consists of a series of sharp peaks, each one produced by a specific state shifting through resonance and providing a momentary enhancement in the MPI rate. While this model explains the electron spectra in great detail, a new observation was made. Using a low-intensity, high-influence probe laser after the short-pulse, high-intensity laser, it was found that there is a significant population left in the excited states of the atom.[2] Moreover, the excited states found to be populated are exactly those that had been identified through the short-pulse electron spectrum as providing intermediate resonances.

From these results a new interpretation of the electron spectra was proposed: In this alternate model, MPI is considered to be a two-step process. When an intermediate state is brought into resonance, the most important effect is a real transfer of population from the ground state to the excited state, rather than an enhancement of the MPI rate. The second step then consists of single or multiphoton ionization out of the excited state. The key feature of this model is that not only is the excited state population ionized while the state is in resonance, but also that the excited state population survives into the laser pulse and can be ionized at later times in the pulse.

Now, even more recent results show this two-step model to be inadequate.[3] Most high-lying levels (Rydberg states) of an atom have an AC Stark shift equal to the ponderomotive energy (the energy of a free electron in a laser field). Unfortunately, the two models discussed above predict identical electron spectra for those states with a ponderomotive AC Stark shift. On the other hand, the two models predict rather different spectra for non-ponderomotively shifted states in short-pulse electron spectra. The behavior of these spectra as a function of laser intensity clearly indicates that the electron spectrum could only have resulted from the resonant enhancement of the MPI rate while the state is in resonance. While this result supports the original explanation for the short-pulse electron spectra, it raises a significant new question: What is the origin and fate of the excited state population that was seen to exist, but not ionize in the intense laser field?

Unlike the earlier interpretation of MPI as a non-resonant perturbative process, we now know that MPI involves a complicated interplay between resonant enhancement and real population transfer that will require more work to unravel.

*Also at University of Maryland, College Park.

REFERENCES

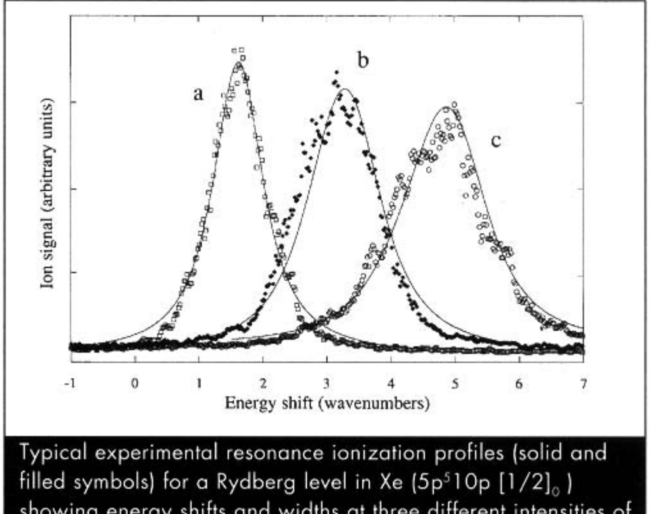
1. R.R. Freeman *et al.*, "Above-threshold ionization with subpicosecond laser pulses," Phys. Rev. Lett. **59**, 1987, 1092.
2. M.P. de Boer and H.G. Muller, "Observation of large populations in excited states after short-pulse multiphoton ionization," Phys. Rev. Lett. **68**, 1992, 2747.
3. G.N. Gibson *et al.*, "Verification of the dominant role of resonant enhancement in short-pulse multiphoton ionization, Phys. Rev. Lett. **69**, 1992, 1904.

The ac Stark Shifts of High-Lying Rydberg Levels in Intense Electromagnetic Fields

By J.-B. Kim, G. Lan, Q. Li,* T.B. Lucatorto, T.J. McIlrath,* and T.R. O'Brian, National Institute of Standards and Technology, Gaithersburg, Md.*

When an atom is subject to an intense, time-varying electric field (such as the electromagnetic field produced by intense laser radiation), the atomic energy levels are shifted by the external field, an effect called the light shift or ac Stark shift. A thorough understanding of these shifts is necessary to interpret results from experiments that use intense lasers to probe atomic structure. For a highly monochromatic laser not tuned to any atomic transition and for a Rydberg level with binding energy much less than the laser photon energy, theory predicts that the energy shift in the level will approach the value given by the so-called ponderomotive potential. In a Rydberg level, a single electron is in a large orbit loosely bound to the nucleus (which is embedded in the core of the remaining electrons), and this electron exhibits near-classical behavior in certain circumstances. The ponderomotive potential is simply the classical average kinetic energy a free electron gains when driven into oscillation by an external electromagnetic field.

Previous measurements of Rydberg level ac Stark shifts disagree with each other and with predictions, with recently reported values less than half the ponderomotive potential.[1] In addition, some measurements of the energy of electrons produced in certain laser ionization experiments, which should also approach ponderomotive values, deviate significantly from the theory.[2] No acceptable theoretical justification has been proposed to explain these apparent



Typical experimental resonance ionization profiles (solid and filled symbols) for a Rydberg level in Xe ($5p^5 10p\ [1/2]_0$) showing energy shifts and widths at three different intensities of the perturbing laser field: (a) 1.9 GW/cm^2, (b) 3.8 GW/cm^2, and (c) 5.6 GW/cm^2. The solid curves show predicted profiles assuming a ponderomotive shifting potential in a detailed model of the two-color, three photon resonantly-enhanced photoionization process as described in Refs. 3-5.

discrepancies.

We embarked on the present experiments to try to determine whether these serious discrepancies result from incomplete understanding of the physical principles or from experimental difficulties. Our first experiments[3] measured the energy shifts caused by an intense laser field (up to 10^{10} W/cm^2 at 1064 nm) for four closely spaced levels in Ca, three levels with Rydberg configurations and one with a more complex configuration. We found that the three Rydberg levels undergo a ponderomotive energy shift, while the other level is shifted only about half as much. The approximation that leads to the ponderomotive value for Rydberg levels breaks down for this latter "non-Rydberg" level. We then studied in detail about 15 Rydberg levels in Xe perturbed by intense 1064 nm laser radiation.[4] All of the levels investigated display ponderomotive energy shifts, including one level that had been previously reported to have an energy shift less than half the ponderomotive value.[1]

In both the Ca and Xe experiments, a relatively weak tunable probe laser excites an atomic level that is energy shifted by a strong Nd:YAG laser (1064 nm). Besides shifting the energy levels, the Nd:YAG laser also ionizes the excited atoms, and the ions are detected as the probe laser is tuned through the transition. The resulting ion signals (as a function of probe laser frequency) agree very well with models of the process that predict essentially ponderomotive energy shifts for the Rydberg levels.[5] The experimental data reproduce well the predicted widths and shapes as well as the energy shifts (see figure). These experiments should restore confidence in the simple picture of a Rydberg electron behaving essentially as a free electron when subject to an intense electromagnetic field with photon energy much larger than the Rydberg binding energy.

* Also with the University of Maryland, College Park, Md.

REFERENCES

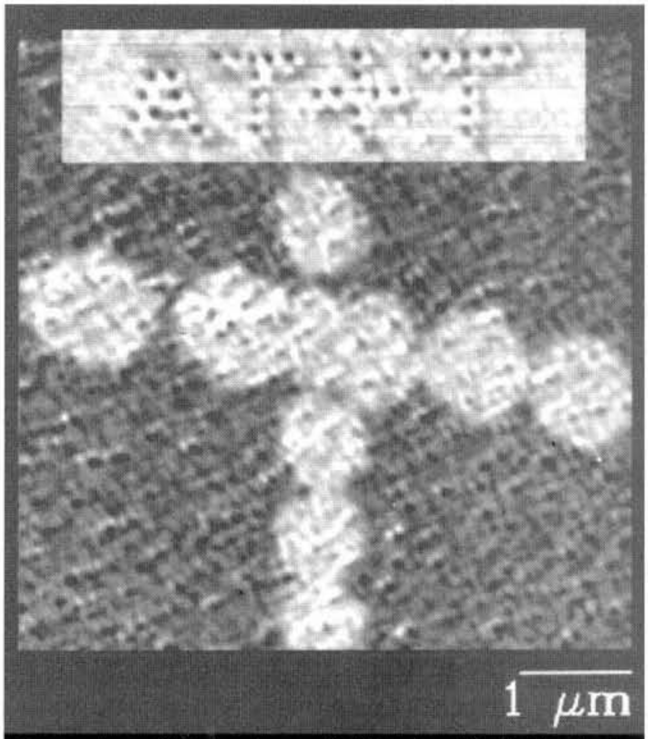
1. D. Normand *et al.*, "AC Stark shifts induced by a YAG laser in the *np* and *nf* Rydberg series in xenon," J. Opt. Soc. Am. B **6**, 1989, 1513-1518.
2. C.Y. Tang *et al.*, "Threshold structures in the multiphoton detachment yield from the H$^-$ ion," Phys. Rev. Lett. **66**, 1991, 3124-3127.
3. Q. Li *et al.*, "Configuration dependent ac Stark shifts in calcium," Opt. Lett. **17**, 1992, 1373-1375.
4. T. R. O'Brian *et al.*, "Observation of ponderomotive ac Stark shifts in Rydberg levels of xenon," submitted to J. Opt. Soc. Am. B.
5. A. L'Huillier *et al.*, "Theoretical aspects of three-photon two-color ionization of xenon through ac-Stark-shifted resonant Rydberg states," J. Opt. Soc. Am. B **6**, 1989, 1790-1795.

Near-Field Magneto-Optics and High Density Storage

By E. Betzig, J. K. Trautman, R. Wolfe, E. M. Gyorgy, and P. L. Finn, AT&T Bell Laboratories, Murray Hill, N.J., and M. H. Kryder and C.-H. Chang, Data Storage Systems Center, Carnegie Mellon University, Pittsburgh, Pa.

We have demonstrated a new read/write data storage technique[1] capable of recording up to 45 billion bits of information per square inch of media, or 100 times more than in current compact disks and 300 times more than in state-of-the-art magnetic hard drives. At this density, a palm sized disk could record up to 17 hours of compressed HDTV programming. Alternatively, two copies of *War and Peace* could be stored in an area about the size of the head of a pin.

As with conventional optical storage systems, our new method uses a laser to read and write bits on the recording medium. However, rather than focusing the light with a lens, which results in a spot of diffraction limited size, we funnel the light through a tapered optical fiber that has been coated with opaque aluminum everywhere except for a small hole at the very tip. If the hole is placed sufficiently close to the medium, in what is known as the near-field region, then the emitted light can form a spot much smaller than can ever be achieved with a lens. For example, the pattern at the top of the accompanying figure was written using our near-field storage method, and consists of individual bits of ~0.1 µm diameter. Elsewhere, we have produced bits as small as 0.06 µm. Over the rest of the figure, much larger bits, approaching 1 µm diameter, can be seen. These were produced by conventional far-field techniques and are representative of the size currently used commercially. In both cases, the medium was a platinum/cobalt (Pt/Co) multilayer film developed for conventional magneto-optic recording.



Comparison of bit sizes in near-field (top) and far-field optical recording.