Laser Extremes Probe Atoms and Molecules

Atomic and molecular physicists find that many frontiers of their field are defined by the advancing state of the art of laser technology

The laser is 25 years old this year. Last month, the Committee on Atomic and Molecular Science of the National Research Council held a 1-day workshop to highlight the role of the laser in understanding atomic and molecular structure and in studying the dynamics of processes involving these particles and to attempt to forecast what may lie ahead.*

The inescapable conclusion was that the laser, derided in its early days as a solution in search of a problem, now paces progress in much of atomic and molecular science. In fact, except for the still underdeveloped vacuum ultraviolet and x-ray regions of the spectrum where synchrotron radiation is so successful, state of the art laser technology pretty much defines what the frontier areas of research are when it comes to probing atoms and molecules with electromagnetic radiation. The most discouraging note sounded was a projected decline in the vitality of the field due to insufficient federal funding, which hits the universities, where future researchers are trained, the hardest.

High-resolution spectroscopy provides probably the clearest example of what lasers make possible and also of how necessary it is to develop experimental techniques that can take advantage of laser technology. At the workshop, Richard Zare of Stanford University considered the spectral purity obtainable from a laser. He pointed out that, by means of a feedback loop to stabilize the frequency, researchers could generate ultranarrow lines less than 500 hertz wide in the visible region of the spectrum from dye lasers and a few hertz from gas lasers. The latter corresponds to a frequency to line-width ratio or resolution of about 10^{15}!

Such narrow line widths are not only ideal for high-resolution spectroscopy but also for more applied enterprises, such as atomic timekeeping. Accurate clocks, for example, are required for precision navigation and can also be used in connection with cryptography for coding and decoding secure communications. But even such methods as saturation and two-photon spectroscopy that have been generally used to defeat the Doppler effect are inadequate for ultrahigh resolution because there are additional velocity-dependent sources of line broadening (second-order Doppler and transit time broadenings). In the end, there is no alternative to slowing atoms and molecules to very low velocities. William Phillips of the National Bureau of Standards outlined some of the new laser cooling and trapping techniques that aim for this goal.

Ions are easier to trap than atoms because of their electric charge. For example, Warren Nagourney and Hans Dehmelt at the University of Washington have confined a single ion for several months and cooled ions to an effective temperature of 0.005 K. Recently, they confined a laser-cooled ion within a volume 165 nanometers in radius, less than a visible light wavelength. Such a tightly confined particle has no ordinary Doppler effect because the particle appears stationary to the light.

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As an example of what could be done with slowly moving atoms, spectroscopists continue to be fascinated by the hydrogen atom, partly because the line width of the so-called forbidden *1S-2S* transition is intrinsically extremely narrow and hence makes for sensitive tests of quantum electrodynamics and measurements of atomic constants. Zare described a proposal by Theodor Hänsch of Stanford to measure accurately the frequency of this transition in atomic hydrogen for just these purposes. If everything works, the experimentally measured line width of the transition would be only 1 hertz.

Among other highlights of the workshop:

- Time-resolved spectroscopy. It is now possible to generate visible laser light pulses that last only 8 femtoseconds, that is, pulses only 4 wavelengths long. And there appears to be no fundamental reason not to be able to reduce that figure to 1 wavelength. David Auston of AT&T Bell Laboratories showed how one could use such short pulses to reconstruct the time evolution of lattice vibrations in solids; that is, one can watch the vibrations as in an ultraslow-motion movie.
- High-field effects. The high degree of collimation of laser light together with short pulse lengths generates very high intensities. Even a 10-millijoule pulse lasting 1 picosecond and focused to a 10-micrometer spot has an intensity of 10^{16} watts per square centimeter. The electric field associated with a light wave of this intensity is equal to that binding the electron and proton in the hydrogen atom. Lloyd Armstrong of Johns Hopkins University pointed out that the perturbation theory scientists normally use to calculate interactions between matter and radiation is no longer sufficient in such strong fields. Several recent experiments have produced quite unexpected results that are so far unexplainable by conventional theory, and physicists may have to come up with a new approach.
- Low noise. In quantum mechanics, the electromagnetic radiation field has a nonzero energy even when there are no photons present. This zero-point energy is due to so-called vacuum fluctuations that are manifested by a nonzero value for the statistical variance of the electric field. The fluctuations appear as noise, which ultimately limits the signal-to-noise ratio in optical devices. It is theoretically possible to beat this quantum limit by means of nonlinear optics techniques that generate so-called squeezed states of light. Squeezed states have now been experimentally confirmed by a Bell Labs group headed by Richard Slusher.

The combination of lasers with atomic and molecular science also has its practical side, as discussed by John Birely of the Los Alamos National Laboratory. Among other uses Birely reviewed, the prospects for identifying infectious agents by means of laser light scattering are promising. A virus, for example, scatters left and right circularly polarized light differently. Moreover, the angular dependence of the differential scattering is apparently unique for each organism, thereby providing a signature by which it can be recognized. The technology is being pursued as a tool for diagnosing diseases caused by viruses and bacteria.—ARTHUR L. ROBINSON

*Workshop on the Laser-Atomic Frontier, Washington, D.C., 11 October 1985.