Holonomic quantum computation with neutral atoms

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We propose an all-geometric implementation of quantum computation using neutral atoms in cavity QED. We show how to perform generic single- and two-qubit gates, the latter by encoding a two-atom state onto a single, many-level atom. We compare different strategies to overcome limitations due to cavity imperfections.

The standard paradigm of quantum computation (QC) [1] is a dynamical one: in order to manipulate the quantum state of systems encoding information, local interactions between low dimensional subsystems (qubits) are switched on and off in such a way to enact a sequence of quantum gates. On the other hand, ever since the discovery of the Berry's phase, it has been recognized that quantum evolutions, besides dynamical contributions can display purely geometrical effects [2]. The latter, in view of their very geometric-topological nature, show an inherent stability against some local perturbations.

It is therefore a natural and intriguing question to ask whether one could take advantage of this geometric features to the aim of processing quantum information. Indeed one would expect the above-mentioned robustness to result in a resilience against some kinds of errors. In other terms a geometry-based strategy for quantum manipulations is expected to have some built-in fault-tolerant features [3]. In the context of NMR [4] and Josephson junction based quantum computing [5] it has been show how to use geometrical phases to implement a two-qubit gate that, along with the dynamically generated one-qubit gates, is universal.

To achieve an all-geometrical implementation of quantum computation one is led to consider more sophisticated, i.e., non-Abelian, structures. This has been originally done in Ref. [6], where the so called holonomic approach to quantum computation (HQC) has been introduced. Quite recently a proposal for implementing an HQC scheme with trapped ions, feasible with the current technology, has been put forward [8]. In this paper we discuss an implementation proposal for HQC by means of neutral atoms in cavity QED. This is to some extent related, at least for what concern the single-qubit operations to the proposal [8]. We shall show how to perform generic single-qubit gates by using a single atom. For realizing universal two-qubit gate a mapping of a two-qubit state onto a single many-level atom will be used. Finally we shall propose a strategy to overcome limitations due to cavity imperfections.

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