feature article

The early days of precision laser spectroscopy

Richard G. Brewer, Aram Mooradian, and Boris P. Stoicheff

In the 1960s and 1970s, spectroscopists developed a host of nonlinear techniques to measure the interaction of light and matter with a resolution fine enough to test quantum electrodynamics and optically detect weak interactions in atoms.

Richard Brewer is a consulting professor of applied physics at Stanford University, in Stanford, California, and IBM Fellow Emeritus. **Aram Mooradian** is founder and chief technology officer of Novalux, Inc in Sunnyvale, California. **Boris Stoicheff** is University Professor Emeritus at the University of Toronto in Ontario, Canada.

For nearly half a century, scientists have celebrated the happy marriage of laser technology and the science of spectroscopy, the study of atoms, molecules, and solids by their emission and absorption of light. The union of the two fields has led to rich and remarkable fundamental discoveries and experimental techniques for investigating matter and its interaction with light.

The first demonstrations of laser emission in 1960 and 1961 prompted an immediate interest in spectroscopy.[1] That's no surprise because the laser's originators and early developers were spectroscopists, eager to exploit the laser's spectral purity, coherence, and optical power density that were orders of magnitude higher than those of conventional light sources. The laser also provided extremely short pulse lengths over a range of discrete wavelengths that would eventually be tunable and stretch from the IR through the visible and into the vacuum UV. Because the polarizabilities and dielectric susceptibilities of atoms and molecules are functions of light's field strength, the laser's high brightness could drive material systems into nonlinear regimes and produce harmonic components of the laser's fundamental wavelength, excite transitions between quantum levels, ionize atoms, and dissociate molecules.

However, a decade elapsed before laser spectroscopy matured into a widely applicable field. Laser spectroscopy now embraces areas including precision atomic and molecular spectroscopy,[2] which can reveal atom recoil, the Lamb shift, and other subtle but fundamental effects; IR heterodyne spectroscopy in astronomy,[3] which allows precise investigation of the cold carbon dioxide regions of planetary atmospheres; precision measurements of time and length standards;[4] low-energy studies of parity violation in atoms;[5] studies of coherent optical transients (see Brewer's article in PHYSICS TODAY, May 1977, page 50); and ultrafast phenomena on time scales as short as femtoseconds.[6] In the past decade alone, 10 optical scientists have received Nobel Prizes for laser-related achievements (see the box on page 50 and Philip Bucksbaum's article in PHYSICS TODAY, June 2006, page 57).

How did this renaissance in optical spectroscopy arise? In the 1950s Alfred Kastler and Jean Brossel (both at the École Normale Supérieure in Paris) pioneered the technique of optical pumping. Incoherent light excited atoms from an initial state to a neighboring hyperfine state and produced a large imbalance in the population distribution. This imbalance yielded a high sensitivity not available in conventional nuclear magnetic resonance, and Kastler and Brossel could observe large optical signals by applying microwave or radio-frequency radiation resonant with the atomic transitions.

The real breakthrough in laser spectroscopy, however, came in 1966 when Peter Sorokin and coworkers at IBM invented the tunable dye laser.[7] A series of fundamental studies followed, using laser light whose frequency could be matched to atomic transitions of interest. In 1973, Stephen Harris and his group at Stanford extended the wavelength range of coherent light into the UV and vacuum-UV regimes using nonlinear optical techniques.[8] Moreover, a new era of Doppler-free spectroscopy was emerging in the early 1970s, based on Willis Lamb's work on optical maser theory.[9] Spectral measurements of atomic or molecular gases had been limited, in pre-laser-era spectroscopies, by the Doppler linewidth—a broad profile that masks the narrow fine and hyperfine spectral lines because of the Doppler frequency shift from moving atoms that absorb or emit. By tuning the frequency of laser light in a cavity to selectively excite only those atoms with zero velocity along the cavity axis, researchers could produce spectacularly narrow resonance lines.

Around this time, two important conferences were held. The first—the 1971 Fundamental and Applied Laser Physics Conference[10] in Esfahan, Iran—was organized by MIT's Ali Javan, inventor of the first gas laser. Researchers spoke on several different subjects, such as nonlinear optics, plasma heating, controlled fusion, and lasers in chemistry, but laser spectroscopy was emphasized. The second—the 1973 International Conference on Laser Spectroscopy (ICOLS)[11] in Vail, Colorado—was organized by two of us (Brewer and Mooradian, posing in figure 1 a few years later). It was the first in what became a series of small biannual meetings organized by local scientists in different countries.

The 1973 conference focused on two major themes—tunable laser sources and lasers in high-precision spectroscopic measurements. Gerhard Herzberg, the foremost atomic and

Nobel laureates and their laser-spectroscopy-related achievements*

2005
Roy J. Glauber for "his contribution to the quantum theory of optical coherence." John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."

2001
Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman "for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates."

1999
Ahmed H. Zewail "for his studies of the transition states of chemical reactions using femtosecond spectroscopy."

1997
Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips "for development of methods to cool and trap atoms with laser light."

1989
Norman F. Ramsey "for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks." Hans G. Dehmelt and Wolfgang Paul "for the development of the ion trap technique."

1981
Nicolaas Bloembergen and Arthur L. Schawlow "for their contribution to the development of laser spectroscopy."

1971
Gerhard Herzberg "for his contributions to the knowledge of electronic structure and geometry of molecules, particularly free radicals."

1966
Alfred Kastler "for the discovery and development of optical methods for studying Hertzian resonances in atoms."

1964
Charles H. Townes, Nicolay G. Basov, and Aleksandr M. Prokhorov "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser–laser principle."

1955
Willis E. Lamb "for his discoveries concerning the fine structure of the hydrogen spectrum."

*Information is from the website http://nobelprize.org.

molecular spectroscopist of his day, gave the opening talk. Lasers did not exist during his most active period, and scientists relied solely on spectrographs, spectral lamps, photographic plates, photomultipliers, and IR detectors. Herzberg said that those working in the new laser spectroscopy should reflect occasionally on the unity of physics and not invent new names and notation. He also admitted that he had not yet used a laser.

In this article, we present a few highlights of those first few conferences, made at a time when the field was beginning to blossom. In some cases, we trace the advances to more recent developments that have built on the early foundation.

Tunable lasers

In 1960 Theodore Maiman demonstrated stimulated emission of red (693 nm) light from a pulsed ruby laser. Shortly thereafter, Javan and his MIT colleagues produced a continuous-wave helium–neon laser that emits in the near IR (1.15 μm) and in the visible (632.8 nm).[1] The development of a variety of solid-state and gas lasers soon followed. Indeed, the challenge in the first two decades of laser development was to fill the gaps in various regions of the electromagnetic spectrum. Sorokin's IBM group and, independently, Fritz Schäfer and colleagues from the University of Marburg, Germany, used ruby-laser excitation of organic dyes to produce stimulated and tunable emission in the 700- and 800-nm regions.[7] Dye lasers pumped by fast flashlamps, and by lasers such as argon-ion, krypton-ion, nitrogen-molecule, and excimer lasers, provided a large family of light sources for atomic and molecular spectroscopy. Highly monochromatic light was produced using a diffraction grating at grazing incidence in the dye cavity resonator; wavelengths of interest could then be tuned by rotating the grating.

Mid-IR (2–30 μm) diode lasers,[12] developed at MIT's Lincoln Laboratory in the early 1970s, could be tuned by varying the electric current flowing through the laser's p–n junction. David Hinkley and Paul Kelley demonstrated that such lasers could reveal narrow-linewidth vibrational and rotational spectra. Particularly important for generating wavelengths in the IR above 1 μm and in the vacuum UV below 400 nm were nonlinear optical techniques. One or two laser frequencies could be mixed in a crystal with a nonlinear polarizability to generate coherent light at the sum, difference, or various harmonic frequencies. Alternatively, optical parametric oscillators used a fixed-frequency laser such as a neodymium-doped yttrium aluminum garnet device (lasing at 1060 nm) as a pump source to generate tunable radiation in the visible or IR by varying the temperature or rotating the incident angle of an appropriate crystal. (For a survey of optical-frequency conversion techniques, see the article by Martin Fejer in PHYSICS TODAY, May 1994, page 25.)

To generate tunable extreme-UV radiation, researchers adopted a resonance-enhanced four-wave-mixing scheme: Take two tunable dye lasers of frequency ω_1 and ω_2, one tuned to a two-photon transition and the other to a frequency such that $2\omega_1 + \omega_2$ corresponds to a transition from the ground state to a broad, autoionizing state of the nonlinear medium. The frequency of the emitted UV radiation could be tuned by varying ω_2. Vapors of strontium, magnesium, zinc, and mercury extended the tunable wavelength range to 100 nm, and gas jets of xenon, krypton, and carbon dioxide, to 50 nm. For details of the various tunable laser systems developed in the mid-1970s, see references 8, 11, and 13.

The Lamb dip

In 1964 Lamb wrote his theory of the optical maser,[9] which predicted an unanticipated spectral feature that accompanies gaseous laser emission: a dip in the peak of an atom's Doppler-broadened lineshape. The physical interpretation of the dip, he wrote, could be visualized in terms of a saturation effect, hole burning. Imagine atoms moving with axial velocities $\pm v_z$ in the standing wave of a laser cavity. The standing wave can be thought of as two traveling waves—one in resonance with atoms having one velocity and the other in resonance with atoms having the opposite velocity. The resonant interaction "burns" two holes in the Doppler lineshape, one for each traveling wave, displaced symetrically from the peak by frequencies $\pm kv_z$. As the laser frequency is tuned to coincide with the frequency ω_0 of the atomic transition, the two holes merge and cut a particularly

Figure 1. Laser spectroscopists, photographed in front of Fudan University's physics building in Shanghai, China, to mark the International Conference on Lasers held there and in Beijing in 1980. Participants included, from left to right, Yu-Fen Li, Zhi-Ming Zhang, John Hall, George Temmer, Aram Mooradian, Herbert Walther, Richard Brewer, an unidentified scientist, and Fu-Ming Li.

deep notch out of the distribution; the laser's emission intensity goes through a local minimum—the Lamb dip—when the laser light is in resonance with the transition frequency of atoms at rest (see figure 2).

Although gas lasers can have extremely narrow natural linewidths—on the order of a few hertz—the linewidth of the accompanying Lamb dip in the case of a He–Ne laser broadens to about 100 MHz, about one-fourth of the Doppler width, because of the significant rates of spontaneous emission from the upper and lower laser transition levels. An important modification was to place a second and different absorbing gas that was not lasing in the path of the external laser beam. This led to extremely narrow linewidth Lamb dips and precision measurements because the second gas could be excited from its ground state to an upper level with a much slower rate of spontaneous emission.

At the l971 Iran conference, John Hall and one of us (Brewer) independently reported two examples of this phenomenon.[2] In the discussion that followed, Lamb said that he never anticipated that researchers would be able to narrow the spectral linewidths so dramatically—to within an order of magnitude of the natural linewidth of the atoms being studied.

The recoil effect

When an atom or molecule absorbs or emits light, the atom suffers a small recoil in a way that conserves energy and momentum. The effect was too small to be resolved using conventional optical methods, but the Lamb dip allowed researchers their first optical measurement of quantized momentum exchange between a molecule and the light field.[14] For the atomic transition $|a\rangle \rightarrow |b\rangle$, a relativistic treatment of conservation of energy and momentum yields the following relations for the transition-frequency ratio: $\omega/\omega_0 = [1 - (v_a/c)^2]^{1/2}/(1 + \varepsilon)$ for emission from an upper state $|a\rangle$, and $\omega/\omega_0 = [1 - (v_b/c)^2]^{1/2}/(1 - \varepsilon)$ for absorption from a

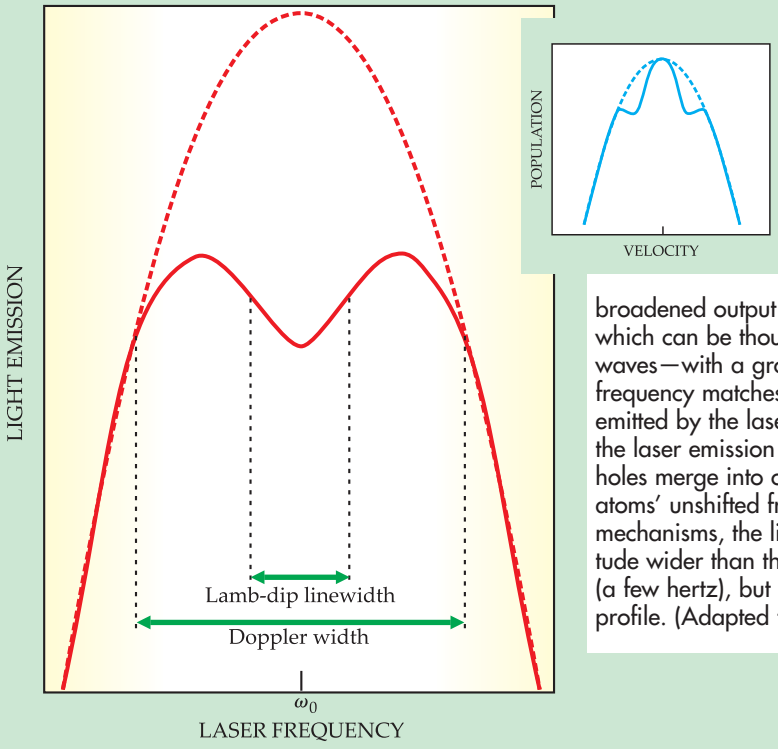

Figure 2. The Lamb dip illustrates the effect of a standing wave on the distribution of excited atoms in a laser cavity. Holes are "burned" in the Doppler-broadened output of a laser from the interaction of the beam—which can be thought of as two counterpropagating traveling waves—with a group of atoms whose Doppler-shifted resonant frequency matches the laser frequency (see inset). The intensity emitted by the laser depends on the population inversion, so the laser emission goes through a minimum—that is, the two holes merge into one—when the laser frequency is tuned to the atoms' unshifted frequency ω_0. Due to various line-broadening mechanisms, the linewidth of the dip may be orders of magnitude wider than the natural linewidth of the laser emission (a few hertz), but still smaller than the width of the Doppler profile. (Adapted from ref. 9.)

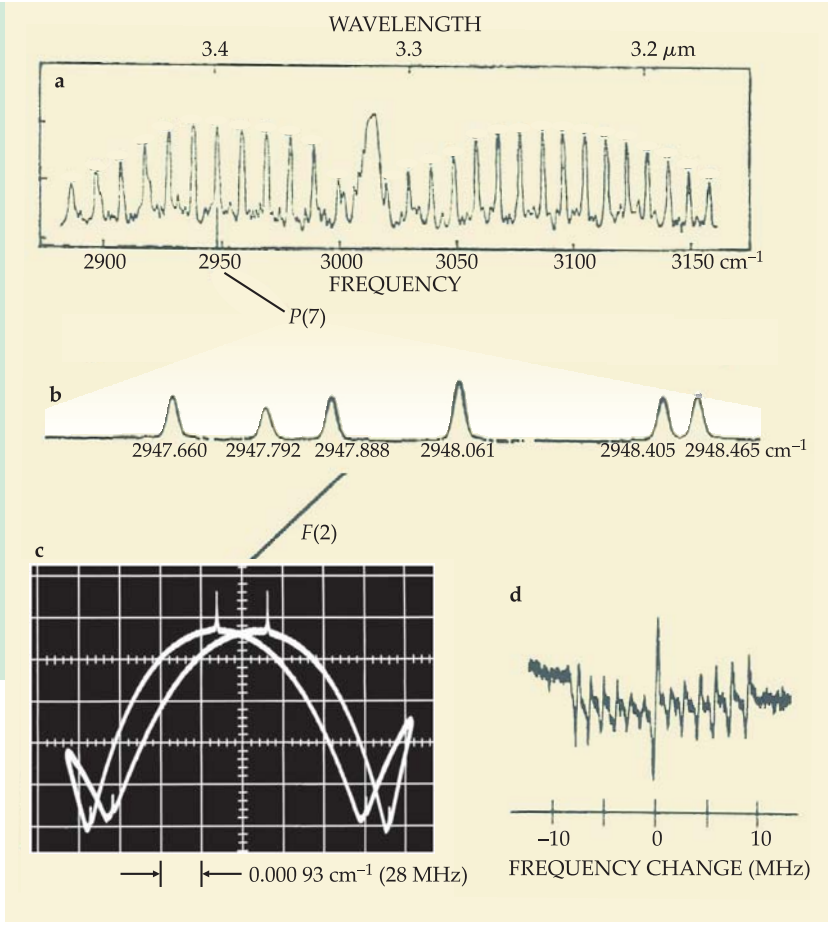

Figure 3. An IR vibration–rotation spectrum of methane around 3.39 μm, revealed with progressively higher resolution. **(a)** This low-resolution pre-laser-era spectrum resolves lines that are 24 000 MHz (or 0.8 cm^{-1}) wide. **(b)** Taken with a grating spectrometer, this higher-resolution spectrum reveals the rotational fine structure of the six *P*-branch lines, each labeled by wavenumber and about 260 MHz wide. **(c)** Doppler-free laser spectroscopy, which selects molecules in a narrow velocity band, reduces the Doppler broadening by nearly a thousandfold and reveals the *F*(2) line. The line shows up as thin 400-kHz-wide spikes (hysteresis of the scan causes trace doubling), obtained by monitoring the output of a methane-filled helium–neon laser cavity as the laser frequency is tuned around 3.39 μm. **(d)** Applying an electric field to the cavity breaks the degeneracy of methane's rotational spectrum and splits the spike into 13 separate Lamb dips in this derivative spectrum. (Adapted from ref. 13, *Laser Spectroscopy III*.)

lower state $|b\rangle$. Here, ω_0 refers to the transition frequency measured in the rest frame, v_a and v_b are the velocities of atoms in the two levels, and the recoil term $\varepsilon = \hbar\omega_0/2Mc^2$, where M is the atomic mass.

When $v_a = v_b$ two resonances in the spectrum will be separated by the recoil term $\pm\varepsilon$. Therefore, resonant light scattering from atoms exhibits a doublet splitting due to the recoil effect; one component corresponds to absorption of light from the lower state and the other from emission from the upper state. Hall and coworkers observed this effect 30 years ago when measuring the IR vibration–rotation transition of methane at 3.39 μm. Because of the low rate of spontaneous emission from the upper to lower laser levels and the transit time through the laser beam, the linewidth was quite narrow, on the order of 10 Hz or less. Hall and coworkers observed a recoil doublet splitting of 2.150 ± 0.005 kHz in methane, whose linewidth (1.27 kHz) was limited mainly due to collision broadening. (For a series of the advances in spectral resolution culminating in the Doppler-free spectroscopy measurement from Hall and company, see figures 3 and 4).

Early recoil-effect studies eliminated the first-order Doppler broadening, but introduced a second-order velocity dependence and line broadening. Sergei Bagayev and coworkers in the Soviet Union showed in 1989 that the Lamb-dip linewidth in methane can be reduced further by selecting cold molecules. The Soviet group achieved a methane line half-width at half-maximum of 50 Hz, or a relative width of 10^{-13} to 10^{-14}, which approaches the resolution of a single molecule at rest. The work stimulated interest in high-resolution optical measurements, particularly since methane was, at the time, widely considered a possible frequency standard.

The Lamb shift

In 1947 Lamb and Robert Retherford (then at Columbia University) reported a spectacular observation: The $2S_{1/2}$ and $2P_{1/2}$ states of the hydrogen atom are not degenerate, as Paul Dirac's relativistic treatment had predicted, but are separated in energy by about 1000 MHz, with the $2S_{1/2}$ state slightly above $2P_{1/2}$. Shortly thereafter, Hans Bethe explained the origin of the shift in energy levels—the Lamb shift—as due to the interaction of the electron with the vacuum radiation field (see the article by Freeman Dyson in PHYSICS TODAY, October 2005, page 48). The quantization of the radiation field introduces zero-point fluctuations in the field that must be included in the physics of the electron itself. These fluctuations effectively spread out the charge of the bound electron and raise the atomic *S*-state energies. Measurements of the Lamb shift of various hydrogenic states served as precise tests of quantum electrodynamics.

Early experiments of the Lamb shift measured the metastable 2*S* state, but Herzberg obtained the first measurement of the Lamb shift for a deuterium 1*S* ground state in 1956 by direct excitation of the 1*S*–2*S* transition using 121.5-nm UV light. A large 30-GHz Doppler broadening and spurious background spectral lines hampered his measurements' precision, though. Two-photon Doppler-free spectroscopy performed by Theodor Hänsch and coworkers at Stanford removed the technical problems associated with vacuum-UV spectroscopy and the Doppler broadening. In 1970 Veniamin Chebotayev and colleagues from the Soviet Union had proposed the two-photon Doppler-free technique.[15] Gas atoms placed in a standing-wave field produced by reflecting a tunable laser beam back onto itself are excited from the ground state to an upper state of the same parity by absorbing two counterpropagating photons. The technique eliminates broadening because the first-order Doppler shifts are equal and opposite. Marc Levenson, Nicolaas Bloembergen, and others[15] carried out the first experiments in 1974, and

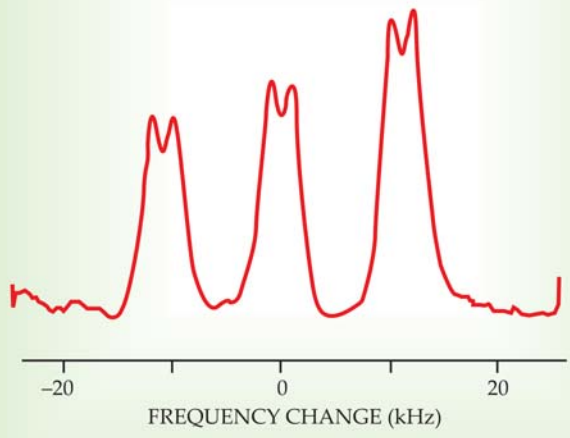

Figure 4. The Lamb-dip spectrum of methane, experimentally measured at a thousand times the resolution shown in figure 3(d)—that is, to 2 kHz or about 2 parts in 10^{11}. The spectrum reveals the hyperfine peaks—apparent as the triplet—and the smaller doublet splittings that arise from the radiative recoil of molecules that absorb or emit IR photons. (Adapted from ref. 14.)

the technique has become a valuable tool because it allows researchers to reach high-lying states—and investigate the spectra and fine-structure splitting of alkali atoms, for example—using longer wavelengths that are easier to generate and measure.

Hänsch and coworkers measured the $2P_{3/2} - 3D_{5/2}$ transition in hydrogen by observing the Lamb dip with a standing light wave from a dye laser tuned to 486 nm (see figure 5). They also obtained a high-precision measure of the 1*S*–2*S* transition interval using frequency-doubled laser light; hydrogen atoms were excited by absorption of two photons of wavelength 243 nm.[16] The intervals did not agree with the $1/n^2$ dependence predicted by Niels Bohr's theory, where n refers to the principal quantum number. Because the P states do not contribute a significant Lamb shift, the remaining interval discrepancy is attributable to a Lamb shift of the 1*S* ground state.

Cold atoms

In 1975 Hänsch and Arthur Schawlow pointed out that it should be possible to cool a gas sample to a fraction of a degree kelvin using radiation pressure from a laser.[17] The idea was to reduce the translational energy and narrow the Doppler width of the spectrum using pairs of counterpropagating laser beams. The effect is akin to atomic recoil. If the lasers are detuned below a resonant transition, atoms moving toward a laser source will find the light Doppler-shifted upward in frequency so as to increase the scattering cross section. To atoms moving away from the beam, the frequency will appear lowered out of resonance with the scattering transition. If the laser frequency is limited to the lower half of the Doppler linewidth, the atoms lose energy and momentum by scattering the laser light.

The problem with cooling neutral atoms was that there was no way, in the late 1970s, to hold them in place. It would take another decade and some oddly named schemes—among them optical molasses, optical tweezers, and Sisyphus cooling—to incrementally cool atoms to temperatures in the nanokelvin regime. For developing the techniques required to accomplish that feat, Steven Chu, Claude Cohen-Tannoudji, and William Phillips were awarded the Nobel Prize in 1997 (see PHYSICS TODAY, December 1997, page 17). Eric Cornell, Wolfgang Ketterle, and Carl Wieman were awarded the Nobel four years later for extending the trapping and cooling techniques to create Bose–Einstein condensates made of dilute gases of alkali atoms (see PHYSICS TODAY, December 2001, page 14). The work has spurred the development of an entirely new research field in condensed-matter physics.

Light scattering

The remarkable spectral properties and high brightness of lasers were quickly seized on to make major breakthroughs in the field of light scattering, which until the advent of the laser was mainly used to investigate rotational and vibrational Raman spectra of molecules. Continuous-wave lasers, monochrometers, and photomultipliers replaced the old discharge lamps and long photographic exposures. In the 1960s Sergio Porto performed seminal work in the area of laser Raman spectroscopy to probe the spectral details of various materials.[18] Using the technology, Porto and others observed new fundamental phenomena, including the inelastic scattering of laser light from optical phonons (vibrational quanta), magnons (magnetic or paramagnetic quanta), polaritons (mixed photon and phonon excitations), and plasmons (single-particle and collective electron excitations).

The tremendously high resolution achievable in Raman scattering in the forward direction of the incident laser beam helped to revive the field of atomic and molecular spectroscopy. Stimulated Raman scattering provided additional wavelengths of intense monochromatic radiation for use in spectroscopy and nonlinear optics. One such use was the production of tunable IR radiation by scattering light from electrons to stimulate electron spin-flip transitions in semiconductors.

Normal and stimulated Brillouin scattering—techniques associated with monitoring the interaction of a laser beam with acoustic quanta—also became widespread methods to study high-frequency phonons in gases, liquids, and solids.

Parity violation in atoms

Parity invariance can be viewed classically as the equivalence between the interactions of an object with the environment and those of its mirror image with the environment. That is, the interactions of a left-handed object and of its right-handed mirror image are identical if parity invariance holds. The left- or right-handedness of an atom in quantum mechanics can be identified by considering its interaction with, for example, a polarized light beam. Parity invariance is a property of quantum electrodynamics (QED), the theory that so accurately predicts the spectrum of atoms.

Parity violation was first observed in nuclear β decay, which breaks right–left symmetry due to the emission of an electron by the weak interaction. And up until the 1960s, it was believed that parity violation could only occur in charged-current interactions—that is, only when there was a change in charge, as in Enrico Fermi's theory of β decay. However, the theory of the weak interaction, developed by Sheldon Glashow, Steven Weinberg, and Abdus Salam, showed that parity violation could also occur in weak interactions without any change of charge; that theory earned them a Nobel Prize. Thus, although parity violation is not predicted

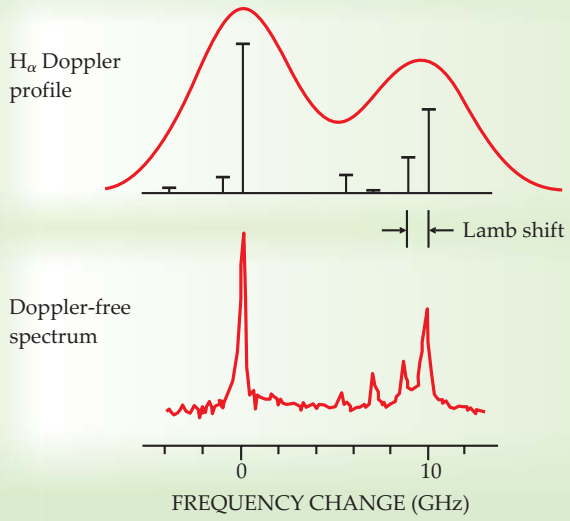

Figure 5. Seeing the Lamb shift. The Doppler-broadened absorption profile and theoretical fine structure of hydrogen's Balmer alpha line (for principle quantum number n=2 to n=3 transitions) pictured at top. Doppler-free spectroscopy, which exploits the Lamb dip, resolves individual components of the spectrum. The most intense component arises from the $2P_{3/2}$–$3D_{5/2}$ transition.[16]

by QED, it can occur in atoms due to the neutral-current weak interaction, a process that can occur between an electron and a nucleus in a stable atom but which is usually totally masked by electromagnetic interactions.

Ordinarily, researchers have used high-energy accelerators to tackle parity violation. But low-energy laser spectroscopy can also be brought to bear on the problem. Three decades ago the husband and wife team of Marie-Anne and Claude Bouchiat (both at the École Normale Supérieure) initiated theoretical and experimental optical studies to verify parity violation in stable atoms.

At the ICOLS III meeting in 1977, Marie-Anne Bouchiat gave a plenary talk on the possibility of observing the violation,[13] and Eugene Commins and colleagues made a preliminary measurement.[5] Glashow, Weinberg, and Salam's model implied that neutral currents can take place between an electron and a nucleus in a stable atom due to the exchange of the Z^0 vector boson (whose mass is about 100 times that of the proton). Bouchiat began her experimental work with collaborator Lionel Pottier on the forbidden $6S_{1/2}$–$7S_{1/2}$ electric dipole transition of cesium because the electromagnetic interaction could be suppressed and thus allow the detection of a neutral current arising from the weak interaction of the valence electron with the nucleus.

Because the $6S_{1/2}$–$7S_{1/2}$ transition is so weak, it was necessary to apply a small DC electric field to induce a stronger dipole-transition amplitude A_{em} that interferes with the very weak interaction whose amplitude A_w contains the right–left asymmetry. The optical signal is measured by exciting the forbidden transition with a beam of elliptically polarized light from a tunable dye laser and monitoring the polarization of the fluorescence. Figure 6 shows the experiment.

The asymmetry appears in the transition probability $|A_{em} \pm A_w|^2 = (A_{em}^2 + A_w^2) \pm 2A_{em}A_w$. The amount of parity violation is given by the interference term $\pm 2A_{em}A_w$. After normalizing the transition probability, one can calculate the interference ratio for an electric dipole transition.

Using an electric field of 100 V/cm, the Bouchiat group found the right–left asymmetry to be $(-1.52 \pm 0.18) \times 10^{-5}$, which compares to a theoretical value of -1.59×10^{-5}. Other groups have performed experiments on different atoms with steadily improving precision. Further work could provide new insight into the standard model, which accounts for the strong force in addition to the electroweak force.

Back to the future

From its beginning in the early 1960s laser spectroscopy revolutionized the science of precision measurement. And during the intervening four and a half decades, the field has made immense contributions to our understanding of atomic, molecular, and nuclear physics. Myriad applications in communications, navigation, interferometry, medical biophysics, time and length standards, and astrophysics fol-

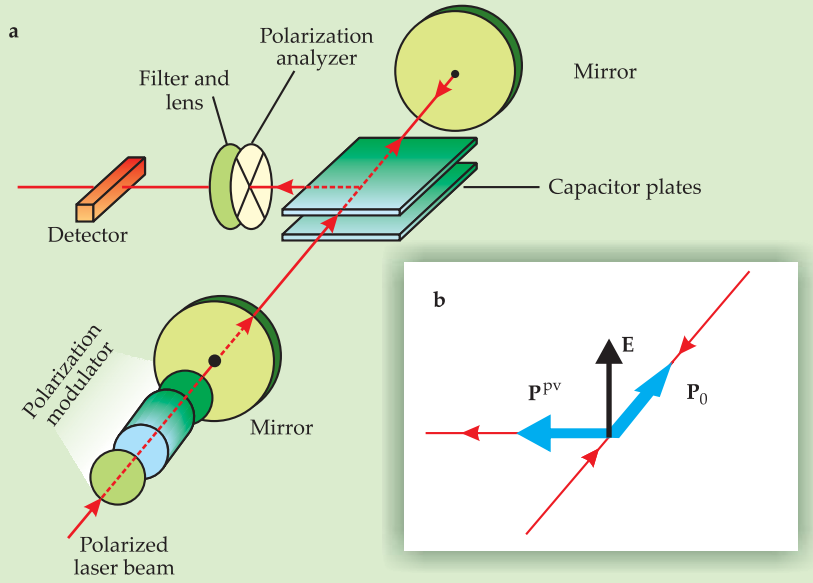

Figure 6. Testing parity violation in cesium atoms. **(a)** An elliptically polarized continuous-wave laser beam bounces back and forth between two mirrors, each time passing through capacitor plates filled with cesium vapor. A small number of Cs atoms are excited and become spin polarized. When the atoms relax to a lower energy level, they emit fluorescent IR light that is then analyzed. **(b)** The polarization of the excited state contains a tiny parity-violating component $\mathbf{P}^{pv}$. That component breaks the mirror symmetry, while $\mathbf{P}_0$ preserves it. The right–left asymmetry is quantified in the ratio $\mathbf{P}^{pv}/\mathbf{P}_0$. **E** refers to the applied electric field. (Adapted from ref. 5, Bouchiat et al.)

lowed naturally. Perhaps unsurprisingly, laser spectroscopy continues to evolve in step with laser development. Lasers are expected to reach beyond a quadrillion watts in the next decade, and lasers with subfemtosecond pulse lengths have already been achieved. Indeed, it is possible to measure time durations at scales approaching 10^{-20} seconds and test a number of physical constants. The new results emerging from spectroscopic studies appear to be as fascinating and exciting as those found during the field's early years.

We would like to acknowledge constructive comments from Stanley Brodsky, Paul Berman, Stephen Harris, James Bergquist, John Hall, Eugene Commins, and Marie-Anne Bouchiat.

References

1. T. H. Maiman, *Nature* **187**, 493 (1960); A. Javan, W. R. Bennett, D. R. Herriott, *Phys. Rev. Lett.* **6**, 106 (1961).
2. R. G. Brewer, in *Fundamental and Applied Laser Physics: Proceedings of the Esfahan Symposium, August 29 to September 5, 1971*, M. S. Feld, A. Javan, N. A. Kurnit, eds., Wiley, New York (1973), p. 421; J. L. Hall, in *Fundamental and Applied Laser Physics*, p. 463.
3. A. L. Betz, E. C. Sutton, R. A. McLaren, in *Laser Spectroscopy III: Proceedings of the Third International Conference, Jackson Lodge, Wyoming, USA, July 4–8, 1977*, J. L. Hall, J. L. Carlsten, eds., Springer-Verlag, New York (1977), p. 31.
4. S. A. Diddams et al., *Phys. Rev. Lett.* **84**, 5102 (2000); R. Holzwarth et al., *Phys. Rev. Lett.* **85**, 2264 (2000).
5. M. A. Bouchiat, C. Bouchiat, *Rep. Prog. Phys.* **60**, 1351 (1997); R. Conti et al., *Phys. Rev. Lett.* **42**, 343 (1979).
6. C. V. Shank, E. P. Ippen, in *Laser Spectroscopy I: Proceedings of the Second International Conference, Megève, June 23–27, 1975*, S. Haroche, J. C. Pebay-Peyroula, T. W. Hänsch, S. E. Harris, eds., Springer-Verlag, New York (1975), p. 408.
7. P. P. Sorokin et al., *IBM J. Res. Dev.* **11**, 130 (1967); F. P. Schäfer, W. Schmidt, J. Volze, *Appl. Phys. Lett.* **9**, 306 (1966).
8. S. E. Harris et al., in *Laser Spectroscopy*, R. G. Brewer, A. Mooradian, eds., Plenum Press, New York (1974), p. 59; R. L. Byer, in *Laser Spectroscopy*, p. 77; P. R. Herman et al., *Can. J. Phys.* **63**, 1581 (1985); R. T. Hodgson, P. P. Sorokin, J. J. Wynne, *Phys. Rev. Lett.* **32**, 343 (1974).
9. W. E. Lamb Jr, *Phys. Rev.* **134**, A1429 (1964).
10. M. S. Feld, A. Javan, N. A. Kurnit, eds., *Fundamental and Applied Laser Physics: Proceedings of the Esfahan Symposium, August 29 to September 5, 1971*, Wiley, New York (1973).
11. R. G. Brewer, A. Mooradian, eds., *Laser Spectroscopy*, Plenum Press, New York (1974).
12. A. Mooradian, in ref. 11, p. 223; E. D. Hinkley, P. L. Kelley, *Science* **171**, 635 (1971). For a review of spectroscopy using diode lasers, see E. D. Hinkley, *Opt. Quantum Electron.* **4**, 69 (1972).
13. S. Haroche, J. C. Pebay-Peyroula, T. W. Hänsch, S. E. Harris, eds., *Laser Spectroscopy I: Proceedings of the Second International Conference, Megève, June 23–27, 1975*, Springer-Verlag, New York (1975); J. L. Hall, J. L. Carlsten, eds., *Laser Spectroscopy III: Proceedings of the Third International Conference, Jackson Lodge, Wyoming, USA, July 4–8, 1977*, Springer-Verlag, New York (1977); A. Mooradian, T. Jaeger, P. Stokseth, eds., *Tunable Lasers and Applications: Proceedings of the Loen Conference, Norway, 1976*, Springer-Verlag, New York (1976).
14. J. L. Hall, C. J. Bordé, K. Uehara, *Phys. Rev. Lett.* **37**, 1339 (1976).
15. L. S. Vasilenko, V. P. Chebotayev, A. V. Shishaev, *JETP Lett.* **12**, 161 (1970); F. Biraben, B. Cagnac, G. Grynberg, *Phys. Rev. Lett.* **32**, 643 (1974); M. D. Levenson, N. Bloembergen, *Phys. Rev. Lett.* **32**, 645 (1974).
16. C. Wieman, T. W. Hänsch, in *Laser Spectroscopy III*, ref. 13, p. 39; B. P. Stoicheff, in *Laser Spectroscopy III*, ref. 13, p. 1.
17. T. W. Hänsch, A. L. Schawlow, *Opt. Commun.* **13**, 68 (1975).
18. J. M. Cherlow, S. P. S. Porto, in *Laser Spectroscopy of Atoms and Molecules*, H. Walther, ed., Springer-Verlag, New York (1976), p. 253. ■