and synapse to network and behavior. The challenge is thus to create links between these different levels and to find simple model preparations (9) appropriate for the particular behavior of interest.

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PHYSICS

Quantum Nondemolition: Probing the Mystery of Quantum Mechanics

Stephen R. Friberg

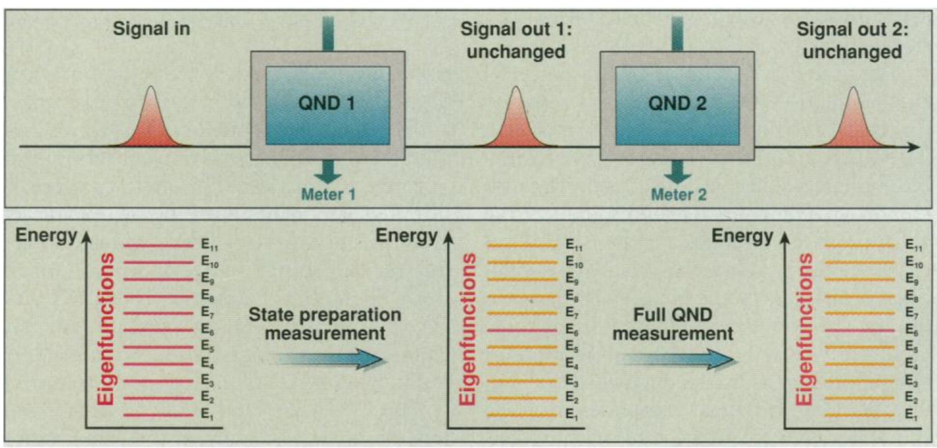
A mystery, many believe, lies at the heart of quantum mechanics. For some, it is the wavelike description of particles or the Heisenberg uncertainty principle. These descriptions, however, have counterparts in classical optics and are rather easily pictured. For others, it is the process of measurement. Our choice of measurement strategies, for example, determines whether quanta act as particles or waves. Suppose we set up a double-slit experiment and slowly send through quanta; they interfere with themselves like waves, building up a spread-out modulated interference pattern. But as we watch, the pattern builds up randomly, one quantum at a time, like particles. Nature, we are forced to confront, is intrinsically random at a fundamental level.

Recent experimental advances in quantum optics allow observation of this and other quantum measurement mysteries in a controlled laboratory environment. One important new technique is the quantum nondemolition (QND) measurement, which allows observation of the quantum measurement process in detail if losses are small. Usually the measurement is done by a nonlinear interaction that writes information from the measured "signal" to a "probe" (or meter), entangling the signal and probe at a quantum mechanical level. Reading out the probe in the usual manner (by converting it to a macroscopic classical signal) gives information about the signal without destroying it.

Current interest in QND stems from efforts by Braginsky and co-workers to enhance the sensitivity of gravitational wave antennas (*1*). The idea, however, is traceable back to "gedanken" experiments (thought experiments) in the pioneering days of quantum mechanics. Braginsky showed that the small signals caused by gravitational waves impinging on a gravitational wave antenna could be measured without the introduction of "back-action" noise, which could wash out subsequent read-outs.

At first, such back-action evasion measurements seemed to violate the Heisenberg uncertainty principle, which stipulates that a measurement always introduces noise. However, as quantum mechanical variables are invariably paired with conjugate variables (say, position with momentum), back-action evasion measurements are possible if the noise of measurement can be made to affect only the conjugate variable. This prospect implied that a gravitational wave antenna could make measurements with accuracies much better than the standard quantum limit of classical-like oscillator systems. Since this realization, there have been continual efforts to implement QND for gravitational wave detection (*2*). However, it is in quantum optics that QND measurements have been most vigorously pursued (*3*).

QND measurements can be made in two ways: single measurements that explore different interaction geometries, and double measurements that test repeatability. The state of the art for a single measurement is an elegant experiment by Roch, Grangier, and co-workers at the Institut d'Optique in Orsay, France (*4*). Using the large optical $\chi^{(3)}$ nonlinearity of cold rubidium atoms in a magneto-optical trap, these researchers achieved sensitive, back-action–evading, low-loss intensity measurements of a 15-μW signal beam by changing the phase of a 0.25-μW meter beam. If the signal is slightly detuned from the 795-nm resonance wavelength of ^{87}Rb, absorption is low. At the same time, it "depumps" the atoms to their ground state, changing the index of refraction



Double quantum nondemolition measurement. This measurement is accompanied by corresponding changes in the quantum state of the measured signal. A typical input signal is in a quantum mechanical superposition of eigenstates E_1 through E_{11} (red lines, lower left). The first back-action evasion measurement QND 1, if ideally strong, collapses the wave function to a single eigenstate, E_6 in this case (red line, lower center). If the state is measured again by QND 2, the eigenstate should be unchanged, as in the lower right. The readouts of meter 1 and meter 2 should be identical and correspond to the eigenstate after the measurement.

The author is in the Basic Research Laboratories, Nippon Telegraph and Telephone Corporation, Atsugi-shi, Kanagawa 243-01, Japan. E-mail: friberg@will.brl.ntt.co.jp

seen by the slightly differently detuned meter beam. This change causes the phase of the meter beam to track the signal beam intensity. Measuring the phase with the help of a homodyne detection system determines the signal beam intensity with excellent fidelity. Signal beam losses were 10%, no perceptible noise was introduced into the signal beam, and correlation measurements showed the meter phase and signal intensity to be strongly quantum correlated after the measurement.

Double QND measurements have recently been carried out by Bruckmeier, Hansen, and Schiller, working at the University of Constance in Germany (5), and by Bencheikh, Levenson, and co-workers at France Telecom (6). Both groups made their first measurements with optical parametric amplifiers constructed from frequency-doubling crystals. For their second measurement, the German group used a 50/50 beam splitter with squeezed light incident on the normally unused input port, whereas the French group used a second optical parametric amplifier. Both experiments showed each of the two successive back-action evasion measurements to give results quantum-correlated with the signal. Bruckmeier and co-workers further showed that the two successive measurements together improved the accuracy with which the signal could be known.

Important to an understanding of these and other QND measurements is the idea of quantum state preparation. Consider a typical signal to be measured: invariably, it will be in a quantum mechanical superposition of eigenstates of the observable to be measured. A measurement then selects out one of the eigenstates with a probability determined by the probability amplitude (assuming nondegenerate eigenstates). Usually, the measurement "demolishes" the wave function: A photodetector, for example, absorbs the light it measures. A QND measurement, if ideally strong, also selects out an eigenstate but leaves the wave function intact (this is sometimes described as the collapse of the wave function). If the signal is measured again, quantum measurement theory postulates that it will be in the same eigenstate. Therefore, QND measurements neither demolish nor change a quantum eigenstate. This property implies that two measurements are necessary to demonstrate QND: the first to prepare an eigenstate, and the second to verify its continued existence (see figure). Bruckmeier and co-workers have demonstrated a two-step quantum state preparation process that cumulatively narrows the distribution of final states, a weak version of QND in agreement with the postulates of quantum measurement theory.

Clearly, stronger QND measurements are desirable. Other aspects could be improved as well. For example, the measurements by Bruckmeier *et al.* were done with continuous waves, hard to define in simple quantum mechanical terms. Better from this standpoint are the results of the two French groups, which measure the properties of optical pulses. Better still would be optical solitons, quantum objects with well-defined particle and optical properties (7). A group at NTT Basic Research Labs in Japan, recently joined by a group at the University of Erlangen in Germany, has been pursuing this option, which allows consecutive photon number measurements of solitons in single optical fibers with very low loss (8). These measurements, however, all have the same failing: The number of quanta in the signals is large, typically 10^5 or more. Therefore, they lack conformity with the textbook criteria for observing quantum effects, namely that the number of quanta be small and that level spacings between eigenstates be readily discernible.

Resolution of these problems may come from QND experiments soon to be undertaken in low-temperature, high-quality factor microwave cavities by Brune, Haroche, and co-workers at l'Ecole Normale Superièure in Paris (9). Many ingredients for a QND measurement of one or a few quanta are already in place and tested: a cavity that can hold photons long enough for consecutive measurements, proven experimental techniques for probing the fields in the cavity by sending through single atoms and measuring their excitation afterwards, and proven capabilities for entangling the state of successive atoms in the cavity. Successful QND measurements with this apparatus could show both the collapse of superpositions of eigenstates to a single eigenstate and repeated observations of that eigenstate. Should this prove feasible, sensitive explorations of the fundamental postulates of quantum measurement theory will have taken, might we say, a quantum jump. Maybe the mystery at the heart of quantum mechanics will come to be seen as commonplace.

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