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Photon science and quantum control

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Recent advances in laser technology have hastened developments in other fields—precision measurement, atomic cooling, gravitational-wave sensing, quantum computing, cryptography, and many more. Like the laser itself, those fields may transform society.

In the past decade, no fewer than four Nobel Prizes—one in chemistry and three in physics—were awarded for work done on the science of atoms and molecules interacting with laser light. The remarkable efforts that led to those prizes mark the latest stage in the gradual transformation of lasers, still less than a half-century old, from sources of directed photons for spectroscopy to something more: tools for the control of the quantum world. New lasers are reaching previously unknown regimes of intensity, stability, wavelength, and pulse duration. And those developments are driving new cross-disciplinary research in atomic, solid-state, and x-ray physics; quantum optics; physical chemistry; and laser engineering.

The 10 laureates who shared the four Nobel Prizes in the past 10 years have helped shape the new discipline of laser-driven quantum control. Nine come from the field of atomic, molecular, and optical physics. A recent National Research Council interim report[1] describes some of the research opportunities in the AMO field and points to anticipated advances in six areas: precision measurements, ultracold matter, ultra-high-intensity and short-wavelength lasers, ultrafast control, nanophotonics, and quantum information science. Keeping in mind Yogi Berra's caveat, "It's tough to make predictions, especially about the future," I describe here some of the opportunities in those areas and try to convey the excitement accompanying them and the rapid growth in photon science generally; the growth appears likely to continue for years.

Clocks and lights

What time is it, really? The most recent Nobel Prize in Physics was awarded in part to John Hall and Theodor Hänsch for advances in one of the oldest subjects in physics: measuring the passage of time (see Physics Today, December 2005, page 19). At the most fundamental level, physicists still don't know what time is, although we surely know how to quantify it more precisely than any other physical property. And things that we can compare to our most accurate clocks—the spin rate of a pulsar, for example, or the frequency of an atomic transition many light-years away—may be the sources of new discoveries. The source of the next great discovery in physics is mere speculation, of course; but the remarkable improvement in atomic-clock precision is a fact, and improvements to the state of the art continue.

Ultrafast pulsed-laser sources, developed in the past decade for such applications as optical digital communication and the investigation of transient phenomena, have found new uses because of their special spectral properties: The pulses in those lasers contain an optical-frequency comb that stretches from the near-UV to the near-IR wavelength range. The frequency comb enables direct and precise conversion between optical frequencies and the microwave frequencies of atomic clocks. We can now literally count the optical-frequency (10^{15} Hz) waves and thereby measure optical-frequency ratios more precisely than ever.

Time reversal—through the looking glass. A clock appears to run backwards, or counterclockwise, when viewed in a mirror. But, of course, it doesn't run more slowly. The mirror's backward minute is precisely the same duration as a forward minute. But what if a physical process went backwards? Could we even tell? That is not just a whimsical remark, but a serious question about the fundamental forces of nature. We have known for years that neutral K mesons created in high-energy collisions display a tiny bit of time-reversal difference, or asymmetry, but we don't yet know why. We don't even know whether ordinary matter has the same property, and we have very few ways to seek the answer.

The measurement of atomic electric-dipole moments (EDMs) could provide clues (see the article by Norval Fortson, Patrick Sandars, and Steve Barr in PHYSICS TODAY, June 2003, page 33). EDMs in atoms cannot exist in a perfect time-symmetric world. Indeed, no one has ever observed a permanent electric-dipole moment in an atom, even though with today's instrumental sensitivity, a relative charge displacement between an atom's electrons and nucleus as small as a trillionth the width of the nucleus would be detectable. Nevertheless, some of the most promising theories that offer explanations for particle-physics time-reversal violations also predict atomic EDMs not much smaller than the present limit. Similar advancements in precision measurements can also search for matter–antimatter *CPT* violations—that is, violations to symmetry under the combined operation of charge conjugation, parity, and time reversal—or even violations of Einstein's famous principle of relativity at levels far more sensitive than ever before possible.

Position sensing—where are we? Laser navigation gyros are not new. They are optical interferometers that detect motion by measuring changes in the relative length of two optical paths. The same operating principle is behind gravitational-wave observatories such as the Laser Interferometer Gravitational-Wave Observatory, which are pushing the concept of relative length to extreme limits: LIGO can measure length changes as small as a hundredth of a proton diameter over the length of a football field. A future space-based gravitational-wave observatory named LISA (Laser Interferometer in Space Antenna) would be even more sensitive.

Cold and fast

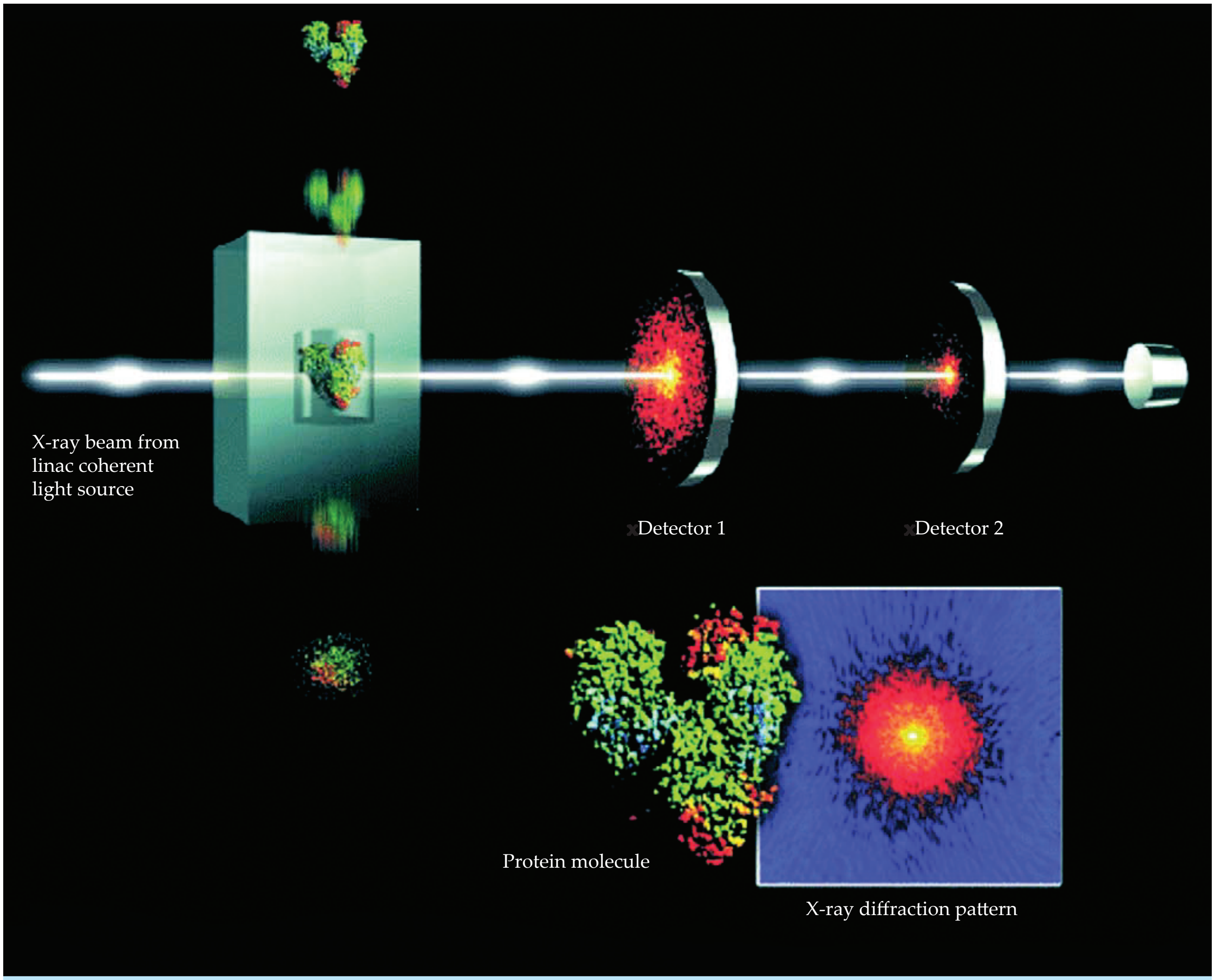
Where is the coldest place in the universe? Boulder, Colorado. That's not just the punchline of a joke about weather on the Front Range. The low-temperature record for any macroscopic object is held by atomic Bose–Einstein condensates at about one billionth of 1 K, far colder than the 2.7 K cosmic background temperature of deep space.

Scientists investigating ultracold atoms captured two of the past decade's Nobel Prizes, and the field itself was the most spectacularly successful research area in atomic, molecular, and optical physics over the period. Meanwhile, ultracold atoms are beginning to have important research and technological applications. For example, ultracold atoms form the inner workings of the highest-accuracy atomic clocks, such as the NIST-F1 atomic fountain clock, which are partly responsible for the advances in precision time measurements.

Quantum interferometers. Interferometry and ultracold gases come together in a revolutionary combination to improve the sensitivity of interferometers by replacing the light waves with quantum matter waves. Matter- wave interferometers could provide huge improvements in the accuracy of navigational systems and systems that measure changes in local gravity. Right now, for example, gravimeters based on laser interferometers that suspend mirrors as test masses are used to explore local gravity anomalies on Earth. The technology has found applications in oil exploration and other endeavors. In quantum matter-wave interferometers, the acceleration of gravity is applied not to the mirror but to the wave itself. These types of interferometers would so greatly extend the sensitivity of gravimeters that it would be possible to detect tiny underground nonuniformities in Earth's gravity from airborne laboratories.

Ultracold gases are a new arena for quantum control as well. They have been used to simulate some of the quantum many-body physics in condensed matter systems. They can be confined to one or two dimensions and can be controlled to mimic periodic structures of crystalline solids. The approach has led to a new research field of quantum simulators, which is beginning to attract attention from the solid- state physics community.

The next superpower. Lasers, already the brightest lights on Earth, will reach peak powers beyond a quadrillion watts in the next decade. That's more power concentrated in the peak of a high-powered laser pulse—if only for a few femtoseconds—than is consumed by all the nations on Earth. That capability will bring to the laboratory bench the plasma conditions that exist in stellar interiors, and high-energy-density physics is poised to make great advances because of it. High-powered lasers also produce very large field gradients that can be used to accelerate particles; that



The linac coherent light source, a free-electron laser under construction at SLAC, will emit femtosecond pulses a billion times brighter than any other existing x-ray source once it begins operating in 2009. The schematic here pictures the diffraction from a protein molecule that falls through the beam. Scientists will merge a series of diffraction patterns of the molecule in many different positions. The resulting three-dimensional reconstruction will reveal the structures of proteins that cannot be crystallized and studied any other way.

approach to particle acceleration will be yet another active research field in the coming decade.

A new kind of high-powered laser is about to switch on for the first time: The x-ray free-electron lasers under construction in the US, Europe, and Asia, which will be about a billion times brighter than any other source operating in the x-ray region, represent a merging of the most advanced technical capabilities of high-energy particle accelerators and x-ray light and laser sources. They derive their energy from relativistic electrons compressed to femtosecond bunches in linear accelerators. The x-ray bursts from such lasers are expected to be brief enough to capture motion on the atomic scale in molecules and bright enough to record an image of a biological molecule like a virus or a protein (see the figure). The first x-ray FEL is scheduled to start operations at SLAC in 2009. International teams have already assembled to plan research on these revolutionary machines.

Ultra-ultrafast pulses. Ordinary molecules at room temperature rotate in picoseconds; they vibrate and collide in femtoseconds. Thus, much can be learned from femtosecond lasers that excite or probe matter. The 1999 Nobel Prize in Chemistry recognized achievements in this fast-moving field (see Physics Today, December 1999, page 19). Subpicosecond lasers are now commercially available and ultrafast pump–probe techniques have become routine. I've already mentioned the contributions of ultrafast lasers to precision measurements, but there is much more to the rapidly expanding field.

One of the most intriguing challenges for the future is to push for still-shorter pulse durations. In the past few years new sources have produced pulses shorter than one femtosecond—an achievement that heralds the age of attosecond science. Just as femtosecond pulses are ideal tools for exploring atomic motion in molecules, attosecond pulses go one step further and can be used to explore electron motion within atoms. Electron motion creates and destroys bonds, the physical basis for chemistry and materials science. The new capabilities are likely to produce new physical insights.

Subfemtosecond pulses are already being used in atomic physics. The rearrangement of electrons in atoms following the excitation of a core-level electron is known to take place at very short time scales, often under one femtosecond. The inaugural experiments with attosecond pulses observed that process three years ago (see Physics Today, April 2003, page 27).

Learning from the quantum world. New advances in optical pulse shaping enable the generation of light pulses whose shape, polarization, intensity, and frequency can all be controlled at will. Such total control of light can be translated into near-total control of the quantum state of a molecule. Many examples now exist of mode-selective chemistry, in which optical pulses are tailored to push a chemical reaction to favor one product or another, simply by changing the pulse shape. The search for pulse shapes that can control reactions to favor the rare over the common can proceed via computer control in learning feedback systems. Those systems are capable of producing hundreds of different pulse shapes per second, performing similar experiments with each one, and analyzing and ranking the results (see the article by Ian Walmsley and Herschel Rabitz, Physics Today, August 2003, page 43).

There are many more examples in which lasers are used to control the quantum world. Quantum computing, photonic crystals, quantum cryptography, and negative-index materials are each new, rapidly growing fields with tremendous potential to expand science. Some of those areas may even transform society, just as the laser itself has done. Certainly the new research areas that explore control of the quantum world are experiencing a decade of rapid progress. As Yogi said, predictions about the future may be difficult; but the general prediction that much rich research in quantum control lies ahead seems a safe bet.

This essay is adapted from a talk given at the 75th-anniversary celebration of the American Institute of Physics in May 2006.

REFERENCE

1. Committee on AMO 2010, National Research Council, *Controlling the Quantum World of Atoms, Molecules, and Photons: An Interim Report*, National Academies Press (2005).

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