Laser spectroscopy and quantum optics

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In this paper the authors discuss recent advances and trends in laser spectroscopy and quantum optics. It is obvious that both are fields that experienced a tremendous development in the last twenty years. Therefore the survey must be incomplete, and only a few highlights are touched on. [S0034-6861(99)04802-3]

I. FRONTIERS OF LASER SPECTROSCOPY

Although spectroscopy has taught us most of what we know about the physics of matter and light, it has repeatedly been overshadowed by seemingly more glamorous pursuits in physics, only to reemerge with unexpected vigor and innovative power. The advent of widely tunable and highly monochromatic dye lasers around 1970 ushered in a revolution in optical spectroscopy that has redefined the purpose and direction of the field. Intense highly monochromatic laser light has not only vastly increased the sensitivity and resolution of classical spectroscopic techniques, it has made possible many powerful new techniques of nonlinear spectroscopy. Laser spectroscopists are no longer just looking at light; they are using laser light as a tool to manipulate matter and even to create new states of matter.

Today, laser spectroscopy has found applications in most areas of science and technology. Voluminous monographs, textbooks, and conference proceedings are devoted to the subject (see Hänsch and Inguscio, 1984; Demtröder, 1996), tens of thousands of research papers have been written, and it has become impossible to do justice to the state, impact, and prospects of the field in an article of this scope. We can only discuss some areas, chosen by personal taste, where advances in laser spectroscopy appear particularly rapid, interesting, and promising. As a caveat we must keep in mind that any attempts at foretelling the future are almost certain to overestimate progress in the short term, only to severely underestimate advances in the more distant future, which will result from less predictable but important discoveries and new ideas.

A. Laser sources and other tools of the trade

In the past, advances in laser spectroscopy have often been driven by technological progress. On this technical side, we are now witnessing the emergence of such an abundance of new tunable sources and other sophisticated optoelectronic tools that we ''old-timers'' often feel that we may have entered the field too early. Aided by applications such as data storage, laser printing, telecommunications, and materials processing, researchers are able to devote large resources, for instance, to the development of diode lasers. Wavelength selection with integrated Bragg gratings or with tuning elements in an extended external cavity can turn such lasers into perfect tools for high-resolution spectroscopy. Tapered diode laser amplifiers or injection-seeded wide-stripe lasers yield substantial average power and can replace much more costly and complex dye-laser systems. Arrays of diode lasers operating at many different wavelengths, blue gallium nitride diode lasers, and quantum cascade lasers covering the important mid-infrared spectral region are further enhancing the arsenal of spectroscopic tools.

The generation of harmonics, sum or difference frequencies in nonlinear crystals, which can extend the wavelength range into the blue and ultraviolet or the infrared spectral region, is gaining much in conversion efficiency and versatility with quasi-phase-matched nonlinear crystals. This was first proposed in the sixties by N. Bloembergen and has now been realized with ferroelectric crystals such as periodically doped lithium niobate.

We are also witnessing dramatic progress with diode-pumped solid-state lasers and fiber lasers. Commercial frequency-doubled Nd:YAG or Nd:YLF lasers are now replacing power-hungry argon ion lasers as pump sources for tunable Ti:Sapphire lasers or dye lasers. With single-frequency output, such lasers have also pumped prototypes of continuous-wave optical parametric oscillators to generate widely tunable highly monochromatic infrared radiation with impressive efficiency.

Spectacular advances are coming from the frontier of femtosecond laser sources. Kerr-lens mode locking of Ti:Sapphire lasers, chirped pulse amplification, and linear or nonlinear pulse compression have created tabletop sources of intense ultrashort pulses with pulse lengths down to just a few optical cycles. Such lasers are revolutionizing the study of ultrashort phenomena in condensed-matter physics, molecular physics, and even in biological science. Nonlinear frequency conversion gives access to a very wide spectral range, from the submillimeter wavelengths of terahertz radiation to the soft x rays generated as high-order harmonics in gas jets. With direct diode pumping of laser crystals or fibers, shoebox-sized self-contained femtosecond laser systems are becoming a reality.

By greatly reducing the cost, size, and complexity of tunable laser systems, we can move sophisticated laser spectroscopic techniques from the research laboratory to the ''real world.'' At the same time, we can now conceive new, more demanding research experiments, which may employ an entire ''orchestra'' of tunable lasers sources, directed and controlled in sophisticated ways by a personal computer.

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B. Ultrasensitive spectroscopy

From its beginnings, laser spectroscopy has far surpassed classical spectroscopic techniques in sensitivity, resolution, and measurement accuracy, and we are witnessing unabated progress in these three directions. Advances in sensitivity have often led to unforseen new applications. When laser-induced fluorescence of single sodium atoms was first observed at Stanford University in the early seventies, nobody anticipated that laser-induced fluorescence spectroscopy would be combined with scanning optical near-field microscopy to study single molecules in a solid matrix on a nanometer scale, that the fluorescence of a rotating molecule would reveal the superfluidity of small helium clusters, as recently demonstrated by J. P. Toennies in Göttingen, or that fluorescence spectroscopy of dye-labeled molecular fragments could greatly speed up the sequencing of DNA. Such examples provide persuasive arguments for curiosity-driven research. The observation of the laser-induced fluorescence of single trapped ions, first accomplished by P. Toschek and H. Dehmelt in Heidelberg around 1978, has opened a rich new regime of fascinating quantum physics to exploration. Extreme sensitivity is also offered by a growing number of other laser techniques, such as resonant photoionization, intracavity absorption spectroscopy, cavity ringdown spectroscopy, bolometric detection of energy deposition in a molecular beam, or sophisticated modulation and cross-modulation techniques, such as the resonator-enhanced conversion of frequency modulation to amplitude modulation, perfected by J. Hall in Boulder. Some obvious applications include spectroscopy of weak molecular vibrational overtones or the detection of trace impurities for industrial materials control, environmental research, or medical diagnostics.

C. Spectral resolution and accuracy—precision spectroscopy of atomic hydrogen

The progress in resolution and measurement accuracy is perhaps best illustrated with our own work on precision spectroscopy of atomic hydrogen, which began at Stanford in the early seventies and is continuing at Garching since 1986. The simple hydrogen atom has played a central role in the history of atomic physics. Its regular visible Balmer spectrum has been the key to deciphering the laws of quantum physics as we describe them today with quantum electrodynamics (QED), the most successful theory of physics. Spectroscopists have been working for more than a century to measure and compare the resonance frequencies of hydrogen with ever increasing resolution and accuracy in order to test basic laws of physics and to determine accurate values of the fundamental constants (Bassani, Inguscio, and Hänsch, 1989).

One of the most intriguing resonances is the two-photon transition from the $1S$ ground state to the metastable $2S$ state with a natural linewidth of only 1.3 Hz, which has inspired advances in high-resolution spectroscopy and optical frequency metrology for almost three decades. By Doppler-free two-photon spectroscopy of a cold atomic beam, we are now observing this transition near 243 nm with a linewidth of 1 kHz, as illustrated in Fig. 1. The resolution of better than one part in 10^{12} corresponds to the thickness of a human hair compared to the circumference of the equator of the earth. Recently, we have measured the absolute optical frequency of this resonance to 13 decimal places. For the hyperfine centroid of the $1S$-$2S$ interval, we find a frequency $f = 2\,466\,061\,413\,187.34 \pm 0.84$ kHz, which is now one of the most accurately measured optical frequencies and the highest frequency that has been compared with the microwave frequency of a Cs atomic clock.

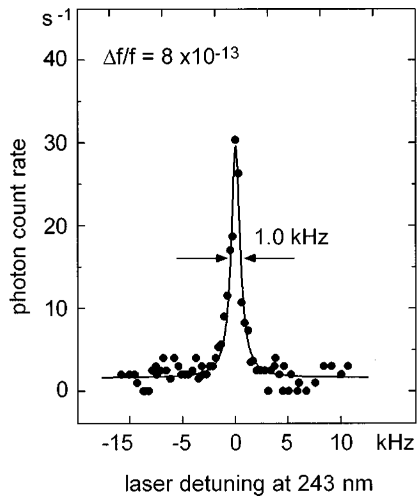

FIG. 1. Doppler-free two-photon spectrum of the hydrogen $1S$-$2S$ resonance, observed by exciting a cold atomic beam with an optical standing wave at 243 nm. The ratio of linewidth to frequency is less than one part in a trillion.

Figure 2 illustrates the progress in the accuracy of optical hydrogen spectroscopy over the past century. Clas-

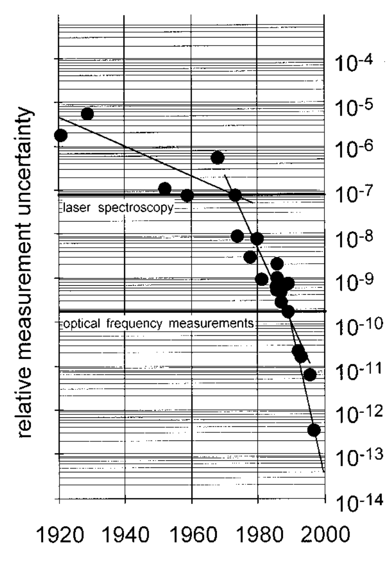

FIG. 2. Advances in the accuracy of optical spectroscopy of atomic hydrogen during the 20th century.

sical spectroscopists were limited to accuracies of a part in 10^6, at best, by the large Doppler broadening due to the random thermal motion of the light atoms, which blurs and masks the intricate fine structure of the spectral lines. This barrier was overcome in the early seventies by the advent of highly monochromatic tunable dye lasers and nonlinear techniques of Doppler-free spectroscopy, such as saturation spectroscopy, as introduced by T. Hänsch and C. Bordé, following earlier work of W. Lamb, W. Bennett, and A. Javan, or polarization spectroscopy, first demonstrated by C. Wieman and T. Hänsch. In both methods, a gas sample is traversed by a strong saturating laser beam and a counterpropagating probe beam so that slow atoms can be selected. If the laser frequency is tuned to the center of a Doppler-broadened line, the two beams can interact with the same atoms, which can only be those at rest or moving sideways. V. Chebotaev in Novosibirsk was the first to realize that Doppler broadening in two-photon spectroscopy can be eliminated without any need to select slow atoms by exciting the atoms with two counterpropagating photons whose frequencies add to the atomic resonance frequency so that the Doppler shifts cancel to first order.

In the late eighties, laser spectroscopists reached another barrier, the limits of optical wavelength interferometry. Unavoidable geometric wave-front errors make it practically impossible to exceed an accuracy of one part in 10^{10}. In the early nineties, this problem was finally overcome in Garching and Paris with new precision experiments measuring the frequency of light with so-called frequency chains.

These new hydrogen experiments at Garching have already yielded a precise new value for the Lamb shift of the $1S$ ground state, which represents now the most stringent test of QED for an atom, a Rydberg constant that is now the most accurately measured fundamental constant, and a deuteron structure radius (from the H-D $1S$-$2S$ isotope shift) that disagrees with the measurements by electron scattering at large accelerators, but is about ten times more accurate and in good agreement with recent predictions of nuclear few-body theory. Future experiments with antihydrogen by two international collaborations at CERN may unveil conceivable small differences in the resonance frequencies or gravitational acceleration of matter and antimatter.

D. Optical frequency metrology

Extrapolation of the exponential advances shown in Fig. 2 suggests that laser spectroscopic experiments will soon reach the accuracy limit of a part in 10^{14}, imposed by the definition of the second in terms of 9-GHz hyperfine splitting of the Cs ground state. New microwave Cs atomic clocks using fountains of laser-cooled atoms, as first proposed by C. Wieman and S. Chu and now developed by C. Salomon in Paris and elsewhere, are pushing this limit to a few parts in 10^{15}. Much sharper resonances have been observed at optical frequencies with atomic hydrogen or other cold atoms and molecules or with laser-cooled trapped ions, as first proposed by H. Dehmelt and perfected in the laboratory of D. Wineland in Boulder and elsewhere. Accuracies of a part in 10^{17} or better should be achievable with future atomic clocks based on such optical transitions. These clocks will open a new era of precision metrology and fundamental physics tests, and they will likely find important applications in telecommunication, navigation, geological sciences, space research, and astronomy.

Only three laboratories (in Garching, Paris, and Braunschweig) have so far constructed harmonic laser frequency chains reaching into the visible spectrum. Traditional harmonic laser frequency chains are large and complex, and they are typically designed to measure just one particular optical frequency. In essence, such a chain synthesizes a high frequency, starting from a microwave Cs atomic clock, by repeated stages of harmonic generation in nonlinear circuit elements or optical crystals, boosting the feeble power after each step with a phase-locked "transfer oscillator." Many different and often delicate technologies are required to traverse a wide region of the electromagnetic spectrum.

New tools are now emerging that make it possible to design much more compact and versatile optical frequency counters and frequency synthesizers, using small and reliable solid-state components. In Garching, we have demonstrated a phase-locked chain of frequency interval dividers, which can reduce any frequency interval by cutting it repeatedly in half until it is small enough to be measured as a beat note with a fast photodetector. [A frequency interval divider stage receives two input laser frequencies f_1 and f_2 and it forces its own laser to oscillate at the precise midpoint, $f_3=(f_1+f_2)/2$. This is accomplished by generating the sum frequency f_1+f_2 and the second harmonic $2f_3$ in nonlinear crystals and by observing a beat signal between these two frequencies. This beat frequency is then forced to zero or some chosen well-known local oscillator frequency with the help of a digital feedback circuit that controls the frequency and phase of the midpoint laser. All stages of the Garching divider chain are nearly identical and employ a small grating-tuned diode laser at visible or near-infrared wavelengths.]

To measure an absolute optical frequency, one may start with a laser frequency f and its second harmonic $2f$. After n bisections, the frequency difference f is reduced to $f/2n$. Once this interval is in the range of a few THz, it can be precisely measured with an optical comb generator, i.e., a fast electro-optic modulator in an optical cavity that produces a wide comb of modulation sidebands with a spacing precisely known from the driving modulation frequency. Even broader combs of precisely spaced longitudinal modes can be generated with a mode-locked femtosecond laser. In a direct comparison of a comb generator and an interval divider chain we have recently demonstrated that both these gears for optical clockworks of the future can work flawlessly over long periods, without losing even a single optical cycle. It is now worth dreaming about new experiments in high-resolution laser spectroscopy of atoms, ions, and molecules that will take advantage of the coming ability to measure any laser frequency quickly with extreme precision.

E. Manipulating matter with light

The ability to use intense laser light to manipulate matter has long fascinated laser spectroscopists. Even the preparation of spin-polarized gases by optical pumping, known from the work of A. Kastler at Paris in the fifties, has gained new importance for applications such as magnetic-resonance imaging of lungs and blood vessels with spin-polarized helium and xenon, as first demonstrated by W. Happer at Princeton. Atoms can be excited to high Rydberg states which approach macroscopic dimensions and have opened rich new fields of physics, such as the study of cavity QED or quantum chaos by S. Haroche in Paris, D. Kleppner in Cambridge, or H. Walther in Garching. Laser manipulation of molecules has advanced from the excitation of vibrational wave packets with ultrashort pulses to "coherent control" introduced by K. Wilson in San Diego and others, in which a specific quantum state is prepared with an elaborate sequence of radiation fields, similar to music creating a particular mood in our mind. The binding potential of a molecule can be drastically altered with an intense laser field once the resonant transition rate between two electronic states exceeds the vibrational frequency, and efforts are now underway to observe new man-made bound states in which the internuclear distance can be changed with the dressing laser wavelength. At even higher intensities, hot dense plasmas can be produced, with electrons reaching relativistic energies, and one can even hope to observe nonlinear optical phenomena such as photon-photon scattering in vacuum.

F. Laser cooling and trapping

On the other end of the energy scale, laser cooling has provided a tool to slow atoms to such low temperatures that the thermal De Broglie wavelength assumes macroscopic dimensions (Arimondo, Phillips, and Strumia, 1992; Adams and Riis, 1997). The original proposal for laser cooling of atomic gases by T. Hänsch and A. Schawlow in 1974 was motivated by the quest for higher resolution in hydrogen spectroscopy. Half a year later, H. Dehmelt and D. Wineland made a similar proposal for laser cooling of trapped ions. If atoms are illuminated from all directions with laser light tuned below an atomic resonance, a moving atom sees oncoming light Doppler-shifted into resonance so that the radiation pressure exerts a strong viscous damping force. Such "optical molasses" was first realized by S. Chu in the eighties, and experiments of W. Phillips in Gaithersburg soon reached temperatures even lower than expected. J. Dalibard and S. Chu were the first to explain this violation of Murphy's law with an additional more subtle cooling mechanism involving light shifts and optical pumping between Zeeman sublevels that comes into play at very low temperatures. Even the remaining limit imposed by the recoil energy due to the emission of a single photon has since been overcome by C. Cohen-Tannoudji in Paris and S. Chu and M. Kasevich at Stanford by pumping the atoms into a velocity-selective dark state that no longer interacts with the light field.

Laser-cooled atoms can easily be trapped in the nodes or antinodes of an optical standing wave by the forces experienced by a light-induced electric dipole in an electric field gradient. Two- and three-dimensional atomic lattices bound by light, as first demonstrated by A. Hemmerich in Munich in 1992, represent an intriguing state of matter, combining the crystalline order of a solid with the density of a good vacuum. Unlike the periodic potential that electrons experience in a solid, the optical potential can be controlled and modulated from the outside at will, and phonons that obscure interesting coherent quantum phenomena in solid state physics are essentially absent. Such optical lattices are therefore intriguing quantum laboratories and provide a rich new playground for laser spectroscopy. High-resolution Raman spectroscopy reveals the vibrational levels of the atoms in their microscopic optical traps, and optical Bragg scattering has been used to probe the long-range order and to study the extension and dynamics of the trapped atomic wave packets. Other phenomena already observed in optical lattices include transport phenomena via Levy flights, Bloch oscillations, quantum tunneling, and quantum chaos. And the deposition of such laser-manipulated atoms on solid surfaces provides a promising tool for the creation of functional nanostructures.

One of the most fascinating phenomena created and studied with laser spectroscopic techniques is the Bose-Einstein condensation (BEC) of cold atomic gases, as discussed elsewhere in this volume by C. Wieman *et al.* If cold atoms are captured in a magnetic trap, and if fast energetic atoms are allowed to escape in "evaporative cooling," the phase-space density of the remaining thermalizing atoms can increase until the wave packets of neighboring atoms begin to overlap, and a large fraction of the atoms condense in the lowest vibrational state, thus losing their identity. Very recently, D. Kleppner has succeeded, after 20 years of effort at MIT, in producing large condensates of spin-polarized atomic hydrogen, which are observed by laser spectroscopy of the $1S$-$2S$ two-photon resonance.

BEC of atomic gases has already become a very active interdisciplinary field. Condensed-matter scientists are fascinated by the possibility of studying degenerate quantum gases at low densities with interactions dominated by simple two-body s-wave scattering. Such research will likely lead to new insights into correlation and damping effects or quantum transport phenomena such as superfluidity. Atomic spectroscopists, on the other hand, are intrigued by a far-reaching analogy between Bose-Einstein condensation and the creation of laser light. Their efforts may lead to atom lasers as intense sources of coherent matter waves, opening new opportunities in atom optics and atom interferometry.

G. From laser spectroscopy to quantum optics

With each new tool, we are extending the reach of laser spectroscopy. The field is in an excellent position to respond to societal pressures and put its emphasis on applied research with marketable products and human benefits as immediate goals. If such a policy had been pursued in the past, however, science and mankind would be much poorer today. Sometimes, seemingly useless and unrelated discoveries have been combined to create unexpected new science and powerful new technologies. And curiosity-driven research has greatly enriched human culture. In this wealthiest period that our planet has ever known, society must continue to make resources available to researchers dedicating their lives to such useless pursuits as the study of parity violation in atoms and molecules, tests of special and general relativity, the search for a dipole moment of the electron, for hypothetical exotic particles, or for conceivable slow variations of fundamental constants.

Atomic physicists have sometimes been pitied by their colleagues because their research is limited to studying a periodic system of just 92 elements. However, they are now becoming "quantum engineers," creating new systems that explore the boundaries between quantum physics and classical physics, which provide incredibly sensitive sensors for rotation or acceleration, or which can function as gates for cryptography or the still elusive quantum computers. The possibilities of such quantum engineering are limited only by human imagination and skill, and laser spectroscopy is sure to play a central role in this exciting endeavor.

II. QUANTUM OPTICS: RECENT ADVANCES AND TRENDS

In this part of the paper we shall review recent advances and trends in the field of quantum optics. As for the laser spectroscopy section, it would be presumptuous to assume that complete coverage of the subject were possible. The field of quantum optics has developed tremendously under the influence of the technological progress in laser sources as well as in signal detection. Therefore the survey must remain incomplete and mainly influenced by the taste of the authors. The field of quantum optics covers quantum phenomena in the radiation-atom interaction in the broadest sense. It therefore provides interesting tools for testing basic quantum features and it is also an arena in which to illustrate and elucidate quantum effects which occasionally appear to be counterintuitive.

A. Introduction

The majority of processes in laser physics can be understood on the basis of semiclassical physics, where the atom is quantized but the radiation field treated classically. Therefore, looking back at the development of quantum optics during the late seventies or even the beginning of the eighties, we find that the only phenomena for which the quantization of the radiation field was important were almost exclusively phenomena related to spontaneous emission. In this way the linewidth of a laser and the related phase diffusion, which is caused by spontaneous emission processes in the laser medium, could only be calculated on the basis of a quantized field. Another related phenomenon was, of course, resonance fluorescence: the spectra of monochromatically driven atoms and the photon statistics of fluorescence radiation of a single atom show sub-Poissonian statistics and antibunching, which are both pure quantum features (Cresser *et al.*, 1982).

With their experiments on intensity or photon correlations in the mid fifties Hanbury-Brown and Twiss directed the attention of physicists to the question of photon statistics. It was found that photon statistics of normal thermal light show photon bunching, referring to the fact that photons are counted with statistical fluctuations greater than would be expected on the basis of purely random (that is, Poisson) statistics. Photon bunching arises from the Bose-Einstein distribution. A coherent photon field, as represented by laser light, shows Poisson statistics, indicating that the photons arrive randomly. A qualitative classical explanation of photon bunching is sometimes made by saying that light from any natural source arises from broadband multimode photon emission by many independent atoms. There are naturally random periods of constructive and destructive interference among the modes, giving rise to large intensity "spikes," or "bunches" of photons, in the light beam. Unbunched light comes from a coherently regulated collection of atoms, such as from a well-stabilized single-mode laser. From this point of view, unbunched coherent light is optimally ordered and corresponds to a classical coherent wave.

However, as mentioned above, in a quantum treatment the statistics of a light beam can also show photon antibunching. For "antibunched" light, photons arrive with lower statistical fluctuations than predicted from a purely coherent beam and represent therefore a nonclassical light. The first observation of an antibunched beam was accomplished by L. Mandel, H.-J. Kimble and others in 1977 in connection with the above-mentioned resonance fluorescence of a single atom (Cohen-Tannoudji, 1977; Cresser *et al.*, 1982). Antibunching occurs in such light for a very simple reason. A single two-level atom "regulates" the occurrence of pairs of emitted photons very severely, even more so than the photons are regulated in a single-mode laser. A second fluorescent photon cannot be emitted by the same two-level atom until it has been reexcited to its upper level by the absorption of a photon from the main radiation mode. The significance of photon statistics and photon counting techniques in quantum optics and in physics is clear from this discussion. They permit a direct examination of some of the fundamental distinctions between the quantum-mechanical and classical concepts of radiation (see Fig. 3).

The experimental situation with respect to the observation of quantum phenomena changed drastically dur-

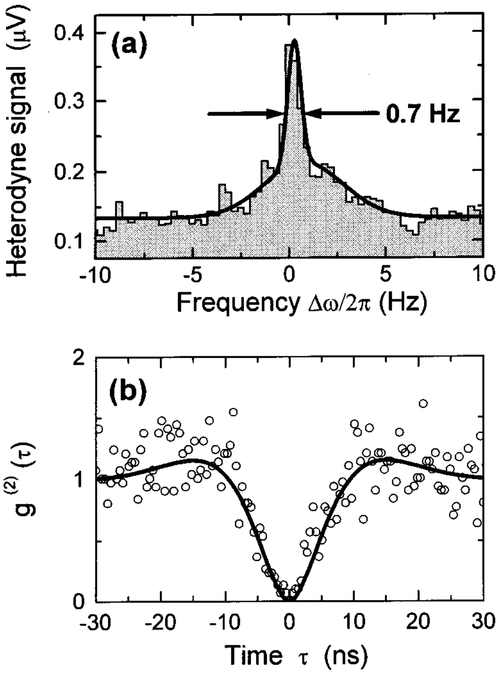

FIG. 3. Resonance fluorescence of a single ion. Part (a) of the figure shows the spectrum measured in a heterodyne experiment. The reemitted fluorescence radiation at low intensities is monochromatic. The linewidth is limited by phase fluctuations of the light beam in the laboratory air. The same radiation was investigated in a Hanbury-Brown and Twiss experiment (b). This setup measures the intensity correlation or the probability that a second photon follows at time τ after the first one. The measurement shows antibunching (anticorrelation of the photon detection events). The statistics of the photons is sub-Poissonian, both being nonclassical properties. Depending on the observation, the radiation shows "wave" (a) or "particle" character (b). The result is thus a nice demonstration of complementarity. See Höffges *et al.* (1997) for details.

ing the eighties. Owing to the progress of experimental techniques it became possible to realize many of the "gedanken" experiments that were previously only found in quantum mechanics textbooks or discussed in respective courses. Furthermore during the last decade many new ideas were developed, allowing the control of fundamental quantum phenomena. This changed the picture of quantum optics completely. Some of the important developments will be summarized in the following sections; owing to the lack of space, only a few main topics can be touched upon.

B. Cavity quantum electrodynamics, micromasers, and microlasers

The simplest and most fundamental system for studying radiation-matter coupling is a single two-level atom interacting with a single mode of an electromagnetic field in a cavity. This system received a great deal of attention shortly after the maser was invented, but at that time, the problem was of purely academic interest as the matrix elements describing the radiation-atom interaction are so small that the field of a single photon is not sufficient to lead to an atom-field evolution time shorter than other characteristic times of the system, such as the excited-state lifetime, the time of flight of the atom through the cavity, and the cavity mode damping time. It was therefore not possible to test experimentally the fundamental theories of radiation-matter interaction such as the Jaynes-Cummings model predicting amongst other effects (Meystre, 1992; Walther, 1992) (a) a modification of the spontaneous emission rate of a single atom in a resonant cavity; (b) oscillatory energy exchange between a single atom and the cavity mode; and (c) the disappearance and quantum revival of optical (Rabi) nutation induced in a single atom by a resonant field.

The situation changed drastically when tunable laser light allowed the excitation of highly excited atomic states, called Rydberg states. Such excited atoms are very suitable for observing quantum effects in radiation-atom coupling for three reasons. First, the states are very strongly coupled to the radiation field (the induced transition rates between neighboring levels scale as n^4); second, transitions are in the millimeter wave region, so that low-order mode cavities can be made large enough to allow rather long interaction times; finally, Rydberg states have relatively long lifetimes with respect to spontaneous decay.

The strong coupling of Rydberg states to radiation resonant with transitions between neighboring levels can be understood in terms of the correspondence principle: with increasing n the classical evolution frequency of the highly excited electron becomes identical with the transition frequency to the neighboring level, and the atom corresponds to a large dipole oscillating at the resonance frequency. (The dipole moment is very large since the atomic radius scales with n^2).

In order to understand the modification of the spontaneous emission rate in an external cavity, we have to remember that in quantum electrodynamics this rate is determined by the density of modes of the electromagnetic field at the atomic transition frequency ω_0, which in turn depends on the square of the frequency. If the atom is not in free space, but in a resonant cavity, the continuum of modes is changed into a spectrum of discrete modes, one of which may be in resonance with the atom. The spontaneous decay rate of the atom in the cavity γ_c will then be enhanced in relation to that in free space γ_f by a factor given by the ratio of the corresponding mode densities (Haroche and Kleppner, 1989):

$$\frac{\gamma_c}{\gamma_f}=\frac{\rho_c(\omega_0)}{\rho_f(\omega_0)}=\frac{2\pi Q}{V_c\omega_0^3}=\frac{Q\lambda_0^3}{4\pi^2 V_c},$$

where V_c is the volume of the cavity and Q is a quality factor of the cavity which expresses the sharpness of the mode. For low-order cavities in the microwave region $V_c \simeq \lambda_0^3$ this means that the spontaneous emission rate is increased by roughly a factor of Q. However, if the cavity is detuned, the decay rate will decrease. In this case the atom cannot emit a photon, as the cavity is not able to accept it, and therefore the energy will stay with the atom.

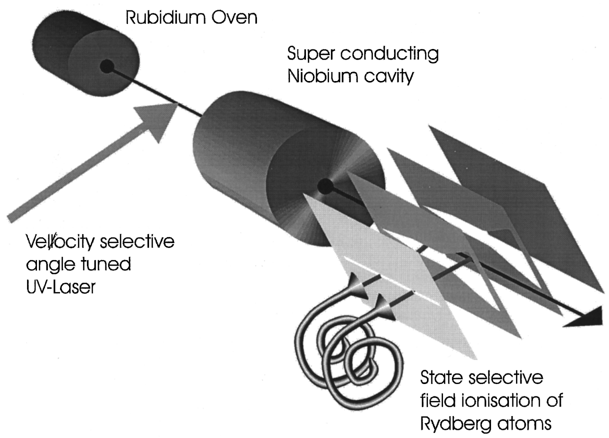

FIG. 4. Micromaser setup of Rb Rydberg atoms. The velocity of the atoms is controlled by exciting a velocity subgroup of atoms in the atomic beam. The atoms in the upper and lower maser levels are selectively detected by field ionization.

Many experiments have been performed with Rydberg atoms to demonstrate this enhancement and inhibition of spontaneous decay in external cavities or cavitylike structures. More subtle effects due to the change of the mode density can also be expected: radiation corrections such as the Lamb shift and the anomalous magnetic dipole moment of the electron are modified with respect to the free-space value, although changes are of the same order as present day experiments allow us to measure. Roughly speaking, one can say that such effects are determined by a change of virtual transitions and not by real transitions as in the case of spontaneous decay (see the articles in Berman, 1994).

If the rate of atoms crossing a cavity exceeds the cavity damping rate ω/Q, the photon released by each atom is stored long enough to interact with the next atom. The atom-field coupling becomes stronger and stronger as the field builds up and evolves into a steady state. The system is a new kind of maser, which operates with exceedingly small numbers of atoms and photons. Atomic fluxes as small as 100 atoms per second have generated maser action, as could be demonstrated by H. Walther *et al.* in 1985. For such a low flux there is never more than a single atom in the resonator—in fact, most of the time the cavity is empty. It should also be mentioned that a single resonant photon is sufficient to saturate the maser transition.

A scheme of this one-atom maser or micromaser is shown in Fig. 4. With this device the complex dynamics of a single atom in a quantized field predicted by the Jaynes-Cummings model could be verified. Some of the features are explicitly a consequence of the quantum nature of the electromagnetic field: the statistical and discrete nature of the photon field leads to a new characteristic dynamics such as collapse and revivals in the Rabi nutation.

The steady-state field of the micromaser shows sub-Poisson statistics. This is in contrast with regular masers and lasers where coherent fields (Poisson statistics) are observed. The reason that nonclassical radiation is produced is due to the fixed interaction time of the atoms leading to a careful control of the atom-field interaction dynamics (Meystre, 1992; Berman, 1994; see also the article on lasers in this issue by W. E. Lamb *et al.* where also a micromaser with ultracold atoms is discussed).

The micromaser also led to interferometry experiments and inspired many gedanken experiments on using two cavities for Ramsey-type interferometry (Briegel *et al.*, 1997).

Recently S. Haroche, J. M. Raimond, *et al.* succeeded in realizing a Schrödinger cat state in a cavity (Haroche, 1998). Studies on the decoherence of this state could be carried out. The experiments are another demonstration of the boundaries between the quantum and the classical world.

There is an interesting equivalence between an atom interacting with a single-mode field and a quantum particle in a harmonic potential, as was first pointed out by D. F. Walls and H. Risken; this connection results from the fact that the radiation field is quantized on the basis of the harmonic oscillator. Therefore the Jaynes-Cummings dynamics can also be observed with trapped ions, as demonstrated recently in a series of beautiful experiments by D. Wineland *et al.* They also produced a Schrödinger cat state by preparing a single trapped ion in a superposition of two spatially separated wave packets, which are formed by coupling different vibrational quantum states in the excitation process (see the contribution by C. Wieman *et al.* in this issue).

Besides the experiments in the microwave region, a single-atom laser emitting in the visible range has also been realized by M. Feld *et al.* Furthermore, cavity quantum electrodynamic effects have been studied in the optical spectral region by J. L. Kimble *et al.* (Berman, 1994).

Today's technology in the microfabrication of semiconductor diode structure allows the realization of low-order cavity structures for diode lasers. In these systems the spontaneous emission is controlled in the same way as in the micromaser. Since spontaneous decay is a source of strong losses, the control of this phenomenon leads to highly efficient laser systems. The quantum control of spontaneous decay has thus important consequences for technical applications (Yamamoto and Slusher, 1993; see also the contribution by R. S. Slusher in this issue).

C. Quantum interference phenomena

Interference occurs in classical optics when two or more wave amplitudes are added with different phases. As a classical particle does not have a phase, only waves can give rise to interference in classical physics. By contrast, interference is a general feature in quantum mechanics which is not limited to waves, but shows up whenever the outcome of a measurement can be arrived at via several indistinguishable paths, the probability amplitudes of which must be added to calculate the result of the measurement. Therefore both particle and wave aspects manifest themselves in the quantum-mechanical description of interference. The particle aspect of a photon is apparent in that it cannot be detected at two separate positions at the same time, i.e., the detection of a photon at one point eliminates the probability of detecting the photon at any other point; therefore classical optics, which treats light only in terms of waves, cannot explain some photon interference effects.

In order that photon interference experiments can be performed, photon pairs have to be generated. This has been done using spontaneous parametric down conversion or parametric fluorescence. In this process an ultraviolet "pump" photon decays inside the crystal into two red photons, called the signal and idler, which are highly correlated. Interferences are observed when both photons can reach a first and a second detector and when the different paths are indistinguishable. The setup introduced by L. Mandel and co-workers has been used to investigate a series of quantum phenomena including photon tunneling, the quantum eraser, the electron-paramagnetic-resonance paradox, and Bell inequalities (Chiao, Kwiat, and Steinberg, 1994; Chiao and Steinberg, 1998; Shih, 1998). With type-II parametric down conversion entangled pairs of photons can also be generated. They are the basis for the experiments performed in connection with quantum information to be discussed later in this paper (see also the contribution of A. Zeilinger in this issue).

D. Quantum nondemolition measurements

In quantum systems the process of measurement of an observable introduces noise; therefore successive measurements of the same observable yield different results in general. A typical example from the field of quantum optics that is useful to illustrate this phenomenon is the detection of the field variables by photon counting techniques, which are, of course, field destructive, i.e., the field is modified as a consequence of the measurement. For general applications it is desirable to find schemes that avoid back action during a measurement. A possible way to perform such a quantum nondemolition measurement is to hide the noise introduced in the measurement in a conjugate observable which is not of particular interest in that case. The original idea of quantum nondemolition was introduced theoretically in connection with gravitational wave detection by Braginski in 1974 and Thorne in 1978 (Braginsky and Khalili, 1992); the first implementation was performed in quantum optics. Several schemes were implemented in the eighties and early nineties. The first experiment to measure a light field was performed by I. Imoto, H. A. Haus, and Y. Yamamoto. It is based on the optical Kerr effect whereby the change of the refractive index depends on the intensity of a transmitted beam. A weak probe wave therefore experiences a phase shift which is proportional to the intensity of the signal wave.

Many other schemes along the same lines were implemented. Two very special ones should be mentioned here: single photons in cavities were measured by S. Haroche *et al.* (Berman, 1994) employing the dispersive level shift of probing atoms; furthermore, the nonlinearity of cold trapped atoms was used by Grangier *et al.*, leading to extremely small excess noise.

Related to the topic of quantum nondemolition measurements is the topic of squeezed radiation, both fields actually developing in parallel and cross-fertilizing each other.

E. Squeezed radiation

A classical electromagnetic field consists of waves with well-defined amplitude and phase. This is not the case in a quantum treatment: fluctuations are associated with both conjugate variables. The case of a coherent state that most nearly describes a classical electromagnetic field has an equal amount of uncertainty in the two variables (when normalized to the field of a single photon). Equivalently the field can be described in two conjugate quadrature components and the uncertainties in the two conjugate variables satisfy the Heisenberg uncertainty principle. The coherent state represents a minimum uncertainty state with equal uncertainties in the two quadrature components. This case is usually called the shot-noise limit.

In a quantum treatment of radiation it is also possible to generate states that are not present in the classical limit. They can show fluctuations reduced below the classical limit in one of the quadrature components, while the canonically conjugate quadrature component must display enhanced fluctuations in order to fulfill the Heisenberg uncertainty principle. Those states are called "squeezed states." An electromagnetic field with fluctuations below the standard quantum limit in one of the quadrature components has in principle many attractive applications, e.g., in optical communication, in precision and sensitive measurements such as gravitational wave detection, or in noise-free amplification. Therefore there has been great interest in generating squeezed radiation. Optical measurements have three characteristics that enable them to reach the quantum noise level more readily than in other fields of physics: (1) optical signals are naturally immune to external sources of noise; (2) thermal noise at room temperature is negligible in the optical domain; (3) the outstanding equalities of the optical sources and detectors allow a very-low-level instrumental noise. The first observation of squeezing was achieved by R. S. Slusher *et al.* in 1987 in an experiment of parametric generation involving four-wave mixing in sodium vapor.

Later many other systems were proposed and realized also involving laser oscillators. The field is still strongly progressing, yet technical applications in any of the above-mentioned fields have not yet evolved (for a review see Berman, 1994).

F. Measurement of quantum states

In quantum theory all information on a quantum system is contained in the wave function. It is only in recent years that the theoretical knowledge and the experimental technology were acquired to prepare a specific system such as light or atoms in a particular quantum state. The preparation of squeezed states discussed above is one example. The ability to "engineer" quantum states offers fascinating possibilities for testing elementary predictions of quantum mechanics. Furthermore there are practical implications involved; specifically designed laser fields (e.g., squeezed light) may allow high-precision interferometry owing to a possible reduction of quantum noise. The preparation of particular molecular states could lead to a detailed control of chemical reactions. Engineering of states also requires a successful measurement. The wave function of a quantum state cannot, of course, be determined in a single measurement. Therefore the initial conditions in a measurement have to be reproduced repeatedly in order to sample the data. There has been impressive progress in theoretical as well as in experimental work in developing strategies to reconstruct the various quasiprobability distributions and other representations of a quantum state. Since pointlike sampling in quantum-mechanical phase space is forbidden by the uncertainty principle, a tomographic method is used, circumventing this problem by investigating thin slices, circular discs, or infinitesimal rings of the quasiprobability distribution in phase space. In this way quasiprobability distributions (the Wigner function or Q function) are obtained as a representation of the quantum state.

The first reconstruction of a Wigner function was demonstrated for a light field by M. Raymer *et al.* Since the quantization of the radiation field is performed in analogy to the harmonic oscillator, the dynamics of a single mode of light correspond to the dynamics of a quantum particle in a harmonic potential. In particular, the amplitudes of the magnetic and electric fields are the conjugate variables corresponding to position and momentum. Hence phase-space considerations can immediately be transferred to light. The actual analysis of the light field is performed by a homodyne detector. The unknown light is mixed at a beam splitter with a strong coherent laser field. The signal in the two arms is analyzed when the phase of the laser light is shifted, leading to the reconstruction of the Wigner function. More recently the group of *D*. Wineland at NIST in Boulder managed to determine the vibrational quantum state of a single ion stored in a Paul trap.

Quantum state measurements is a new and fascinating area of research that opens an important new window on the quantum world. It has now become possible to extract complete information about an elementary quantum system such as a single mode of light, a molecule, or a single trapped particle and to determine the wave function of such a system.

G. Quantum information

Quantum physics provides means for processing and transmitting information that differ fundamentally from classical physics. It turns out that information theory and quantum mechanics fit together very well. The entanglement of quantum objects and the inherent quantum nonlocality as the basis of the Einstein-Podolsky-Rosen paradox and the Bell inequalities forms the essential new ingredient that distinguishes quantum from classical information theory. The new disciplines can essentially be subdivided into three overlapping areas: quantum computation, quantum cryptography, and quantum communication (Zeilinger *et al.*, 1998).

Quantum computers as introduced by D. Deutsch in 1985 make use of the special properties of quantum theory. The binary information is stored in a quantum object. In principle, any two-state system can be used as a quantum bit (qu bit). Examples used in experiments include the polarizations of photons, the orientations of electron and nuclear spins, and energy levels of atoms or quantum dots. For simplicity we shall limit the discussion here to a two-level atom. Apart from the information that the atom is in either an upper or lower state, superpositions of the states are also possible. The reason why quantum computers are faster is their ability to process quantum superpositions of many numbers in one computational step, each computational step being a unitary transformation of quantum registers. The ability of particles to be in a superposition of more than one quantum state naturally introduces a form of parallelism that can, in principle, perform some traditional computing tasks faster than is possible with classical computers. In recent years a new quantum theory of computation has been developed and it has been shown that the computer power grows exponentially with the size of the quantum register. An open question is whether it would ever be possible or practical to build physical devices to perform such computations or whether they would forever remain theoretical curiosities. Quantum computers require a coherent, controlled evolution of the quantum system and a certain period of time to complete the computations. Quantum states are notoriously delicate, and it is not clear at the moment whether the system could be isolated sufficiently from environmental influences to present the original states from being destroyed (Williams and Clearwater, 1997; Steane, 1998).

Quantum logic gates perform unitary operations on qu bits, and in order to implement them it is necessary to perform a unitary transformation on one physical subsystem conditioned upon the quantum state of another one. A basic operation of this sort is the quantum-controlled NOT gate. The special feature of this operation is that it transforms superpositions into entanglements. This transformation can be reversed by applying the same controlled NOT operation, again being equivalent to a Bell measurement. Controlled NOT operation has been demonstrated for a single trapped ion by D. Wineland *et al.*, and for an atom in an optical cavity by H. J. Kimble *et al.*

To bring atoms into an entangled state, strong coupling between them is necessary. This can be realized in experiments described in the chapter on cavity quantum electrodynamics in Englert *et al.* (1998). These experiments achieve an entanglement between cavity field and

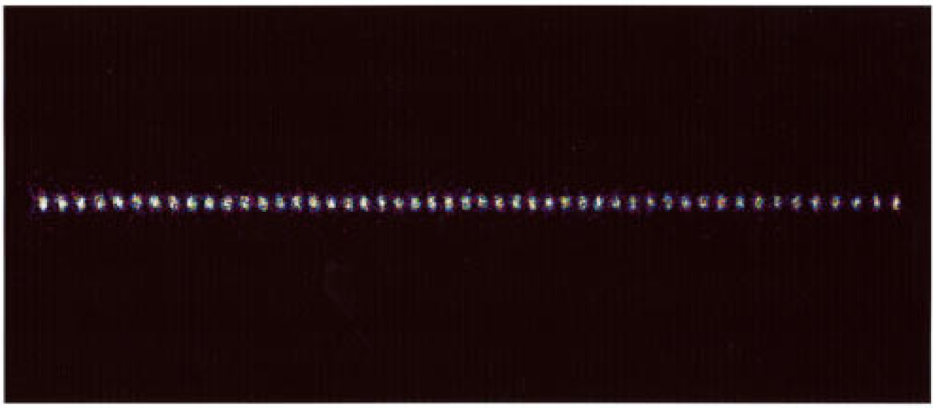

FIG. 5. (Color) Linear chain of ions in a trap. The position of the ions is marked through the fluorescence radiation. They are constantly emitting when illuminated by a laser beam. The laser beam is used simultaneously to cool the ions so that they stay in an ordered configuration. Such an ion chain has been proposed as the register of a quantum computer.

atoms through the strong coupling between both. Therefore entanglement between subsequent atoms via the field is also possible. Another way to entangle atoms is to use ion traps. The ions are harmonically bound to their position of rest. If they are in the quantum limit of their motion, an entanglement between vibrational and electronic excitation may be generated with the help of laser pulses. It is even possible to entangle different ions when a collective vibration is excited. A linear ion chain can thus be an ideal quantum register. The common center-of-mass oscillation of the ion chain along the axis is used to entangle different ions (see Fig. 5).

While the experimental realization of a quantum computer is still lagging behind, the realization of elements of quantum cryptography and quantum communication is much closer. In quantum cryptography, or quantum key distribution, the secret key is sent encoded in single-photon pulses, so that eavesdroppers will leave their mark behind due to the Heisenberg uncertainty principle when they try to read the information, which makes them immediately noticeable. The theory of quantum cryptography has been worked out in quite some detail (Bennett, 1992), and practical quantum channels have been realized by the use of optical fibers and low-intensity light pulses containing, on average, fewer than one photon. Current state-of-the-art techniques provide kilobit-per-second transmission rates with errors at the level of 1%, this being sufficiently low for practical purposes. The main problem, however, is the noise in the avalanche photodiodes used as simple photon detectors today, with the photodiodes still showing very bad performance, especially in the region of 1.55 μm where the optical fibers have their smallest losses.

Quantum information, another widely discussed new field, also offers very interesting new possibilities. We shall mention just two: quantum dense coding and quantum teleportation. The term dense coding describes the possibility of transmitting more than one bit by manipulating only a single two-state particle. This is possible when sender and receiver share a pair of entangled photons. The information that can be coded in one of the photons is twice as large as in the case of a classical information channel. An entangled photon pair also plays the decisive role in the case of teleportation, experimentally demonstrated by the groups of F. de Martini and A. Zeilinger and recently also by H. J. Kimble (see also the contribution by A. Zeilinger in this issue). Teleportation enables information to be sent on a particular quantum state, e.g., of a photon, by sending classical information containing the result of a joint Bell state measurement performed on the photon to be teleported and one auxiliary photon provided by the entangled photon pair. This measurement projects the other photon of the pair into a quantum state uniquely related to the original one owing to entanglement. With the result of this measurement transmitted classically to the receiver, a transformation of the auxiliary state is performed to reproduce the original quantum state.

H. Conclusion—quantum optics

The examples given in this review demonstrate that the field of quantum optics has been branching out tremendously in recent years. Whereas the pure quantum phenomena observed in the late seventies were very few and mostly connected to spontaneous emission processes, the field has now broadened to include many basic phenomena of quantum physics, for example, the measurement process and the preparation of quantum states leading to a deeper understanding of quantum physics and the peculiarities of the quantum world. On the other side it is also obvious that important new technical applications may evolve. It is still too early to make predictions about applications like quantum computing, but it is already clear that quantum cryptography will be a useful tool. Another development is the microlaser which resulted from the studies of cavity quantum electrodynamics. It has proven to be an efficient laser system, which is already in use in optical communication.

REFERENCES

Adams, C. S., and E. Riis, 1997, Prog. Quantum Electron. **21**, 1.

Arimondo, E., W. D. Phillips, and F. Strumia, 1992, Eds., *Laser Manipulation of Atoms and Ions, Proceedings of the International School of Physics Enrico Fermi, Course CXVIII* (North-Holland, Amsterdam).

Bassani, G. F., M. Inguscio, and T. W. Hänsch, 1989, Eds., *The Hydrogen Atom* (Springer, Berlin).

Bennett, C. H., 1992, Science **257**, 737.

Berman, P., 1994, Ed., *Cavity Quantum Electrodynamics* (Academic, New York).

Georgia Southern University, 1998, Bose-Einstein Condensation Homepage, http://amo.phy.gasou.edu/bec.html/

Braginsky, V. B., and F. Ya. Khalili, 1992, *Quantum Measurement* (Cambridge University, Cambridge, England).

Briegel, H., B.-G. Englert, M. O. Scully, and H. Walther, 1997, in *Atom-Interferometry*, edited by P. Berman (Academic, New York), p. 217.

Chiao, R. Y., P. G. Kwiat, and A. M. Steinberg, 1994, in *Advances in Atomic, Molecular, and Optical Physics*, edited by Benjamin Bederson and Herbert Walther (Academic, New York), Vol. 34, p. 35.

Chiao, R. Y., and A. M. Steinberg, 1998, in *Progress in Optics*, edited by E. Wolf (North-Holland, Amsterdam), Vol. 37, p. 345.

Cohen-Tannoudji, C., 1977, in *Frontiers in Laser Spectroscopy*, edited by R. Balian, S. Haroche, and S. Libeman (North-Holland, Amsterdam), Vol. 1, p. 3.

Cresser, J. D., J. Häger, G. Leuchs, M. Rateike, and H. Walther, 1982, in *Dissipative Systems in Quantum Optics*, edited by R. Bonifacio, Topics in Current Physics No. 27 (Springer, Berlin), p. 21.

Demtröder, W., 1996, *Laser Spectroscopy: Instrumentation and Basic Concepts*, 2nd edition (Springer, Heidelberg).

Englert, B. G., M. Löffler, O. Benson, B. Varcoe, M. Weidinger, and H. Walther, 1998, Fortschr. Phys. **46**, 6.

Hänsch, T. W., and M. Inguscio. 1994, Eds., *Frontiers in Laser Spectroscopy, Proceedings of the International School of Physics Enrico Fermi, Course CXX* (North-Holland, Amsterdam).

Haroche, S., 1998, Phys. Today **51**, 36.

Haroche, S., and D. Kleppner, 1989, Phys. Today **42**, 24.

Höffges, J. T., H. W. Baldauf, W. Lange, and H. Walther, 1997, J. Mod. Opt. **44**, 1999.

Leonhardt, U., 1997, *Measuring the Quantum State of Light* (Cambridge University, Cambridge, England).

Meystre, P., 1992, in *Progress in Optics*, edited by E. Wolf (North-Holland, Amsterdam), Vol. 30, p. 261.

Reynaud, S., H. Heidmann, E. Giacobino, and C. Fabre, 1992, in *Progress in Optics*, edited by E. Wolf (North-Holland, Amsterdam), Vol. 30, p. 1.

Schleich, W. P., and M. Raymer, 1997, Eds., Quantum State Preparation and Measurement, Special Issue, J. Mod. Opt. **44**.

Shih, Y., 1998, in *Advances in Atomic, Molecular, and Optical Physics*, edited by Benjamin Bederson and Herbert Walther (Academic, New York), Vol. 41, p. 1.

Steane, A., 1998, Rep. Prog. Phys. **61**, 117.

Walther, H., 1992, Phys. Rep. **219**, 263.

Williams, C. P., and S. H. Clearwater, 1997, *Explorations in Quantum Computing* (Springer, Berlin).

Yamamoto, Y., and R. S. Slusher, 1993, Phys. Today **46**, 66.

Zeilinger, A., D. Deutsch, A. Ekert, W. Tittel, G. Ribordy, N. Gisin, D. DiVincenzo, and B. Terhal, 1998, Phys. World **11**, 33.