

## UNIVERSAL QUANTUM COMPUTATION WITH QUANTUM-DOT CELLULAR AUTOMATA IN DECOHERENCE-FREE SUBSPACE

Z. Y. XU

*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics  
and Mathematics, Chinese Academy of Sciences, Wuhan, 430071, China  
Graduate School of the Chinese Academy of Sciences, Beijing, 100049, China*

M. FENG<sup>a</sup>

*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics  
and Mathematics, Chinese Academy of Sciences, Wuhan, 430071, China*

W. M. ZHANG

*Department of Physics and Center for Quantum Information Science, National Cheng Kung University  
Tainan 70101, China*

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We investigate the possibility to have electron-pairs in decoherence-free subspace (DFS), by means of the quantum-dot cellular automata (QCA) and single-spin rotations, to deterministically carry out a universal quantum computation with high-fidelity. We show that our QCA device with electrons tunneling in two dimensions is very suitable for DFS encoding, and argue that our design favors a scalable quantum computation robust to collective dephasing errors.

*Keywords:* Decoherence-free subspace (DFS), Quantum-dot cellular automata (QCA), Universal quantum computation (UQC)

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Spin degrees of freedom of electrons in quantum dots have been considered as good candidates to encode qubits over past years, due to their long decoherence time and full controllability. Of particular interest is the recent achievements of ultrafast manipulation of electron spin in conduction band of the quantum dot [1, 2] and coherent tunneling of electrons between neighboring quantum dots [3, 4]. These technical progresses have led to more and more concerns on movable electron based quantum gates.

It has been shown in [5, 6, 7, 8] that, by manipulating spin degrees of freedom, we are able to perform universal quantum computation (UQC) with movable electrons. The key idea is that we encode qubits in the electron spins, but make measurement [5, 6] or make entanglement [7, 8] by means of the electron charges. As spin and charge (i.e., orbit) degrees of freedom commute, a measurement on the charge of an electron does not affect the spin of the electron. With these ideas, we could use the movable (or say, free) electrons to entangle

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<sup>a</sup>mangfeng@wipm.ac.cn

the spin states of different electrons [5, 6, 7, 8, 9], to analyze the multipartite entanglement [5, 9], and to purify the existing entanglement [10].

However, the electron spins in quantum dots severely suffer from decoherence regarding environmental noise, such as the surrounding nuclear spins, background charge fluctuation and noise, electron–phonon interaction, low-frequency noise and so on [11] and it is evident that the confinement of the quantum dots makes the decoherence enhanced. Fortunately, as long as our operation on the electron spin is quick enough, the influence from the surrounding nuclear spins, also called Overhauser effect, could be effectively considered as from a constant magnetic field [12]. In principle, we may employ spin echo technique to remove any errors due to constant magnetic field, whereas experimental evidence has shown that the spin echo pulses could not fully eliminate errors regarding dephasing [4]. To defeat decoherence, people have worked out a number of ideas, such as in [13, 14, 15, 16, 17, 18, 19], where the error avoiding strategies carried out in decoherence-free subspaces (DFS) are useful for suppressing collective dephasing errors, and are relatively simpler, because they only require some special encodings immune from certain system–environment disturbances but no error correction steps are needed.

We focus in the present work on the recent proposal with quantum-dot cellular automata (QCA), in which spin entanglement of different electrons could be achieved without spin-spin interaction [7, 8]. We will show that UQC in DFS could be carried out by QCA settings in a relatively simpler way than by other systems. QCA was originally proposed as a transistorless alternative to digital circuit devices at the nanoscale [20], and then employed in quantum systems [21, 22, 23]. In the present paper, we show our idea of DFS encoding with QCA applied to quantum dots, in which electron spins would be involved to encode qubits, and QCA behaves quantum mechanically with two electrons tunneling coherently between two antipodal sites on the QCA due to Coulomb repulsion. As shown in [7, 8], different from the free-electron QC models under screening assumption [5, 6], the QCA quantum computation makes use of the Coulomb interaction between electrons throughout the operations, and could thereby achieve deterministic entanglement between electron spins.

The DFS we employ is spanned by the encoding states  $|0_L\rangle = |01\rangle$  and  $|1_L\rangle = |10\rangle$  with  $|0\rangle$  and  $|1\rangle$  the spin up and down states of the electron in the dot, respectively, which constitutes a well-known DFS scheme immune from dephasing induced by the system–environment interaction in the form of  $Z \otimes B$ , where  $Z = \sigma_z^1 \oplus \sigma_z^2$  and  $B$  is a random bath operator. For clarity, we will call  $|0_L\rangle$  ( $|1_L\rangle$ ) logic qubit and  $|0\rangle$  ( $|1\rangle$ ) physical qubit. As there is no spin-spin coupling between the electrons, we have degeneracy between  $|0_L\rangle$  and  $|1_L\rangle$ , implying that no noise from collective dephasing would affect the encoded subspace we employ. It also means that the dot-dot spacing in our design must be bigger than those in [4, 24, 25]. As collective errors due to coupling to environment are generally considered to be the main problem in solid-state system at low temperature [26], we will focus throughout this work on overcoming the collective dephasing. Other noise beyond collective dephasing could also be removed by some additional operations, as shown later. We will demonstrate that three basic logic gates for a UQC could be carried out by our DFS-encoded electron spins, without any auxiliary spin qubit required. As dephasing is strongly suppressed and the QC is run strictly within the DFS, the entangled state generated in our design could be kept in high fidelity for a long time.

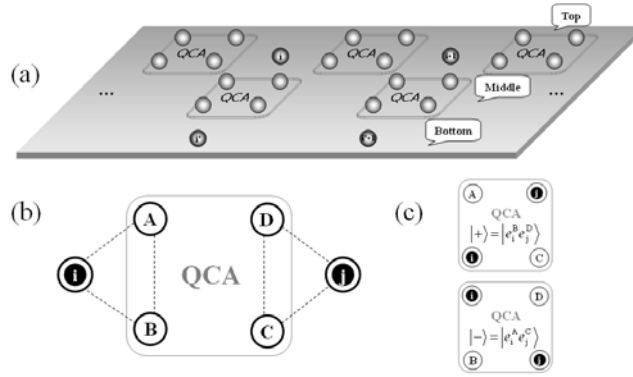


Fig. 1. (a) Schematics for our proposed design, where the dots  $i$ , with  $i = 1, 2, 3, \dots$ , are initially prepared in  $|0\rangle$ , and dots  $i'$ , with  $i' = 1', 2', 3', \dots$ , are initially in  $|1\rangle$ . The logic qubits are constructed by  $|ii'\rangle$ . (b) Four initially neutral quantum dots in the square constitute a QCA, and two initially charged quantum dots are separated by the QCA, where the black dots represent single electrons and the dashed lines connecting quantum dots denote possible tunnelings. (c) Coulomb repulsion causes two fully polarized charge states  $|+\rangle = |e_i^B e_j^D\rangle$  and  $|-\rangle = |e_i^A e_j^C\rangle$ , where A, B, C and D mean the sites and  $i$  and  $j$  denote the different electron spins.

As shown in Fig. 1(a), the QCA blocks and the quantum dots encoding the qubits are arranged in alternate way in two dimensions, where the large spacing between the qubits, e.g., hundreds of nanometers or even of the order of micrometer to make the spin-spin interaction negligible, is helpful for individual manipulation on the qubits. To have a UQC in DFS, we have to construct three logic-qubit gates. The first is the Hadamard gate  $H_L : |0_L\rangle = |01\rangle_{ii'} \Rightarrow \frac{1}{\sqrt{2}}(|0_L\rangle + |1_L\rangle) = \frac{1}{\sqrt{2}}(|01\rangle_{ii'} + |10\rangle_{ii'})$ , and  $|1_L\rangle = |10\rangle_{ii'} \Rightarrow \frac{1}{\sqrt{2}}(|0_L\rangle - |1_L\rangle) = \frac{1}{\sqrt{2}}(|01\rangle_{ii'} - |10\rangle_{ii'})$ , where  $i$  and  $i'$  denote different dots with  $i, i' = 1, 2, 3, \dots$ . The second gate is the two-logic-qubit conditional gate. We will construct a controlled-phase flip (CPF) as an example, i.e., a phase  $\pi$  appearing as the prefactor of  $|1_L 1_L\rangle$  after the gating, and the third one is for a single-logic-qubit rotation  $Q_L(\theta)$ , i.e.,  $a|0_L\rangle + b|1_L\rangle \Rightarrow a|0_L\rangle + be^{i\theta}|1_L\rangle$ .

Consider the initial state of the two electrons in quantum dots  $i$  and  $j$  to be  $|e_i e_j\rangle \otimes |S_i S_j\rangle$ , where  $|e_i e_j\rangle$  are charge states to be auxiliary,  $|S_i S_j\rangle$  are spin states for qubit encoding, and  $j$  could be  $i'$  in the case of  $H_L$  gating or  $i + 1$  for achieving CPF. By the same operations as in [8], after the electrons tunnel to dots A and C, we switch off the channels between the dots  $i, j$  and the QCA, and then turn on the bias for the electron tunneling between the sites A and B, and between the sites C and D (See Fig. 1(b)). We may describe the quantum behavior on the QCA by following Hamiltonian in units of  $\hbar = 1$  [3, 8],

$$H_{QCA} = \frac{\omega_0}{2}(|+\rangle\langle+| - |-\rangle\langle-|) + \frac{\gamma}{2}(|+\rangle\langle-| + |-\rangle\langle+|), \quad (1)$$

where  $|+\rangle = |e_i^B e_j^D\rangle$  and  $|-\rangle = |e_i^A e_j^C\rangle$  are polarized charge states defined in [7, 8] and in Fig. 1(c).  $\omega_0$  represents the energy offset of the polarized states  $|\pm\rangle$  from the balance of on-

site potential, Coulomb repulsion and the external bias energy.  $\gamma$  accounts for the tunneling between these two polarized states.

To carry out the first gate  $H_L$ , we set  $\omega_0$  to be zero (i.e., a symmetric QCA) and start the tunneling from the state  $|-\rangle \otimes |S_i S_{i'}\rangle$  where the subscripts correspond to the dots the electrons come from, and the electron with spin  $|S_i\rangle(|S_{i'}\rangle)$  will tunnel between A(C) and B(D). During the electron tunneling on the QCA, we perform single-spin rotations  $U_{BD}$  and  $U_{AC}$  (defined later) on the electronic states at the sites B, D and A, C. As the tunneling is coherent, these single-spin operations could be done simultaneously [8]. At  $t = \pi/2\gamma$ , we stop our operations on the QCA, and drive the electrons back to dots  $i$  and  $i'$  [8]. Then we get

$$|e_i e_{i'}\rangle \otimes \frac{1}{\sqrt{2}}(U_{AC} - iU_{BD})|S_i S_{i'}\rangle,$$

where  $U_{AC} = R_x^A(\pi) \otimes R_x^C(3\pi)$  and  $U_{BD} = R_z^B(3\pi) \otimes I^D$ , with the superscripts being the sites where the electron is rotated,  $R_k(\theta) = \exp(-i\theta\sigma_k/2)$ ,  $k = x, y, z$ , and  $I$  being an identity operator. As electrons tunnel back from dots A(C) and B(D) to  $i(i')$  simultaneously [8], we may simply rewrite  $U_{AC}$  and  $U_{BD}$  as  $U_{AC} = R_x^i(\pi) \otimes R_x^{i'}(3\pi)$  and  $U_{BD} = R_z^i(3\pi) \otimes I^{i'}$ . It is easy to verify that above operations yield  $H_L : a|0_L\rangle + b|1_L\rangle \Rightarrow \frac{1}{\sqrt{2}}[a(|0_L\rangle + |1_L\rangle) + b(|0_L\rangle - |1_L\rangle)]$ , as shown in Fig. 2(a).

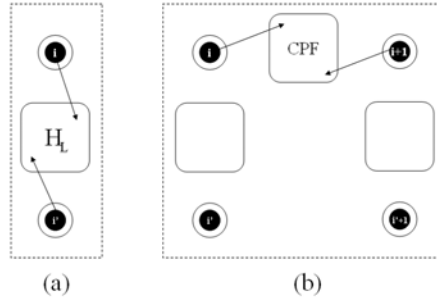


Fig. 2. Logic-qubit quantum gates, where (a) is for  $H_L$  carried out between dots  $i$  and  $i'$ . (b) is for CPF between dots  $i$  and  $i + 1$  in the top line.

The second gate happens between pairs  $i - i'$  and  $(i + 1) - (i' + 1)$  of the initial state  $(a|01\rangle_{i,i'} + b|10\rangle_{i,i'}) \otimes (c|01\rangle_{i+1,i'+1} + d|10\rangle_{i+1,i'+1})$ . The CPF yields

$$ac|0101\rangle_{i,i',i+1,i'+1} + ad|0110\rangle_{i,i',i+1,i'+1} + bc|1001\rangle_{i,i',i+1,i'+1} - bd|1010\rangle_{i,i',i+1,i'+1},$$

which is actually equivalent to a CPF on electrons  $i$  and  $i + 1$  in the top line (See Fig. 2(b)). To achieve such a CPF, we may employ the controlled-NOT (CNOT) gate in [8] sandwiched by two Hadamard gates on the target physical qubit. But we hope to accomplish the CPF directly to make our implementation simple. So under the Hamiltonian  $H_{QCA}$  with

$\omega_0 = 0$  and the initial state  $|-\rangle \otimes |S_i S_{i+1}\rangle$ , we start the tunneling assisted with single-spin rotations. Like in above  $H_L$  gating, we stop the electron tunneling at  $t = \pi/2\gamma$ , and drive the electrons back to the dots  $i$  and  $i + 1$ . So we have  $|e_i e_{i+1}\rangle \otimes \frac{1}{\sqrt{2}}(\bar{U}_{AC} - i\bar{U}_{BD})|S_i S_{i+1}\rangle$ , with  $\bar{U}_{AC} = R_z^A(\pi/2) \otimes R_z^C(\pi/2) = R_z^i(\pi/2) \otimes R_z^{i+1}(\pi/2)$  and  $\bar{U}_{BD} = R_z^B(3\pi/2) \otimes R_z^D(3\pi/2) = R_z^i(3\pi/2) \otimes R_z^{i+1}(3\pi/2)$ , which yields

$$|\varphi\rangle = \frac{1}{\sqrt{2}}|e_i e_{i+1}\rangle \otimes (1-i) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} |S_i S_{i+1}\rangle. \quad (2)$$

If we neglect the additional global phase, we have fulfilled the CPF operation:  $|S_i S_{i+1}\rangle \Rightarrow (-1)^{S_i S_{i+1}} |S_i S_{i+1}\rangle$  between the dots  $i$  and  $i + 1$ , with  $S_i, S_{i+1} = 0, 1$ . This physical-qubit CPF also implies the logic-qubit CPF between pairs  $i - i'$  and  $(i + 1) - (i' + 1)$ , as shown in Fig. 2(b).

The third gate  $Q_L(\theta)$  could be achieved by rotating one of the physical qubits. So different from the first and the second gates, the implementation of the third gate employs Faraday rotation [27, 12], instead of the tunneling on QCA. We apply  $\sigma_{(z)}^+$  polarized light on a certain dot in the bottom line. A phase  $e^{i\delta_0}$  ( $e^{i\delta_1}$ ) will be created if the electron spin of the dot is initially  $|0\rangle$  ( $|1\rangle$ ), due to virtual excitation of exciton including heavy (light) hole state [27, 12]. As  $\delta_0$  is larger than  $\delta_1$  and both of them could be exactly controlled, we could achieve  $Q_L(\theta)$  with  $\theta = \delta_0 - \delta_1$ .

With the three basic gates above, we could carry out a universal quantum gating with the electron pairs. However, in terms of DiVincenzo's checklist [28], a UQC also requires high-quality preparation of initial states and the efficient readout, besides the universal quantum gating. In our case, the initial qubit states on the top line should be in  $|00\dots 0\rangle$  (i.e., all spins up) and the qubit states on the bottom line are initially  $|11\dots 1\rangle$  (i.e., all spins down), which correspond to the logic state  $|0_L\rangle$ . As the interdot separation is big, this job could be accomplished individually by the techniques in [2, 29], where a single conduction band electron was produced [29] and single-spin manipulation on the conduction band electron has been achieved [2]. The single-spin rotation could also be made by ultrafast laser pulses which accomplish substantial and accurate spin rotation at the timescale of femtosecond [1]. The efficient readout of qubit states has been available optically by nondestructive detection of the electron spin in the conduction band of the quantum dot [30]. The same job could also be done by single-shot technique [31] based on the charge signal due to electron jumping. If the electron could jump back to the original site after the detection, this readout is also nondestructive [8]. Therefore, up to now, we have proved that a UQC with the DFS encoded electron pairs is available in our QCA-based device.

As it strongly suppresses the collective dephasing, the DFS encoding could much reduce the operations for spin echo and thereby actually reduce the gating time and enhance the fidelity, although it seems to increase the overhead resource. Besides collective dephasing, however, there would be other dephasing errors in a real system, such as logic errors regarding  $\sigma_r^i \sigma_r^{i+1}$  with  $r = x, y, z$ , and the leakage errors related to following undesired operations:  $\sigma_x^i, \sigma_x^{i+1}, \sigma_y^i, \sigma_y^{i+1}, \sigma_x^i \sigma_z^{i+1}, \sigma_z^i \sigma_x^{i+1}, \sigma_y^i \sigma_z^{i+1}, \sigma_z^i \sigma_y^{i+1}$  [26, 32]. To eliminate the logic errors, we may employ deliberately designed Bang-Bang pulse sequences including  $\sigma_x^i \sigma_x^{i+1}, \sigma_y^i \sigma_y^{i+1}$ , and

$\sigma_z^i \sigma_z^{i+1}$  respectively, with further amendment by refocusing on individual physical-qubits [26]. Bang-Bang pulses are strong and fast, which could effectively average out the environment-induced noise, and keep the quantum state from dissipation by repeatedly kicking the qubit [33, 34]. The leakage errors could be in principle fully removed by the leakage-elimination operator introduced by [32], which is actually associated with projection operations and could be easily applied to our design. So after the treatment above, dephasing errors could be much suppressed in our scheme, and thereby  $T_2$  in our design should be in principle much longer than that without using DFS. Moreover, since the errors are brought about by unpredictable factors, e.g., the fluctuation of the magnetic field, we have to first use interrogative Bang-Bang pulses to determine the required values for correction, which has been actually a sophisticated technique [35]. A very recent experiment [36] has shown the power of Bang-Bang pulses to decouple the qubit from the environmental noise. So, with the encoding plus Bang-Bang pulses assisted sometimes by individual physical-qubit refocusing, all dephasing errors could be strongly suppressed in our design.

For other sources of decoherence beyond dephasing, the mechanism is very complicated and not fully clear yet. They yield decoherence time  $T_1$ . It was reported that  $T_1$  could be of the order of millisecond in GaAs and In(Ga)As quantum dots [37], and in a preliminary experiment for QCA with two electrons involving no spin [38], the coherent tunneling of the electrons diminished very quickly. Although we have not yet fully understood these decoherence sources, lower temperature is helpful for suppressing most of them. We have also noticed that elaborately controlled spin-echo pulses could extend  $T_2$  to 1 microsecond [4], and thereby we guess that  $T_1$  should be longer. As there is no fluctuation regarding spin-spin exchange energy and hybridized states [25] in our design due to negligible inter-spin coupling, we may expect  $T_1$  in our design to be longer than microsecond in the low temperature.

In addition, spin-orbit interaction could also affect the spin coherence and spin-spin coupling [39]. But in our case, there is no direct spin-spin coupling, and the electron staying in the ground state of the conduction band is of the *s*-orbit wavefunction. As a result, the effect due to spin-orbit interaction is negligible in our scheme.

There have been some preliminary QCA experiments without involving electron spins [20, 21, 38]. But as the electron tunneling involving spin degrees of freedom has been available, we believe the QCA experiment relevant to electron spin would also be achievable soon. In what follows, let us briefly discuss the experimental feasibility of our proposed scheme. Using the values in [40], we may assess an entangled state between the electrons  $i$  and  $j$  to be achievable within 70 picosecond, provided that the electron tunneling rate on the QCA could be as fast as 200 GHz [40]. As the implementation time is much shorter than  $T_1$  and  $T_2$ , we may neglect decoherence in our discussion. But due to the rapid operation, we have to pay attention to the possible imprecision in the single-spin rotation and in the bias voltage control. For an estimate, we have assumed in our numerical calculation a laser induced phase error  $\epsilon$  for every  $\pi/2$  single-spin rotation and a phase error  $\delta$  by voltage control in each tunneling on the QCA. Fig. 3 demonstrates the fidelity of  $H_L$  and CPF on different states under these errors. We could find that the error  $\epsilon$  is more destructive than  $\delta$ , which implies the accurate manipulation by laser to be more essential to our implementation. Another point is that the CPF works better than  $H_L$  under the same condition. The reason is that  $H_L$  involves larger rotations which bring about more phase errors regarding  $\epsilon$ . The results remind us to pay more

attention to the operations by the ultrafast laser pulses.

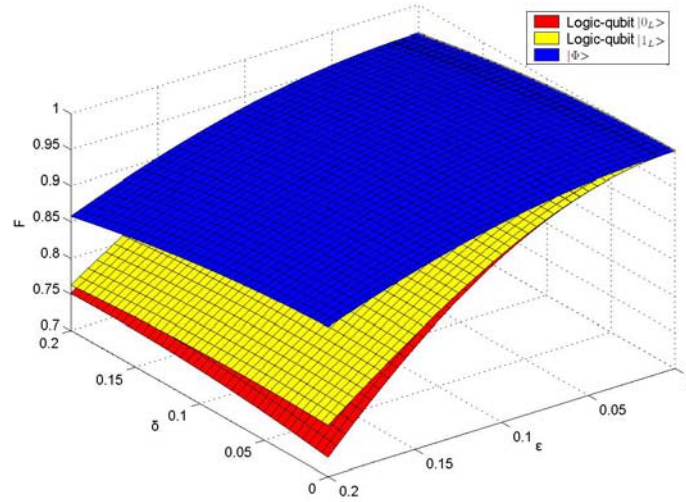


Fig. 3. (Color online) Numerical simulation for the fidelity of the gating  $H_L$  and CPF under imprecise operations, where  $\epsilon$  and  $\delta$  are phase errors induced, respectively, in the laser manipulation and the voltage control. The curved surfaces in red and yellow represent  $H_L$  on logic-qubits  $|0_L\rangle$  and  $|1_L\rangle$ , respectively, and the blue surface is for CPF on the state  $|\Phi\rangle = (|00\rangle + |01\rangle + |10\rangle + |11\rangle)/2$ .

Compared with previous devices producing entanglement between free electrons [5, 6, 9], our QCA-based design could achieve the logic-qubit quantum gates straightforwardly in a simpler fashion. For example, the CPF gating could be made with much reduced steps compared to [5, 6, 9]. This is because that the free electrons under screening model [5, 6, 9] interact only by measurement, which is probabilistic, while our implementation, under Coulomb interaction, is made straightforwardly and deterministically. In addition, the measurement in [5, 6, 9] is made by the time-resolved charge detector which is technically unavailable at present, whereas no charge detector is required in our design. Furthermore, as the movable electrons are distinguishable throughout our scheme, no concern about quantum characteristic of identical particles is needed. More importantly, as dephasing errors are strongly suppressed, the entangled states in our design could be kept in high-fidelity for a longer time than in any proposal without using DFS.

To some extents, our scheme is similar to that with multizone trap by moving ions [41]. Both the electrons in our design and the ultracold ions in the trap are exactly controllable, e.g., to be static and moving under control. Besides, both the designs are scalable, and deterministically operated. It has been shown in [41] that the DFS encoding could suppress the collective dephasing errors in trapped ions separated by  $5 \sim 10 \mu\text{m}$  to  $10^{-4}$ . So it should work better in our design with the dots' spacing being approximately  $1 \mu\text{m}$ . On the other hand, due to controllable tunneling in a two-dimensional configuration, our designed QCA setting is more favorable for UQC in DFS than ion traps or other systems: We need no movement of qubits for a long distance as in multizone trap [41], and the dephasing resisted UQC could be achieved with no need of auxiliary qubits [42] and no danger going beyond the

DFS during operation [43]. What is more, the above proposals [42, 43] are probabilistic due to measurement involved, whereas our implementation is deterministic.

In summary, we have demonstrated the possibility to carry out a DFS encoding for UQC robust to collective dephasing errors by a QCA-based device using electronic tunneling and single-spin rotations. Our scheme only involves gate voltage controls of the electron tunneling and optical manipulation of the electron spin in quantum dots. To suppress other errors beyond collective dephasing, we may employ some additional means, which are in principle achievable in our design. Although some of the necessary steps are still challenging with current experimental techniques, our proposed design without spin-spin interaction and dephasing errors, but with relatively large dot-dot spacing, is helpful for experimental observation of coherence and entanglement of electron spins in quantum dots and provides a promising way towards scalable QC with quantum dots.

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