Coming of age in quantum optics

S. Stenholm

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By S. Stenholm

Helsinki Institute of Physics, PO Box 9, FIN-00014,
University of Helsinki, Finland

This paper reviews the historical development of laser physics and quantum optics. The various stages are exemplified and their role in the emergence of the present situation is emphasized. Some important directions for future developments are offered.

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1. In search of the self

(*a*) *The roots*

Many of the techniques and, indeed, many of the researchers came to laser physics from a background in resonance spectroscopy. After World War II, the technology to generate radio and microwaves became freed for academic exploitation. The many applications (nuclear magnetic resonance (NMR), electron spin resonance (ESR) and molecular microwave spectroscopy) provided much insight into the structure and dynamics of matter. The spectral structures were determined, and transient techniques were developed to measure relaxation parameters.

When the laser source was introduced in 1960, all the accumulated knowledge was available for applications in the new frequency range. However, the first decade was mainly spent developing the understanding of the device itself; many physical problems were encountered and mastered along the way.

(*b*) *The heroic age*

In the 1970s, the laser sources were mainly used to perform spectroscopy inside the cavity. The tuning ranges of the devices were small, and hence only a few atoms or molecules could be investigated. The main ones were as follows.

(i) Neon. This was very popular, because the work horse of lasers was the He–Ne system, still widely used in applications.

(ii) CO_2. This strong laser in the infrared operates nearly as reliably, and it has been widely used in many kinds of applications.

(iii) NH_3. This molecule resonates with an infrared lasing line of Ne, and hence it could be used as an intracavity absorber. Its narrow lines provide an excellent frequency standard. The resolving of the 2 kHz recoil shift long remained the highest resolution in laser spectroscopy. Only the recently developed quantum jump methods offer the opportunity to see much narrower resonances. The theoretical work carried out in calculating the recoil shifts constituted the forerunner of modern laser cooling theory.

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(c) Down to essentials

It seemed that the applications of laser physics would become integrated with the corresponding special fields, like so many other technologies; NMR can hardly be regarded as a unified area of physics any more. During the 1980s, however, the technical progress gave quantum optics new life. The semiclassical approach used in spectroscopy had to give way to a new wave of experiments which penetrated down to the level where single quantum units manifested themselves. We have here the following fields:

cavity QED ⇒ oscillator with a few photons only,
laser cooling ⇒ velocity resolution down to a single photon recoil,
traps for atomic particles ⇒ one or a few atomic particles can be observed.

These techniques initiated some very interesting and novel work, which formed the foundations for the work in the 1990s.

2. Coming of age

In the present decade, quantum optics and laser physics are coming of age. Much of the limitations of past times can now be dispensed with; new areas of physics and novel applications can be envisaged. These fall, in my opinion, into the following three categories: (1) time-dependent phenomena; (2) many-atom effects; and (3) quantum device synthesis.

I will discuss each one in turn.

(a) Time-dependent phenomena

Pulsed laser can now provide well controlled pulses down to a few femtoseconds. The materials technology allows the construction of structures which display phenomena characterized by space and time structures which can be monitored and analysed. Semiconductor heterostructures especially can realize many textbook examples of quantum phenomena.

The development has led to progress in the following areas.

(i) One can excite and observe molecular dynamics on electronic energy surfaces. With laser cooled and trapped atoms, collisional events can be studied in an energy range where the lessons from conventional scattering theory have to be abandoned and new theories are needed. With selective laser excitation, one may gradually approach the goal of steered chemical reactions.

(ii) In semiconductor heterostructures, it is possible to follow the time scale of individual electrons moving. The Bloch oscillations and their corresponding terahertz radiation have been observed. One may also try to monitor the electronic tunneling times, and learn both some basic physics and some technically important facts. In the artificial mesoscopic structures, collisions are few and the charge transport partly takes place through ballistic electrons. Following their motion offers and interesting and challenging task.

(iii) The ability to selectively induce and follow simple dynamic phenomena offers a novel opportunity to test the time dependent aspects of Schrödinger quantum mechanics. No such real time monitoring of quantum evolution has been possible before.

(*b*) *Many-atom effects*

Laser spectroscopy has worked for decades to eliminate the effects of atomic interactions. Dilute gases, sparse beams and single particle traps have been the tools used. Now, however, the very interactions between the atoms have become essential aspects of the novel developments. The following areas of research have emerged.

(i) Laser cooling, atomic traps and evaporative cooling have made it possible to reach the goal of Bose–Einstein condensation in a dilute interacting gas. It has not yet been possible to perform the corresponding cooling of Fermionic systems to the conditions where their Fermi degeneration can be observed.

(ii) The observation of Bosonic condensation has given new impetus to the search for an atomic laser. This device should produce a beam of quantum correlated atoms, which could be used for various novel experiments. This requires a pump mechanism and a coherent generation process.

(iii) In an ionic trap, one can observe a variety of collective phenomena. The ions carry out correlated motion, they order or go into chaotic motion. All this is mainly classical, but detailed investigations show that quantum localization and diffusion are to be found even here.

(*c*) *Quantum device synthesis*

All physical fields start from the analysis of spontaneously occurring natural phenomena. The experimentalists then interrogate nature by bringing in technical artifacts that perturb it. In this manner the fundamental processes are identified and understood. When they are mastered well enough, the age of synthesis arrives. Devices can be planned and constructed to satisfied predetermined needs.

Conventional electronics has clearly undergone such an evolution. At one time electron motion in vacuum was investigated. Quantum theory made it possible to understand the behaviour of electrons in solids, conductors and semiconductors. No scientist constructing an electronic device needs today bother about the quantum states in the components. This is the stage of a mature science.

I am claiming that quantum optics is approaching the stage of a mature science. In the preceding decades we have investigated what the lasers offered by their technology. Now we think about tests and uses of quantum mechanics even without having any particular hardware implementation in mind. Some examples follow.

(i) Starting from the pioneering work by John Bell, many researchers have devised fundamental tests of quantum correlations. These are non-local and behave differently from their classical counterparts. In these experiments, the probabilistic character of quantum mechanics and the complementarity of observations give unexpected results. So far, quantum theory has survived every test; nature does indeed seem to behave just the way dictated by quantum mechanics.

(ii) When information is coded into a quantum channel, the peculiarities of quantum mechanics can be utilized to ensure security of communication and protection against eavesdropping. The method is already nearly at the commercial state of application.

(iii) When information is stored in a quantum degree of freedom, and it is subsequently manipulated there, a new situation ensues. The performance of logic operations and the observation of the results now satisfy the rules of quantum theory. This may also be used as an advantage as the case of quantum computers shows. No realistic device has yet been suggested.

All the topics discussed above are based directly on the properties of quantum theory itself. They may thus, in principle, be realized in many different ways, three of which are listed below.

(1) Transmission of single or a few photon states. Such devices are reality today, and they can be used to test and develop the suggestions above. The photons do not interact with each other, and they are only weakly perturbed by a neutral environment. They can be transmitted through fibres with small losses. Thus they have been used in most experiments.

(2) Ions or atoms trapped. Ions in traps behave in very well controlled ways, and their relaxation times are rather long. Thus they may serve as information storage devices, where the information can be manipulated and transferred with standard optical techniques. A future field for interesting experiments consists of atoms localized in extended optical lattices.

(3) If we want to make commercially viable electronic devices, we should use solid state structures for information storage and manipulation. Quantum wells and quantum dots in semiconductor heterostructures offer, in principle, the tools for such applications. However, the quantum states in solids are coupled to many degrees of freedom, and hence they relax rapidly.