Quantum computing with nuclear spin qudits

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In the standard paradigm of quantum computing, information is encoded in qubits, i.e. two-dimensional quantum systems. However, the power of quantum computing only becomes apparent when combining and entangling many qubits to form non-classical resource states and error-correctable logical qubits. An alternative paradigm makes use of intrinsically high-dimensional systems, i.e. qu*d*its, where nonclassical states and logical qubits can be encoded and manipulated within a single physical object. Here I will present breakthrough results on the manipulation of a single ^{123}Sb nuclear spin qudit in silicon. Its spin $I = 7/2$ yields a $d = 8$ dimensional Hilbert space. This dimension is sufficient to encode a logical qubit able to correct X, Y and Z errors [1], or use the spin equivalent of Schrödinger cat codes to correct up to three phase-flip errors [2].

We have demonstrated the creation and manipulation of Schrödinger cat states of a ^{123}Sb nucleus, and applied a bespoke tomography protocol to reconstruct the density matrix of the system, and plot its Wigner function. We introduced a novel method for universal control of a high spin, comprising covariant *SU(2)* rotations using a 7-frequency drive, plus virtual-SNAP operations obtained by shifting the phase of the internal clocks of the FPGA that defined a generalized rotating frame (Figure 1). The Wigner function reveals parity oscillations with contrast up to 0.982(5).

Beside quantum information, this system has a wide range of application in foundations of quantum mechanics. For example, we show that it is possible to certify the quantumness of certain states by simply monitoring the uniform spin precession at regular intervals [4]

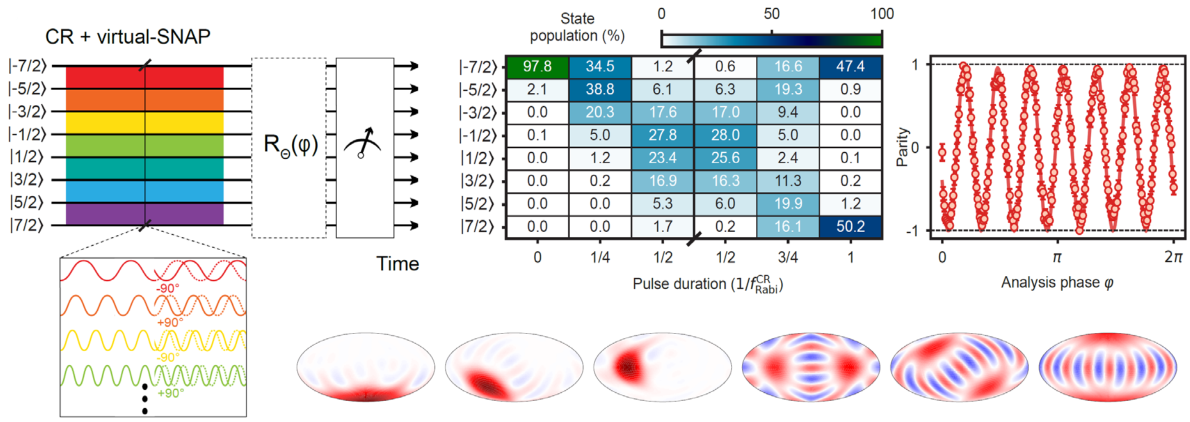

Figure 1, Creation of a Schrödinger cat state of a single ^{123}Sb nuclear spin using covariant SU(2) rotations and virtual-SNAP gates. The Wigner tomography shows the state evolution at each step.

[1] J. A. Gross, *Designing Codes around Interactions: The Case of a Spin*, Phys. Rev. Lett. 127, 010504 (2021)
[2] J. A. Gross et al., *Hardware-efficient error-correcting codes for large nuclear spins*, Phys. Rev. Appl. 22, 014006 (2024)
[3] X. Yu et al., *Creation and manipulation of Schrödinger cat states of a nuclear spin qudit in silicon*, arXiv:2405.15494 (2024)
[4] L.H. Zaw et al., *Detecting quantumness in uniform precessions*, Phys. Rev. A 106, 032222 (2022)