QUANTUM OPTICS

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WHAT IS QUANTUM OPTICS IN 1999?

Quantum optics has been an active research field for some years. Technological developments drive experiments into new areas. Theorists either attempt to explain the new features, or else develop models for even more exotic ideas. Subfields are now growing, so it's not clear just what to include! In this talk I will:

- Start by focusing on new developments.
- Finish with challenges and unsolved problems.

GROWTH AREAS

- BEC and atom lasers
- Quantum computing/cryptography
- Mesoscopic, nonclassical devices
- Solitons
- High precision measurements
- Tests of quantum mechanics

He ATOMS IN HOLLOW FIBERS

- **Maarten Hoogerland**, et al, at ANU have shown hollow fiber guiding of Helium atoms.
- Previously rubidium atoms had been sent down fibers but alkali atoms are prone to stick along the way.
- The helium atoms flow more smoothly (guided by ”evanescent light” impinging upon the fibers from outside) since they have first been put into a long-lived excited state which is almost impervious to interactions with the walls of the fiber.
- Possible applications include atom interferometers useful for gyroscopes or gravity wave detectors and for atom-laser transmission.

OPTICAL ATOM TRAPS

- **Wolfgang Ketterle** and his colleagues at MIT have developed an all-optical trap which can hold condensate atoms in a number of distinct (hyperfine) internal states.

- The multi-component MIT condensate exhibits behavior not seen in single-component BEC, including domain structures for different hyperfine states ($m=0$ and $m=1$).

- **John Thomas** of Duke has made an optical trap for atomic fermions in lithium-6: - atomic superconductors could be next.

ZERO-POINT MOTION IN A BEC

- **Wolfgang Ketterle** at MIT has measured ”zero-point motion” in a sodium BEC.

- The researchers used a technique known as Bragg scattering.

- Atoms absorb photons at one energy from a laser beam and are stimulated by a second laser to emit a photon at another energy.

- Multiplying this measured momentum spread Δp by the size of the condensate Δx gave an answer of approximately $\hbar/2$–the minimum value allowed by Heisenberg’s uncertainty relation and quantum physics.

A CONTINUOUS ATOM LASER BEAM

- **Theodor Haensch** described a continuous atom laser lasting as long as 100 milliseconds.

- The beam can potentially have a radius of a nanometer, thousands of times narrower than the focus of an optical laser beam.

- The conversion process occurs gradually, with a beam emerging at a slower and more controlled rate than in previous atom- laser demonstrations.

- **Bill Phillips** of NIST developed a Raman atom laser that can produce beams in any direction, not just downwards.

NONLINEAR ATOM OPTICS.

- Four-wave mixing of atom waves, a process in which three matter waves combine to produce a fourth wave while conserving energy and momentum, has been demonstrated by researchers at NIST.

- This experiment provides the first example in atoms of "non-linear optics" effects which are important in laser beams.

- The NIST researchers created three overlapping Bose- Einstein condensates of sodium atoms moving at different velocities relative to one another. The three BECs interfered to create a fourth condensate moving at a different velocity.

BEC JOSEPHSON EFFECT

- **Mark Kasevich** and **Brian Anderson** at Yale have loaded a Bose-Einstein condensate of rubidium atoms (occupying a single quantum state) into an optical lattice.

- With the help of gravity, atoms from one part of the condensate can tunnel to another part by the Josephson effect.

- The spaced-out drops of atoms constitute a pulsed atom laser beam.

2D BEC

- **Safonov** et al have observed a two-dimensional BEC.
- The condensate occurred in hydrogen atoms sitting on top of a layer of liquid helium-4 at a temperature of 120-200 mK .
- Strong magnetic fields force the nuclei and electron spins of the hydrogen atoms to align.
- Explanations for this type of 2D quantum fluid are lacking.

SUPERCHEMISTRY

- **Karen Kheruntsyan** et al, and **Juha Javanainen** have suggested that coherent interactions of BEC, combined with external photo-association lasers, could lead to a form of superchemistry.
- This is the atom optics version of second-harmonic generation, in which molecules are formed coherently via stimulated emission.
- Experiments are now underway at Texas and Connecticut.
- Main problem: Raman photoassociation requires two lasers with a large, stable frequency difference.

QUANTUM SEARCH ENGINE

- **Isaac Chuang** et al (IBM) have experimentally demonstrated the Grover quantum search algorithm.
- This allows researchers to successfully find one of four possible pieces of data in a single computational step.
- They employed a liquid chloroform "NMR" quantum computer, in which the binary digits 0 and 1 are represented by atomic nuclear spins.
- By measuring the response of the collection of molecules, the researchers were then able to deduce the nuclear spins in a single step.

QUANTUM ERROR CORRECTION

- **Raymond Laflamme** et al has demonstrated quantum error correction.
- Aiming radio-frequency pulses at a liquid solution of alanine or trichloroethylene molecules, researchers spread a single bit of quantum information onto three nuclear spins in each molecule.
- Measuring the spins directly would destroy this superposition and force the bit to become a 0 or a 1.
- Using entangled states, they were able to detect and fix errors in a bit's "phase coherence," the phase relationship between the quantum waves corresponding to the 0 and 1 states.

A SINGLE-PHOTON TURNSTILE

- **Yamamoto** et al, have created a device in which the quantization of electrical conductance is used to produce a quantization of photon emission.

- They put together a quantum well containing a single electron (using a "Coulomb blockade" effect) with a quantum well containing a lone hole.

- They cycle the voltage across the whole stack of layers in such a way that the lone electron and lone hole meet, mate, and make a lone photon.

- The resulting device, which operates at mK temperatures, is typically a tiny post some 700 nm tall and with a diameter of 200-1000 nm.

c= 17 METERS/SECOND

- **Lene Hau** has used a BEC with a system of laser beams whose pattern of interference created an effect called electromagnetically induced transparency (EIT), as predicted by **Steve Harris**.

- This allowing light to propagate unabsorbed but at greatly reduced speeds.

- The researchers also observed unprecedentedly large intensity-dependent light transmission.

- Such an extreme nonlinear effect can perhaps be used in a number of opto-electronic components.

SPATIOTEMPORAL SOLITONS

- **Boris Malomed, Hao He,** et al, in a joint UQ/ Technion project *predicted* the existence of spatio-temporal solitons in parametric media.

- **Liu** et al, at Cornell has now reported the experimental formation of optical spatiotemporal solitons.

- Intense femtosecond-duration pulses experience a strong coupling of the interacting fundamental and harmonic waves, which produces solitons that overcome diffraction in one spatial dimension as well as group-velocity dispersion.

- Spatiotemporal solitons are observed both with nearly zero and with large group-velocity mismatch between fundamental and harmonic pulses.

MEASURING THE FREQUENCY OF LIGHT TO NEW LEVELS OF PRECISION

- **Thomas Udem** et al. have shown that a femtosecond laser pulse can be used to measure the frequency of light.

- The researchers have now shown that the very regular spacing of mode-locker peaks can potentially be used to measure differences of at least 20 THz (20,000 GHz) with a precision as high as 3 parts in 10^{17} .

- Locking the wave of interest to the low-frequency end of the femtosecond comb and locking a reference wave to the high-frequency end can determine the frequency difference between the two waves.

SPACE-TIME FOAM?

- **Giovanni Amelino-Camelia** of CERN suggests that the notion that space is like an irregular foam at the smallest of size scales (the Planck scale, 10-35 m) foreseen in current theories, should be detectable with gravity-wave detectors now under construction.

- High-precision instruments like the Laser Interferometer Gravitational Observatory (LIGO), being built to detect the infinitesimal distortions of space caused by a passing gravitational wave, would also be able to probe the fundamental "noise" of the Planck froth.

PARITY NONCONSERVATION (PNC) IN ATOMS

- **Carl Wieman** of the University of Colorado sees PNC transitions in cesium by detecting the fluorescence from 6S atoms boosted into the 7S state.

- A photon, with an angular momentum unit of one, cannot link to S states, but a Z boson can.

- New precision in theoretical calculations of the transitions have progressed to a point where the theory of the electroweak force can be put to the test.

- The Colorado comparison reveals a small but intriguing discrepancy between theory and observation.

ENTANGLEMENT OF THREE PHOTONS

- **Harald Weinfurter** et al has demonstrated GHZ entanglement.

- Sending individual photons through parametric crystals can sometime converted a photon into two pairs of entangled photons. After detecting a "trigger" photon, and interfering two of the three others in a beamsplitter, an entangled state is produced.

- The researchers deduced that this entangled state is the GHZ state.

- Studying a single set of properties in the GHZ particles could verify the predictions of quantum mechanics while contradicting those of local realism.

QUANTUM TELEPORTATION

- **De Martini**, **Anton Zeilinger**, and **Jeff Kimble**, have all independently demonstrated different versions of quantum teleportation.

- The Innsbruck experiment teleported the polarization value of a third, distinct "message photon" to one of the entangled photons.

- The Rome scheme encodes one of the entangled photons with a specific polarization state and transmits this state to the other entangled photon.

- The Caltech scheme extends quantum teleportation from transmitting discrete variables such as polarization to transmitting continuous quadrature variables .

UNSOLVED PROBLEMS

One of the original motivations for the quantum computer, was Feynman's hypothesis that complex quantum dynamical problems - interacting many-body systems - could not be treated exactly with a classical computer, except with an exponentially large cost in memory and time. It was necessary to build a quantum computer.

- Can the hypothesis be resolved definitively?
- Can we prove whether or not factorization is classically soluble?

FUTURE METHODS FOR COMPLEX QUANTUM DYNAMICS

Evidence indicating how classical computers may overcome this problem is provided by the positive-P method for stochastically mapping a quantum problem into a classical problem. This was used in 1987 to successfully calculate squeezing quantum soliton evolution for 10^9 interacting particles, a prediction that was experimentally confirmed.

- Do algorithms exist for classical computation of quantum dynamics?
- Can we build large quantum computers?

UNSOLVED PROBLEMS: BEC

While BEC is observed experimentally, it presents an outstanding challenge to the theorist. Almost all existing analyses of BEC rely on earlier techniques developed by Bogoliubov, Gross and Pitaevskii. However, these do not give much understanding into issues of coherence, needed to understand atom lasers, and nonlinear dynamics.

The BEC is an example of a complex quantum system with strong interactions, a large Hilbert space, and very low dissipation.

- What methods can we develop to deal with this problem?
- Can we test quantum mechanics in a complex environment, with large numbers of massive particles?