Grading Procedure and Optional Extra Credit Writing Assignment:

The grade for the course will be determined with a weighting of 60% for homework and 40% for the midterm. We will assign grades to everyone taking the course for credit based on their total score (possibly weighting some homework assignments differently than others). To these scores we will add the results of the optional extra credit assignment, weighted at an additional 20%. This can only make your grade go up, and no one's grade will go down as a result of others doing the optional extra credit writing.

The assignment: Choose a short research paper, for example from the list below, and write an essay about it, of 1500 to 3000 words (text and captions) with as many figures and tables as you like. The essay should explain in your own words, using the concepts you have learned in the course and elsewhere, the essential ideas of the paper. It should be understandable to someone else who has successfully completed the PHY721.

You may, if you wish, choose to write about a paper that is not on the list, but you must first get approval from the instructors. Send an email with the full literature reference and we will decide if it is acceptable.

We encourage you to consult the referenced contained in the paper you select and any other resources that will help to clarify the paper to you. All of the composition of the essay, however, must be your own. Never copy material from any of the resources you consult, and reference any ideas that you find in those resources.

The essay is due on 19 December, but may be handed in at any time before that. Include a copy of the paper about which you are writing with your essay. You may submit hardcopy or digital.

List of papers:

Science 28 October 2005:
Vol. 310. no. 5748, pp. 648 - 651
Reports

Hanbury Brown Twiss Effect for Ultracold Quantum Gases

M. Schellekens,[1] R. Hoppeler,[1] A. Perrin,[1] J. Viana Gomes,[1,2] D. Boiron,[1] A. Aspect,[1] C. I. Westbrook[1]*

We have studied two-body correlations of atoms in an expanding cloud above and below the Bose-Einstein condensation threshold. The observed correlation function for a thermal cloud shows a bunching behavior, whereas the correlation is flat for a coherent sample. These quantum correlations are the atomic analog of the Hanbury Brown Twiss effect. We observed the effect in three dimensions and studied its dependence on cloud size.

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Science 15 July 2005:
Vol. 309. no. 5733, pp. 454 - 456
Reports

Controlled Single-Photon Emission from a Single Trapped Two-Level Atom

B. Darquié, M. P. A. Jones, J. Dingjan, J. Beugnon, S. Bergamini, Y. Sortais, G. Messin, A. Browaeys,* P. Grangier

By illuminating an individual rubidium atom stored in a tight optical tweezer with short resonant light pulses, we created an efficient triggered source of single photons with a well-defined polarization. The measured intensity correlation of the emitted light pulses exhibits almost perfect antibunching. Such a source of high-rate, fully controlled single-photon pulses has many potential applications for quantum information processing.

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Phys. Rev. Lett. 82, 000871 (1999)

Coherent Splitting of Bose-Einstein Condensed Atoms with Optically Induced Bragg Diffraction

M. Kozuma, L. Deng, E. W. Hagley, J. Wen, R. Lutwak, K. Helmerson, S. L. Rolston, and W. D. Phillips
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We have observed Bragg diffraction of a Bose-Einstein condensate of sodium atoms by a moving, periodic, optical potential. The coherent process of Bragg diffraction produced a splitting of the condensate with unidirectional momentum transfer. Using the momentum selectivity of the Bragg process, we separated a condensate component with a momentum width narrower than that of the original condensate. By repeatedly pulsing the optical potential while the atoms were trapped, we observed the trajectory of the split atomic wave packets in the confining magnetic potential.

Phys. Rev. Lett. 82, 004569 (1999)
Bragg Spectroscopy of a Bose-Einstein Condensate

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Properties of a Bose-Einstein condensate were studied by stimulated, two-photon Bragg scattering. The high momentum and energy resolution of this method allowed a spectroscopic measurement of the mean-field energy and of the intrinsic momentum uncertainty of the condensate. The coherence length of the condensate was shown to be equal to its size. Bragg spectroscopy can be used to determine the dynamic structure factor over a wide range of energy and momentum transfers.

Science 31 January 1997:
Vol. 275. no. 5300, pp. 637 – 641

Research Articles

Observation of Interference Between Two Bose Condensates

M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, W. Ketterle

Interference between two freely expanding Bose-Einstein condensates has been observed. Two condensates separated by ~40 micrometers were created by evaporatively cooling sodium atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of ~15 micrometers were

observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap. This demonstrates that Bose condensed atoms are "laser-like"; that is, they are coherent and show long-range correlations. These results have direct implications for the atom laser and the Josephson effect for atoms.

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Phys. Rev. Lett. 76, 1796 (1996)
Generation of Nonclassical Motional States of a Trapped Atom

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Received 11 October 1995

We report the creation of thermal, Fock, coherent, and squeezed states of motion of a harmonically bound 9Be+ ion. The last three states are coherently prepared from an ion which has been initially laser cooled to the zero point of motion. The ion is trapped in the regime where the coupling between its motional and internal states, due to applied (classical) radiation, can be described by a Jaynes-Cummings-type interaction. With this coupling, the evolution of the internal atomic state provides a signature of the number state distribution of the motion.

Phys. Rev. Lett. 91, 223001 (2003)
Spectroscopy of the 1S0–3P0 Clock Transition of 87Sr in an Optical Lattice

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We report on the spectroscopy of the 5s2 1S0(F = 9/2)-->5s5p 3P0(F = 9/2) clock transition of 87Sr atoms (natural linewidth of 1 mHz) trapped in a one-dimensional optical lattice. Recoilless transitions with a linewidth of 0.7 kHz as well as the vibrational structure of the lattice potential were observed. By investigating the wavelength dependence of the carrier linewidth, we determined the magic wavelength, where the light shift in the clock transition vanishes, to be 813.5±0.9 nm.

Vanishing electric dipole transition moment
Phys. Rev. A 19, 000700 (1979) (4 pages)

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We have discovered an interference which results in the vanishing of some electric dipole transition amplitudes. A transition-matrix element T between certain S and P sublevels with the same value of MF vanishes when an applied magnetic field satisfies Xs + Xp = –2MF, where X = μBgJB/A, and A is the hfs constant. There must be an avoided crossing between the two states of the same MF which can only occur when one of the hyperfine manifolds has an inverted Zeeman effect. These conditions imply MF < 0 and I >~ J. We observed the vanishing of T in Na23 for one of the Delta MF = 0 optical transitions of the 3S1/2 (F = 1) --> 3P1/2(F = 1) manifold. Absorption of cw laser light was monitored by observing total fluorescence perpendicular to both the atomic and laser beams, and absorption vanished near an applied field of 155 G. T vanishes for a large number of cases including rf and microwave frequencies and is a rather general consequence of angular momentum selection rules and perturbation theory. This phenomenon may have application in optical pumping, Lamb-shift measurements, and atomic weak neutral-current experiments.

Altman, E., E. Demler, et al. (2004). "Probing many-body states of ultracold atoms via noise correlations." Physical Review A 70(1).

We propose to utilize density-density correlations in the image of an expanding gas cloud to probe complex many-body states of trapped ultracold atoms. In particular, we show how this technique can be used to detect superfluidity of fermionic gases and to study spin correlations of multicomponent atoms in optical lattices. The feasibility of the method is investigated by analysis of the relevant signal to noise ratio including experimental imperfections.

Arndt, M., O. Nairz, et al. (1999). "Wave-particle duality of C-60 molecules." Nature 401(6754): 680-682.

Quantum superposition lies at the heart of quantum mechanics and gives rise to many of its paradoxes. Superposition of de Broglie matter waves(1) has been observed for massive particles such as electrons(2), atoms and dimers(3), small van der Waals clusters(4), and neutrons(5). But matter wave interferometry with larger objects has remained experimentally challenging, despite the development of powerful atom interferometric techniques for experiments in fundamental quantum mechanics, metrology and lithography(6). Here we report the observation of de Broglie wave interference of C-60 molecules by diffraction at a material absorption grating. This molecule is the most massive and complex object in which wave behaviour has been observed. Of particular interest is the fact that C-60 is almost a classical body, because of its many excited internal degrees of freedom and their possible couplings to the environment. Such couplings are essential for the appearance of decoherence(7,8), suggesting that interference experiments with large molecules should facilitate detailed studies of this process.

Boca, A., R. Miller, et al. (2004). "Observation of the vacuum Rabi spectrum for one trapped atom." Physical Review Letters 93(23).

The transmission spectrum for one atom strongly coupled to the field of a high finesse optical resonator is observed to exhibit a clearly resolved vacuum Rabi splitting characteristic of the normal modes in the eigenvalue spectrum of the atom-cavity system. A new Raman scheme for cooling atomic motion along the cavity axis enables a complete spectrum to be recorded for an individual atom trapped within the cavity mode, in contrast to all previous measurements in cavity QED that have required averaging over 10(3)-10(5) atoms.

Bouwmeester, D., J. W. Pan, et al. (1997). "Experimental quantum teleportation." Nature 390(6660): 575-579.

Quantum teleportation-the transmission and reconstruction over arbitrary distances of the state of a quantum system-is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will he a critical ingredient for quantum computation networks.

Chang, D. E., J. Ye, et al. (2004). "Controlling dipole-dipole frequency shifts in a lattice-based optical atomic clock." Physical Review A 69(2).

Motivated by the ideas of using cold alkaline-earth atoms trapped in an optical lattice for realization of optical atomic clocks, we investigate theoretically the perturbative effects of atom-atom interactions on a clock transition frequency. These interactions are mediated by the dipole fields associated with the optically excited atoms. We predict resonancelike features in the frequency shifts when constructive interference among atomic dipoles occur. We theoretically demonstrate that by fine tuning the coherent dipole-dipole couplings in appropriately designed lattice geometries, the undesirable frequency shifts can be greatly suppressed.

Durr, S., T. Volz, et al. (2004). "Observation of molecules produced from a Bose-Einstein condensate." Physical Review Letters 92(2).

Molecules are created from a Bose-Einstein condensate of atomic Rb-87 using a Feshbach resonance. A Stern-Gerlach field is applied, in order to spatially separate the molecules from the remaining atoms. For detection, the molecules are converted back into atoms, again using the Feshbach resonance. The measured position of the molecules yields their magnetic moment. This quantity strongly depends on the magnetic field, thus revealing an avoided crossing of two bound states at a field value slightly below the Feshbach resonance. This avoided crossing is exploited to trap the molecules in one dimension.

Dutton, Z., M. Budde, et al. (2001). "Observation of quantum shock waves created with ultra-compressed slow light pulses in a Bose-Einstein condensate." Science 293(5530): 663-668.

We have used an extension of our slow light technique to provide a method for inducing small density defects in a Bose-Einstein condensate. These subresolution, micrometer-sized defects evolve into large-amplitude sound waves. We present an experimental observation and theoretical investigation of the resulting breakdown of superfluidity, and we observe directly the decay of the narrow density defects into solitons, the onset of the "snake" instability, and the subsequent nucleation of vortices.

Gehm, M. E., S. L. Hemmer, et al. (2003). "Unitarity-limited elastic collision rate in a harmonically trapped Fermi gas." Physical Review A 68(1).

We derive the elastic collision rate for a harmonically trapped Fermi gas in the extreme unitarity limit where the s-wave scattering cross section is sigma(k)=4pi/k(2), with (h) over bark the relative momentum. The collision rate is given in the form Gamma=gamma I(T/T-F)-the product of a universal collision rate gamma=k(B)T(F)/(6pi(h) over bar) and a dimensionless function of the ratio of the temperature T to the Fermi temperature T-F. We find that I has a peak value of similar or equal to4.6 at T/T(F)similar or equal to0.4, Isimilar or equal to82 (T/T-F)(2) for T/T(F)less than or equal to0.15, and Isimilar or equal to2(T-F/T)(2) for T/T-F>1.5. We estimate the collision rate for recent experiments on a strongly-interacting degenerate Fermi gas of atoms.

Hamann, S. E., D. L. Haycock, et al. (1998). "Resolved-sideband Raman cooling to the ground state of an optical lattice." Physical Review Letters 80(19): 4149-4152.

We trap neutral Cs atoms in a two-dimensional optical lattice and cool them close to the zero point of motion by resolved-sideband Raman cooling. Sideband cooling occurs via transitions between the vibrational manifolds associated with a pair of magnetic sublevels, and the required Raman coupling is provided by the lattice potential itself. We obtain mean vibrational excitations (n) over bar(x) approximate to (n) over bar, < 0.024, corresponding to a population >95% in the vibrational ground state. Atoms in the ground state of an optical lattice provide a new system in which to explore quantum state control and subrecoil laser cooling.

Katori, H., M. Takamoto, et al. (2003). "Ultrastable optical clock with neutral atoms in an engineered light shift trap." Physical Review Letters 91(17).

An ultrastable optical clock based on neutral atoms trapped in an optical lattice is proposed. Complete control over the light shift is achieved by employing the 5s(2) S-1(0)-->5s5p P-3(0) transition of Sr-87 atoms as a "clock transition." Calculations of ac multipole polarizabilities and dipole hyperpolarizabilities for the clock transition indicate that the contribution of the higher-order light shifts can be reduced to less than 1 mHz, allowing for a projected accuracy of better than 10(-17).

Kraus, B. and J. I. Cirac (2004). "Discrete entanglement distribution with squeezed light." Physical Review Letters 92(1).

We show how one can entangle distant atoms by using squeezed light. Entanglement is obtained in steady state, and can be increased by manipulating the atoms locally. We study the effects of imperfections, and show how to scale up the scheme to build a quantum network.

Ma, Z. Y., M. B. d'Arcy, et al. (2004). "Gravity-sensitive quantum dynamics in cold atoms." Physical Review Letters 93(16).

We subject a falling cloud of cold cesium atoms to periodic kicks from a sinusoidal potential created by a vertical standing wave of laser light. By controllably accelerating the potential, we show quantum accelerator mode dynamics to be highly sensitive to the effective gravitational acceleration when close to specific, resonant values. This quantum sensitivity to a control parameter is reminiscent of that associated with classical chaos and promises techniques for precision measurement.

Massar, S. and E. S. Polzik (2003). "Generating a superposition of spin states in an atomic ensemble." Physical Review Letters 91(6).

A method for generating a mesoscopic superposition state of the collective spin variable of a gas of atoms is proposed. The state consists of a superposition of the atomic spins pointing in two slightly different directions. It is obtained by using off resonant light to carry out quantum nondemolition measurements of the spins. The relevant experimental conditions, which require very dense atomic samples, can be realized with presently available techniques. Long-lived atomic superposition states may become useful as an off-line resource for quantum computing with otherwise linear operations.

McKeever, J., A. Boca, et al. (2003). "Experimental realization of a one-atom laser in the regime of strong coupling." Nature 425(6955): 268-271.

Conventional lasers (from table-top systems to microscopic devices) typically operate in the so-called weak-coupling regime, involving large numbers of atoms and photons; individual quanta have a negligible impact on the system dynamics. However, this is no longer the case when the system approaches the regime of strong coupling for which the number of atoms and photons can become quite small. Indeed, the lasing properties of a single atom in a resonant cavity have been extensively investigated theoretically(1-11). Here we report the experimental realization of a one-atom laser operated in the regime of strong coupling. We exploit recent advances(12) in cavity quantum electrodynamics that allow one atom to be isolated in an optical cavity in a regime for which one photon is sufficient to saturate the atomic transition. The observed characteristics of the atom-cavity system are qualitatively different from those of the familiar many-atom case. Specifically, our measurements of the intracavity photon number versus pump intensity indicate that there is no threshold for lasing, and we infer that the output flux from the cavity mode exceeds that from atomic fluorescence by more than tenfold. Observations of the second-order intensity correlation function demonstrate that our one-atom laser generates manifestly quantum (nonclassical) light, typified by photon anti-bunching and sub-poissonian photon statistics.

Pan, J. W., D. Bouwmeester, et al. (2000). "Experimental test of quantum nonlocality in three-photon Greenberger-Horne-Zeilinger entanglement." Nature 403(6769): 515-519.

Bell's theorem(1) states that certain statistical correlations predicted by quantum physics for measurements on two-particle systems cannot be understood within a realistic picture based on local properties of each individual particle-even if the two particles are separated by large distances. Einstein, Podolsky and Rosen first recognized(2) the fundamental significance of these quantum correlations (termed 'entanglement' by Schrodinger(3)) and the two-particle quantum predictions have found ever-increasing experimental support(4). A more striking conflict between quantum mechanical and local realistic predictions (for perfect correlations) has been discovered(5,6); but experimental verification has been difficult, as it requires entanglement between at least three particles. Here we report experimental confirmation of this conflict, using our recently developed method: to observe three-photon entanglement, or 'Greenberger-Horne-Zeilinger' (GHZ) states. The results of three specific experiments, involving-measurements of polarization correlations between three photons, lead to predictions for a fourth experiment; quantum physical predictions are mutually contradictory with expectations based on local realism. We find the results of the fourth experiment to be in agreement with the quantum prediction and in striking conflict with local realism.

Phillips, D. F., A. Fleischhauer, et al. (2001). "Storage of light in atomic vapor." Physical Review Letters 86(5): 783-786.

We report an experiment in which a light pulse is effectively decelerated and trapped in a vapor of Rb atoms, stored for a controlled period of time, and then released on demand. We accomplish this "storage of light" by dynamically reducing the group velocity of the light pulse to zero, so that the coherent excitation of the light is reversibly mapped into a Zeeman (spin) coherence of the Rb vapor.

Sage, J. M., S. Sainis, et al. (2005). "Optical production of ultracold polar molecules." Physical Review Letters 94(20).

We demonstrate the production of ultracold polar RbCs molecules in their vibronic ground state, via photoassociation of laser-cooled atoms followed by a laser-stimulated state transfer process. The resulting sample of X(1)Sigma(+)(v=0) molecules has a translational temperature of similar to 100 mu K and a narrow distribution of rotational states. With the method described here it should be possible to produce samples even colder in all degrees of freedom, as well as other bialkali species.

Sanguinetti, S., J. Guena, et al. (2003). "Prospects for forbidden-transition spectroscopy and parity violation measurements using a beam of cold stable or radioactive atoms." European Physical Journal D 25(1): 3-13.

Laser cooling and trapping offers the possibility of confining a sample of radioactive atoms in free space. Here, we address the question of how best to take advantage of cold atom, properties to perform the observation of as highly forbidden a line as the 6S-7S Cs transition for achieving, in the longer term, atomic parity violation (APV) measurements in radioactive alkali isotopes. Another point at issue is whether one might do better with stable, cold atoms than with thermal atoms. To compensate for the large drawback of the small number of atoms available in a trap, one must take advantage of their low velocity. To lengthen the time of interaction with the excitation laser, we suggest choosing a geometry where the laser beam exciting the transition is colinear to a slow. cold atomic beam, either extracted from a trap or prepared by Zeeman slowing. We also suggest a new observable physical quantity manifesting APV, which presents several advantages: specificity, efficiency of detection, possibility of direct calibration by a parity conserving quantity of a similar nature. It is well adapted to a configuration where the cold atomic beam passes through two regions of transverse, crossed electric fields, leading both to differential measurements and to strong reduction of the contributions from the M-1-Stark interference signals, potential sources of systematics in APV measurements. Our evaluation of signal-to-noise ratios shows that with available techniques, measurements of transition amplitudes, important as required tests of atomic theory, should be possible in Cs-133 with a statistical precision of 10(-3) and probably also in Fr isotopes for production rates of greater than or equal to 10(6) Fr atoms s(-1). For APV measurements to become realistic, some practical realization of the collimation of the atomic beam as well as multiple passages of the excitation beam matching the atomic beam looks essential.

Takamoto, M., F. L. Hong, et al. (2005). "An optical lattice clock." Nature 435(7040): 321-324.

The precision measurement of time and frequency is a prerequisite not only for fundamental science but also for technologies that support broadband communication networks and navigation with global positioning systems (GPS). The SI second is currently realized by the microwave transition of Cs atoms with a fractional uncertainty of 10(-15) (ref. 1). Thanks to the optical frequency comb technique(2,3), which established a coherent link between optical and radio frequencies, optical clocks(4) have attracted increasing interest as regards future atomic clocks with superior precision. To date, single trapped ions(4-6) and ultracold neutral atoms in free fall(7,8) have shown record high performance that is approaching that of the best Cs fountain clocks(1). Here we report a different approach, in which atoms trapped in an optical lattice serve as quantum references. The 'optical lattice clock'(9,10) demonstrates a linewidth one order of magnitude narrower than that observed for neutral-atom optical clocks(7,8,11), and its stability is better than that of single-ion clocks(4,5). The transition frequency for the Sr lattice clock is 429,228,004,229,952(15) Hz, as determined by an optical frequency comb referenced to the SI second.