Controlling entanglement in a double quantum dot

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The production of entanglement, obtained by unitary transformations (quantum gates), is a basic prerequisite for any quantum computer. Due to the comparatively long spin coherence time and the feasibility of coherent manipulation of entangled pairs [1], semiconductor nanostructures are one of the best candidates to obtain an adequate set of quantum gates, through which individual electron spins (representing the basic qubits) can be manipulated. As an example, the possibility of controlling the wave function of two electrons in quasi-one-dimensional nanorods has been explored recently [2].

In this work, we analyze the physical realization of different quantum gates through two interacting electrons confined in a quasi-1D double quantum dot. Starting from different initial states (device initialization) several basic operations, such as SWAP or entanglement creation are performed by tuning the time evolution with a variable electric field.
In our model, the electrons are strongly confined in both the vertical and one lateral direction, giving rise to an effective quasi-1D system with a corresponding effective coulomb interaction. The potential in the remaining dimension is modulated with external gates to create a finite double well profile with a controllable interdot barrier height. The spin independent Hamiltonian, in effective atomic units (a.u.) corresponding to typical GaAs-AlGaAs parameter heterostructures, is given by

$$\mathcal{H} = -\frac{1}{2}\left(\frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2}\right) + V(x_1) + V(x_2) + \mathcal{V}_c(|x_1 - x_2|),$$

where $V(x)$ represents the confining (including time dependent barrier) potential and $\mathcal{V}_c(|x_1 - x_2|)$ is the effective interaction responsible for non-trivial correlations and hence for the entanglement of the two qubit system. Both for the SWAP and entanglement creation operations the system is initialized with a definite electron spin in each potential well ($L_\downarrow R_\uparrow$), representing a non-entangled mixture of the lowest energy singlet and triplet states. The appropriate quantum gate is then obtained by a suitable modulation of the interdot barrier height leading at the end of the time evolution to the desired final state.
The evolution is computed by numerically integrating the time dependent Scrhödinger equation with a unitary implicit finite difference scheme in space and time coordinates. The amount of entanglement as well as several spin-localization measures are followed through the evolution and serve as signals of the success and quality of the gate operation. Our results, which are exact for the model hamiltonian, are compared with the predictions of a two-level Landau-Zener model [3].

References:

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