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An atomtronics transistor for quantum gates

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ABSTRACT

We present a mechanism for quantum gates where the qubits are encoded in the population distribution of two-component ultracold atoms trapped in a species-selective triple-well potential. The gate operation is a specific application of a different design for an atomtronics transistor where inter-species interaction is used to control transport, and can be realized with either individual atoms or aggregates like Bose–Einstein condensates (BEC). We demonstrate the operational principle with a static external potential, and show feasible implementation with a smooth dynamical potential.

1. Introduction

As research in ultracold atoms shifts more towards practical applications, two of the most promising areas are that of quantum computation [1] and atomtronics or electronics with trapped ultracold atoms [2–4]. Whereas classical computation is intimately tied to electronics, quantum computation in the context of ultracold atoms has so far evolved independently of the relatively new field of atomtronics. Taking a cue from classical computers, it is likely that analogs of standard electronic components like diodes and transistors can be valuable in quantum computation as well. In this paper we propose a different design for an atomtronics transistor which can also be used to implement a two-qubit quantum gate.

Our proposal has several distinguishing features: (a) qubit encoding in the spatial coordinates of particles allows implementation with single particle as well as with multi-particle entities such as BEC, (b) a system-independent principle that offers broad choices for physical realization, (c) operation does not require manipulation of internal states, and (d) easily optimizable for high fidelity and speed.

In our proposed gate mechanism, qubits are directly encoded in and read out from the spatial distribution of atoms. Spatial mode encoding has been primarily used in optical qubits, in the context of continuous variable quantum computation [5], or in dual-rail schemes [6]. Certain clever proposals for realizing phase gates in double-well potentials [7–9] have also employed vibrational modes of trapped atoms. However, the gate outcome is contained in the phase of the states and readout was shown to require intermediate encoding on atomic internal states [10]. In contrast, we encode qubits in the population distribution of atoms in a triple-well potential, and readout simply involves determining the presence or absence of atoms in specific wells, possible even for single atoms by direct imaging methods [11].

Likewise, a simpler operational principle underlies our atomtronics transistor, where the atom transport is directly controlled by interspecies interaction. Existing designs are based on manipulating resonant coupling of lattice sites by adjusting the chemical potential or external bias fields [2,3,12]; or on manipulating atomic internal states to transport holes [13], or spin [14].

2. Quantum gate operation, static case

We consider two independently controlled orthogonal triple wells that can be switched between two 'T-shaped' configurations, shown in Fig. 1(a, b), containing two mutually-interacting species, each free to move only along one direction. Single qubits are encoded in the spatial degrees of freedom of the two species, with $|0\rangle$ and $|1\rangle$ corresponding to localizations in the respective extreme wells. In any given operation cycle the motion of one species is kept frozen by deep potentials, so *only one spatial dimension (1D) needs to be considered at a time*. Without loss of generality *further we refer to the active species as A and the passive as B* as in Fig. 1(a). Along the active direction we label the wells *left, central, right*, with effective qubit definitions [Fig. 1(d, e)]: Qubit A is in state $|0\rangle$ or $|1\rangle$ if species A is localized in the left or right well respectively; Qubit B is in state $|0\rangle$ or $|1\rangle$ when species B is absent or present in the well that overlaps with the central well of A. A two-qubit CNOT

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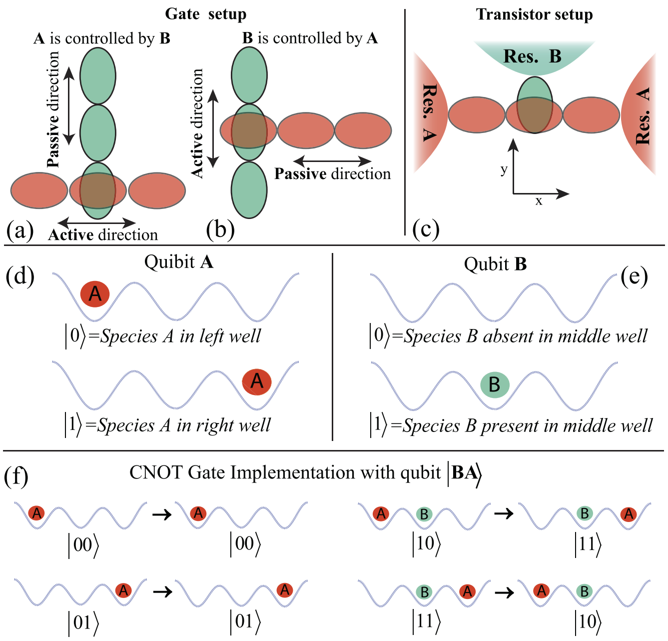

Fig. 1. (a)–(b) Interchangeable gate configurations where role of A and B can be swapped; (c) Transistor configuration connected to reservoirs. (d)–(e) Effective qubit definitions in a specific cycle; (f) CNOT quantum gate operation.

gate can be then designed [Fig. 1(f)] such that after a set time T, qubit A is negated if qubit B is in $|1\rangle$, but is unchanged if qubit B is in $|0\rangle$. Notably, such a configuration allows for simple scalability since the roles ('control' or 'controlled') of the two species can be switched in different cycles.

We first consider a *static* triple-well potential to describe the gate operation principle, which involves the three lowest eigenstates ϕ_0, ϕ_1 and ϕ_2 for species A in the triple-well, with eigenenergies $E_0 < E_1 < E_2$. The term "static" distinguishes the case in which the potential does not change in time from the dynamic case studied in Section 5. The potential is symmetric about the central well minimum [Fig. 2], so ϕ_1 has its *node* there while ϕ_0 and ϕ_2 have anti-nodes. Therefore, when species B is present in the central well, the repulsive A–B interaction V_{AB} will shift up the energies E_0 and E_2, but hardly affect E_1. A class of potentials exists where the presence of atom B will raise E_0 and E_2 by the same amount, thus leaving $\Delta E_2 = E_2 - E_0$ unchanged while decreasing $\Delta E_1 = E_1 - E_0$.

Species A is prepared in a state $|\psi_A(t=0)\rangle$ localized in one of the two extreme wells. Even though we choose this state to be simply a Gaussian with minimized energy, the projection on the three lowest eigenstates is almost complete. The initial phase relations among the eigenstates, shown in Fig. 2(a, b), are such that $\phi_0(0)$ and $\phi_2(0)$ add up constructively with $\phi_1(0)$ in one extreme well and destructively in the other. If present, $|\psi_B(0)\rangle$ is a minimum energy Gaussian in the tight selective potential for species B, overlapping with the central well of the active potential for atom A. To ensure perfect execution of the gate, one should be able to adjust ΔE_1 and ΔE_2 both with and without atom B. This requires four independent parameters such as separation and height of the barriers, depth of the side wells relative to the middle well and the interaction strength V_{AB}. By simple reparametrization [15], we can find a configuration such that with species B absent, $\Delta E_2 = 2 \times \Delta E_1$, and with species B present $\Delta E_2^B = \Delta E_2$ and $\Delta E_2^B = 4 \times \Delta E_1^B$, as seen in Fig. 2. Since all the energy separations are integer multiples of a common energy unit, in both cases (with and without B) species A will undergo periodic dynamics with a revival of the initial state (in the *initially occupied* extreme well) at

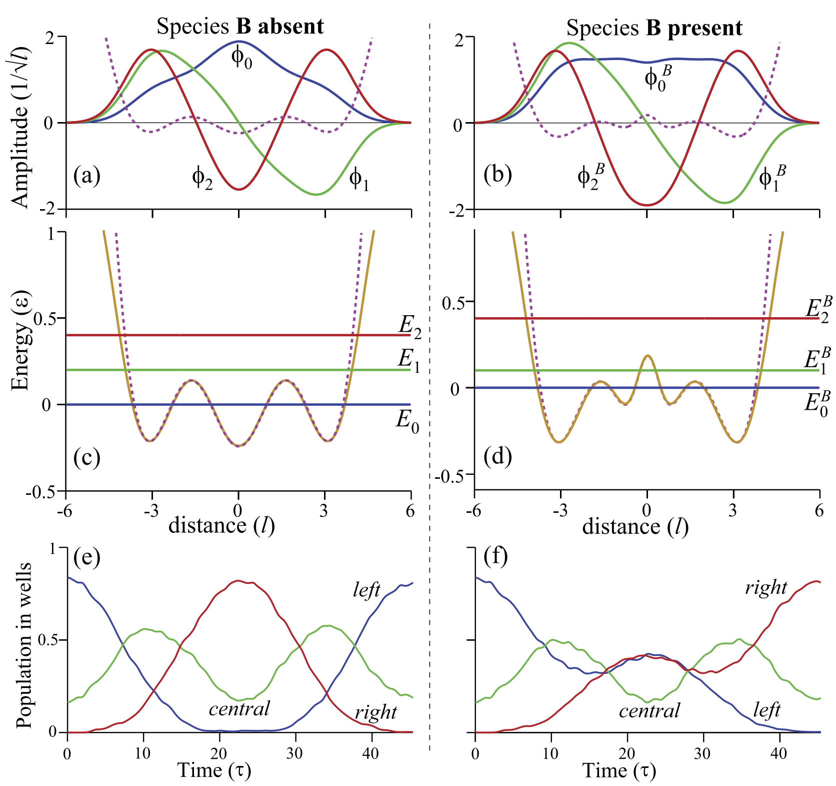

Fig. 2. *Static potential*: Species B absent (left), present (right): (a, b) The three lowest eigenstates and (c, d) corresponding eigenenergies of species A in the triple-well. The dotted lines show the potential from Eq. (3), which generally matches a lattice potential (solid line in (c), (d)) created with three harmonics. With B absent, $\Delta E_2 = 2 \times \Delta E_1$ but with B present, $\Delta E_2^B = 4 \times \Delta E_1^B$. (e, f) The single-well occupation versus time for species A, with species B absent/present.