Experimental Quantum Measurement: New Techniques and New Applications

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Abstract: Quantum information science has reinvigorated the study of quantum measurement, and created a new sense of urgency. I present several classes of "measurement" and discuss their applications, their practical feasibility, and some outstanding theoretical issues.

OCIS Codes: (270.5570) Quantum detectors; (020.7010) Trapping

Recent years have seen great strides made in the control of quantum systems, leading in particular to the hope that it may be possible to harness their power for quantum information processing. However, continued progress requires that we develop new techniques to characterise the quantum systems we manipulate, particularly since the soft underbelly of quantum computing is quantum error correction, which is known to be theoretically possible (and has been experimentally demonstrated under controlled circumstances), but which will need to be accurately tailored to the behaviour of real-world systems. This realisation has led to a renaissance in the study of "quantum tomography," the complete characterisation of both states and processes, but now that this characterisation is a matter of necessity rather than merely of curiosity, its practical intractability has also motivated researchers to investigate "incomplete" ways of characterising systems. At the same time, motivated by applications to quantum communications protocols, physicists have begun moving beyond "textbook" quantum measurements and demonstrating that for certain tasks, "generalised" measurements may be much more powerful. In parallel, it has been recognised that measurement, as the paradigmatic "non-unitary" operation in quantum mechanics, has features which may allow it to be used to engineer interactions which do not exist in pure Hamiltonian evolution. The study of such "post-selected" quantum evolution is fraught with paradoxes, and a novel formalism known as "weak measurement" helps resolve some of these – naturally, only at the cost of creating new ones.

In this talk, I will survey a few of these aspects of quantum measurement from an experimental perspective. I describe our experiments characterising the quantum state of ultracold atoms, both in terms of density matrices and in terms of Wigner functions. I go on to discuss an extension of quantum state tomography which we have developed for characterising systems of experimentally indistinguishable photons, in cases where it is possible that "inaccessible" information exists which could distinguish them. I will show that there are tasks which generalised quantum measurements (POVMs) can accomplish more than twice as effectively as standard projective measurements. Finally, I will discuss recent applications of Aharonov *et al.*'s formalism of "weak measurements" to studying a number of controversies and paradoxes related to post-selection.

We trap ^{85}Rb atoms in a periodic potential (an optical lattice formed by a standing wave of far-detuned light), sufficiently shallow that in each 1-μm-wide well, the atom only has two possible bound states. By using a combination of adiabatic release, spatial shifts, and time delays, we are able to completely characterise the state of the ensemble. Figure 1 shows an approximate Wigner function extracted for a situation where atoms are prepared mostly in the excited state [1]. The preparation was accomplished by using a pulse sequence originally discovered by using process tomography to optimize a "pulse echo" for quantum-error-correction purposes [2]. The large negative value at the origin indicates the nonclassical nature of this state.

Recently, we demonstrated experimental preparation of a "maximally path-entangled" state of three photons[3], exciting for its potential applications to interferometry. Combining the three photons into a single state requires carefully engineering them to be indistinguishable, and characterisation of the state's imperfection must therefore focus on residual distinguishing information. This information corrupts the state even if the experimenter does not have the ability to measure it directly, however. We show how state tomography must be generalized in order to deal with such systems, and experimentally characterize multi-photon systems.

A common problem in quantum information is that of "unambiguous non-orthogonal state discrimination," in which the goal is to determine which of two or more pre-specified non-orthogonal states one has been given, with certainty. While quantum mechanics denies us the possibility of achieving this goal 100% of the time, it is clear upon some thought that it can be accomplished a fraction of the time. Surprisingly, one cannot achieve the optimal

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efficiency if one limits oneself to textbook-style projective measurements; a broader class of measurement known as POVMs proves to be essential. We demonstrate in an experiment that by using such measurements, we can increase the success rate of unambiguous state discrimination by more than a factor of two.

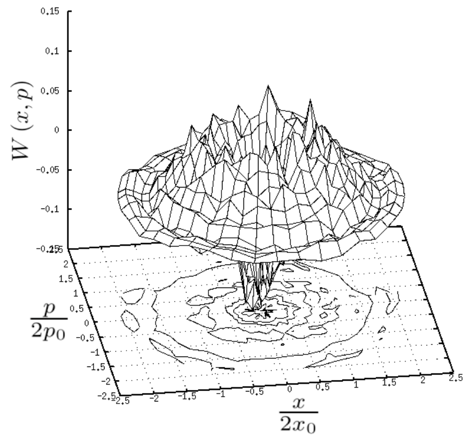

Fig. 1: The Wigner function for an ensemble of atoms trapped in the excited state of optical-lattice wells demonstrates the nonclassicality of this state.

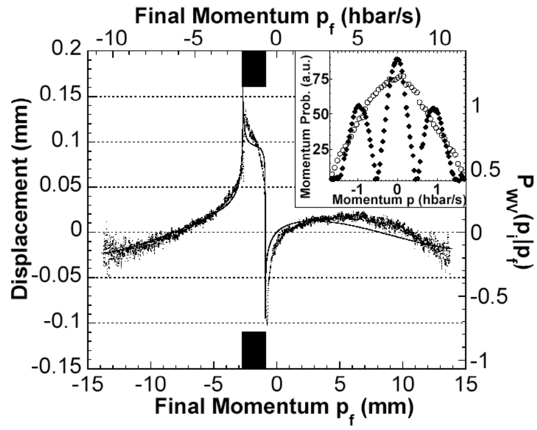

Fig. 2: A weak measurement of the probability distribution for the momentum of a photon before it undergoes a which-path measurement, conditioned *on a particular final momentum, constitutes a measurement of momentum disturbance.*

Like the proposals for linear-optical quantum computation, the above effects rely on post-selecting a subensemble. Describing the quantum state of a system defined both by state preparation and by post-selection is a curious problem for those who think about the foundations of quantum mechanics. After all, preparation alone is sufficient to determine the state vector, which is supposed to be a complete description of the state. This leads to a number of seeming "retrodiction paradoxes," such as the famous one due to Hardy [4], based on interaction-free measurement. In this paradox, the detection of two particles at appropriate detectors leads one to infer that both particles were in a certain interaction region at the same time. However, the design of the experiment is such that two particles meeting in that region are guaranteed to annihilate, and this contradicts the fact that they are detected.

One formalism which allows one to rigorously describe the state of a post-selected subensemble is Aharonov *et al.*'s "weak measurement"formalism [5]. We have implemented Hardy's paradox experimentally using a two-photon switch [6] to play the role of the "annihilation" process, and carried out weak measurement on the joint state of the photons [7]. We confirm the theoretical predictions [8], which in a certain sense resolve the paradox. At the same time, we confirm that a weakly measured probability may yield a negtive value, which is clearly problematic, but in fact essential to the resolution of the paradox. We have also used weak measurements to carry out Wiseman's proposal [9] for addressing the long debate over the role of momentum disturbances in complementarity experiments [10]. While it is common knowledge that measurement of which path a particle takes in an interferometer destroys the interference pattern, one camp has held that this may always be attributed to a momentum disturbance introduced by the which-path measurement, while another has argued that certain which-path measurements may leave the momentum undisturbed. Of course, it is difficult to determine whether or not the momentum of an individual particle has been disturbed, since it does not begin in a momentum eigenstate. Weak measurement offers us a way to probe the probability that a given particle (defined by preparation and by selection of its final momentum) had a given initial momentum; see Fig. 2. In this way, for the first time we are able to directly observe the momentum disturbance due to which-path measurements. We find that due to the non-positive-definite character of the measured distribution, it is possible to reconcile the seemingly contradictory viewpoints.

[1] J.F. Kanem, S. Maneshi, S.H. Myrskog, and A.M. Steinberg, J. Opt. B. **7**, S705 (2005)
[2] S.H. Myrskog, J.K. Fox, M.W. Mitchell, and A.M. Steinberg, Phys. Rev. A **72**, 013615 (2005)
[3] P. Kok, H. Lee, and J.P. Dowling, Phys. Rev. A **65**, 052104 (2002); J. Fiurasek, Phys. Rev. A **65**, 053818 (2002); M.W. Mitchell, J.S. Lundeen, and A.M. Steinberg, Nature **429**, 161 (2004)
[4] L. Hardy, Phys. Rev. Lett. **68**, 2981 (1992)
[5] Y. Aharonov, D.Z. Albert, and L. Vaidman, Phys. Rev. Lett. **60**, 1351 (1988)
[6] K.J. Resch, J.S. Lundeen, and A.M. Steinberg, Phys. Rev. Lett. **87**, 123603 (2001)
[7] K.J. Resch and A.M. Steinberg, Phys. Rev. Lett. **92**, 130402 (2004)
[8] Y. Aharonov, A. Botero, S. Popescu, B. Reznik, and J. Tollaksen, Phys. Lett. A **301**, 130 (2002)
[9] H.M. Wiseman, Phys. Lett. A **311**, 285 (2003)
[10] M.O. Scully, B.-G. Englert, and H. Walther, Nature **351**, 111 (91); E.P. Storey, S.M. Tan, M.J. Collett, and D.F. Walls, Nature **367**, 626 (94)