addition to the tracking detectors, the electromagnetic calorimeter (of which only 10% will be ready for initial RHIC operation) will measure the transverse energy of events, and measure photons, particles, and jets having high transverse momentum. The STAR collaboration has emphasized detection of the global features of the hadrons and jets as the signatures for quark–gluon plasma formation. A ring-imaging Čerenkov detector for a limited solid angle is being installed in STAR as a joint venture with the ALICE collaboration at CERN, which is contributing one of its large-area prototypes.

PHENIX (which stands for pioneering high energy new ion experiment) is intended to detect leptons, photons, and hadrons in selected solid angles with a high rate capability, which will provide a broad range of quark–gluon plasma indicators. PHENIX spokesperson William Zajc (Columbia University) explains that with the detector's four spectrometers, the team will be able to detect both e^+e^- and $\mu^+\mu^-$ pairs. By detecting thermal photons from $q\bar{q}$ annihilation, one can study the evolution of the radiation produced in the collision, analogous to detecting x rays from a conventional plasma. The emphasis on lepton pairs also gives PHENIX excellent sensitivity to the rate of production of J/ψ particles; currently a drop in this rate is the leading "unambiguous" candidate to signal the formation of a quark–gluon plasma. A glimpse of such suppression was found in 1987 at the CERN SPS, but it hasn't been clear that's evidence for quark–gluon plasma formation. The decay of the J/ψ into either e^+e^- or $\mu^+\mu^-$ pairs has completely different experimental constraints, which are reflected in the vastly different designs of the various spectrometers. The central region of PHENIX has an axial magnetic field and two detector arms that contain, among other items, ring imaging Čerenkov and time-of-flight counters, and electromagnetic calorimeters. Additional, simpler arms will detect muons.

The Phobos detector is designed to examine a very large number of collisions (10^9 per year) because the Phobos experimenters believe interesting collisions might be rare. For each collision, Phobos will give a global picture of what happened, and detailed information about a small subset of the fragments ejected from the very central hottest collision regions (by means of two high-precision multiparticle spectrometers). Phobos is able to detect particles with very low transverse momentum. These slower particles streaming transverse to the beam direction from the collision region are expected to be especially sensitive to the larger coherent effects that would be indicative of a phase change, according to Phobos spokesperson Wit Busza (MIT). As Phobos experimenter Russell Betts (Argonne National Laboratory) explains, "As the quark–gluon plasma cools, the quarks coalesce, forming mostly mesons. The number of particles that come out, their angles, their type, and momentum spectrum can be used to determine the thermodynamic properties of the plasma."

BRAHMS (broad range hadron magnetic spectrometers) will use two movable aperture spectrometers to identify and study charged hadrons emerging over a 90° range, including very forward angles (0.8 millisteradian). Says spokesman Flemming Videbaek (Brookhaven), "We'll detect identified charged hadrons over a wide rapidity and momentum range."

Computing will also involve a major effort at RHIC. Comparing RHIC's planned capability with that of Fermilab's Advanced Computer Program four years ago, then the biggest computing effort in particle physics (see the article by Joel Butler and David Quarrie, PHYSICS TODAY, October 1996, page 50), Brookhaven's Bruce Gibbard says the data volumes and transfer rates will be about 15 times higher and the CPU capacity is about 100 times greater. Two-thirds of the computing costs at RHIC will be spent on robotic storage.

GLORIA B. LUBKIN

Single Microwave Photons Can Be Measured Nondestructively

> Individual atoms passing through a microwave cavity can sense whether it contains zero photons or one—and leave the photon number unchanged.

A deeply held tenet of quantum mechanics, dating back to its infancy, is that one can't measure a system without disturbing it. That doesn't mean, however, that one can't influence the form such a disturbance takes. Over the past 25 years, researchers have been developing schemes for controlling the effects of measurements so that the properties of interest emerge unscathed. Now a group led by Serge Haroche at the Ecole Normale Supérieure (ENS) in Paris has demonstrated such techniques at the most fundamental level—detecting the presence of a single photon in a nondestructive way.[1]

Quantum nondemolition

The Heisenberg uncertainty principle fundamentally expresses the effect of a measurement on a quantum system: The better we know one observable of a system, such as its position, the less we can know about other, noncommuting observables, such as its momentum. But the dispersion that a measurement imparts to noncommuting observables can later influence the observable we care about, producing so-called back action. Thus, although we can measure a particle's position at one time, uncertainty in its momentum prevents us from saying anything about its exact position at a later time.

Quantum nondemolition (QND) provides a way around such back action. The idea of QND measurements—developed in the 1970s by Vladimir Braginsky (Moscow State University), Kip Thorne (Caltech), Carlton Caves (University of New Mexico), and others, originally in the context of gravitational-wave detectors—is to configure the measurement around an observable that is totally decoupled from the other observables. In this way, the back action in the other observables doesn't interfere with the measured quantity, whose value can be preserved throughout successive measurements.[2,3]

QND measurement ideas started being applied to the field of quantum optics in the mid-1980s (for a review, see ref. 3). Researchers have been able to determine the intensity of lasers without absorbing any of the light: In a nonlinear medium, the interaction between the laser to be measured and another laser, which serves as the "meter," can produce a phase shift in the meter beam that can be detected using interferometry. Those experiments involved microwatts to milliwatts of power, corresponding to macroscopic numbers of photons. In contrast, the ENS group has measured whether just one photon is present in their cavity.

Detecting a single photon

Unlike photomultipliers and other devices that measure light by absorbing photons, a QND measurement leaves the photon number unchanged. To accomplish that at the single-photon level, the ENS researchers probed the light field in their microwave cavity using a single rubidium atom, combining cavity quantum electrodynamics (QED) with atom interferometry. A similar setup had previously been used by the group in studying quantum decoherence (see the article by Haroche in PHYSICS TODAY, July 1998, page 36).

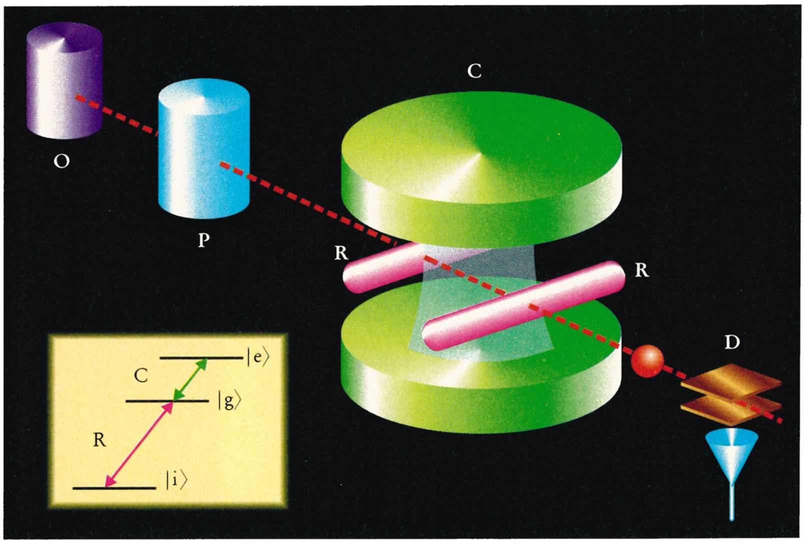
The cavity consists of two spherical, superconducting niobium mirrors surrounded by a cylindrical ring. Cooled to about 1 K, it has a Q of about 3×10^8, with a corresponding photon lifetime of 1 ms—sufficiently long for repeated measurements.

The cavity supports a transverse field that is resonant with the transition between two circular Rydberg levels $|g\rangle$ and $|e\rangle$ of the rubidium atom (see the figure at right). Circular Rydberg levels (with $l = |m| = n - 1$) are long-lived and strongly couple to microwave photons, making atoms in such states ideal for the job of "photon number meters." When an atom originally in the lower resonant level $|g\rangle$ traverses the cavity and there is a photon present, the atom undergoes quantum Rabi oscillations between the two levels, alternately absorbing and emitting the photon.

Rubidium atoms are prepared using an optically pumped thermal beam of atoms. The researchers excite atoms into circular Rydberg states at controllable times, and the process typically produces either one atom or none in the appropriate state.

Once prepared, the rubidium atoms pass through the microwave cavity. By carefully controlling the atom velocity and tuning the energy levels using an electric field applied to the cavity mirrors, the researchers can adjust the atom–field interaction time to make an atom in $|g\rangle$ undergo one full cycle of photon absorption and emission—a so-called 2π pulse (analogous, in the classical picture of magnetic resonance, to an up spin rotating 360°, through the down position and back up). Although the atom ends up back in level $|g\rangle$, its wavefunction has picked up a minus sign (a phase shift of π). "It's the same minus sign you get with a 2π rotation in space of a spin-½ system," explains Jean-Michel Raimond, of the ENS team.

This phase shift can be detected with atom interferometry techniques using a third level of the atom, $|i\rangle$, as a reference. Instead of sending in an atom in state $|g\rangle$, the researchers prepare the atom in a superposition of $|g\rangle$ and $|i\rangle$ using a pulsed auxiliary field tuned near that transition frequency. Following the atom–field interaction, the two levels are recombined with another pulse and the atom goes through a state-sensitive detector. When there is one photon in the cavity, the atom's π phase shift from the quantum Rabi oscillation flips the probabilities of detecting the atom in states $|i\rangle$ and $|g\rangle$. Thus, the probability of detecting the atom in $|i\rangle$ is correlated to the number of photons.



SINGLE-PHOTON QUANTUM NONDEMOLITION MEASUREMENTS use individual atoms to detect the presence of a single microwave photon in a microwave cavity. Rubidium atoms from an oven (O) are prepared (P) in circular Rydberg states before entering the cavity (C), which consists of two superconducting niobium mirrors surrounded by a cylindrical ring (not shown). A pulsed auxiliary field (R) produces a superposition of atomic states for atom interferometry. A single photon in the cavity field produces a phase shift in the atom's wavefunction that is revealed in the atomic state found by the detector (D). The photon itself is not absorbed but remains in the cavity. The inset shows the three atomic levels used in the experiment.

Complete Rabi cycles like the one used in the ENS experiment leave the photon number unchanged. In their experiments on one-atom masers ("micromasers"), Herbert Walther's group (the Max Planck Institute for Quantum Optics in Garching and the University of Munich) has observed evidence of such cycles for a variety of photon numbers as they vary the interaction time between rubidium Rydberg atoms and a high-Q microwave cavity.[4] When the interaction time corresponds to an integer number of complete Rabi cycles, the statistics of the states of the atoms leaving the cavity reveal that the cavity photon number remains unchanged—it is "trapped."

Measuring a photon twice

The measurement scheme used by the ENS group is not perfect: If the cavity starts with an equal probability of containing zero photons or one and the experimenters detect one, the actual probability that there is one photon in the cavity is about 80%. Sources of imperfection arise from the atom–field interaction—including finite photon lifetime in the cavity and interaction times that are slightly off—and from the detection of the final states of the atoms.

But is the measurement truly nondemolition? To find out, the researchers examined a second atom that traversed the cavity following the initial measurement. For the second atom, the researchers cut the interaction time with the field in half, so that the atom underwent a π pulse instead of a 2π pulse and absorbed the photon if present. Accounting for the known imperfections, the two measurements of the photon number were in agreement—the initial measurement lived up to its QND billing.

The measurement employed by the ENS team relies critically on the 2π pulse—the complete cycle of photon absorption and emission—that is produced when there is one photon in the cavity. For higher photon numbers, the oscillation frequency is higher (scaling with the square root of the photon number), and the correlation between the photon number and the final state of the probing atom is lost. Thus this scheme works only for a photon number of 0 or 1—it is truly a *single photon* QND measurement. Going to higher photon numbers requires a nonresonant, dispersive measurement, rather than a resonant, absorptive one, says Haroche.

A building block

In addition to providing insights into fundamental quantum measurements,

Long X-Ray Observation Probes Black Hole Infall

What do you get if you look at an active galaxy for five days? The answer, in the form of this lopsided iron emission line, is compelling evidence of matter whirling closely and relativistically around a supermassive black hole. And, if you're willing to bet on a 3-sigma result, the small dip just below 6 keV provides the first tentative evidence of matter actually falling into a black hole.

For the past 20 years or so, astronomers have assumed that the luminous, variable cores of certain galaxies—known as active galactic nuclei (AGNs)—are powered by the accretion of matter into a supermassive black hole. Also part of the AGN paradigm is a rotating disk-shaped reservoir of matter whose gravitational energy ultimately fuels the AGN. (See Roger Blandford and Neil Gehrels's article, "Revisiting the Black Hole," PHYSICS TODAY, June 1999, page 40.)

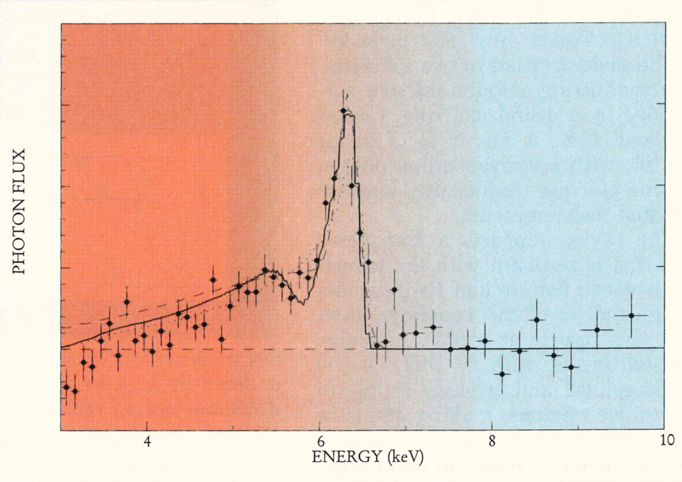
Evidence for the presence of disks in AGNs comes partly from iron emission lines, whose energy (6.4 keV) and relatively high luminosity are consistent with material fluorescing in a large region, assumed to be a disk, around the hole and illuminated by the central x-ray source. But evidence for disk–hole interaction had been circumstantial until the Advanced Satellite for Cosmology and Astrophysics (ASCA), a Japanese–US x-ray astronomy satellite, observed a distorted iron emission line in the AGN known as MCG-6-30-15.[1] These distortions were consistent with the combination of two effects that arise from the black hole's intense gravitational field—gravitational redshift and the relativistic Doppler shift.

Now, by looking with ASCA at a brighter target (NGC 3516) for longer, Paul Nandra and his colleagues have probed an AGN's inner disk in unprecedented detail.[2] They've found, for example, that the shape of NGC 3516's emission line can be plausibly modeled in terms of a rotating black hole. (A nonrotating black hole is also consistent with the data, but some of the parameters of the corresponding model are contrary to astrophysical expectations.)

Thanks to the length of the observation, Nandra's team, which is based at NASA's Goddard Space Flight Center in Greenbelt, Maryland, has also been able to study how the continuum, the line core, and the redshifted and blueshifted wings of the line vary in time. The continuum and core seem to be correlated with each other, as do the blue and red wing. Curiously for a line supposed to originate in reprocessed emission, the line wings vary more than the continuum—evidence, suggests Nandra, that another process plays a part.

One of the most intriguing—and tantalizing—aspects of the NGC 3516 observation is the 3-sigma detection of an absorption feature at 5.89 keV (that's the small depression to the left of the main peak). It could arise from matter being caught in the act of falling into the black hole.

As it approaches the hole, a blob or sheet of matter could find itself between ASCA and the x-ray source, absorbing some



of the x rays that would otherwise reach ASCA's detectors. Resonant absorption would result in a redshifted, broadened absorption line—redshifted because of the gravitational redshift, and broadened because of tidal effects.

Although the data are consistent with this interpretation, other explanations are conceivable. For instance, gravitational redshift could be responsible without the need to invoke infall. But, more important, the absorption line itself is of only marginal statistical significance and, given the modest resolution of ASCA's detectors, possibly unresolved.

With hopes of discovering more about black holes and their environments, Nandra and other AGN watchers avidly anticipate the launches in 2000 of the European Space Agency's XMM mission, which will collect substantially more photons than ASCA, and of the Japanese–US Astro-E, which will provide significantly better energy resolution.

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the ENS experiment shows potential for quantum information processing. One way to get either zero photons in the cavity or one is to send in an atom in the excited state, but let it interact for a shorter time so that it has only a 50% chance of emitting a photon. If a second atom traverses the cavity for a QND measurement, it becomes entangled with the first atom. Just recently, Haroche tells us, his group has extended this method to entangle a third atom, as well, using a sequence of coherent emission, QND reading, and absorption of zero photons or one.

Because of their necessarily low atom fluxes and limited detector efficiency, however, the ENS researchers had to collect data for 16 hours. One possible alternative in the optical domain has been demonstrated by Jeff Kimble's group (Caltech): They have succeeded in trapping a single atom inside an optical QED cavity in a regime of strong coupling.[5]

With these advances in optical and microwave cavity QED, as well as in ion traps, researchers are learning to make the building blocks for quantum information processing, according to Peter Zoller (University of Innsbruck). "I'm optimistic that in a few years we'll have different systems, in the context of cavity QED as well as ion traps, for implementing quantum logic on the level of five to ten qubits."

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