Quantum State Reductions and the Uncertainty Principle

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Measurements are important components in any quantum information processing. According to Bohr and Heisenberg, a measurement was considered to always disturb the measured object with random intervention from the apparatus as described by the uncertainty principle: any measurement of an observable causes a back-action to disturb the conjugate observable. This yields many difficulties in precision measurements such as monitoring free mass position for the purpose of accurate monitoring of a clock [1] or detecting the gravitational wave [2].

However, recent investigations have unveiled this mysterious interventions to show that the back-actions of measurements are not necessarily be random but controllable, as breaching the standard quantum limit for monitoring free mass position [3]. In Ref. [4], the controllability of quantum state reduction is generally characterized as follows. The ensemble after a measurement of an observable can be controlled to be an arbitrary family of states by choosing the object-probe interaction properly. In particular, an explicit Hamiltonian model is constructed to realize a position measuring apparatus that does not disturb the object prepared in a momentum eigenstate just before the measurement.

With rigorous definitions of noise and disturbance, it is also shown that this model disproves the following interpretation of the uncertainty principle: in any position measurement, the position measurement noise $\epsilon(x)$ and the momentum disturbance $\eta(p)$ satisfies the relation $\epsilon(x)\eta(p) \geq \hbar/2$.

The above model can be applied to any conjugate pair of observables. Especially, in applications to optical quadrature measurements, the above model has a better performance than the back-action evading measurements the accuracy of which are always limited by the uncertainty principle. Applications of this model to optical quantum computing will be an interesting subject that deserves future investigations.

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