approx 1/2$$

$$\mathcal{H}_{cqb} = -\frac{1}{2}B_z\sigma_z - \frac{1}{2}B_x\sigma_x$$

Artificial atoms

We can also control the Josephson energy by slightly modifying the junction

$$H = 4E_C \sum_n (n-n_g)^2 |n\rangle\langle n| - \sum_n \left[\frac{\mathcal{E}_J(\Phi)}{2} |n\rangle\langle n+1| + \frac{\mathcal{E}_J^*(\Phi)}{2} |n+1\rangle\langle n| \right]$$



$$\mathcal{E}_J(\Phi) \equiv E_{J\Sigma} \left\{ \cos\left(\pi \frac{\Phi}{\Phi_0}\right) + i\alpha \sin\left(\pi \frac{\Phi}{\Phi_0}\right) \right\}$$

$$\alpha \equiv (E_{J1} - E_{J2})/E_{J\Sigma}$$

$$E_{J\Sigma} \equiv E_{J1} + E_{J2}$$

$$\beta \equiv |\mathcal{E}_J|/(4E_C) \ll 1$$

Microreversibility

If $\quad H(t) = H_p[\lambda(t)] \quad \xrightarrow{\tilde{\lambda}(t) = \lambda(-t)} \quad P_{n|m}[\lambda] = P_{m|n}[\tilde{\lambda}]$

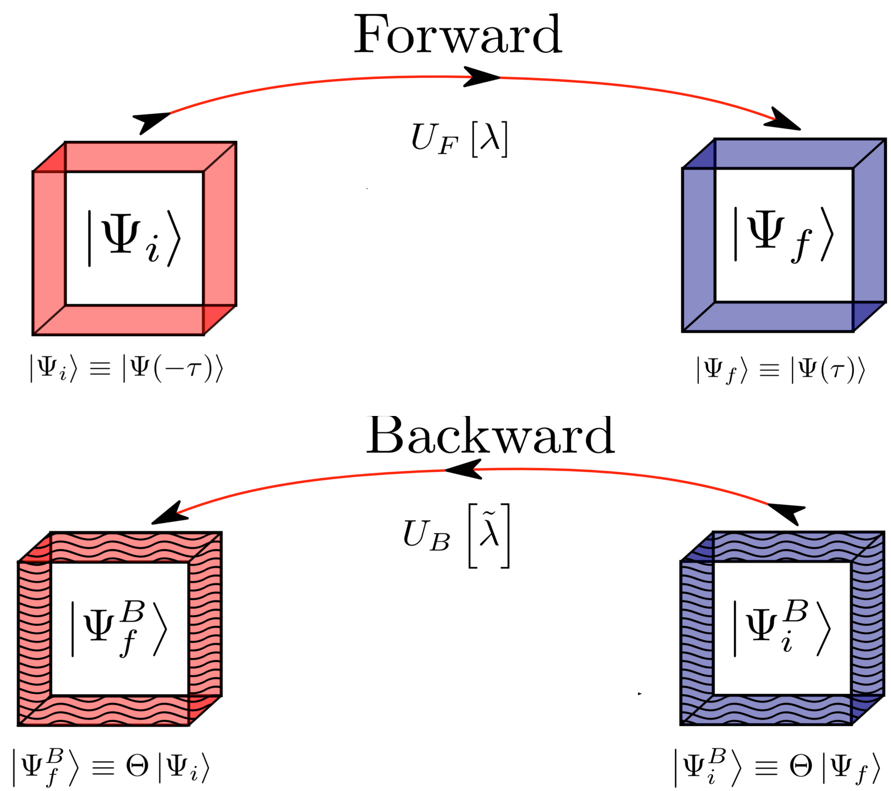
Where $P_{n|m}(P_{m|n})$ is the probability for the system to make a transition to state $|m\rangle(|n\rangle)$ when it stars in $|n\rangle(|m\rangle)$

$$|\Psi_i\rangle = \sum_n c_n |n\rangle$$

$$|\Psi_i\rangle \longrightarrow |\Psi_f\rangle = U_F[\lambda]|\Psi_i\rangle$$

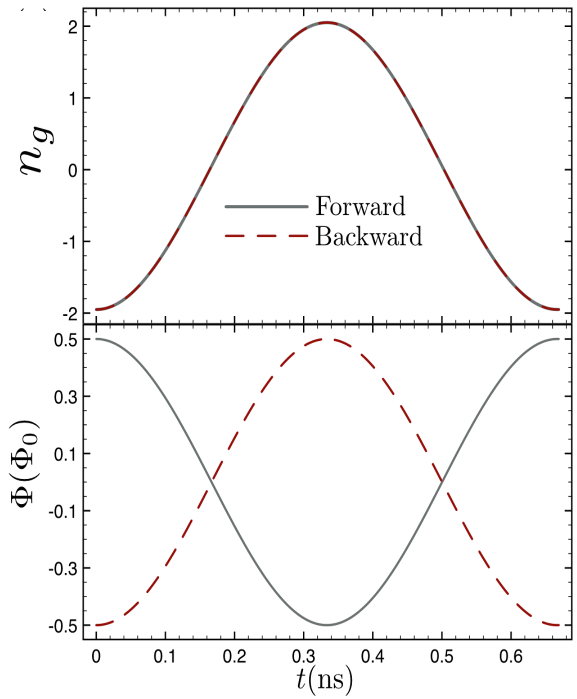
$$|\Psi_f^B\rangle \equiv \Theta|\Psi_i\rangle = U_B[\tilde{\lambda}]\Theta|\Psi_f\rangle$$

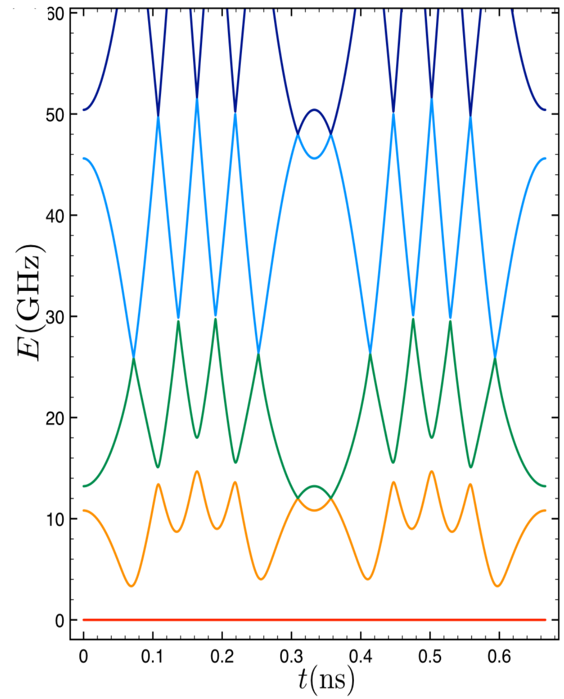
For our device



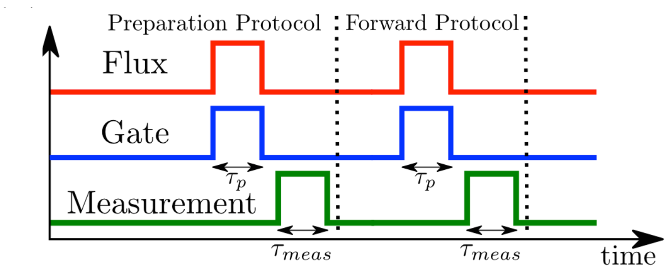
Microreversibility

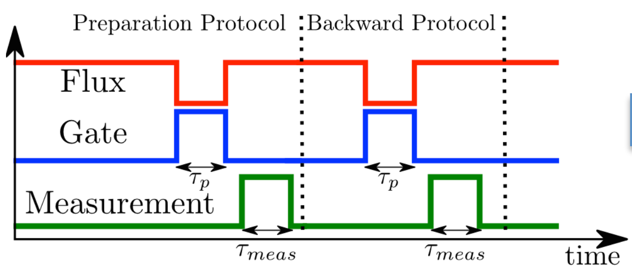
$$\Phi(t) = (\Phi_0/2)\cos(2\pi \times \frac{3}{2} \times t) \qquad n_g(t) = 0.05 - 2\cos(2\pi \times \frac{3}{2} \times t)$$





$E_C/\hbar = 2\pi \times 3\text{GHz} \qquad E_{J\Sigma}/\hbar = 2\pi \times 10\text{GHz} \qquad \alpha = 0.05$

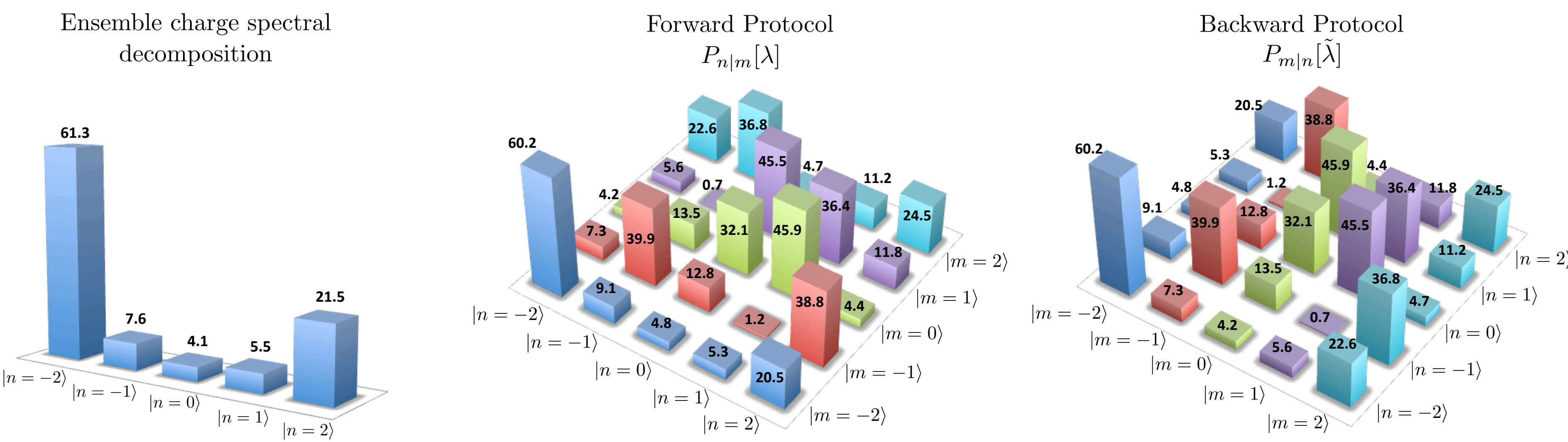




Superposition of five charge states

Microreversibility

Using an N=51 dimensional charge Hilbert space for numerical simulations of the time – ordered evolution operator



(a) (b) (c)

Measurements of charge states (approximately energy eigenstates for $\beta \ll 1$) require high – speed and high sensitivity measurements which can be achieved coupling the device to a superconducting single electron transistor (SSET)

Microreversibility

General considerations on relaxation and decoherence (time scales for unitary evolution) – device + bath of oscillators

T_1 – relaxation time, T_2 – decoherence time, T_Φ – pure dephasing

$$\frac{T_\phi}{T_1} \sim \frac{4|\langle e_k|n|e_{k+1}\rangle|^2}{|\langle e_k|n|e_k\rangle - \langle e_{k+1}|n|e_{k+1}\rangle|^2} \frac{e_{k+1}-e_k}{2k_B T} \coth \frac{e_{k+1}-e_k}{2k_B T}$$

$$T_2^{-1} = T_1^{-1}/2 + T_\phi^{-1}$$

Usually $T_\phi \gg T_1$ and $T_2 = 2T_1$ except if $\beta \ll 1$ which implies that $T_2 \sim 0.02T_1$. For $T_1 \approx 50ns$, protocol time $\tau_p \approx 1ns$

Measurement procedure: $\tau_{meas} \ll T_1$. With SSTs it is possible to resolve charge states with an error of the order of 0.5 % for $\tau_{meas} \sim 20ns$

Important implication: quantum fluctuation relations (QFR)

Two main ingredients for the QFR: microreversibility and the initial equilibrium state described by the Gibbsian distribution

$$\rho_0 = \frac{e^{-H_0/k_B T}}{Z_0} \qquad \text{with} \qquad Z_0 = \text{tr}\; e^{-H_0/k_B T}$$

Within the *exclusive work* point of view: Bochkov – Kuzovlev relation

$$\langle e^{-W/k_B T} \rangle = 1 \qquad \text{where} \qquad W = E_n - E_m$$

and averages are taken with respect to $H(t) = H_0 + H_p[\lambda(t)]$

$$H_0 = H(t=0) \qquad\qquad H_p[\lambda(t)] = H(t) - H_0$$

Important implication: quantum fluctuation relations (QFR)

Between the initial and final equilibrium states the dynamics is unitary: extremely weak coupling to a heat bath.

Preparing the initial equilibrium state at finite temperatures may enhance decoherence effects

Emulation of the initial Gibbs state by randomly keeping previous ensemble elements in such a way that

$$|c_n|^2 = \frac{N_n}{N} \longrightarrow p_n = \frac{\tilde{N}_n}{\tilde{N}} = \frac{e^{-E_n/k_B T}}{Z_0}$$

Now we implement the previous protocol and…

Important implication: quantum fluctuation relations (QFR)

$$\langle e^{-W/k_B T} \rangle = 1$$

Temperature (K)	$1 - \langle e^{-W/k_B T} \rangle$
1	$(-0.4 \pm 5.8) \times 10^{-2}$
10	$(-2.7 \pm 7.9) \times 10^{-4}$
20	$(-2.1 \pm 4.2) \times 10^{-4}$
30	$(-0.6 \pm 3.0) \times 10^{-4}$
40	$(-0.1 \pm 2.2) \times 10^{-4}$
50	$(-0.3 \pm 1.7) \times 10^{-4}$

Conclusions

Theoretical proposal for a realistic experiment to directly test TRS in macroscopic quantum systems (artificial atoms)

Positive result: another evidence that QM still works in this limit and consequently rules out some alternative theories such as the dynamical reduction theory

Low temperature results can be used within the emulation scheme of an initial Gibbs distribution in order to test the quantum fluctuation relations.

http://arxiv.org/abs/1406.7182