power densities using relatively small lasers. High intensity light pulses allow us to access previously unexplored extreme states of matter—for example to generate very short pulses of light at new wavelengths. Although atoms within such a focused laser are very quickly torn apart, in recent work we demonstrated that this does not occur instantly, but takes a few femtoseconds. We then used this fact to our advantage to generate the shortest x-ray pulses ever, only a few femtoseconds in duration. Using a technique for converting optical frequency light into x rays,[10,11] we found that by using very short laser pulses we could generate higher-energy x rays than previously possible—more efficiently, with greater tunability, and with an unprecedented short duration.[12] These x rays, by virtue of x rays' ability to more directly observe atomic structure, will make it possible to study with unprecedented clarity the most basic processes which occur in our natural world—for example, the motion of atoms in chemical reactions and in material phase transitions. This new, table-top sized x-ray apparatus will allow some of the types of experiments previously performed using synchrotron facilities, to now be performed with an added dimension: ultrahigh time-resolution.

Many other potential applications of very short optical pulses exist. Ongoing research by others may mean that extremely short duration optical pulses will be used to perform on-site characterization of silicon surfaces during chip manufacture,[13] and to take 3-D pictures of living cells.[14] The applications are becoming a reality because ultrashort pulses combine two seemingly contradictory characteristics: extremely high peak power (which makes it possible to access nonlinear processes such as how molecules jump to a higher-energy state by simultaneously absorbing two photons instead of a single photon) with very low average power (which makes the laser small and the disturbance caused by it relatively noninvasive). Very short duration ultrahigh-power optical pulses have the potential to efficiently drive future laser-based particle accelerators[15] and to perform more accurate micromachining and laser surgery.[16]

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A New "Momentum Microscope" Views Atomic Collision Dynamics

A new "microscope" is providing spectacular views of the correlated motion of the fragments of atomic breakup processes. Whereas ordinary microscopes reveal the spatial structure of an object, this new approach provides multidimensional "pictures" of momentum distributions for all particles produced in fundamental atomic reactions such as ionization of an atom by charged particles or by photons. The technique, termed "cold target recoil ion momentum spectroscopy" (COLTRIMS), allows the measurement of previously undetectable small momenta of ions emerging from atomic reactions. Furthermore, this is done with high-resolution, large 3-D slices of the collision volume, and often includes measurement of the momenta of electrons produced in the reaction.

In 10 years of development, researchers have progressed from making the first successful measurements of such ion momenta[1] to creating today's high-resolution reaction "microscopes." This effort was pushed by groups at the University of Frankfurt and GSI (Germany), and at Kansas State University.[2] Today additional systems are in use at CIRIL/GANIL (France),[3] Riken (Japan), and the Lawrence Berkeley National Laboratory and are being installed at University of Missouri at Rolla and at Argonne National Laboratory.

The COLTRIMS technique collects the low-energy collision products (a recoil ion and electrons) in a weak, uniform electric field which projects their 3-D motions onto 2-D position-sensitive ion and electron detectors. Combined with measurement of the time-of-flight to the detectors, the 3-D momentum distributions

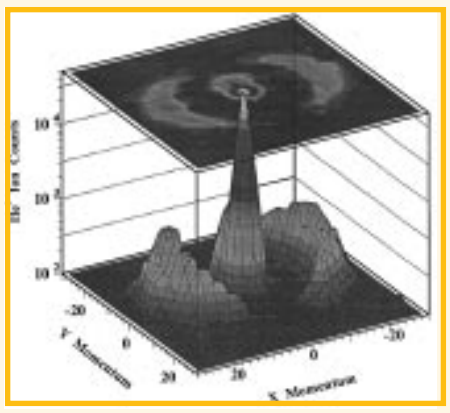

FIGURE 2. The momentum distribution of ions produced by collisions of 9-keV photons with helium atoms. The sharp needle in the middle (at near-zero momentum) contains ions produced by Compton scattering (in which photons surrender part of their energy to the collision), while the circular "reef" shows ion momenta created by photoabsorption (in which photons surrender all their energy). In the experiment, the photon electric field is directed along the x axis.

can be determined. The result is similar to that obtained from nuclear or high-energy particle collision experiments, i.e., an event-by-event accounting of the momentum components of the reaction products. To gain the highest precision measurements of final momenta, a cold, supersonic helium jet target is used. In the case of atomic reactions, the relevant particle energies are truly tiny, only fractions of an electron volt, whereas nuclear or high-energy particle collision products have energies millions (or billions) of times higher.

In many cases, images of the momentum distributions of the ions and electrons from atomic reactions directly "display" the processes responsible for the breakup of the atom. Thus some longstanding puzzles in atomic collision physics were solved recently using this new approach and many new questions and challenges to theory were raised.

For example, Lutz Spielberger (U. Frankfurt) and coworkers[4] have recently separated different mechanisms of photoionization—in which light removes electrons from atoms or molecules to produce ions—by measurement of the final ion momenta. If a photon completely surrenders its energy to an atom, the atom breaks into two fragments (a positive ion and an electron) of equal momenta, while for Compton scattering (in which the photon loses only part of its energy) the photon makes a billiard-ball-like collision with one target electron without direct momentum transfer to the atom's nucleus (see Fig. 2). This allowed for the first time the study of how the helium atom's second electron responds to these different interactions with the first electron. The new measurements provided a long-needed conclusive experimental answer to intense controversy among theorists about the ratio of the probability for Compton-scattered light to remove two helium electrons to that for single ionization.

In another application of this new approach, Robert Moshammer (GSI-Darmstadt) and coworkers[5] have demonstrated that the impact of a fast, highly charged projectile ion (moving 16 times faster than the mean velocity of electrons within the target atom) acts like a high-intensity light pulse, causing the atom to break into an ionic core and one or more electrons. The recoil of the ionic core is so large that it almost compensates the total momentum of the electrons. The measured momentum distributions of the freed electrons carry information on their correlated movement inside the atom on a time scale of 10^{-18} s—a billionth of a billionth of a second.

In lower-energy collisions, with proton projectiles moving slower than the electrons in the target helium atoms, Reinhard Dörner (U. Frankfurt) and coworkers and Scott Kravis (Kansas State Univ.) and coworkers were able to see that electrons appear to be "left stranded" on the saddle point between the two receding heavy partners[6,7] (in this case, the saddle point refers to the location between the proton and helium ion at which they exert a net force of zero on the electron). This effect was predicted by Ron Olson (U. Missouri, Rolla) in 1983 and has since been a subject of intense theoretical and experimental research. The new momentum spectroscopy results have provided a definitive observation of this phenomena.

A collaboration led by Kansas State University and the University of Frankfurt has employed this new technique to investigate photon-induced breakup of a helium atom into its three constituents (nucleus and two electrons) using light from the Lawrence Berkeley National Laboratory Advanced Light Source. The photons used were chosen near-threshold for the process, that is, they had barely enough energy to achieve double ionization.[8] The results show how the mutual forces between the three charged fragments yield simple momentum configurations in the final state which follow from basic arguments proposed by Wannier in 1953. Owing to the long-range nature of the Coulomb potential, the behavior of as few as three particles in the continuum is hard to treat by first-principles quantum mechanical calculations and successful theoretical approaches have only recently been developed.

Although this new technique has already brought a rich harvest in ion–atom, electron–atom, and photon–atom collision physics, its use is just beginning to flower. Future applications can extend to fields like molecular physics or to tests of quantum electrodynamics (the theory that unifies quantum mechanics, special relativity, and classical electromagnetism) in collisions between heavy ions travelling near light speeds. Another exciting application is in the study of the radioactive process known as beta decay. With this new technique, one can expect precise measurements of the angular correlations between the decay products (the daughter nucleus, a positron or electron, and a neutrino). One may even imagine a high-resolution neutrino mass measurement for each beta decay event. Such a measurement, which would provide coveted information on whether neutrinos have mass, would employ an accurately determined neutrino momentum value deduced from measuring the momentum values of the daughter nucleus and the emitted electron or positron.

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Precision Molecular Spectroscopy with Cold Trapped Atoms

By using light to combine two colliding, cold trapped atoms into a molecule, a new kind of high precision molecular spectroscopy is probing the long-range forces between the atoms. This approach of "photoassociation spectroscopy" has been used to make the most precise measurements yet of the lifetimes of the first excited state of the Na and Li atoms, and to observe the influence of retardation corrections to the long-range force between one ground-state and one excited-state atom. (Retardation refers to the ultrashort, but finite, time for light to cross the molecule—in seconds, roughly the fraction 10 divided by a billion times a billion.) Since particles interact electromagnetically through the exchange of photons, the finite speed of light affects the long-range forces between the atoms.

In any atomic or molecular system, absorption of light often occurs at a set of unique narrow frequencies. A plot of the response of the system, which can be observed in many ways, against the frequency of the light is the "spectrum" of that system and it displays unique narrow features, often called "lines" because they were first observed as lines on photographic plates. Each of the spectral lines has a width, that is, a narrow but finite range of frequencies where the light is absorbed. A part of this width arises from the spread of velocities of the moving atoms, by the familiar Doppler effect: the shift in frequency caused by a moving source. (The shift heard from a moving train whistle is an example of this effect for sound waves.) For the case of a collection of atoms moving at different velocities, one has a superposition of many different Doppler shifts which contribute to the total spread seen in the absorption line. If one can arrange to have all the atoms moving with the same velocity, the Doppler spread is nearly zero. One does not, however, reach zero width because (even for motionless atoms or molecules) there is an irreducible width—the natural linewidth—which is determined by the lifetime of the excited state.

To measure the lifetimes of the atoms' excited states, a laser of variable frequency ν is tuned so that the energy of its photons, $h\nu$, matches the energy difference between an excited state of the diatomic molecule formed from the atom pair, and the ground state of the colliding atoms. The formation of the excited molecular state is observed either by ionizing it with a second photon and detecting the ions or by detecting the loss of trapped atoms due to decay of the excited state to untrapped states. Scanning the laser frequency gives an excitation spectrum (the photoassociation spectrum) for production of the molecular excited states. The spectral line shapes are very sharp, rivaling those seen with conventional methods of high-resolution laser spectroscopy. This is because the kinetic energy of the cold ground-state atoms is sharply defined; the very small kinetic energy of the cold atoms yields a Doppler spread less than a natural linewidth of the atomic line used to laser cool the atoms. A careful consideration of the actual spectral line shapes is necessary for the most precise use of these spectra, since they are strongly influenced by the quantum nature of the cold colliding atoms.[1]

A combined experimental and theoretical effort at NIST[2] has concentrated on a very special excited state of the sodium diatomic molecule. This state is a "pure long-range state"[3] which correlates at large separations of the atoms, to the combination of one atom in the ground state and one in its first excited state. The long-range form of the force between two atoms of the same species, one in the ground state and one excited, is similar to that between two bar magnets; it varies as the inverse cube of the separation between them and is proportional to the product of their dipole strengths. (The dipole strength is a quantity which determines how strongly an atom absorbs light.) Here, the dipole strength product is proportional to the decay rate of the excited-state atom, that is, to the inverse of the atomic lifetime. The potential energy of this state, plotted against the interatomic separation, has a very shallow minimum about 55 GHz deep. (1 GHz = 1 billion cycles/s; spectroscopists often express energies as frequencies, omitting the conversion factor of Planck's constant. Visible light photons have energies equivalent to ~1/2 million GHz.) This minimum occurs at a separation near 71 a_0 (1 a_0, the radius of the hydrogen atom, is ~50 trillionths of a meter) and a repulsive wall that never lets the atoms get closer than about 55 a_0. (In contrast in the common diatomic molecule formed from two oxygen atoms, O_2, the atoms are separated by about 2.4 a_0.)

The long-range molecular state is entirely determined by the properties of the separated atoms. However unlike a single atom, a diatomic molecule can absorb light at frequencies which excite vibrational motion (that is, motion of the two atoms toward or away from each other) or rotational motion (where the two atoms rotate as if at the ends of a twirling baton), or a combination of both. Because the molecule is a quantum system, these motions occur at sets of discrete vibrational or rotational energies. Careful measurement of the photoassociation spectrum of the long-range state, along with theoretical modeling of the line shapes, determines the positions of the rotational lines of the lowest seven vibrational levels to ~5 MHz (1 MHz = 1 million cycles/s). By adjusting the dipole strength used to match these molecular spectra, the NIST researchers determined the Na excited state lifetime to an accuracy of 0.1%. The vast majority of atomic lifetime measurements have uncertainties at least 10 times larger. In addition, the 121 MHz shift in binding energy of the ground vibrational level due to the retardation corrections to the interatomic force is evident from the measurements.

A group at Rice University, led by Randall Hulet, has recently reported a Li atomic lifetime with 0.03% accuracy[4] measured using photoassociation spectroscopy of trapped Li atoms. These researchers did not use a "pure long-range state" of the Li_2 molecule, but rather one which experiences chemical bonding at short range. The improved accuracy follows from the wider range of lines surveyed, supplemented by conventional spectroscopic data.[5] The Rice group also detected the effect of retardation corrections to the long-range force.

The atomic lifetimes determined from these molecular spectra are the most accurate to date for Li and Na. Although these measurements are much more accurate, they agree (within error limits) with other recent determinations, thus essentially setting to rest longstanding questions and discrepancies about the lifetimes of these simple excited atoms. Photoassociation spectroscopy has also determined an atomic Rb lifetime at the 1% level,[6] and work is in progress on K.[7] In addition, conventional molecular spectroscopy on long-range excited states of the Na molecule has also been used to determine the atomic Na lifetime with 0.3% accuracy.[8] In the study of excited-state lifetimes, researchers have therefore made dramatic progress not only in opening new avenues but also in enhancing traditional routes.

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Experimental Realizations of Quantum Thought Experiments

Physicists traditionally construct imaginary experiments, termed "thought experiments," to explain the strange behavior of physical systems to which quantum or relativity theories (or both) must be applied. These thought experiments "run" only on paper because they are generally technically impossible to realize with hardware in the laboratory. However, a class of thought experiments—in which single atoms, photons, and other quantum systems are precisely manipulated and observed—have recently graduated to become real experiments in quantum optics laboratories. Some of the most intriguing experiments involve investigations of the behavior of quantum parts of a total quantum system. These new studies have provided fundamental insights into the quantum nature of the electromagnetic

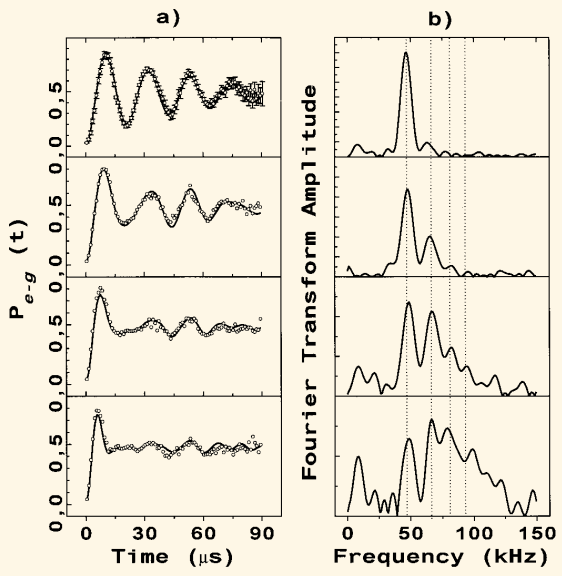

FIGURE 3. (a) Data from an experiment explicitly showing, for the first time, how the quantized nature of an electromagnetic field affects the interchange of energy between the field and an atom. $P_{e-g}(t)$ is the probability of finding the atom in energy level g after interacting with a weak coherent microwave field for a time t. The four recordings correspond (from top to bottom) to increasing field intensities. In the present experiments, the probability that the atom resides in level g exhibits a simple oscillation when the field is in its vacuum state (top) but exhibits more complex oscillations when the higher field excitation levels are considered. The complex oscillations demonstrate the quantum nature of the field and, moreover, tell us that under experimental conditions, the field is in a superposition of photon states. (b) Performing a mathematical operation known as a Fourier transformation on the lower data recordings reveals that there are several distinct "Rabi frequencies," each corresponding to the frequency of energy exchange for a different quantum energy level of the electromagnetic field.