A short history of atomic physics in the twentieth century

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[S0034-6861(99)02302-8]

This brief account describes some of the developments of atomic physics during the twentieth century that particularly appeal to the author's sensibility, that of an experimental physicist. It makes no pretense to being comprehensive. On the contrary, major theoretical and experimental areas have been omitted because of the space limitations. Several excellent historical studies that can help to fill out the picture are listed in the Biblography.

In 1943 the American Physical Society established the first of the many divisions by which physics is now split into subfields. This was the Division of Electron Physics, later to become the Division of Electron and Atomic Physics, and later yet to become the Division of Atomic, Molecular, and Optical Physics. At the beginning of the century, however, such distinctions were unnecessary. What we now call atomic physics was then the very core of physical science.

Here are some of the concepts that were on hand at the turn of the century. There was overwhelming but indirect evidence for the existence of atoms, including the success of kinetic theory, Mendeleev's periodic table, the association of spectral lines with elements, the existence of electrons and ions, and an understanding of the electromagnetic origin of radiation by matter. (If the Nobel Prize can be regarded as the ultimate sanction of scientific credibility, however, then official recognition of the existence of atoms came surprisingly late, in 1926, when the prize was given to Jean Baptiste Perrin for research on the "discontinuous structure of matter.") In the background were the great edifices of Newtonian mechanics and electromagnetic theory, and, on a somewhat less firm pedestal, thermodynamics and statistical mechanics.

Towards the close of the 19th century the accomplishments of physics were so astonishing that Oliver Lodge exclaimed that "the whole subject of radiation is working out splendidly," and at the opening of the Ryerson Laboratory of the University of Chicago in 1894 A. A. Michelson stated that "The more important fundamental laws and facts of physical science have all been discovered . . . ." Nevertheless, there were vexing problems, for instance the failure of simple gases to have the predicted heat capacities, the lack of any real understanding of atoms, and the failure to discover a key for interpreting the thousands of pages of accurate spectral data that had been accumulated over the decades. Then as the century drew to a close a revolution was precipitated by the discoveries of radioactivity, x rays, electrons, and the electrical nature of matter, and particularly the recognition of the complete failure of statistical mechanics to describe a thermal radiation field.

I. THE FIRST THIRTY-FIVE YEARS

The scientific revolution that led to the creation of modern physics was largely accomplished in the first three decades of this century. Its major achievements were Einstein's theories of relativity and gravitation, and the creation of quantum mechanics. It is quantum mechanics that plays the most important role in this history, for before its creation atomic theory was crude and fundamentally empirical—which is to say there really was no theory—while afterwards there existed a comprehensive theory that provided a new language for describing nature and could account for atomic and molecular structure and dynamical processes in exquisite detail. The major figures in the development of quantum mechanics are well known: Planck, Einstein, Bohr, and later de Broglie, Heisenberg, Schrödinger, Dirac, Pauli, and Born. Such a confluence of theoretical genius represents one of those remarkable episodes in history when great minds profoundly change our world view, but their achievements were inspired and guided by the discoveries of experimenters who were also scientists of genius.

The first intimations that the foundations of physics might be fundamentally flawed surfaced in 1900 when Planck first introduced the concept of quantization. Planck's proposal was directly inspired by an experiment. An accurate spectrum in the near infrared of energy radiated by a hot body had been obtained in 1897 by E. Paschen and G. Wien, who discovered that the data could be accurately described by an expression that decreased exponentially with frequency. In October, 1900, while attempting to find a physical justification for Wien's exponential rule, Planck learned of surprising results from two groups, O. Lummer and E. Pringsheim, and H. Rubens and F. Kurlbaum. Using new techniques for infrared detection they were able to extend the radiation measurements farther into the infrared regime. To his confusion, Planck found that the new data seriously departed from the exponential behavior predicted by Wien. Before the end of the year, however, Planck found a new empirical expression that fitted the thermal spectrum throughout the infrared and visible range. He pointed out that one could "derive" his expression from statistical mechanics by simply quantizing the energies of the fictitious oscillators with which he modeled matter. This quantum hypothesis was so outlandish, however, that Planck regarded it as little more than a mathematical trick.

 0034-6861/99/71(2)/78(7)/$16.40

Planck's hypothesis had essentially no impact until 1905 when Einstein treated it seriously, pointing out that it implied that light itself must have quantum properties. Planck's hypothesis was motivated by experiment, but it had little direct consequence. Characteristically, Einstein's theory seemed to be motivated by no experimental evidence, but it had lots of consequences. One was that the energy of a photoelectron should depend only on the frequency of light, not its intensity. The photoelectric effect had been discovered by H. Hertz in 1887. In 1899 J. J. Thomson showed that the effect resulted from the ejection of electrons. In 1909 R. A. Millikan carried out the first of a series of studies of photoelectron energy and the results were consistent with Einstein's hypothesis. Nevertheless, the hypothesis itself remained controversial. However, in a 1916 paper, Einstein showed that light quanta also carry momentum and this was experimentally confirmed by A. Compton in 1923. Compton measured the energy loss in x-ray scattering due to the electron recoil. His experiment left little doubt as to the physical reality of light quanta.

The driving force for the quantum theory of radiation was the problem of thermal radiation, but the driving force for the actual creation of quantum mechanics was the need to understand atoms. The crucial event was Bohr's 1913 paper on the hydrogen atom, in which he introduced the concept of stationary energy states and quantum jumps accompanied by the emission of monochromatic radiation. The paper is remarkable for its daring introduction of radical ideas and its cavalier disregard of classical electromagnetic theory.

Bohr's starting point was the discovery of the atomic nucleus. In 1911 E. Rutherford, building on his studies of radioactive transformations, carried out the classic experiment on alpha-particle scattering from gold, which resulted in his discovery of the nucleus and led him to propose that atoms have planetary-like properties. By combining the classical description of an electron moving in the field of a proton with rules that were absurd by contemporary standards, Bohr accounted for the existence of atomic spectral lines, the exact form of the hydrogen spectrum, and the precise numerical value for the single constant in Balmer's empirical formula—the arguably misnamed Rydberg constant. This was one of those rare syntheses in physics in which apparently unrelated data are combined to describe phenomena that previously seemed unrelated, such as Newton's derivation of the acceleration of gravity on earth from the period of the moon, or Maxwell's deduction of the speed of light from the electric and magnetic force constants. All of these achievements led to a flowering of activity that confirmed the theory, but while Newton's gravitational theory and Maxwell's electromagnetic theory were essentially complete (at least, for their own epochs), Bohr's model of the atom was fundamentally incomplete. It was intended to serve as a guide and an imperative for a revolutionary new mechanics. The esteem in which Bohr was held by those who knew him can be traced to the vision with which he saw what was to come and to his role in guiding the revolution.

At the heart of Bohr's model was his concept of stationary energy states, an idea totally incompatible with traditional physics. Nevertheless, within a year its physical reality was demonstrated by J. Franck and G. Hertz in a study of the energy loss of electrons in a gas. Spatial quantization of angular momentum, a concept proposed by A. Sommerfeld that was equally at odds with traditional theory, was demonstrated in 1921 by O. Stern and W. Gerlach in an experiment on the deflection of atoms in an inhomogeneous magnetic field.

Early attempts by Bohr, Sommerfeld, and others to describe these phenomena, the "old" quantum theory, ultimately failed. The correct theory came in what seems, in retrospect, like a series of thunderbolts. In 1923 de Broglie pointed out that energy quantization could be achieved by associating a wavelength with the electron, in 1924 Heisenberg published his theory of matrix mechanics, and within a half year Schrödinger published his theory of wave mechanics. There was deep confusion about the interpretation of these theories until Born, in 1926, showed how to interpret them in terms of probability theory. In 1928, when Dirac presented his relativistic theory for the electron, quantum mechanics came of age.

Throughout the period of these developments, the major features of the nucleus were identified: the relation between nuclear charge and nuclear mass, isotopes, nuclear spin and statistics, and nuclear magnetic moments. The final nuclear constituent, the neutron, was discovered by Chadwick in 1932. With this understanding of the nucleus, and the creation of quantum mechanics, the foundations of atomic physics were complete.

Nearly all the major players in this history received the Nobel Prize in physics: Thomson (1906), Wien (1911), Planck (1919), Einstein (1921), Bohr (1922), Millikan (1923), Franck and Hertz (1926), Perrin (1926), Compton (1927), de Broglie (1929), Heisenberg (1932), Schrödinger (1933), Dirac (1933), and Born (1955). Rutherford received the Nobel Prize in chemistry in 1908, and in 1935 Chadwick received the prize in physics.

II. THE NEXT THIRTY YEARS

We break this chronological narrative for a moment and skip ahead to June, 1947, when a group of physicists met to discuss fundamental problems in physics at Shelter Island, New York. High on the agenda were questions about the validity of the Dirac theory of the electron, particularly the problem of the electron's self-energy and the possibility that there might be observable effects of the vacuum, issues that had been raised by H. Bethe, H. Kramers, and others. The problems had been in the air since the early 1930s, and late in the decade the possibility of an experimental test had been raised. According to the Dirac theory, the principal optical spectral line of hydrogen has two components, separated by the small fine-structure interval. There was some suggestion that a third component might exist, but the evidence—a possible substructure with a splitting much smaller than the width of the spectral line—was hardly definitive.

The Shelter Island meeting was devoted to theory, but three new experimental results were reported whose impact was profound. I. I. Rabi described the first atomic-beam resonance measurements of the hyperfine structure of hydrogen. The hyperfine interval was found to be larger than predicted by the Dirac theory by a little over one part in a thousand. In spite of this small size the discrepancy was big, for the experiment was accurate to about one part in a hundred thousand. G. Breit suggested that the discrepancy could signify a discrepancy in the size of the magnetic moment of the electron from the value predicted by the Dirac theory—in other words, a breakdown of the Dirac theory. Rabi also described a series of atomic-beam resonance experiments by P. Kusch, which confirmed that the electron's magnetic moment was indeed anomalous.

W. Lamb reported results of an experiment that left no doubt that the Dirac theory was in error. Lamb showed that there was indeed a third component in the fine-structure spectrum of hydrogen, using a radio-frequency resonance technique with a resolution hundreds of times superior to the best that could be achieved optically. The extra component was due to an energy splitting between two states which, according to the Dirac theory, should have had identical energy.

All three of these experiments gave precise values for effects that one decade earlier would have been unobservably small. Their impact was immediate: they triggered the creation of the modern relativistic theory of quantum electrodynamics (QED) by J. Schwinger, and R. P. Feynman, both of whom were at the Shelter Island meeting, and S.-I. Tomanaga. For these advances the Nobel Prize was awarded to Lamb and Kusch in 1955, to Feynman, Schwinger, and Tomanaga (who was not at Shelter Island) in 1965. Rabi received the prize in 1944 for the invention of molecular-beam magnetic resonance. Rabi's prize was for the experimental advance that made these experiments possible and that catapulted discoveries and new technologies for decades to come.

Molecular-beam magnetic resonance had its origin in the magnetic deflection technique developed by O. Stern to demonstrate spatial quantization. In 1933 Rabi set up a laboratory at Columbia University to apply the deflection method to improve on Stern's measurement of the proton's magnetic moment. In attempting to understand some problems in this experiment, Rabi realized that by applying a magnetic field that oscillates at the frequency with which the proton precesses in an applied magnetic field, one could reorient the proton's spin. The reorientation would be detectable because it would alter the trajectory of the molecule in a subsequent field gradient. In short, Rabi made it possible to determine a magnetic moment by measuring a frequency. Furthermore, the moment could be measured to a precision incomparably higher than had been obtainable by any previous method.

Molecular-beam magnetic resonance could achieve breathtaking precision by making it possible to observe atomic and molecular systems free from collisions or other perturbations, essentially in total isolation. The method revealed internal interactions in atoms and molecules and provided a wealth of information not only on atomic and molecular structure, but also on nuclear properties. Among the very first discoveries by Rabi's group was that the deuteron possesses a quadrupole moment. This was the very first evidence that the force between nucleons is noncentral. War abruptly brought the research to a halt, but at the war's conclusion, the research rushed forward. One new stream of studies was devoted to determining the spins, magnetic moments, and higher-order moments in nuclei by atomic-beam magnetic resonance; another to determining magnetic and electronic interactions in molecules using magnetic and electric molecular-beam resonance.

The inherent resolution of molecular-beam magnetic resonance is determined by the uncertainty principle. The resolution increases directly with the time during which the atom interacts with the oscillating field. In principle one can increase this time simply by making the apparatus longer, but this strategy soon ran into technical difficulties. However, these were largely overcome by N. F. Ramsey's invention of the separated oscillatory field method in 1950. Ramsey's method opened the way to a wealth of studies on the internal interactions in molecular hydrogen and other molecules, and on hyperfine structure in atoms. When this method was used to measure the hyperfine interval of cesium, the transition frequency could be determined with such high accuracy that it could be employed as a frequency standard, providing the basis of an atomic clock. The first cesium atomic clock was operated in a standards laboratory by L. Essen and J. V. L. Parry in 1955, and J. R. Zacharias pioneered the construction of a practical, portable, cesium atomic-beam clock. Cesium clocks were soon constructed in the world's major standards laboratories. These clocks have been steadily refined over the decades and now provide the timing basis and the satellite-borne clocks that made possible the Global Positioning System. Ramsey was awarded the Nobel Prize for the separated oscillatory field method in 1989.

Increasingly sensitive tests of QED have been carried out up to the present day. The free electron and the hydrogen atom continue to provide principal testing grounds, as will be described, but high-precision studies have also been carried out on the spectrum of helium and high hydrogenlike and heliumlike heavy ions. Quantum electrodynamic tests using hydrogen are eventually limited by uncertainties in the structure of the proton, and to overcome this problem V. W. Hughes created muonium (the muon-electron atom) in 1960. Studies of the hyperfine structure of muonium by Hughes and V. L. Telegdi, and later studies of the optical spectrum, are among the critical tests of QED. Positronium (the electron-positron atom), first created by M. Deutsch in

1952, has been similarly employed, with early measurement of its hyperfine structure followed by later studies of its optical spectrum.

A related development during this period was the creation of nuclear magnetic resonance by F. Bloch and, independently, by E.M. Purcell, in 1946. Nuclear magnetic resonance (NMR) provided a new method for measuring the spins and magnetic moments of nuclei. The principle applications have been to the study of molecular structure, the structure and dynamics of solids, liquids and gases, and to biological and medical applications, including the technique of magnetic-resonance imaging. However, because these applications are somewhat distinct from atomic physics, we mention these developments only in passing.

The wartime advances in electronics, particularly in radar, played a profound role in advancing the magnetic-resonance experiments of the late 1940s. Concerns about the absorption of microwave signals by the atmosphere, particularly by water vapor, had stimulated microwave absorption measurements in gases. At the war's end these methods were employed to measure molecular rotational and vibrational structure. Working at Columbia, C. H. Townes realized that if he selected molecules occupying the upper of two energy levels and applied a field oscillating at the transition frequency, the radiated energy would stimulate the molecules to radiate, adding to the energy in the applied field and thereby amplifying it. If the fields were large enough, the device would oscillate. For such a device the name "maser" was coined, an acronym for microwave amplification by stimulated emission of radiation.

Stimulated emission—the physical process at the heart of maser operation—was first recognized by Einstein in 1916. Under normal conditions of thermal equilibrium, however, in populations of atoms or molecules, the number of particles in a lower state always exceeds that in a higher energy state, and radiation is absorbed rather than amplified. The first maser was demonstrated by Townes in 1954, using a microwave transition in ammonia which had been prepared in an excited state by molecular-beam methods. The principle of maser operation was recognized independently in the Soviet Union by N. G. Basov and A. M. Prokhorov, who shortly afterward also achieved maser operation with ammonia. The statistical properties of the maser's radiation were of immediate interest: these studies inaugurated the field of quantum optics. The maser was also investigated as a frequency standard and as an amplifier. In 1956 N. Bloembergen proposed a solid-state three-level maser in which microwave pumping created a population inversion, operating on paramagnetic ions in a host lattice. Such solid-state masers were soon developed by a number of groups and found immediate application as low-noise amplifiers by radio astronomers. Among the discoveries made with these masers was the existence of the 3-degree cosmic background radiation by A. Penzias and R. W. Wilson in 1965.

The possibilities for achieving maser action for frequencies extending into the optical region were discussed by A. L. Schawlow and Townes in 1958. In 1960 the first optical maser, soon to be dubbed a laser, was demonstrated by T. H. Maiman, using a ruby system that was optically pumped with a flashlamp. Shortly afterwards continuous laser action was achieved by A. Javan, using a gaseous discharge of helium and neon to generate infrared radiation in an inverted population of neon ions. Soon thereafter the helium-neon was operated in the optical region on a red transition, forming the familiar red "HeNe" laser that has been a workhorse ever since.

Two other advances in this period deserve mention, for they established a major theme for atomic physics in the decades to come: control of the motions and the internal states of atoms and ions. A. Kastler devised a method for polarizing atoms by absorption of circularly polarized optical resonance light. Atoms in a thermal distribution of internal magnetic states could be transformed into a single state. The state could be changed by applying a radio-frequency field and detected by monitoring the transmitted light. This effect, called optical double resonance, was first observed by J. Brossel and Kastler in 1953. The method opened the way to new measurements of atomic interactions and to the creation of magnetometers and optically pumped atomic clocks.

In attempting to develop new ways to guide and focus ions, W. Paul discovered that by combining an oscillating and a static quadrupole electric field he could achieve regions of stability in which ions of a certain charge-to-mass ratio are efficiently channeled. The method provided the basis of an extremely simple and sensitive mass spectrometer, which is now widely used in research and industrial applications. He went on to operate the device in three dimensions, creating a trap for ions that would hold the particles almost indefinitely. This work established a theme that has continued ever since—increasingly precise control of the motions of ions and atoms.

Townes, Basov, and Prokhorov received the Nobel Prize in 1964 for the maser and the laser. Kastler received the Prize in 1966 for his method of radio-frequency spectroscopy with optically pumped atoms, and Paul received the Nobel Prize in 1989 for development of the ion trap technique.

III. ATOMIC PHYSICS SINCE 1965

During the final third of this century lasers became ubiquitous in daily life. They revolutionized communications and found applications from heavy manufacturing to eye surgery. Lasers also became ubiquitous throughout the sciences, with applications ranging from aligning great telescopes and gargantuan accelerators to measuring sizes and shapes of macromolecules. In atomic physics the advent of tunable lasers caused a fundamental change in the concept of spectroscopy. Initially lasers "merely" increased spectroscopic resolution by several powers of ten, but then they opened the way to the creation of new atomic species, the extension of spectroscopy from the frequency to the time domain, the development of nonlinear optics, and the creation of powerful ways to manipulate and control atoms. In addition, the generation of laser light precipitated new studies in the statistical properties of light, the nature of light-matter interactions, and nonlinear optics. It created the field that grew into quantum optics. In this brief history one can only pick among some of the highlights.

Following the creation of the first ruby laser and the gaseous helium-neon laser, an arsenal of other types of lasers was developed and rapidly employed in atomic physics: gaseous lasers operating on rare-gas ions and various molecular species, solid-state lasers operating in the infrared and visible regimes, ultraviolet excimer lasers, and semiconductor diode lasers. All of these emit radiation at one of a series of discrete frequencies. Laser spectroscopy, however, requires continuously tunable radiation. This became a reality in 1965 when P. P. Sorokin invented the dye laser.

In traditional spectroscopy the resolution is limited by the thermal motion of the atoms—the first-order Doppler effect. The high spectral purity of a laser does not by itself overcome this problem. However, as pointed out by Lamb, the Doppler effect can be eliminated by using one laser beam to excite atoms that happen to be at rest, and a second to probe them. This technique, known as saturation spectroscopy, was applied by T. W. Hänsch in 1974 to study spectra in alkali atoms, the workhorses of atomic physics. Hänsch employed a relatively simple tunable dye-laser design that was quickly taken up by other laboratories, essentially opening a floodgate of new research.

Once Doppler broadening is eliminated, spectral resolution is often limited by the time available for the particle to interact with the radiation field. In the 1970s J. Hall and V. Chebotayev constructed a spectrometer designed to lengthen this time for a molecular gas by employing a wide-diameter radiation field with carefully controlled optical properties. With such spectrometers a series of spectral "atlases" were created that provided ultraprecise frequency markers across wide spectral regions. Laser stabilization techniques have been steadily refined by Hall, Hänsch, and others, and stability of greater than one part in 10^{14} over a period of many seconds has been achieved.

Schawlow played a major role not only in the creation of the laser but in many of the innovations of laser spectroscopy. For these contributions he received the Nobel Prize in 1981.

The intense fields of laser light make it possible to observe high-order radiation processes such as multiphoton transitions that are essentially unobservable with conventional light sources. Hydrogen, which continues to serve as a touchstone for spectroscopy, has yielded the most precise test of QED in an atom though study of such a transition—the two-photon transition from the ground state to the metastable 2S state. V. Chebotayev pointed out that by exciting the hydrogen in counter-propagating laser beams, one could excite every atom in the gas with no broadening due to the first-order Doppler effect. Hänsch observed the Doppler-free transition in hydrogen in 1975, and in a continuing series of advances in the control of atoms, the stabilization of lasers, and optical frequency metrology he eventually measured the transition to an absolute accuracy of four parts in 10^{13}. Combining this result with other ultraprecise measurements of hydrogen yields a value for the Lamb shift in which the comparison with QED is limited only by uncertainty in the charge distribution in the proton.

The most stringent of all low-energy tests of QED is a comparison of the experimental and theoretical values of the magnetic moment of the free electron. In the initial measurements of Rabi and Kusch, the magnetic moment anomaly—the discrepancy with the Dirac value—was precise to one percent. H. Dehmelt achieved a precision of three parts in 10^9 by observing a single electron confined in a trap consisting of a static quadrupole electric field and a magnetic field (the Penning trap). The electron in such a trap executes both cyclotron and spin precessional motions at frequencies which should be identical according to Dirac. Transitions between the two motions are induced by a weak oscillating field, and the state of the electron is monitored by measuring its vibrational amplitude through the current it induces in the electrodes. The difference between the experimental value for the anomaly and the prediction of QED, as calculated by T. Kinoshita, is $51\pm30\times10^{-9}$. Whether the small discrepancy is real or due to a possible error in the fine-structure constant, which sets the scale for all the QED effects, remains to be determined. Within this uncertainty, this result represents the most precise low-energy test of QED and indeed the most precise test of any theory in physics. For this achievement, Dehmelt was awarded the Nobel Prize in 1989.

The tradition of extracting nuclear interactions from atomic measurements dates back to early studies of hyperfine structure in the 1920s, but a new line of research was created in 1974 when C. and M.-A. Bouchiat pointed out the possibility of measuring effects from parity-nonconserving electron-nucleon interactions predicted by the electroweak theory. Experimental searches were carried out by several groups, as were major theoretical efforts to calculate the effect of the electroweak interactions on atomic structure. In 1996 C. E. Wieman succeeded in measuring the ratio of two electron-quark parity-violating interactions in cesium. The ratio adds a further constraint to the standard model, taking its place with the large body of data from high-energy physics on which the standard model is built.

In a work published the year after his 1916 paper that introduced stimulated emission, Einstein pointed out the intimate connection between momentum exchange and energy exchange in establishing the motional equilibrium of atoms and radiation. Fifty years were required for stimulated emission to be exploited in the creation of the maser and the laser; another twenty years were needed for atom-radiation momentum interchange to be exploited to manipulate and control atomic motion, and then to cool atoms to the microdegrees kelvin regime. A number of streams of research converged to achieve these advances.

Studies carried out by A. Ashkin in the early 1970s on the force of light on dielectric particles helped to stimulate research on the force of light by atoms. The research also produced the technology of ''optical tweezers'' for manipulating small particles, making it possible, for instance, to manipulate not only cells, but also the material within them. In the mid 1970s V. S. Letokhov and V. G. Minogin demonstrated effects of the alteration of atomic velocities with laser light.

The possibility of cooling atoms with radiation was proposed in 1975 by D. J. Wineland and Dehmelt, as well as by Hänsch and Schawlow. The key idea is to provide a portion of the energy needed for an atom to absorb radiation from the atom's kinetic energy by tuning the laser slightly to the red of the transition wavelength. (Alternatively, one can think of exploiting the Doppler effect to shift the radiation into resonance.) If the atom returns to its initial state by spontaneous emission, then as the process is repeated the atom cools. The process was demonstrated on a cloud of trapped ions by Wineland and also by Dehmelt in 1978. Applied to a gas, the method is known as Doppler cooling. Cooling ceases when the Doppler shift due to thermal motion becomes comparable with the natural linewidth for the transition, a situation called the Doppler limit, typically at a temperature of a few hundred microdegrees kelvin.

In 1982 W. D. Phillips and H. Metcalf slowed an atomic beam of sodium and cooled its longitudinal motion, using a counterpropagating beam of laser light and a spatially varying magnetic field to maintain the resonance condition. S. Chu demonstrated three-dimensional Doppler cooling with orthogonal laser beams in 1985. The motion of atoms at the intersection of the beams is so heavily damped that the gas behaves like a viscous fluid, dubbed ''optical molasses.'' Phillips measured the temperature of optical molasses and found it to be far below the predicted Doppler limit. The full theoretical explanation was provided by C. Cohen-Tannoudji, who showed that sub-Doppler cooling arises from an interplay between an atom's internal and translational states, involving energy shifts induced by the radiation field and optical pumping effects. When this ''polarization gradient'' cooling occurs, the temperature approaches the so-called recoil limit, typically one microdegree kelvin, set by the momentum kick due to the emission of a single photon. For these advances in laser cooling and trapping, the 1997 Nobel Prize was awarded to Chu, Phillips, and Cohen-Tannoudji.

For experimental studies cold atoms generally need to be confined, and of the various optical and magnetic traps that have been used for this purpose, the magneto-optical trap emerged as a workhorse because of its great strength and the ease of loading. The trap, created in 1987 by D. E. Pritchard and colleagues, employs a combination of magnetic-field gradients and circularly polarized standing waves to provide a relatively simple and open geometry.

With these tools for cooling and trapping atoms it was possible to study processes such as ultracold collisions, molecular photo-association, and the tunneling of atoms in optical lattices. In dense atomic clouds, scattering and absorption prevents laser cooling. The atoms can nevertheless be cooled efficiently by evaporation, as demonstrated by H. Hess, T. J. Greytak, and D. Kleppner in 1987. In 1995 Bose-Einstein condensation of an atomic gas was achieved by E. Cornell and Wieman, and W. Ketterle, using a strategy of laser cooling and trapping followed by evaporative cooling. Shortly thereafter R. Hulet demonstrated Bose-Einstein condensation in an atom with attractive interactions, previously believed not capable of condensing. The creation of Bose-Einstein condensates opened a new field of quantum fluids, attracting wide theoretical and experimental interest, and enabling studies of collective motions, atomic coherence, sound propagation, condensation dynamics, interactions between multicomponent condensates, and the demonstration of an atom laser.

In parallel with these developments, the field of atom optics was created, in which matter waves are manipulated coherently with the tools of geometrical and wave optics. A seminal experiment in this advance was the diffraction of a matter wave from a grating composed of light by Pritchard in 1983. Pritchard and several other groups demonstrated atom interferometers in 1991. Atom interferometers have been employed to measure the refractive index of atoms, to study decoherence in quantum systems, to monitor geophysical effects revealed by variations in the acceleration of gravity, and to create a matter-wave gyroscope. Familiar components of optics that have now been replicated for matter waves include lenses, mirrors, gratings (composed of light waves and also fabricated structures), and waveguides.

With the creation of the laser, the field of quantum optics came into being. The seminal experiment in this field actually predated the laser. This was the R. Hanbury Brown and P. Q. Twiss experiment of 1954 in which the diameter of a radio source was measured by observing intensity fluctuations. Brown and Twiss demonstrated that the amount of coherence between two points in a radiation field could be inferred from the intensity correlations from two radio antennas. The spectral properties of radiation from a maser were analyzed in 1955 by J. P. Gordon, H. J. Zeiger, and C. H. Townes, and those from a laser in 1958 by Schawlow and Townes. A seminal work on the quantum theory of optical coherence was presented by R. J. Glauber in 1962, and in 1965 F. T. Arecchi experimentally characterized the counting statistics from a laser source and a pseudo-Gaussian source. In 1966 Lamb and M. O. Scully presented a quantum theory of the laser. During that same period the foundations of nonlinear optics were developed in a series of papers by Bloembergen, for which he received the Nobel Prize in 1981. The light from a laser operating far above the threshold for oscillation has the statistical properties of a classical radiation source, but nonclassical light rapidly moved to center stage in quantum optics. In a series of experiments L. Mandel generated light with nonclassical statistics and demonstrated purely quantum entanglement phenomena using correlated photons. The so-called ''squeezed states'' of light, in which quantum fluctuations in two conjugate variables are divided nonsymmetrically, were demonstrated in an atomic system by H. J. Kimble.

The Lamb shift and other QED effects can be pictured as arising from the interactions of an electron and the vacuum. Vacuum effects are unimportant in laser fields where the photon occupation number is very high. However, dynamical effects of the vacuum can be important for atoms in cavities, where only one or a small number of vacuum modes are important. The study of atom-radiation systems in cavities in low-lying quantum states has become known as cavity quantum electrodynamics. Starting in the early 1980s cavity QED effects were observed with Rydberg atoms in cavities, including suppressed spontaneous emission (Kleppner), the micromaser—a maser in which the number of radiating atoms is less than one—(H. Walther), and experiments on atom-cavity interactions, including the entanglement of single atoms with the fields of cavities (S. Haroche). Such experiments were later extended to the optical regime by H. J. Kimble and M. S. Feld.

Looking back over the century, each of the three stages of this short history advanced with its own particular element of drama. In the first third of the century, quantum mechanics itself came into being, providing a new language and an arsenal of theoretical tools. In the second, a series of powerful experimental methods were developed on the basis of elementary quantum ideas, including molecular-beam magnetic resonance, the maser, and the laser. The new techniques were applied to basic problems in quantum electrodynamics, to studies of atomic and nuclear properties, and to devices such as atomic clocks. In the final third of the century, an explosion of new studies—far too many to summarize here—occurred, many of them made possible by lasers. Prominent among these were basic studies of the radiation field and the manipulation of atoms, culminating in the achievement of Bose-Einstein condensation of an atomic gas.

This brief and biased history has omitted major areas of theoretical and experimental development: advances in relativistic many-body theory, electron correlations, transient states and collision dynamics, multiply charged ions, atoms in intense radiation fields, and more. Also neglected are the applications of atomic physics—save brief mention of the role of atomic clocks in the Global Positioning System. Applications for the concepts and techniques of atomic physics are to be found in chemistry, astronomy, atmospheric science, space science, surface science, nuclear physics, and plasma physics, to name some areas. It has numerous applications in defense scenarios and environmental science. Practically every aspect of energy production involves some component of atomic physics. Metrological techniques from atomic physics are of broad importance in science, industry, and the military.

Perhaps one concrete example provides a more useful summary than a list. Kastler's method of optical pumping led to a flowering of activity in the 1960s that largely subsided when laser spectroscopy was introduced. However, W. Happer continued to use optical pumping to study the mechanism of polarization transfer between alkali-metal atoms and rare-gas atoms. From these studies he developed methods for polarizing rare-gas nuclei at high density that found applications in nuclear physics. The techniques also found an application in medicine: a new type of magnetic-resonance imaging based on the production of polarized rare gases at high density. By providing detailed images of the lung, rare-gas magnetic-resonance imaging provides a powerful diagnostic tool for pulmonary problems.

It is tempting to predict the future direction of atomic physics. However, recognizing that in each of these periods the progress far exceeded the most optimistic vision at its commencement, the author will forbear.

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