Title: On-chip Extraction of Quantum Correlations from the Vacuum

Date: Jun 26, 2012 02:30 PM

URL: http://pirsa.org/12060056

Abstract: <span>On-chip extraction of quantum correlations from the vacuumCarlos Sabn, Borja Peropadre, Marco del Rey, Eduardo Martn-MartnezCircuit Quantum Electrodynamics provides a framework in which the interaction of two-level systems with a quantum field can be naturally considered [1]. The combination of superconducting qubits with transmission lines implement an artificial 1-D matter-radiation interaction, with the advantage of a large experimental accessibility and tunability of the physical parameters. Using these features, fundamental problems in Quantum Field Theory hitherto considered as ideal are now accessible to experiment, as in the recent celebrated test of the Dynamical Casimir Effect.In this talk we will exploit the possibility of achieving an ultrastrong coupling regime in circuit QED to propose a feasible test of the extraction of vacuum entanglement to a pair of qubits [2]. First, we will analyze a setup in which the qubits are spacelike separated and interact with the vacuum of the quantum field at the same time. After that we will focus on an even more intriguing possibility [3]: that the qubits interact with the field at different time intervals -one in the past and the other one in the future- with an intermezzo of no interaction at all. We will see how the qubits can get entangled while remaining spacelike or timelike separated and in the latter case with or without a certain probability of photon exchange. In addition to its interest from the fundamental viewpoint, the extraction of past-future quantum correlations enables its use as a quantum channel for quantum teleportation in time". We will show how this opens the door to a novel kind of quantum memory in which the information of the quantum state of some ancillary qubit P' is codified in the field during a certain time and then recovered in F using classical information stored in the past - regardless whatever may happen to P after its interaction with the field. Our scheme is fully within reach of current circuit QED technologies. [1] Carlos Sabn, Marco del Rey, Juan Jos Garca-Ripoll, Juan Len, Phys. Rev. Lett. 107, 150402 (2011).[2] Carlos Sabn, Juan Jos Garca-Ripoll, Enrique Solano, Juan Len, Phys. Rev. B 81, 184501 (2010).[3] Carlos Sabn, Borja Peropadre, Marco del Rey, Eduardo Martn-Martnez, arXiv: 1202.1230.

On-chip extraction of quantum correlations from the vacuum

Carlos Sabín (RQI,Nottingham)

QUINFOG, Madrid:

Borja Peropadre

Marco del Rey

Juanjo García-Ripoll

Juan León

IQC, Waterloo:

Eduardo Martín-Martínez

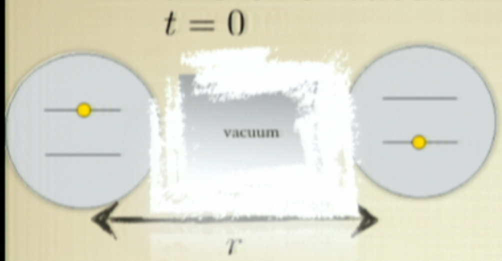
RQI-N June 2012

Introduction

- The vacuum of a quantum field is an entangled state... seriously.
- Can we extract these correlations to qubits? Proof of principle + QI tasks.
- Correlations between "here and there" (Reznik et al.) and also between "now and then" (Ralph et al.)
- We will show how to extract these correlations in a Circuit QED setup.
- Circuit QED= experimentally amenable 1D QFT


PERIMETER
INSTITUTE
FOR THEORETICAL PHYSICS
PERIMETER
INSTITUTE
FOR THEORETICAL PHYSICS

Transfer of vacuum entanglement in the Fermi problem



Fermi problem with artificial atoms in circuit QED

C. S., M. del Rey, J.J. García-Ripoll, J. León, PRL ,107 150402 (2011)

A pair of superconducting qubits coupled to a 1-D field along an open transmission line

$$H = H_0 + H_I$$

$$H_0 = \frac{1}{2}\hbar\Omega(\sigma^z_A + \sigma^z_B) + \int_{-\infty}^{\infty} dk\, \hbar\omega_k a^\dagger_k a_k$$

$$H_I = \sum_{J=A,B} d_J\, \sigma^x_J\, V(x_J)$$

$$V(x) = i \int_{-\infty}^{\infty} dk\, \sqrt{N\omega_k}\, e^{ikx} a_k + \text{H.c.}$$

$$[a_k, a^\dagger_{k'}] = \delta(k - k')$$

Propagation velocity: $v = 1/\sqrt{cl}$

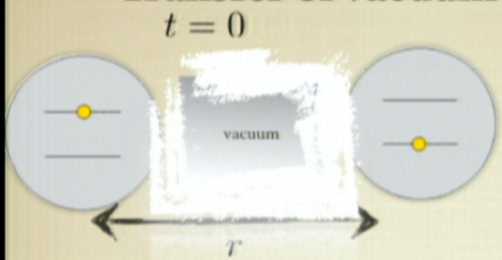
c = capacitance per unit length l = inductance per unit length

Second order perturbation theory beyond RWA

Entanglement dynamics vs. vt/r for two superconducting qubits initially in a separable state

C. S., J.J. García-Ripoll, E. Solano, J. León, PRB 81, 184501 (2010)

Transfer of vacuum entanglement in the Fermi problem



Fermi problem with artificial atoms in circuit QED

C. S., M. del Rey, J.J. García-Ripoll, J. León, PRL ,107 150402 (2011)

A pair of superconducting qubits coupled to a 1-D field along an open transmission line

$$H = H_0 + H_I$$

$$H_0 = \frac{1}{2}\hbar\Omega(\sigma_A^z + \sigma_B^z) + \int_{-\infty}^{\infty} dk\, \hbar\omega_k a_k^\dagger a_k$$

$$H_I = \sum_{J=A,B} d_J\, \sigma_J^x\, V(x_J)$$

$$V(x) = i\int_{-\infty}^{\infty} dk\, \sqrt{N\omega_k}\, e^{ikx} a_k + \text{H.c.}$$

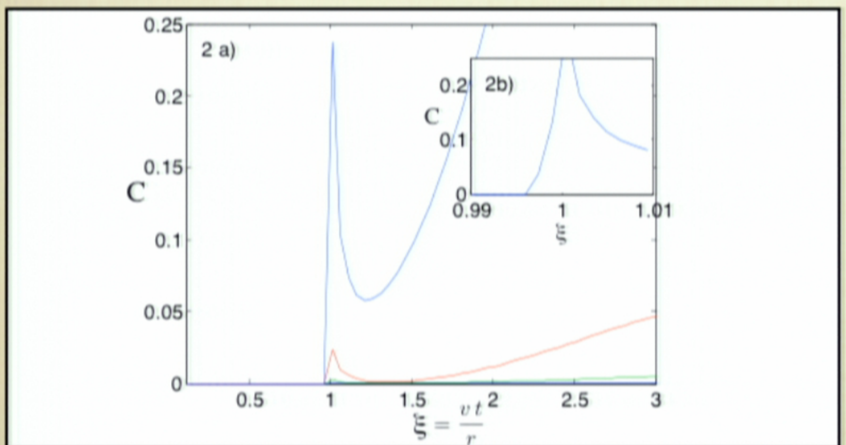
$$[a_k, a_{k'}^\dagger] = \delta(k - k')$$

Propagation velocity: $v = 1/\sqrt{cl}$

c = capacitance per unit length l = inductance per unit length

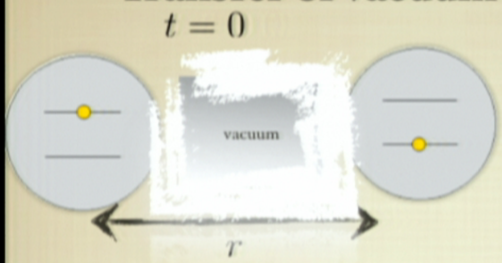
Second order perturbation theory beyond RWA

Entanglement dynamics vs. vt/r for two superconducting qubits initially in a separable state



C. S., J.J. García-Ripoll, E. Solano, J. León, PRB 81, 184501 (2010)

Transfer of vacuum entanglement in the Fermi problem



Fermi problem with artificial atoms in circuit QED

C. S., M. del Rey, J.J. García-Ripoll, J. León, PRL ,107 150402 (2011)

A pair of superconducting qubits coupled to a 1-D field along an open transmission line

$$H = H_0 + H_I$$

$$H_0 = \frac{1}{2}\hbar\Omega(\sigma^z_A + \sigma^z_B) + \int_{-\infty}^{\infty} dk\, \hbar\omega_k a^\dagger_k a_k$$

$$H_I = \sum_{J=A,B} d_J\, \sigma^x_J\, V(x_J)$$

$$V(x) = i\int_{-\infty}^{\infty} dk\, \sqrt{N\omega_k}\, e^{ikx} a_k + \text{H.c.}$$

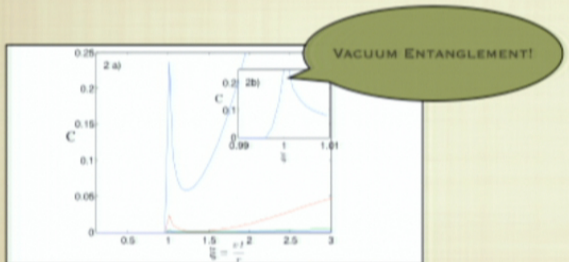
$$[a_k, a^\dagger_{k'}] = \delta(k - k')$$

Propagation velocity: c = capacitance per unit length l = inductance per unit length

$$v = 1/\sqrt{cl}$$

Second order perturbation theory beyond RWA

Entanglement dynamics vs. vt/r for two superconducting qubits initially in a separable state



Conclusion

✓ Entanglement can be generated at $t < r/v$ without a measurement.

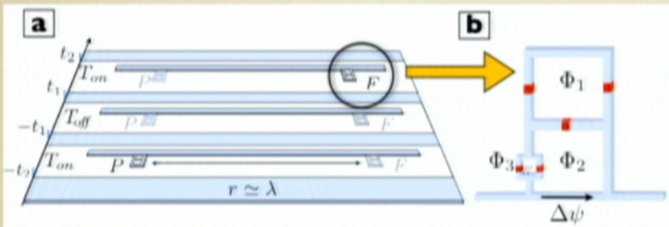
✓ Entanglement dynamics is sensitive to the existence of a light cone, so it is a probe for single photons in circuit QED.

✓ These effects are proportional to the coupling strength.

C. S., J.J. García-Ripoll, E. Solano, J. León, PRB 81, 184501 (2010)

On-chip past-future quantum correlations

A little step further:



Qubit P interacts with the field $T_{\rm on}$

Interaction is disconnected for $T_{\rm off}$

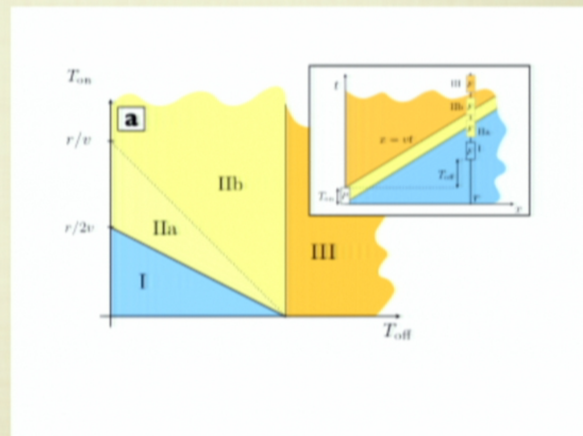
Qubit F interacts with the field $T_{\rm on}$

$$|\Psi(t_2)\rangle = \mathcal{T} e^{-i\int_{-t_2}^{t_2}\frac{dt'}{\hbar}[\Theta(-t'-t_1)H_{\rm IP}^{(t')}+\Theta(t'-t_1)H_{\rm IF}^{(t')}]}|eg0\rangle$$

Region I: spacelike separated

Region II: timelike separated, photon exchange allowed

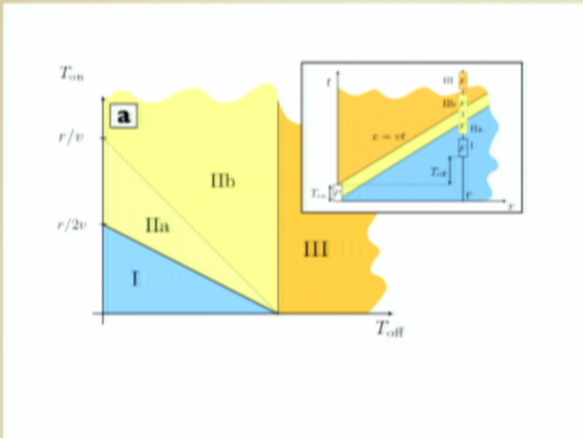
Region III: timelike with no photon exchange

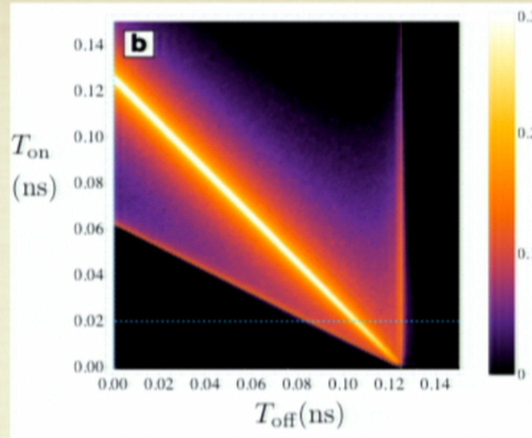


I and III= pure vacuum entanglement

C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

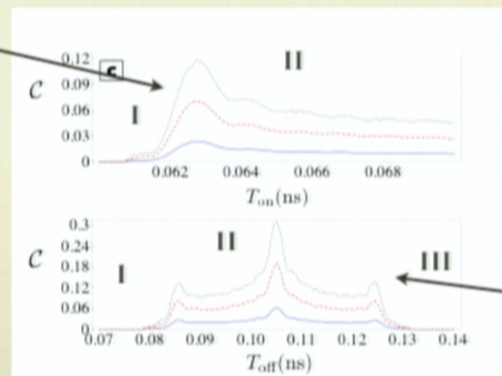
On-chip past-future Quantum correlations





Concurrence for $r = \lambda/8$

Generation of entanglement in region I

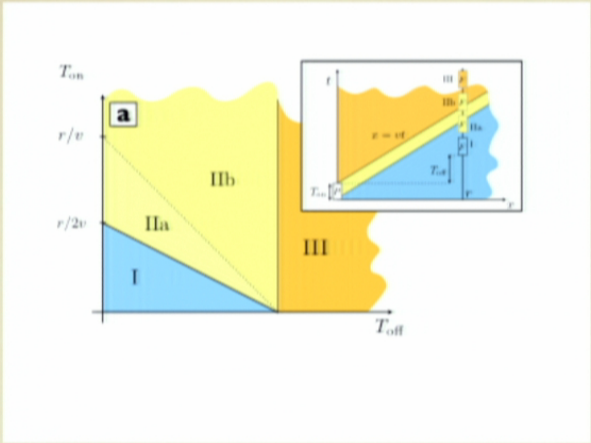


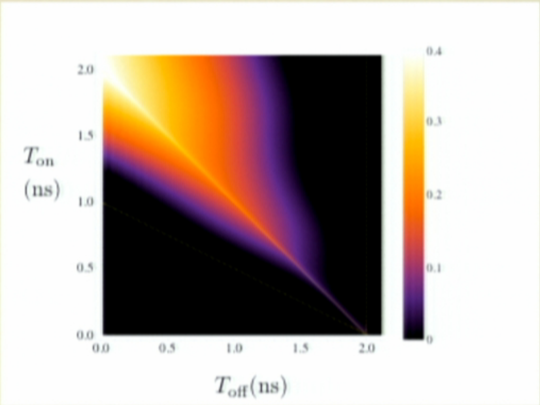
I-III Symmetry

C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

5

ON-CHIP PAST-FUTURE QUANTUM CORRELATIONS





CONCURRENCE FOR $r = 2\lambda$

FOR **LONG** DISTANCES, ENTANGLEMENT IS RESTRICTED TO REGION II

IN REGION II VACUUM CORRELATIONS ARE ASSISTED BY A CERTAIN PROBABILITY OF PHOTON EXCHANGE.

NO MEASUREMENT OF THE FIELD STATE IS PERFORMED. UNDER THAT CONDITIONS THE **HIGH-DEGREE** GENERATION OF **QUANTUM** CORRELATIONS IS NON-TRIVIAL

C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

Teleportation in time: a Hitchcockian approach

Just like standard teleportation but the quantum channel is created **after** the Bell measurement

Guess that you want to **preserve** something, e.g

qubit K

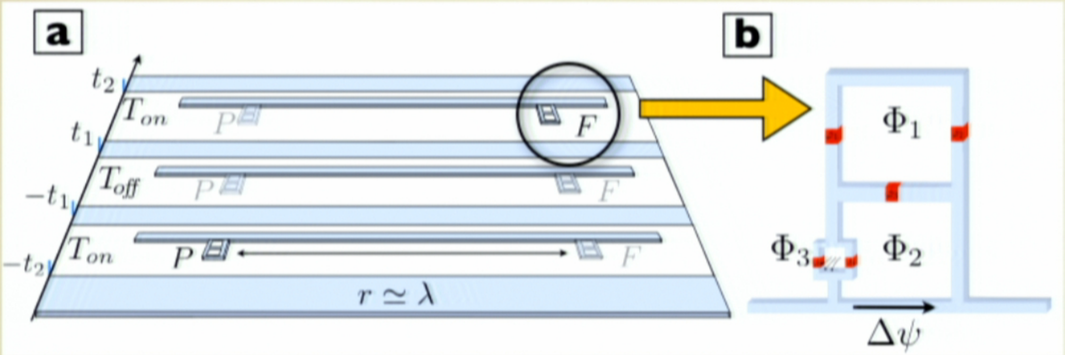
C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

Teleportation in time: a Hitchcockian approach

Quantum
Memory !

C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

Experimental implementation



$$H_I = \sum_{J=A,B} d_J(t)\, \sigma_J^x \, V(x_J)$$

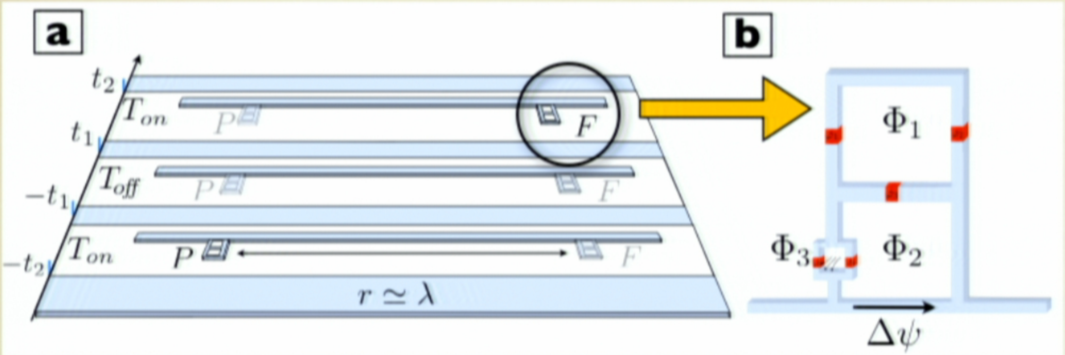
Superconducting qubits with ultrastrong switchable couplings to an open common transmission line

The interaction strength is controlled with the external magnetic flux through the SQUID and can be switched on-off extremely fast.

B. Peropadre, P. Forn-Díaz, E. Solano, J. J. García-Ripoll , PRL 105 023601 (2010).

C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

Experimental implementation



$$H_I = \sum_{J=A,B} d_J(t)\,\sigma_J^x\,V(x_J)$$

Superconducting qubits with ultrastrong switchable couplings to an open common transmission line

The interaction strength is controlled with the external magnetic flux through the SQUID and can be switched on-off extremely fast.

B. Peropadre, P. Forn-Díaz, E. Solano, J. J. García-Ripoll , PRL 105 023601 (2010).

C. S., B. Peropadre, M. del Rey, E. Martín-Martínez, PRL (in press).

Conclusions

- We propose a realistic setup for the extraction of quantum correlations from the vacuum of a quantum field.
- Both correlations between different space points and between different times.
- Teleportation in time and quantum memory.
- The framework is circuit QED, an artificial 1D matter-radiation interaction with superconducting qubits and transmission lines.
- We exploit the possibility of achieve ultrastrong switchable couplings.

- “Time present and time past
  Are both perhaps present in time future,
  And time future contained in time past. [...]
  Time past and time future
  What might have been and what has been
  Point to one end, which is always
  present.”
  (T. S. Eliot, *Burnt Norton*)