Enhancing metrology sensitivity by weak measurements

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The counterintuitive ability of weakly coupled probes to amplify measured properties in certain situations has application in both fundamental physics and technology.

Quantum mechanics imposes strict limits on the precision attainable for various sets of measurements. Understanding the fundamental principles of these restrictions enables the realization of metrology schemes that can fully exploit available resources, resulting in significant improvement of both classical and quantum measurements. Quantum photonic resources can be employed for novel metrology schemes based on weak measurements, which allow examination of phenomena previously deemed inaccessible.1

In a weak measurement,2 a system is probed with very low precision without experiencing a significant disturbance. Although the information gained about the measured quantity in a single low-precision trial is limited, averaging over a large number of trials makes it possible to obtain an accurate (so-called weak) value for the property. More specifically, the physical system is prepared in some initial state and eventually post-selected to be in a certain final state. This post-selection causes a probe, weakly coupled to the system, to move to values outside the normal range of the observable of interest due to interference. By selecting a set of less-probable measurement outcomes, weak measurements can result in an amplification of the measured property that can overcome noise in certain cases.3 These weak values have been used to demonstrate fundamental concepts as well as practical applications such as ultrasensitive measurement of beam deflection and photon polarization.4,5 We have employed this weak-measurement technique for various experiments in fundamental physics and technology.

Unlike the premeasurement uncertainty relations for non-commuting variables that have been proven experimentally, another relation postulated by Heisenberg6—one that sets a limit on the precision of measurements resulting in disturbance—was proven to be inaccurate.7 This inaccuracy puts in doubt previously widely accepted limitations of high-precision microscopy, spectroscopy, and other metrology concepts, and changes some of the insights into fundamental quantum physics. Theoretical schemes for testing this precision-disturbance relation, based on quantum information concepts, have been proposed,8 where the

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main issue in the realization of the testing schemes of destructive measurement is addressed by the weak-value approach. The weak measurement scheme requires several quantum gates of variable strength with a common control qubit (quantum bit), which is difficult to implement using conventional techniques due low fidelity of practical quantum gates.

We have demonstrated a realization of Heisenberg’s precision limit violation based on weak-value measurements implemented by a one-way quantum-computing technique with entanglement as the substrate for quantum gates.\(^9\) We have also shown that weak measurements can be used to enhance optical nonlinearities at the single-photon level, offering an improvement in signal-to-noise ratio in the presence of noise with long correlation time. In addition to classical nonlinear optics applications, enhanced optical nonlinearities are especially interesting in the context of quantum computing as they provide the tools to implement deterministic two-qubit gates that are needed to be able to universally implement quantum computation. In our scheme, the single photon goes through a Mach–Zehnder interferometer where it interacts with a probe laser through Kerr nonlinearity (see Figure 1). The effect of weak measurement is that the nonlinearity is enhanced and the phase imposed on the probe is as if there were many photons in the system interferometer.\(^3\)

This technique can also be applied to study systems of fermions such as electrons in atoms or in ‘artificial atoms,’ namely, semiconductor quantum dots with various applications ranging from biomedical imaging to quantum computing. These systems require characterization of the interactions using one particle at a time due to the Pauli exclusion principle. This makes slow technical noise unavoidable, and weak-value amplification may provide a unique solution. This kind of measurement is important in studying quantum dots, where slow noise poses a significant limitation on how well different parameters of the quantum dot can be characterized.

We have proposed the use of weak measurement to study the quantum dot energy-level structure with much higher resolution than with conventional spectroscopy. The detection of the photon resulting from the decay of the biexciton to exciton initializes the system (the spin of the electron). The energy spectrum of the photon emitted during exciton decay provides information about the energy difference of the exciton levels. The next important steps are experimental realization of the single-photon nonlinearity weak measurement to be employed in quantum-computing schemes and of single-quantum-dot weak-measurement-enhanced spectroscopy.

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References