ERC Starting Grant 2012

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Project „CirQys“ : Circuit QED with hybrid electronic states

*The tools of atomic physics to study experimentally condensed matter problems*
Emergence of model systems for condensed matter

- Experimental study of artificial atoms, molecules or wires
- Natural probe of electronic systems = transport
- Single Wall Nanotubes (and nanowires) as building block

Model systems for 1D to 0D electrons: coherent manipulation of the quantum state of electrical circuits or strongly correlated electronic systems
Nanotubes and hybrid structures

Artificial magnetic impurity

Combining nanotubes with electrodes of very different nature

Depending on nature/regime/geometry of contacts, different fundamental physics can be probed.

L.G. Herrmann et al. PRL’10
Cooper pair splitter

S. Sahoo et al. Nature Phys’ 05

Quantum dot spin valve

How to go beyond such transport experiments?
Project „CirQys“: the tools of atomic physics to study condensed matter problems

Hybrid circuit quantum electrodynamics

- Use of light-matter interaction to probe and manipulate nano-circuits
- Versatility of nano-circuits
- Beyond conventional atomic physics experiments

Quantum information but also condensed matter problems addressed

M.R. Delbecq et al. PRL 107 256804 (2011)


**Key experiments** of CirQys project

A. Cottet and T. Kontos, PRL’10

**Strong spin/photon coupling**

A. Cottet, T. Kontos and A. LevyYeyati, PRL’12

**Subradiant split Cooper pairs**

A. Cottet and T. Kontos, in preparation (see also Trif et al. Arxiv 1202.2649)

**Observation of Majorana Fermions**

- Probe of Majorana fermions in solid state via their anomalous interaction with light

- Probe of entanglement with electronic states

- « all electrical » spin Qbit in a photonic cavity (scalability of spin Qbits)

- Novel method for study and manipulation of exotic quantum states in condensed matter.
Use of singlet state of Cooper pairs to create a bipartite entangled electronic state

Recent realizations of Cooper pair splitters in nanotubes (Paris) or InAs nanowires (transport experiments)

How to probe coherence of Cooper pairs emitted?

Embedding a Cooper pair splitter in a photonic cavity.
Coherence of Cooper pair splitting

\[ |S> = (|\uparrow\downarrow> - |\downarrow\uparrow>)/\sqrt{2} \]

- State decoupled from field
- Each spin coupled to photons (electric field) via spin orbit interaction
- Singlet state decoupled from field (destructive interference due to minus sign)

Photon emission properties of Cooper pair splitter characteristic of coherence of Cooper pairs emitted

Requested grant: 1,456,608 Euros

Main budget

Equipment (640,000 euros)
- Cryofree dilution refrigerator system: 300,000 Euros
- Microwave equipment (several parts): 220,000 Euros
- Evaporation chamber for a UHV system: 120,000 Euros

1 Postdoc (110,400 for 2 years)

- Dedicated very low temperature/high frequency experiment
- Evaporation chamber for a UHV system for good control over hybrid structures
- Only 1 postdoc for 2 years requested (access to very talented students of ENS)
- Very close connection with leading experts in cavity QED (team of S. Haroche, J.M. Raimond and M. Brune) in physics department of ENS
Scientific profile

- CNRS fellow since 2005 at physics department of Ecole Normale Supérieure Paris, France
- Guidance of PhD thesis of Dr. Delattre, Dr. Herrmann and Dr. Feuillet-Palma
  3 ongoing theses (M.R. Delbecq, J. Viennot et A.D. Crisan)
- 21 invited conference since 2005.
- Total citations on 23/04/2012 : 1341. Hirsch index = 16

Key papers
- « Carbon nanotubes as Cooper pair beam splitters» L.G. Herrmann et al. PRL (2010)
  (joint thesis Lorenz Herrmann with Regensburg)
- « Josephson junction through a thin ferromagnetic layer : Negative coupling » T. Kontos et al PRL (2002). 310 citations
- « Inhomogeneous superconductivity induced in a ferromagnet by proximity effect », T. Kontos et al. PRL (2001). 272 citations
Conclusion

- Implementation of an « all electrical » spin Qbit in photonic cavity

- Generation and characterization of entangled electronic states in a circuit

- Probe of Majorana fermions in solid state via light-matter interaction.

- Novel method for study and manipulation of exotic quantum states in condensed matter.
Spin/electric field coupling

Effective transverse field caused by the spatial modification of the double dot eigenstates

\[(1) \quad D = D_{ON} + \delta D \text{ and } \theta \neq 0[\pi] \implies \langle 0 | \hat{H}_{\text{double dot}} | 1 \rangle = C\delta D\]
Radiative transitions between 2 electron states lead to lasing effect.

Generation of dark states « smoking gun » of coherence of Cooper pairs

The number of photons accumulated in the cavity will allow us to detect the coherence of Cooper pairs emitted.

Probe of Majorana fermions via light matter interaction

- Topological superconductivity (finite spin polarization, superconductivity+spin-orbit coupling)
- Essentially neutral object but residual fermion-photon coupling very non-linear in photonic field
- Generation of squeezed states of microwave light.

Probe of non-local character of Majorana fermions
General principle of our spin qubit

Two working points: $D_{\text{ON}} = 2.8 \, \delta$, $D_{\text{OFF}} = 20 \, \delta$

$\theta = \pi/6$, $2\delta = 32 \, \mu\text{eV}$, $t = 2\delta/3$, $V_{\text{rms}} = 2 \, \mu\text{eV}$

Main decoherence sources:
- Low frequency charge noise
- Phonons mediated by spin-mixing

ON point: $g = 5.6 \, \text{MHz}$, $T_2 = 1.2 \, \mu\text{s}$

$\iff$ strong coupling regime reached

OFF point: $g = 13 \, \text{kHz}$, $T_2 = 2 \, \text{ms}$

$\iff$ quantum register at the OFF point

Rydberg atom coupled to a superconducting mirror cavity

Superconducting quantum bit coupled to a superconducting coplanar waveguide cavity


Jaynes-Cummings Hamiltonian

\[
\hat{H}_{\text{eff}} = -\hbar \nu_0 \hat{S}_z / 2 + \hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar g (\hat{a}^\dagger \hat{S}_- + \hat{a} \hat{S}_+)
\]

\( \hat{S}_z, \hat{S}_+, \hat{S}_- \): two-level (true or artificial) atom

\( \hat{a}, \hat{a}^\dagger \): cavity photons

\( g \): atom/photon coupling \( \to \) decoherence time of atom and photons
Recent realizations of Cooper pair splitters in nanotubes or InAs nanowires

- L.G. Herrmann et al. PRL 104, 026801 (2010)
- L.G. Herrmann et al. in preparation ‘12 (at finite bias)

- L. Hofstetter et al. PRL’11 (at finite bias)

What about coherence of non-local Cooper pairs?

- Embedding a Cooper pair splitter in a photonic cavity.

- Recent realizations of Cooper pair splitters in nanotubes or InAs nanowires
- Transport experiments which do not probe the coherence of Cooper pairs emitted
- How to probe coherence of Cooper pairs emitted?

Embedding a Cooper pair splitter in a photonic cavity.
Injection of non-local Cooper pairs visible in asymmetry of left and right current

In-situ control of splitting of Cooper pairs

L.G. Herrmann et al. PRL 104, 026801 (2010)