flat surface, which is an efficient, dynamic process. Although there is some cocontraction of opposing muscles to ensure stability, particularly in the stance phase, the resulting load is limited and transient. This is not the case, it turns out, when one rises from a sitting position. "This involves a huge cocontraction in what is an essentially static process," says Harris.

For comparison, peak focal pressures during walking are in the range of 6 megapascals (MPa, where 1 MPa = 10 atm) but can be as high as 18 MPa in rising from a sitting position. "Many people were surprised to see such high pressures from this kind of activity," comments Brown. Clinically, this discovery is extremely important, particularly in improving total hip replacement procedures, in which the pelvis is partially reconstructed.

Harris and his colleagues are just completing a 5-year retrospective study of total hip replacement. They find that if the acetabulum cracks or fails, it often does so toward the back of the joint. "The reason for this is now clear," says Harris. "Not only is the pressure from cocontraction very high during rising from a sitting position, but it is directed posteriorly." There has generally been the assumption that most pressure on the joint would be on the top, not at the back, again because of the concentration on the mechanics of walking. Bone remodeling during total hip replacement has therefore often neglected a point where the highest pressure is exerted.

Because Mann and Harris have been able to monitor pressures in Mrs. F's hip joint throughout the recovery phase they are now in a position to evaluate more critically some of the rehabilitation regimes. For instance, it turns out that loading of the joint when the patient uses a cane for support is only 5% greater than if a single crutch is used. This also is contrary to conventional wisdom, and it means that it might be possible to move patients from a crutch to a more convenient cane sooner than is currently done, thereby accelerating their progress.

Dramatic and important though these results undoubtedly are, they of course represent only one case and will therefore have to be replicated to improve their value. And the data are limited to pressures within the microenvironment of the joint and do not give total resultant force across the joint, which remains a separate and equally important piece of information for orthopedic surgeons. ■ **ROGER LEWIN**

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Atoms in Strong Laser Fields Obey the Rules

Experimentalists and theorists now agree that the multiple ionization of rare gas atoms by infrared, visible, or ultraviolet laser light takes place one electron at a time

When the intensity of laser light reaches 10^{16} watts per square centimeter, the strength of the light wave's electric field is comparable to that of the field binding the electron and proton in a hydrogen atom; that is, the light is no mere perturbation as assumed in the conventional theory of the interaction of electromagnetic radiation with matter. Since this intensity can now be easily reached with the focused light from a laser with picosecond pulses, it is hardly surprising that atomic physicists have been finding seemingly out-of-the-ordinary behavior as they crank up the power of their light sources.

An unresolved question is, At what laser intensity is a new theoretical approach necessary? Over the past 4 years, for example, atomic physicists have been puzzled by the apparent ease with which rare gas and some other atoms can be multiply ionized by absorption of laser light over a wide range of wavelengths from the infrared to the ultraviolet. Naive application of conventional thinking results in much lower probabilities for stripping away subsequent electrons than for removing the first one.

A series of ultraviolet experiments by Charles Rhodes and several co-workers at the University of Illinois at Chicago, who were able to generate such highly charged ions as U^{10+}, has provoked the most excitement during the period, partly because the researchers proposed a new, highly efficient collective excitation process in which an entire shell of electrons could be simultaneously removed. The group also argued that such an efficient excitation process might provide a way to overcome the principal difficulty in making an x-ray laser, selectively and quickly pumping enough energy into the laser medium to generate a so-called population inversion before the excited atoms spontaneously relax to lower-energy quantum states.

The most recent ultraviolet findings at Chicago, reanalysis of infrared and visible experiments at the Saclay Nuclear Research Center in France, and several new theoretical studies, however, are converging on the proposition that such novel atomic physics notions are not needed to explain any of the results up to now. In particular, the ionization process is almost always a sequential one with electrons coming off one at a time.

Interest in the multiple ionization of rare gas atoms grew after a 1982 publication by Anne L'Huillier, Louis-André Lompré, Gérard Mainfray, and Claude Manus of Saclay, who observed the production of singly, doubly, triply, and quadruply charged krypton ions after irradiation with 50-picosecond pulses from a high-power near-infrared laser (mode-locked Nd:YAG emitting at 1.06 micrometers). The results were surprising, not only because of the multiple ionization, but also because higher charge states occurred at comparatively low intensities, ranging from 10^{13} to 10^{14} watts per square centimeter, where the laser's electric field is still much weaker than the internal field binding the outer electrons.

During the next 2 years, the Saclay researchers reported similar findings with other rare gases, including xenon, argon, neon, and helium, irradiated with 1.06-micrometer infrared laser light. And they saw the same kind of behavior with xenon and neon irradiated with 0.53-micrometer visible light, also obtained from their Nd:YAG laser by the standard nonlinear optics technique of second harmonic generation or frequency-doubling. Finally, for xenon, the group studied the effect of varying the length of visible laser pulses between 5 and 200 picoseconds.

To see more explicitly why these results were surprising, consider the multiphoton absorption of visible light by which ionization occurs in xenon. For this atom, it takes 12.1 electron volts to remove one electron, 33.3 electron volts to shake off two electrons, 65.4 electron volts for three electrons to be stripped away, and 111.4 electron volts for four electrons. Since each visible photon has an energy of 2.34 electron volts, the number of photons needed to make these ions ranges from 6 to 48.

If only one photon is needed to ionize the atom, there is no particular difficulty, and the difference between the photon energy and the photoionization threshold is carried away as kinetic energy by the photoelectron. However, if several photons are needed, one must visualize a stepladder of successive transitions between atomic quantum states

until the absorbed energy exceeds the photoionization threshold.

However, atoms are not so cooperative as to have uniformly spaced quantum states, and the wavelengths of nontunable lasers such as Nd:YAG do not in general match any of the atomic transitions anyway. Nonetheless, quantum mechanics allows a stepladder of transitions between fictitious or virtual quantum states, albeit with a very low probability for each step. Consequently, the overall multiphoton ionization probability is quite small and, according to this line of thinking, drops precipitously as the number of steps n or, equivalently, photons increases.

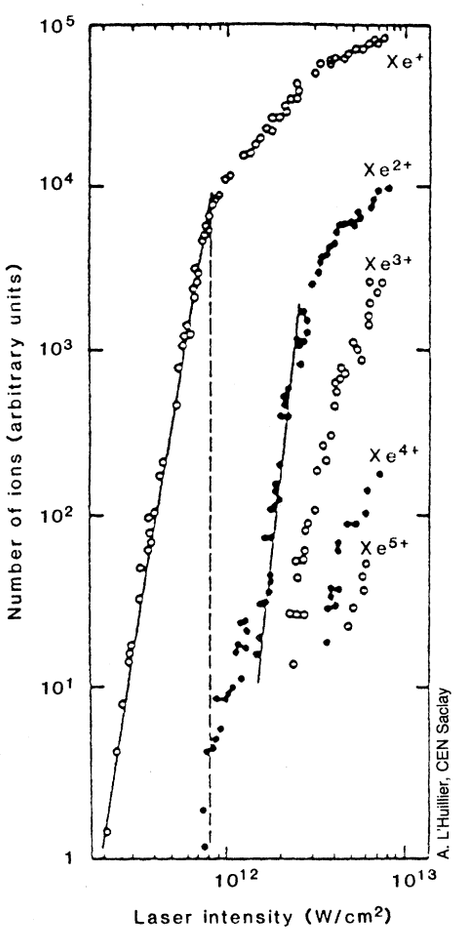
The ionization probability also depends on the light intensity I, varying as I^n, so that as the intensity grows, the likelihood of so-called higher-order absorption processes increases dramatically, which is why high-powered lasers are needed to see multiphoton ionization. The surprising thing about the Saclay results is the comparatively small intensity range over which processes requiring such a large difference in the number of photons become prominent (see figure, p. 1194).

Last year, See Leang Chin and François Yergeau of the University of Laval in Quebec and Pierre Lavigne of INRS Energie in Varennes, Quebec, demonstrated that multiple ionization of xenon can occur at much longer infrared wavelengths as well. Using 9.55- and 10.55-micrometer light from a carbon dioxide laser in the intensity range from 10^{13} to 10^{14} watts per square centimeter, the Canadian physicists observed singly, doubly, and triply charged xenon ions.

One conclusion drawn by the Saclay researchers is that multiple ionization is a sequential process, at least most of the time. In the figure, doubly charged xenon ions occur mainly at intensities greater than the so-called saturation intensity for neutral atoms. At the saturation intensity, all the atoms are singly ionized (the continued slow increase in singly charged ions above the saturation intensity is due to the nonuniform intensity across the laser beam, so that the effective size of the gas sample above saturation grows with intensity). Removal of the second electron at still higher intensities must therefore be from already singly charged ions, as corroborated by the slope of the linear part of the log-log curve, which is about 10 rather than the 15 corresponding to the number of photons needed to remove two electrons directly. In the sequential process, six electrons remove the first electron and ten the second.

At Chicago, Ting Shan Luk, Herbert Pummer, Keith Boyer, Mahnaz Shahidi, Hans Egger, and Rhodes reached quite different conclusions beginning with their 1983 report of ultraviolet multiple ionization experiments on several atoms spanning the periodic table from helium to uranium. They used an argon fluoride excimer laser emitting at 193 nanometers to generate 10-picosecond pulses at an intensity of 10^{14} watts per square centimeter. Subsequent experiments raised the intensity to 10^{16} watts per square centimeter, on the edge of the intensity range where unusual effects might be expected.

Direct comparison of the lower intensity infrared-visible studies with the higher intensity ultraviolet experiments is not possible because the two groups did different experiments. Rather than examine the number of ions as a function of laser intensity, the Chicago researchers measured the number of ions and took detailed photoelectron spectra at a few intensities. The ease of obtaining highly charged ions—including Ar^{6+}, Kr^{6+}, I^{7+}, Xe^{8+}, Eu^{6+}, Yb^{5+}, Hg^{4+}, and U^{10+}—the apparent inability of conventional theory to explain the observed abundances of charge states, and the pattern of ionization states with atomic number suggested to the group that, rather than individual electrons, entire atomic shells of electrons were interacting collectively with the laser light. In xenon, for example, some or all of the two 5*s* and six 5*p* electrons could come off as a group, which would explain the comparatively small variation in the numbers of ions with charges up to eight.



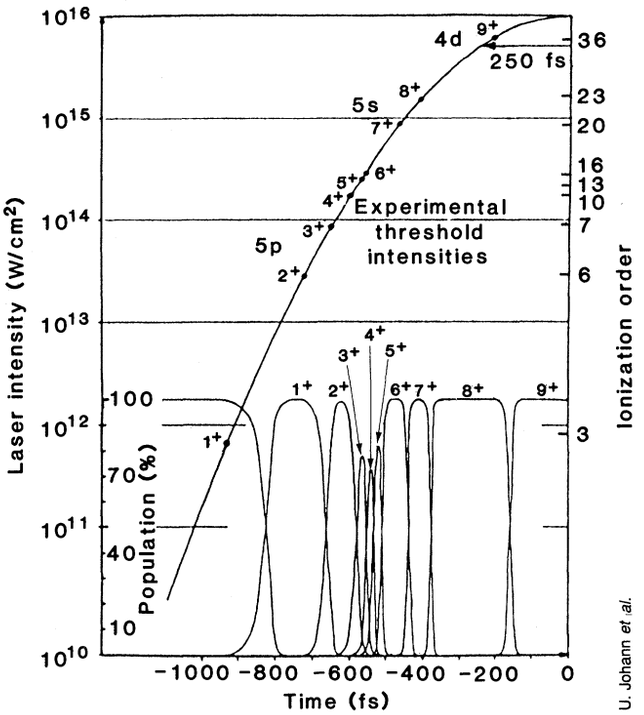
Multiple ionization of xenon

The Saclay researchers explain the number of xenon ions in each charge state by the sequential stripping away of electrons one at a time as the intensity of the visible laser light rises, except for the small number of doubly charged ions near the saturation intensity (dashed line), which are probably generated directly from the neutral atoms.

Though it now seems higher intensities are needed, the photoelectron spectra at first indicated that in xenon the inner shell 4*d* electrons were also being excited. The possibility of efficient excitation of such quantum states by collective motion of the outer shell electrons together with the projected ease of scaling up the power of excimer lasers raised the promise of a laboratory-scale x-ray laser. Two publications by Boyer and Rhodes and by Abraham Szöke of the Lawrence Livermore National Laboratory and Rhodes contained theories for inner shell excitation by this means.

It now seems, however, that new theories are not yet needed. Last year, for example, Michèle Crance of the Laboratoire Aimé Cotton in Orsay, France, published a statistical analysis of the multiple ionization of heavy atoms by ultraviolet light. By considering all the ways in which the energy from the absorption of a large number of photons could be distributed among the electrons in the outer shell of an atom, by assuming that all electrons had an equal chance of being ionized, and by assuming that ionization was a sequential process, Crance could calculate a probability for ionization of the atom. The analysis, which also took account of the spatial nonuniformity of the intensity of the laser beam and of the shape of the light pulse, agreed well with the experimentally determined abundances of ionic charge states.

A more recent statistical analysis was published last month by Xing-Dong Mu and Bernd Crasemann of the University of Oregon and Teijo Åberg and Anita Blomberg of the Helsinki University of Technology in Finland. The group's method of analysis begins with the maximum entropy technique of information theory. In short, maximization of an entropy function defined in terms of the probabilities of observing an ion of charge q for every possible q and ionic quantum state yields a hypothetical probability for observation of each ion charge that has one adjustable parameter to be fit to the experimental data for the abundances of charge states. In the end, they arrived at a



Xenon ions

The top curve shows the time evolution of a 0.5-picosecond ultraviolet laser pulse in a Chicago experiment. Points along the curve mark the minimum intensity (left ordinate) and number of photons (right ordinate) needed to generate each charge state. The bottom set of curves indicates the changing population of each charge state during the course of the laser pulse.

so-called truncated Poissonian distribution of charge states that fit the Chicago data well for different laser intensities and different atoms. The Poissonian distribution implies that the ionization events are independent; that is, multiple ionization is a sequential process.

The virtue of statistical analyses is that they are independent of most of the details of the atoms. The Oregon-Helsinki researchers did not need to know what the ionic quantum states were, for example, to maximize their entropy function. This feature makes it possible to treat complex multielectron atoms that would be prohibitively difficult to attack head on with quantum mechanics. Nonetheless, physical insight is hard to come by. Late last year, Peter Lambropoulos of the University of Southern California published a simple physical argument that succeeded in providing some of that insight without getting tangled up in details.

The gist of Lambropoulos' argument is that it is not possible to put an atom in an intense laser beam instantaneously. Real pulsed lasers always have a rise time during which the intensity grows to its maximum value. In particular, as the intensity grows, it first reaches the saturation intensity for the production of singly charged ions from neutral atoms, then the saturation intensity for the generation of doubly charged ions from singly charged, and so on up to the maximum charge state accessible. Lambropoulos used calculations based on a simplified model of xenon to demonstrate that, even for subpicosecond pulses, there is time for the transition from one ion charge state to the next to be saturated before the intensity grows enough to drive transitions requiring a larger number of photons. In this way, the production of highly charged ions takes place by the sequential stripping away of electrons one at a time.

An important point of the argument is that at each ionization stage, the laser electric field is low enough for conventional perturbation theory to be applicable. The neutral atom is singly ionized at a relatively low intensity. The field binding the remaining outer shell electrons after one electron is lost is stronger than the original binding field, so the laser intensity for which perturbation theory becomes suspect rises. As the electrons are sequentially stripped during the pulse, perturbation theory remains applicable despite the increasing intensity. No new atomic physics needs to be invoked.

The newest Chicago experiments now support this idea. In March, at the Optical Society of America's Third Topical Meeting on Short Wavelength Coherent Radiation, in Monterey, California, Ulrich Johann, Luk, Iain McIntyre, Armon McPherson, Pieter Schwarzenbach, Boyer, and Rhodes reported high-resolution photoelectron spectra taken from helium and xenon irradiated with argon fluoride and krypton fluoride (248-nanometer wavelength) ultraviolet lasers at comparatively moderate intensities up to 10^{16} watts per square centimeter.

Central to the interpretation of the spectra is a process called "above threshold ionization" in which more photons are absorbed than the minimum needed to strip away an electron. The pattern of photoelectrons generated by these processes for singly and doubly charged ions (higher charge states had spectra too complex to unravel) yielded the conclusion that ionization was sequential. "It's plain that the electrons come off stepwise," Rhodes told *Science* (see figure, p. 1195). Similar findings for the other rare gas atoms are about to be published.

If no new atomic physics concepts need be introduced to explain any of the results up to now, quantitative understanding of the observed phenomena remains to be achieved. For example, it is not yet clear why multiple ionization occurs at such low intensities. One hint has been provided independently by Mainfray and Manus and by Lambropoulos. From different starting points, they reached the same conclusion that the cross section for the absorption of large numbers of photons n does not decrease as rapidly with n as extrapolations of cross sections calculated for low n would imply. The larger cross sections make the absorption of the many photons required for multiple ionization more probable.

Another insight comes from a theoretical treatment published in March by Göran Wendin and Lars Jönsson of the Chalmers University of Technology in Göteborg, Sweden, together with L'Huillier, that discusses the role of electron screening on the photoionization probability. In effect, the electrons act together to reduce the effective light intensity seen by any one of them. But, as each electron is stripped away, the screening effect is lessened, raising the effective intensity and making it easier to remove the subsequent electron.

Finally, there is the question of whether faster, more intense laser pulses can overwhelm the atoms and rush them into a new physics regime, such as that proposed by the Chicago group. Rhodes and his colleages are boosting the power of their lasers and hope to reach above 10^{18} watts per square centimeter with light pulses of less than 1 picosecond within the next few months, and these experiments may provide an answer. ■ **ARTHUR L. ROBINSON**

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