Andreev spin qubits based on magnetically doped two-dimensional topological insulators

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Abstract: We show that robust Andreev spin qubits can be realized in Josephson junctions based on the helical edge states of a magnetically doped two-dimensional topological insulator proximized by superconducting films.

Andreev spin qubits (ASQ), theoretically proposed by Nazarov & coworkers [1-2], represent a quite promising solid-state implementation of qubits, based on the spin degree of freedom and enabling the readout of the qubit state by Josephson current measurements. However, the current realizations based on semiconductor nanowires exhibit an unexpected short decoherence time [3-4], which makes them not competitive with transmon qubits yet. For these reasons, the search for an alternative implementation of ASQ is one of the most challenging open problems in quantum science.

Here, we propose a novel route to solve this problem, based on topological insulators, which can outperform current ASQ realizations. We show that Andreev spin qubits can be realized in a Josephson junction based on the helical edge states of a two-dimensional topological insulator, namely a quantum spin Hall insulator (QSHI), proximized by superconducting films, in the presence of magnetic doping (see Fig.1). We demonstrate that the electric dipole transitions between the Andreev spin states induced by the magnetic doping can be harnessed to optically manipulate the Andreev spin qubit by microwave radiation pulses.

We numerically simulate the realization of quantum logic gates, analyze the robustness of the ASQ to inelastic scattering, and discuss the decoherence effects of the spin qubits. Finally, we propose implementations in realistic setups at experimental reach.

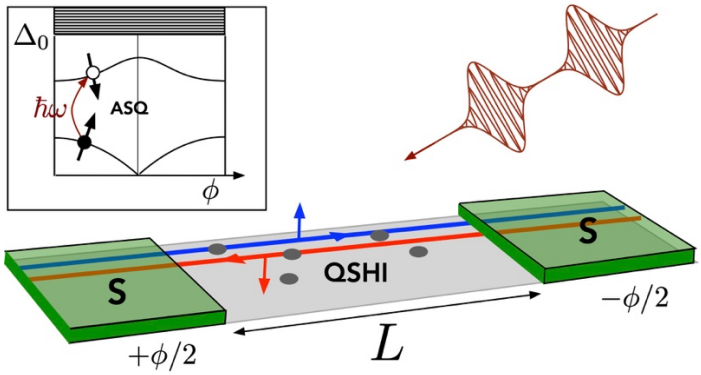

Fig. 1 Scheme of realization of an ASQ based on the edge states of a quantum spin Hall insulator (QSHI): A helical Josephson junction realized by proximizing the helical edge states of a QSHI with s-wave superconducting (S) films. The presence of magnetic doping (black spots) induces electric dipole transitions between the ABSs localized in the weak link (inset), enabling optical control of the qubit via coupling with an electromagnetic radiation.

References

[1] N. M. Chtchelkatchev and Y. V. Nazarov, "Andreev quantum dots for spin manipulation", Phys. Rev. Lett. 90, 226806 (2003).
[2] C. Padurariu and Y. V. Nazarov, "Theoretical proposal for superconducting spin qubits", Phys. Rev. B 81, 144519 (2010).
[3] M. Hays, V. Fatemi, D. Bouman, J. Cerrillo, S. Diamond, K. Serniak, T. Connolly, P. Krogstrup, J. Nygård, A. L. Yeyati, A. Geresdi, and M. H. Devoret, "Coherent manipulation of an Andreev spin qubit", Science 373, 430 (2021).
[4] M. Pita-Vidal, A. Bargerbos, R. Zˇitko, L. Splitthoff, L. Grünhaupt, J. Wesdorp, Y. Liu, L. Kouwenhoven, R. Aguado, B. Heck, A. Kou, and C. Andersen, "Direct manipulation of a superconducting spin qubit strongly coupled to a transmon qubit", Nature Physics 19, 1 (2023).
[5] E.Latini, F.Rossi, F. Dolcini, "Andreev spin qubits based on the helical edge states of magnetically doped two-dimensional topological insulators", ArXiv: 2601.22226