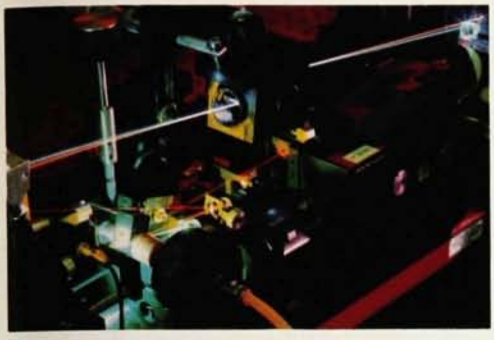
Laser beam's frequency is increased in a series of steps: First a green laser beam passes through a dye and emerges as a red beam; then that beam's frequency is doubled with a nonlinear device.



Atomic, molecular and optical physics

Atomic, molecular and optical physics encompasses a broad range of theoretical and experimental research on matter at the atomic and molecular level and on light. In the United States it is pursued by over 300 small groups in university, national and industrial laboratories. Advances in this branch of physics not only add to our understanding of the basic laws of physics but lead to new instruments and techniques vital to other areas of science, to industry and to national programs. In their report the Panel on Atomic, Molecular and Optical physics has proposed a program of research initiatives intended to support scientific innovation and to provide an environment for rapid scientific advance. But the panel is quick to point out that in attempting to predict the most promising avenues for scientific advancement one is likely to miss whole new boulevards. The panel admits that had it met ten years ago it would have failed to mention or would have seriously underestimated many important developments: laser cooling of atoms and ions, low-energy highly charged ions, transient molecular states, Rydberg atoms, molecular clusters, four-wave mixing, phase conjugation, ultrasensitive detection. "Nevertheless," writes the panel, "we believe that the program of research initiatives represents a realistic basis for scientific advance in the near future." The research initiatives include:

Atomic. The panel chose three areas in which the rapid theoretical and experimental progress of the last decade might be exploited: fundamental tests and high-precision techniques, many-electron atoms and transient states of atomic systems.

The techniques of atomic physics have been used to provide accurate tests of some of the elementary laws of nature. During the past decade, for instance, time-reversal invariance has been tested at new levels of sensitivity through searches for the dipole moment of the neutron, the isotropy of space with respect to the speed of light has been confirmed to a few parts in 10^{15} by laser interferometry, parity violation by the electroweak interaction has been observed in atoms, and the effect of Earth's gravity on the passage of time has been measured using a rocket-borne atomic clock with a stability greater than 1 part in 10^{14}. The anomalous magnetic moment of the electron has been measured to an accuracy of 40 parts in 10^9 in an experiment that employs a single electron or positron in an electromagnetic trap. This, together with a new measurement of the Lamb shift to an accuracy of 9 parts in 10^6, is one of the most demanding tests of quantum electrodynamics, and indeed of any theory, ever performed.

A hundredfold improvement in the measurement of the electron magnetic moment appears feasible using new types of single-particle traps. If theoretical calculations can keep pace, this will provide a further test of quantum electrodynamics as well as checking CPT invariance to a precision of 1 part in 10^{13}.

There will soon be further opportunities for testing QED. Highly charged ions with only one or a few electrons can now be produced in fast ion beams. Uranium with 91 of its 92 electrons removed has recently been produced. Studies of this hydrogenlike uranium will open up a new range of phenomena where both radiative and relativistic effects are large.

Many-electron atoms pose a major intellectual challenge for physics. Theories treating the electrons as independent particles have successfully described the grosser features of many-electron atoms, but experiments reveal a rich array of phenomena that cannot be explained by these simple models. Electron–electron interactions, which give rise to correlated motion, must be taken into account. Theoretical advances such as the recognition of the role of dynamical symmetries in correlated systems and the discovery of correspondences between correlated motions and single-electron motions in strong applied fields have furthered our understanding. Two-electron systems are now studied in new types of high-resolution electron-scattering experiments. For example, "planetary" atoms—atoms with two very excited electrons—have been produced with multiple-laser systems and studied spectroscopically. These experimental and theoretical advances are preparation for a frontal attack on the full many-electron atom. Success in this attack would lead to numerous applications to chemistry and materials science.

Study of the transient electronic states that occur during violent collisions between ions and atoms or other ions has led to the discovery of approximate conservation laws, such as the electron-promotion model that explains the unexpected x-ray emission during ion–atom collisions.

The ability to carry out scattering

Panel on Atomic, Molecular and Optical Physics

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Spectra of SF_6. The progression from conventional infrared through diode-laser and saturation spectroscopy and finally to a study with an electronically controlled laser reveals increasing detail up to the maximum resolution allowed by the uncertainty principle, illustrating the revolution in spectroscopy.

experiments in which every important variable is measured, complemented by the development of quantitative theories of complex collision phenomena, provides an unprecedented opportunity for studying the transient states of atoms. The goal is to seek hidden symmetries that will help to organize and simplify the description of the dynamics of a large class of complicated multi-electron systems.

Molecules. Progress in laser and molecular-beam methods and a host of other experimental and theoretical developments has caused a renaissance in molecular physics. Opportunities abound for major advances, the panel believes, if initiatives are taken in two broad areas: the physics of isolated molecules and the physics of molecular collisions.

With the aid of laser methods, synchrotron light sources, modern molecular-beam techniques and other experimental advances, it is now possible to prepare almost any simple molecule in any desired quantum state and to study its structure in detail.

The spectra and structures of simple molecular systems and the study of unusual molecular species such as molecular ions, van der Waals and Rydberg molecules, metal cluster molecules and metastable species present new opportunities for understanding molecular structure. The goal is to understand the evolution of the electronic properties of matter, from isolated atoms through dimers and trimers to high states of aggregation.

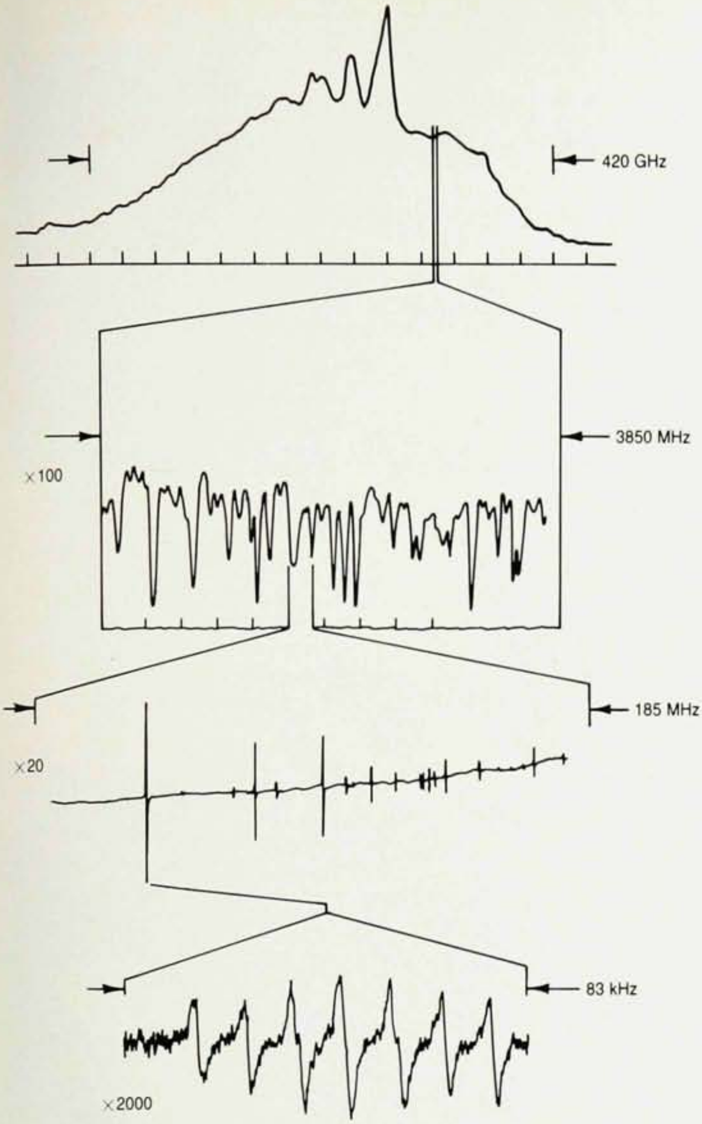
An isolated molecule is a microcosm of elementary chemical behavior: The electron cloud of an isolated molecule continuously distorts in response to the slow vibrational motion of the nuclei, which in turn travel on a potential-energy surface determined by the electrons' motions. The motions of electrons in molecules can now be studied with unprecedented clarity. Picosecond and femtosecond laser experiments elucidate the energy flow from one part of a molecule to another, the transitions to chaotic vibrational motion and the rates and mechanisms that determine the system's choice of a particular decay mode. Multi-laser methods for photodissociation studies, double-resonance spectroscopy and photoelectron spectroscopy are but a few of the techniques recently demonstrated.

Among research opportunities in the study of isolated molecules are investigations of short-lived, highly reactive species including ions, free radicals and metastable molecules—which can now be produced in supersonic beams for detailed study. These offer new insights into chemical dynamics and methods for controlling chemical processes. The study of the transition from clusters of atoms to condensed matter is basic to the understanding of materials and to industrial, technological and environmental processes.

It is now possible to study molecular collisions between a wide range of unusual molecules with the quantum states fully resolved. Modern lasers can dissociate molecules, creating a "half-collision"—a dynamical interaction that occurs only during the separation of the products, so that the details are not obscured by unknown features of the collision dynamics. Such techniques now make possible the study of the most fundamental aspects of molecular collisions, presaging a new and deep physical understanding of simple chemical reactions.

Optics. In the past decade the invention of new lasers and other novel light sources, the development of new methods of spectroscopy and nonlinear optics, and the continued discovery of scientific and practical applications of these technologies have combined to promote optics and optical physics to the forefront of contemporary physics. To assure the continued productivity and growth of this area the panel proposes initiatives in the development of new light sources, advanced spectroscopy and quantum optics.

In the past decade the refinement of the semiconductor, dye and excimer lasers has revolutionized spectroscopy and communication. Powerful neodymium glass lasers have ignited thermonuclear fusion reactions. In the coming years, exploitation of new techniques such as multiphoton excitation and inner-shell excitation of atoms and molecules should lead to opportunities for the development of short-wavelength lasers—ranging from the far



ultraviolet to the x-ray regions.

Nonlinear processes can generate harmonics of visible and near-ultraviolet laser light to complement synchrotron light sources, providing extremely bright light in certain spectral regions with relatively small-scale equipment. New methods of image formation and optical processing based on phase conjugation and other nonlinear processes can have important applications in optical communication, astronomy and the manufacture of integrated circuits.

Such techniques as saturation spectroscopy and two-photon Doppler-free spectroscopy have effectively eliminated Doppler broadening, the major source of line broadening in conventional spectroscopy. Stabilized tunable lasers used in conjunction with these techniques have improved spectroscopic resolution by as much as a millionfold. Optical-frequency counting methods have achieved such precision and range that the definition of the meter has been fundamentally altered: Previously the meter was defined in terms of the wavelength of a spectral line of krypton; now it is defined as the distance light travels in a given time.

The statistical properties of light and the electrodynamics of its interaction with matter are central to understanding how light is generated and propagated, how information is transmitted and many other physical processes. Among the research opportunities singled out by the panel are the preparation of light in novel statistical states, the use of bi-stable optical devices to study the transition from uniform to chaotic motion and the investigation of electrodynamics at long wavelengths.

The high quality of many of the groups pursuing atomic, molecular and optical physics in the United States is the field's primary strength. But after a decade of severe cuts, the remaining groups are seriously threatened by underfunding and lack of equipment. "To assure that the scientific opportunities in AMO physics can be pursued in the United States," the panel writes, "the first priority must be to assure the continued vitality of the best of these groups and at the same time to create opportunities for young scientists to enter the field."

To pursue its goal of continued vitality, the panel proposes a four-year program at the end of which a total of approximately 140 groups would be pursuing new research in the initiative areas identified above.

The panel also laments the shortage of sustained support for basic atomic, molecular and optical physics, which deprives groups of the flexibility to move in new directions and to provide adequate support for graduate students, postdoctoral fellows and visitors. Essential equipment cannot be purchased and instrumentation in many laboratories is obsolete. Support services—shops, technicians and special facilities essential to effective research—have seriously deteriorated throughout the United States. The panel believes that this pattern of chronic underfunding "threatens to stifle the freedom of imagination that is essential for science to flourish." However, they do see hope: "The panel notes with pleasure that Federal priorities for research in the past few years have placed increasing emphasis on the support of basic research. This provides a constructive climate for addressing the serious problems that confront AMO physics."

—Bruce Schechter □