Abstract

Projective measurement is used as a fundamental axiom in quantum mechanics, even though it is discontinuous and cannot predict which measured operator eigenstate will be observed in which experimental run. The probabilistic Born rule gives it an ensemble interpretation, predicting proportions of various outcomes over many experimental runs. Understanding gradual weak measurements requires replacing this scenario with a dynamical evolution equation for the collapse of the quantum state in individual experimental runs. In this work, I revisit the quantum trajectory framework that models quantum measurement as a continuous nonlinear stochastic process. I describe the ensemble of quantum trajectories as noise fluctuations on top of geodesics that attract the quantum state towards the measured operator eigenstates. In this e_ective theory framework for the ensemble of quantum trajectories, the measurement interaction is specific to each system-apparatus pair—a context necessary for understanding weak measurements. Also in this framework, the constraint to reproduce projective measurement as per the Born rule in the appropriate limit, requires that the magnitudes of the noise and the attraction are precisely related, in a manner reminiscent of the fluctuationdissipation relation. This relation implies that both the noise and the attraction have a common origin in the underlying measurement interaction between the system and the apparatus. I analyse the quantum trajectory ensemble for the scenarios of quantum diffusion and binary quantum jump, and show that the ensemble distribution is completely determined in terms of a single evolution parameter.

I test the trajectory ensemble distribution predicted by the quantum di_usion model against the experimental data for weak measurement of superconducting transmon qubits. There is a good fit between theory and experiment for di_erent initial states and several weak measurement couplings. This test vindicates the continuous stochastic measurement framework for quantum state collapse, where the rate of collapse is a characteristic parameter for each system-apparatus pair and is not a universal constant. Furthermore, it implies that the environment can influence the measurement outcomes only via the apparatus and not directly. These are important clues in construction of a complete theory of quantum measurement.

The framework of weak measurements can also be used to construct quantum error correction protocols that protect a quantum state from external disturbances. Unlike projective measurements, one can extract only partial information about the error syndrome from the encoded state using weak measurements. I construct a feedback protocol that probabilistically corrects the error based on the extracted information. Using numerical simulations of one-qubit error correction codes, I show that the error correction succeeds for a range of the weak measurement strength, where (a) the error rate is below the threshold beyond which multiple errors dominate, and (b) the error rate is less than the rate at which weak measurement extracts information. It is also obvious that error correction with too small a measurement strength should be avoided.