Probability amplitudes with `QD_SIM`

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The evolution of qubits using simulated quantum dots is performed in the laboratory frame. The final results will also include effects arising from the natural frequencies of the qubits, that will only be apparent in the returned probability amplitudes. We will discuss the origin of these effects, and how to find alternatives if full system characterization is desired.

I. INTRODUCTION

Qubits are quantum mechanical systems with two distinct states, typically labeled $|0\rangle$ and $|1\rangle$ [1, 2]. Abstract qubits are simple systems with only two isolated levels. However, practical quantum systems are never quite as simple, with careful consideration required for selection of a suitable system to form a qubit [3]. These requirements and the thought process behind the selection of some currently favored types of qubits were reviewed by Ladd *et al.* [4]. One important fact common to all of these qubits is the presence of a characteristic resonance frequency or natural frequency. The frequency usually refers to the energy difference (expressed as a frequency) between the qubit levels (computational states) of the quantum system being considered for digital gate-based quantum computing. Resonance frequencies for most types of qubits are 1 GHz to 30 GHz, though there are exceptions with much higher or lower frequencies.

II. SIMULATION OF QUBITS

Simulation of quantum systems is a field of great importance [5]. In quantum computing, there are benefits in accurately simulating quantum systems for the purpose of evaluating their strengths and weaknesses for use as qubits. Simulations help drive design decisions on the critical characteristics for physical realizations [6]. Though there are many ways of performing quantum simulations, here we focus on Schrödinger evolution for simulating quantum dot qubits. This quantum dot simulator (`QD_SIM`) is used as the realistic qubit simulation backend for Version 1.0 of the Intel Quantum SDK [6, 7].

III. ROTATING VS. LABORATORY FRAME

Typically, if time dependence of the system can be set aside, simulation of quantum systems is convenient and fast. For certain quantum systems, it is possible to craft unitary transformations to analytically discard the overhead due to the resonance frequency of each qubit [2, 8, 9]. This is typically referred to as moving into the *rotating frame* of the qubit. This terminology is apt since the qubit is always precessing and incrementing its phase around the z-axis at a rate given by its resonance frequency. A further analytical approximation, known as the *rotating wave approximation* [10], is usually required to make the time-dependence fully transparent. These transformations and approximations usually have the effect of drastically reducing the burden on simulation resources, since evolution will then happen at kHz or MHz scales instead of GHz scales.

In the case of these simulated quantum dots [6], we are not in the rotating frame, nor using the rotating wave approximation. A future version of the Intel Quantum SDK should support these techniques. Currently, the evolution of the coupled multi-quantum-dot system (faithful to Intel's quantum hardware) is performed in the *laboratory frame*. The laboratory frame is the original environment of the quantum system, where the natural frequencies of the qubits are fully visible. This also means that the qubits are constantly accumulating z-phases as is the case for real qubits.

IV. USING `getAmplitudes` WITH `QD_SIM`

The Schrödinger evolution is carried out in a Hilbert space that encompasses several energy levels per quantum dot, to ensure accurate modeling of the interactions. Since `QD_SIM` is performing a full quantum simulation, users have access to the fully evolved state vector (following truncation to the computational subspace) at the end of a simulation. As evolution is happening in the lab frame, the probability amplitude results returned from `FullStateSimulator::getAmplitudes` will include the extra z-phases that were accumulated due to natural precession, and the extra phases will be dependent on the resonance frequencies as well as its full evolution history during algorithm execution. Since this detailed history is currently unavailable to users, the use of the latter function for full state characterization is discouraged.

This further highlights how close the simulations with `QD_SIM` reflect actual quantum dot qubits. With physical qubits it is impossible to obtain actual probability amplitudes after evolution. Just as with physical qubits, techniques such as quantum state tomography [11] should be required to reconstruct the full state when using `QD_SIM`.

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