Hole Flying Qubits in Quantum Dot Arrays

David Fernández-Fernández, Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC)
Calle Sor Juana Inés de la Cruz, 3, Madrid, Spain
T: +34 677877106, david.fernandez@csic.es
Yue Ban, Departamento de Física, UC3M
Gloria Platero, Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC)

Recent advancements in semiconductor Quantum Dot Arrays (QDAs) have propelled the field towards greater scalability, unlocking novel applications in quantum computation, information processing, and simulation [1-3]. Notably, hole spin qubits have garnered attention for their minimal hyperfine interaction and intrinsic Spin-Orbit Interaction (SOI) [4].

This study investigates the capability of QDAs as quantum links, facilitating information transfer between distant dots (Fig. 1). Despite the increasing popularity of long-range transfer protocols [5], the advantages of SOI in QDAs are largely untapped. We propose a novel method employing Shortcuts to Adiabaticity (STA) to implement hole-flying qubits in QDAs.

Our investigation demonstrates the tunability of hole spin rotation during transfer by adjusting the number of dots and SOI via external electric fields. This tunability not only controls the rotating angle but also modulates the rotation vector. By employing a sequence of up to three long-range transfers, we achieve simultaneous implementation of a general one-qubit gate, accelerating quantum entanglement generation between distant sites (Fig. 2, top).

The low population of intermediate sites protects the qubit against possible electric fluctuations acting over the QDA. Furthermore, we propose effective strategies to mitigate dephasing effects, integrating dynamical decoupling protocols during the transfer process (Fig. 2, bottom). These findings extend to systems with multiple interacting particles, enabling long-range quantum entanglement distribution. Additionally, we demonstrate long-range spin transfer in half-filled QDAs, leveraging SOI in combination with high magnetic fields to establish dark states that prevent population of intermediate states.

Our study contributes to advancing the understanding of long-range transfer in QDAs, addressing critical aspects for practical quantum computation. We propose QDAs to overcome scalability issues, employing them as quantum links to interconnect computing nodes within a sparse architecture on a quantum chip.

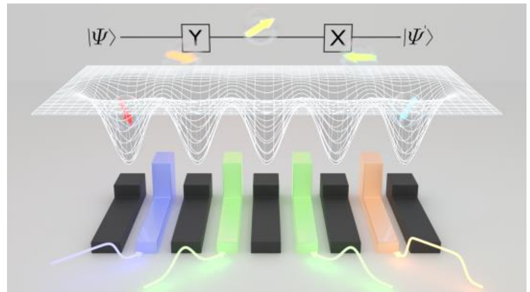

Fig.1. Scheme of a five QDA with SOI. The pulses applied to the tunnel barriers give rise to hole spin quit long-range transfer (colored arrows). These pulses are obtained by combining STA (blue and orange gates) and straddling pulses (green gates). Simultaneous to the transfer, one-qubit gates can be implemented via electric fields, schematically shown at the back of the QDA with the quantum gates Y and X.

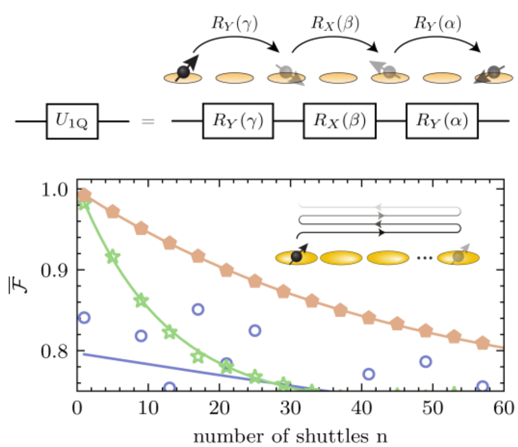

Fig.2. (top) Implementation of a general one-qubit gate by dividing the total QDA into three parts. Quantum gates around two perpendicular axes (Y and X, for instance) are applied during each sub-array. (bottom) Average fidelity after n shuttles in a QDA with 19 sites in the presence of hyperfine interaction, using a sequential (circles, blue) and a long-range (stars, green) transfer. Dynamical decoupling protocols can be applied simultaneously to the transfer (pentagons, orange) improving the fidelity.

References

[1] S. G. J. Philips, et al., Nature **609**, 919 (2022).
[2] I. Seidler, et al., npj Quantum Inf **8**, 100 (2022).
[3] A. Zwerver, et al., PRX Quantum **4**, 030303 (2023).
[4] N. W. Hendrickx, et al., Nature **591**, 580 (2021).
[5] Y. Ban, et al., Nanotech. **29**, 505201 (2018).
[6] D. Fernández-Fernández, arXiv: 2312.04631 (2023).