Solid-state quantum information

Quantum information allows to solve efficiently some problems which are belived to be intractable classically. Impact and advantages of quantum information protocols emerge in numerous situations and it is now believed that they will play a leading role in future technologies. Together with the ongoing development of more efficient schemes to solves new and old tasks in information science, a great deal of interest is devoted to select suitable physical systems where one can implement realize these ideas. Nanoelectronics is the natural arena to realize physical implementation of quantum hardware and superconducting nanocircuits have already proved to be ideal candidates for qubits. Our works in this period aimed at developing new quantum protocols in computation and communication as well as at the theoretical analysis of superconducting qubits.

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Among all possible applications of quantum mechanics to information science, communication is the branch that already is mature for technological applications. The paradigmatic approach to quantum communication assumes the possibility of encoding quantum information into mobile physical systems that are then transmitted from the sender of the messages to their intended receiver. This architecture finds its natural implementation in optics where photons, propagating in free-space or through fibers, carries the information from site to site. In [1] we have provided a rather comprehensive analysis of the physics of such channels introducing a general classification of the noise sources that affect them. The typical rates of coherence loss that photons suffer in these systems make it plausible to think at more complex strategies in which the signalling among distant parties is mediated by a network of quantum repeaters located at relatively short distances from each others [2]. Similar ideas have also been proposed to solve the scalability problem of quantum computation [3]. Inspired by such attempts we have developed cluster-like quantum computational and communication models [4,5] in which networks of coupled quantum memories (spin networks) are used as mediators for coordinating the action of otherwise independent, small size quantum computational devices. The underlying idea of this approach is schematically illustrated in Fig. 1.

Spin networks proved also to be fundamental in designing efficient Quantum Random Access Memory (Qram) elements [6] and thus in addressing security problems such as the private querying of a remote database [7] (the latter being solved by employing our recently developed Quantum Private Query

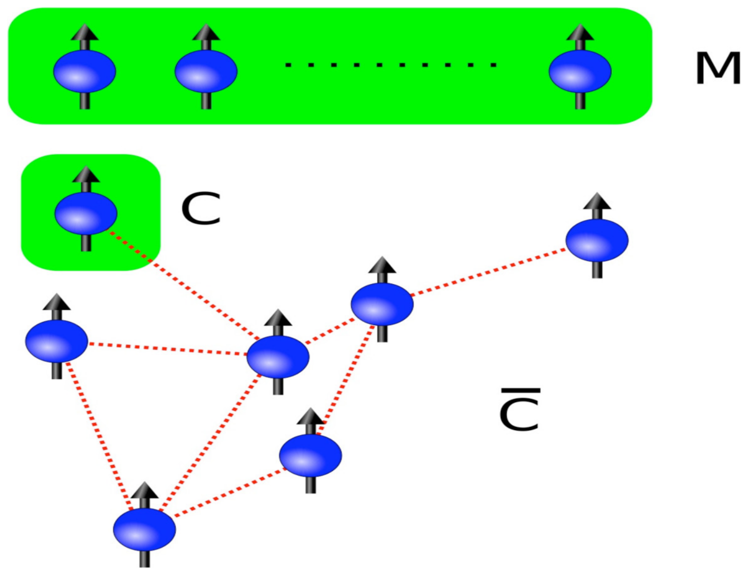


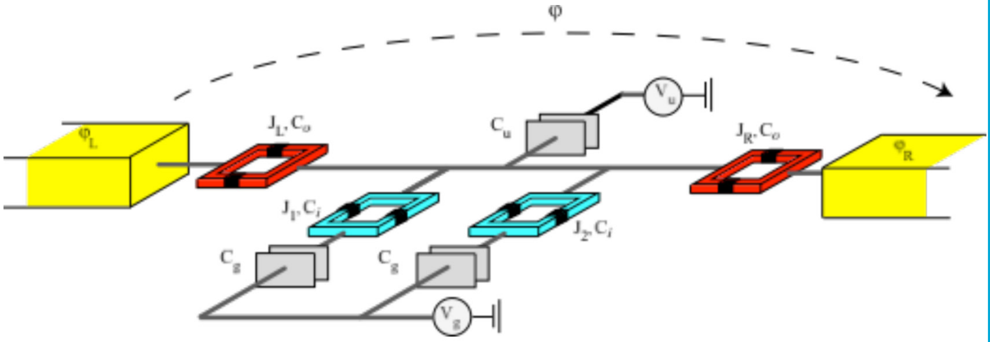
Fig.1.
Exploiting the scheme developed in Ref. [5] the large system $C\bar{C}$ (formed by 7 spins characterized by some time-independent Hamiltonian H - the coupling being represented by red lines connecting the spins), can be controlled by acting on a (small) subsystem C (in this case represented by the uppermost spin of the network) by performing regular swap operations between it and a 2-dim quantum memory elements M

algorithm which exploits explicitly Qram-transformations). To test the feasibility and the efficiency of the above protocols we found it useful to refine our understanding of the mechanisms which superintend at the information flow in spin networks. To this aim we conducted an intense research on the way entanglement emerges in such systems [8-11] and its degradation due to the interaction with neighbouring elements [12].

Our research on implementations of quantum information processing we concentrated on Josephson-junction qubits which are considered among the most promising due to their design flexibility and potential scalability. We applied optimal quantum control to superconducting charge qubits [12]. We analysed in detail the effect of noise and leakage, and we showed that optimisation yields a considerable improvement in gate fidelities even under such realistic conditions. Our protocol considerably increases the fidelity of the gate and, more important, it is quite robust in the disruptive presence of 1/f noise. The improvement in the two-bit gate performances (errors of the order of $10^{-3} \div 10^{-4}$ in realistic cases) allows to cross the fault tolerance threshold. The use of quantum optimal control theory to Josephson systems is not confined to the area of solid state quantum information. We recently applied to quantum pumping as well [13]. We showed that it is possible to obtain very accurate pumps in the non-adiabatic regime by a suitable choice of the shape of the gate voltage pulses (the shape of these pulses being dictated by quantum optimal control theory). In the optimal case the error, with respect to the quantized value, can be as small as of the order of 10^{-6} e (e=electron charge). In addition to their importance for metrological applications, Cooper pair pumps allow to study fundamental effects in quantum physics. It has been shown that the charge pumped during one cycle is related to the accumulated geometric phase. We showed that by proper designing the Cooper pair pump it is possible to investigate non-Abelian connections [14]. We derived an expression for the pumped charge in the presence of a degenerate spectrum and relate it to the non-Abelian connection of Wilczek and Zee. We proposed a superconducting network (see the scheme on Fig.2) where this relation can be tested and discuss two clear signatures of non-abelian holonomies.

First, under appropriate conditions, the pumped charge per cycle is quantized. Second and most important here the pumped charge depends both on the cycle and the point where the cycle starts. If tested experimentally this would be a clear proof of the non-Abelian nature of pumping.
Within the research area on the quantum dynamics of superconducting nanocircuits we also investigated the exciting new area of circuit-QED. In this framework we study the properties of arrays of cavities and determined the phase diagram in the one-dimensional case [15]. Furthermore

Fig.2.
Scheme for a non-Abelian Cooper pair pump.



we designed [16] an new devices that we termed the *Quantum optical Josephson interferometer*. It is shown in the Fig.3 and it consists of two coherently driven linear optical cavities connected via a central cavity with a single-photon nonlinearity. The interplay of tunneling and interactions is analyzed in the steady state of the system, when a dynamical equilibrium between driving and losses is established.

Strong photonic correlations can be identified clearly in the suppression of Josephson-like oscillations of the light emitted from the central cavity as the nonlinearity is increased. In the limit of a single nonlinear cavity coupled to two linear waveguides, we show that photon correlation measurements provide a unique probe of the crossover to the strongly correlated regime.

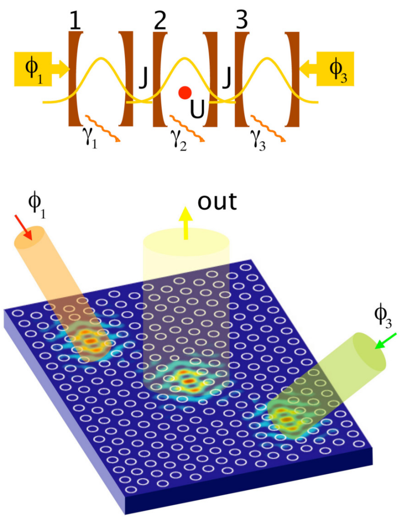


Fig.3.
(a) Schematic of the quantum optical Josephson interferometer with three coupled cavities. (b) A possible photonic crystal-based implementation (with calculated cavity mode profiles), where the middle cavity can contain a quantum dot or a quantum well in strong coupling with the high-Q photonic crystal cavity mode.

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