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Quantum Computation under Micromotion in a Planar Ion Crystal

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We propose a scheme to realize scalable quantum computation in a planar ion crystal confined by a Paul trap. We show that the inevitable in-plane micromotion affects the gate design via three separate effects: renormalization of the equilibrium positions, coupling to the transverse motional modes, and amplitude modulation in the addressing beam. We demonstrate that all of these effects can be taken into account and high-fidelity gates are possible in the presence of micromotion. This proposal opens the prospect to realize large-scale fault-tolerant quantum computation within a single Paul trap.

Scalable quantum computation constitutes one of the ultimate goals in modern physics[1,2]. Towards that goal, trapped atomic ions are hailed as one of the most promising platforms for the eventual realization[3,4]. The linear Paul trap with an one-dimensional (1D) ion crystal was among the first to perform quantum logic gates[5–7] and to generate entangled states[8–10], but in terms of scalability, the 1D geometry limits the number of ions that can be successfully trapped[11,12]. Another shortcoming of the 1D architecture is that the error threshold for fault-tolerant quantum computation with short-range gates is exceptionally low and very hard to be met experimentally[13–15].

Generic ion traps, on the other hand, could confine up to millions of ions with a 2D or 3D structure[16–18]. More crucially, large scale fault-tolerant quantum computation can be performed with a high error threshold, in the order of a percent level, with just nearest neighbor (NN) quantum gates[19–22]. This makes 2D or 3D ion crystals especially desirable for scalable quantum computation. Various 2D architectures have been proposed, including microtrap arrays[23], Penning traps[16,24–26], and multizone trap arrays[27,28]. However, the ion separation distance in microtraps and penning traps is typically too large for fast quantum gates since the effective ion-qubit interaction scales down rapidly with the distance. In addition, fast rotation of the ion crystal in the Penning trap makes the individual addressing of qubits very demanding. Distinct from these challenges, Paul traps provide strong confinement; however, they are hampered by the micromotion problem: fast micromotion caused by the driving radio-frequency (rf) field cannot be laser cooled. It may thus create motion of large amplitudes well beyond the Lamb-Dicke regime[29,30], which becomes a serious impediment to high-fidelity quantum gates.

In this paper, we propose a scheme for scalable quantum computation with a 2D ion crystal in a quadrupole Paul trap. We have shown recently that micromotion may not be an obstacle for design of high-fidelity gates for the two-ion case[31]. Here, we extend this idea and show that micromotion can be explicitly taken into account in the design of quantum gates in a large ion crystal. This hence clears the critical hurdle and put Paul traps as a viable architecture to realize scalable quantum computation. In such a trap, DC and AC electrode voltages can be adjusted so that a planar ion crystal is formed with a strong trapping potential in the axial direction. In-plane micromotion is significant, but essentially no transverse micromotion is excited due to negligible displacement from the axial plane. We perform gates mediated by transverse motional modes and show that the in-plane micromotion influences the gate design through three separate ways: (1) It renormalizes the average positions of each ion compared to the static pseudopotential equilibrium positions. (2) It couples to and modifies the transverse motional modes. (3) It causes amplitude modulation in the addressing beam. In contrast to thermal motion, the fluctuation induced by micromotion is coherent and can be taken into account explicitly. Several other works also studied the effect of micromotion on equilibrium ion positions and motional modes[32–34], or used transverse modes in an oblate Paul trap to minimize the micromotion effect[35]. Here, by using multiple-segment laser pulses[36–38], we demonstrate that high-fidelity quantum gates can be achieved even in the presence of significant micromotion and even when many motional modes are excited. Our work therefore shows the feasibility of quadrupole Paul traps in performing large scale quantum computation, which may drive substantial experimental progress.