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Atomic Stabilization by Super-Intense Lasers

J. H. Eberly and K. C. Kulander

Supercomputer simulations predict the creation of an unexpectedly stable form of atomic matter when ordinary atoms are irradiated by very intense, high-frequency laser pulses. In the rising edge of a very intense pulse of ionizing radiation, the atom's wave function distorts adiabatically into a distribution with two well-separated peaks. As the intensity increases, the peak spacing increases so that the atomic electron spends more time far from the nucleus and the ionization rate decreases. This leads to the surprising and counter-intuitive result that the atom becomes more stable as the ionizing radiation gets stronger.

In ordinary light beams, there is only a small probability that an electron can be stripped from its atom by the photoelectric effect. As the intensity of a light beam is increased, the stripping probability increases, owing to the more frequent impacts on the atom by the greater number of photons. However, over the past two decades, suggestions have been advanced (*1–3*) that at asymptotically high values of laser frequency and laser intensity, this pattern reverses itself. Such a reversal has recently been realized in a series of supercomputer simulations (*4, 5*). These simulations show that specific finite values of frequency and intensity are adequate for the reversal, and that a unique spatial form predicted for the hydrogen wave function (6) can be achieved even under non–steady-state (that is, reasonably realistic) laser pulses. As we increase the photon intensity further above the critical point, the stripping rate slows down dramatically, and the atom assumes a new bi-local form (Fig. 1). Because the bi-local form is maintained as the photon intensity increases, the new atomic configuration is referred to as "stabilized," and the process has become known as atomic stabilization.

The stabilized, bi-local atomic electron not only spends most of its time far from the atomic nucleus but has high kinetic energy as well, a kinetic energy much larger than its binding energy. This situation is ordinarily a certain prescription for rapid ionization, not stabilization. Therefore, laser-induced stabilization is the latest, and in some ways the clearest, indicator that a dramatic shift in viewpoint is required to explain the physics of atoms in very strong laser fields.

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Atomic Emission Processes in Strong Laser Fields

For almost 75 years following Einstein's explanation (*7*) of the photoelectric effect in 1905, a "scarce photon" theory adequately described photoabsorption processes. Such a theory is based on the fact that in experiments with conventional light beams containing a low density of photons, a light-activated process requiring only one photon is much more likely to occur than a competing process that requires two photons, which in turn is enormously more likely than a process requiring 10 photons. In this situation, mechanisms involving individual photons dominated the understanding of light-induced processes.

However, there are now lasers available that are intense enough to send thousands or even millions of photons through a typical atomic cross section during a pulse of a picosecond or less. Beginning around 1980, as a result of atomic physics experiments with these more intense lasers, a strikingly different view of photoabsorption has been suggested. These experiments first uncovered several surprising effects that can be seen as "precursors" of laser-induced stabilization.

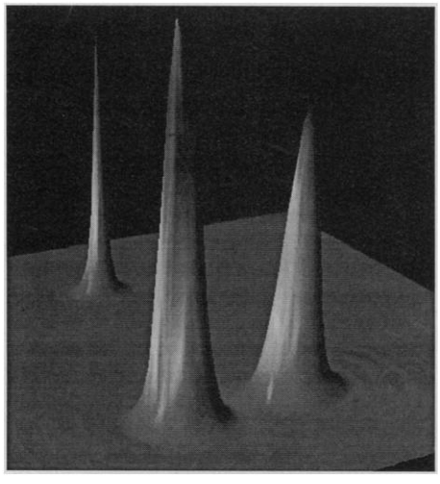

Fig. 1. Normal hydrogen ground-state electron density distribution (background) and the strikingly distorted, bi-local distribution (foreground) for the new ground state created in a short, super-intense, high-frequency laser pulse. In this state, an atom becomes more difficult rather than easier to ionize as the intensity of the laser pulse is increased.

In a strong laser field, both the bound and free states of an atom are strongly altered (*8*). This strong alteration of the atom's states signals that the atom can, in a sense, become supersaturated with photons. By this we mean it ceases to make sense to think about photoinitiated processes in terms of one or two or any well-defined number of individual photons; rather, we think in terms of the collective electric field of the photons. It is common to say the electron becomes "dressed" by the field. Emission of both electrons and photons by supersaturated atoms has been observed in the laboratory (in each case, before they were predicted theoretically). These emission processes have been named above-threshold ionization (ATI) and high harmonic generation, respectively. In the past 5 years, ATI and high harmonic generation have been studied extensively with short-pulse, strong-field lasers, meaning lasers with pulse durations of 1 ps or less (10^{-13} to 10^{-12} s) and intensities around 10^{13} W/cm^2. More than 1000 photons pass through an atomic cross section of about 1 Å^2 during these pulses.

The first of these precursor effects to be observed was ATI (*9, 10*). In ATI, the principal effect of photon supersaturation is to cause atoms to eject electrons with more energy than is predicted by the Einstein photoelectric theory (*7*). The excess energy can be any integer multiple of $\hbar\omega$, the photon energy, and the energy spectrum of the photoelectrons becomes a sequence of equally spaced peaks, perhaps dozens of them, instead of the single peak explained by Einstein.

Furthermore, even while bound in the atom before its ejection, the electron experiences shifts in its quantized energies because of the photon supersaturation. At a certain photon density (or laser intensity), the transition energy $\Delta E = E_{ex} - E_{gr}$ between an excited state and the ground state may become equal to an integer multiple of $\hbar\omega$. Then the ejection probability of the electron can be resonantly enhanced, introducing a substructure on the ATI

peaks (*11, 12*). The spectroscopy of ATI peaks and their substructure is now an active area of study in atomic physics.

The second precursor effect to be discovered was high harmonic generation (*13, 14*). Harmonic generation is a term from nonlinear optics meaning the coherent emission of photons with shorter wavelength than the incident photons. The new wavelengths are integer submultiples of the incident laser's wavelength, $\lambda_q = \lambda/q$, where q denotes an integer (usually 2, 3, or 4), and the harmonic photon's energies are correspondingly higher. These higher energy photons are typically produced by irradiation of special crystalline materials that can be easily damaged, so the irradiation cannot be too intense.

In striking contrast to normal experience in nonlinear optics, harmonics higher than the third or fourth (values of q higher than 3 or 4) can be very easily produced by a supersaturated atom. Within the past 12 months, values of q have been reported (*15*) up to at least 133, and the ultimate limit is expected to be much higher. Loosely speaking, the atom combines many of the supersaturating photons and ejects the combination as a single photon with q times as much energy. More precisely, the high-energy harmonic photons come from direct transitions to the ground state from the supersaturation-altered free states of the atom (*16*).

Because atoms have inversion symmetry, only odd multiples of the driving frequency are emitted. These harmonic photons are coherent, occur in a short pulse, and are so copiously produced that this nonlinear optical technique appears to offer a practical laboratory source of short-wavelength light in the difficult-to-reach range between 50 and 5 nm, where many important studies of the dynamics of molecules, surfaces, and materials in general have been waiting for a readily accessible source of coherent photons with adequate intensity and narrow bandwidth. This high harmonic generation process makes use of gas atoms rather than special crystals so target damage is not a consideration.

Both ATI and high harmonic generation provide ample evidence that when incident laser light is strong enough, many-photon processes can occur with equal or even greater probability than few-photon processes (and it is agreed that "many-photon" can easily mean hundreds of photons). These processes are now reasonably well understood, and both are being actively studied in many laboratories. It is an important research goal to understand them together (*17*) because they both arise from the same supersaturated atom. It is also possible to go further; still higher intensities than those used in experiments on ATI and high harmonic generation appear to open a new regime of behavior in which the response of an atom becomes simplified and even "stabilized" by the laser light.

Super-Intense Fields

Although extremely high even by recent standards, the intensities normally used in ATI and high harmonic generation studies are well short of the "atomic unit" of laser intensity. The atomic unit of intensity is achieved with laser light whose electric field delivers a force to an electron equal in strength to the static electric force of the proton. It is the latter force that binds the electron and is responsible for the stability of normal matter. Given the strength of normal atomic binding, 1 atomic unit of intensity is extremely high, 3.5×10^{16} W/cm^2. This corresponds to more than 10 million photons passing through every atomic cross section during a 1-ps laser pulse, a number at least three orders of magnitude greater than the intensities needed for ATI and high harmonic generation.

In this regime, most of the exchange of energy between the field and the electron is attributable not to photon absorption but to highly coherent and very high order momentum-transfer collisions (stimulated Compton scattering). This scattering produces the supersaturated bound and free states of the electron already mentioned, shifting their energies by causing the electron to oscillate with the field. These dressed states can have a very high kinetic energy but remain bound because this same energy of oscillation must also be carried by an electron in order to reach the continuum and escape from the atom. In fields as strong as this, individual photons are not very important. Therefore, the quantum-mechanical view of photon-triggered atomic processes is rather clumsy and can be replaced by a more traditional, classical representation, without any photons at all. In this regime, the laser is better characterized as a light wave instead of a beam of bullet-like photons. Thus, we can sidestep the particle view of light that arose with Planck and Einstein at the beginning of the 20th century and go back to the wave view that dominated the 19th century.

Our discussion will now focus on the regime of super-intense fields, which begins at 1 atomic unit of intensity, and consider, in particular, the simplest case: a hydrogen atom in a linearly polarized field. But first, to highlight the unusual features of this regime, we consider a hypothetical laser beam with intensity very much greater than 1 atomic unit. We can easily understand that in such a laser beam, the single electron in a hydrogen atom would pay much more attention to the dynamic electric force of the light wave than it would to the static electric force of the proton. Therefore, we imagine the proton's attractive forces to be completely ineffective, so the electron responds exclusively to the electric force of the laser light. We also initially overlook the pulsed character of most lasers and assume that the laser intensity is constant in time. These two simplifications define a zero-order scenario for laser-atom interactions by removing completely the main complications. It is a question whether any interesting physical behavior can remain in this limit, but we will see that the answer is yes.

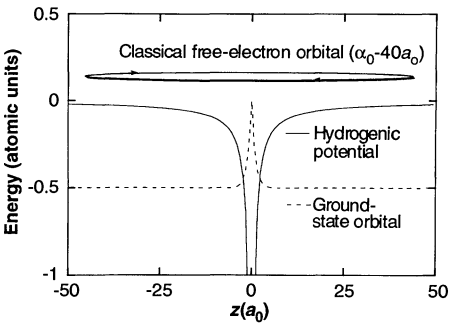

Fig. 2. The electron excursion in a super-intense field is much greater than the size of the atomic binding potential.

When the electron interacts only with the laser light, it simply oscillates, basically on a straight line back and forth along the direction of laser polarization, in step with the oscillating electric force of the light wave. But we find that such an unbound electron is still not really free; it cannot become "ionized" because it remains stably localized in a new oscillating "orbit." The maximum displacement of such an electron, α_0, is given by the relatively simple formula

$$\alpha_0^2 = I/c\varepsilon_0 e^2 m^2 \omega^4 \qquad (1)$$

where I and ω are the intensity and angular frequency of the laser field, e and m are the charge and mass of the atomic electron, and c and ε_0 are the vacuum speed of light and permittivity.

We can easily predict other features that will arise in our zero-order scenario. Because the electron slows down to stop and reverse its direction at the two limits of its back-and-forth motion, it must spend proportionally more time at, and is therefore more likely to be located at, these extreme limits. In addition, if the field is as strong as we imagine, the extent of the electron's oscillation can be enormously large on an atomic scale (Fig. 2). If the oscillation frequency is also high, the electron's maximum velocity and kinetic energy can be huge. Nevertheless, it is effectively trapped: The center of its oscillatory orbit does not move.

There is an interesting paradox here.

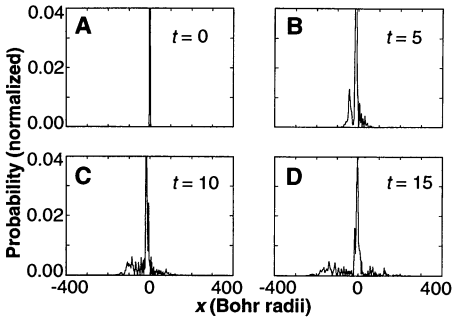

Fig. 3. Four snapshots (*4*) of the electron's probability packet showing its location in relation to the nucleus (at $x = 0$). (**A**) Before the laser pulse is turned on, the electron tightly localized in its bound orbit within 1 Bohr radius (~1/2 Å) of the nucleus. In the electron's probability distribution after (**B**) 5 cycles, (**C**) 10 cycles, and (**D**) 15 cycles (a cycle of the laser field equals about 0.3 fs), it is easy to see a fraction of the electron's probability moving away from the nucleus, corresponding to normal ionization, while a very substantial fraction (about 50% in this example) remains near the nucleus, corresponding to the new phenomenon of stabilization. Higher spatial resolution shows that the stabilized fraction extends about 20 Bohr radii on either side of the nucleus, consistent with the prediction of extended localization on the scale given by α_0 in Eq. 1. The ionized fraction is not right-left symmetric because the oscillating laser field first pushes the electron to the left, and this initial bias is preserved.

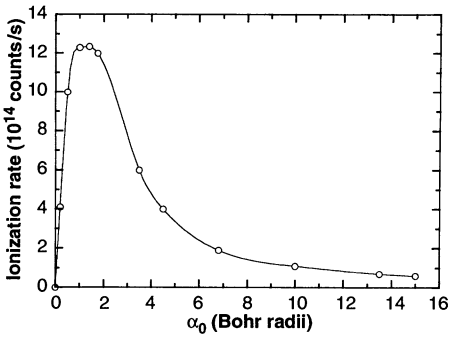

Fig. 4. Ionization rate of a hydrogen atom in a laser field with frequency twice the binding energy. We show the rate as a function of the classical displacement distance α_0 defined in Eq. 1. The onset of stabilization is found to occur when the intensity exceeds 1 atomic unit, at the threshold of the super-intense regime.

After "freeing" the electron by increasing the laser intensity and ignoring the attractive force of the proton, we find the electron motion is nevertheless still bound, this time by the force from the light wave. Conversely, if we greatly reduce the laser intensity and reintroduce the proton into our considerations, we inevitably thereby return to the traditional atomic setting in which the light wave easily ionizes the electron. Counter-intuitively, we conclude that to be able to become truly ionized, a bound electron must really feel the forces that bind it. Therefore, the ionizing radiation, if it is to be ionizing, cannot be too intense.

Atomic Stabilization

Many features of our zero-order scenario were anticipated in the period 1974–84 by Geltman (*1*), Mittleman (*2*), Gavrila (*3*), and their collaborators in theoretical work that first called attention to the possibility of stabilization, but only for asymptotically high frequencies and intensities. We carried out a large number of computer simulations to understand the nature of the atomic electron's behavior under more realistic conditions. Surprisingly, our numerical experiments (*4, 5*) show that to a remarkable degree, the zero-order picture provides a valid description of the electron's actual motion. Even in the presence of the atomic binding force, and even when the laser is pulsed rather than steady, high-intensity laser light forces the electron to move back and forth along a line and very effectively traps it in this new kind of much larger "orbit."

The time evolution of a strongly excited electron's wave function had not previously been calculated throughout an entire laser pulse for a spatial region large enough to include such an orbit. Because our numerical approach permits us to treat both the static proton-electron binding force and the time-dependent laser-electron force on an equal footing, we can solve Schrödinger's time-dependent wave equation over a large spatial region and obtain accurate solutions for a wide range of laser field strengths. This is necessary because a realistic laser pulse, lasting only a picosecond or less, is very strong only near its peak and goes smoothly to zero before and after, when the atomic binding force determines the motion.

In these space-time simulations (see Fig. 3), the atom can quickly adjust to the presence of a strong laser field. Only a few cycles of the field (a few femtoseconds at most) are sufficient to produce a nearly steady response. The particular case shown here (*4*) is for a pulse in which the intensity rises smoothly to the super-intense regime during the first 5.25 cycles of laser oscillation and is constant thereafter. The pulse is applied to an artificial one-dimensional "atom" that we developed (*18*) specifically for the purpose of studying the generic response of strongly perturbed atomic systems. This atom immediately begins to ionize, and small packets of electron probability begin to stream away from the nucleus (Fig. 3, B through D). Subsequent analysis shows that these packets represent the positive-energy electrons that show up in ATI spectra. However, after only 15 cycles, a large remnant of electron probability is still clustered near the nucleus, and the ionization process has almost stopped. Close inspection shows that the remnant packet (Fig. 3D) is split into two main peaks that spread over a significantly wider range than the original ground-state packet (Fig. 3A). The peaks maintain their separation while oscillating back and forth in step with the laser field, in agreement with our zero-order scenario.

A fully three-dimensional simulation of hydrogen (*5*) provided confirmation of these observations and a wealth of detailed information. In these calculations, both the two-peaked structure and the wide spread of the remnant packet are clear (Fig. 1). The back-and-forth oscillations are reproduced as well, and the anomalously long lifetime of the remnant has been confirmed. By considering many pulses with different peak intensities, we generated wave functions from which we calculated points along the ionization rate curve (Fig. 4). These rates are determined after the transient ionization effects of the pulse rise have passed. For low intensities, we find the linear dependence on intensity expected from weak-field, scarce-photon theories. At a point corresponding fairly closely to 1 atomic unit of intensity (which depends somewhat on ω), the curve turns over and then decreases with increasing intensity. Although the curve predicts a high ionization rate at its peak, this value is many orders of magnitude below what we would have expected from an extrapolation of the scarce-photon portion of the curve. The predicted atomic lifetimes (inverse rates) become comparable to or longer than the expected pulse lengths in this super-intense regime. This clearly deserves to be called atomic stabilization.

Our first simulations leading to stabilization (*4, 5*) showed the basic validity of our zero-order scenario, but our results indicate a number of deviations from its oversimplified predictions. A key contribution to understanding the detailed quantum dynamics of stabilization was provided earlier by a suggestion made by Henneberger (*19*) and later by Mittleman (*2*) and Gavrila (*3*) and their collaborators in connection with multiphoton ionization theory. This idea is based on even earlier work by Kramers (*20*) and by Pauli and Fierz (*21*) in the 1930s on the fundamental theory of quantum electrodynamics. In principle, it is possible to deal with an atomic electron's motion in any coordinate frame, the standard choice being identified with a stationary nucleus. However, in the regime of the super-intense field, it turns out to be much more appropriate and informative to fix the co-

ordinate system on the electron, specifically to move on the trajectory of an electron following our classical zero-order scenario. The transformation is given (for z-polarized laser light) by

$$\mathbf{r} \rightarrow \mathbf{r} - \alpha_0 z \cos\omega t \quad (2)$$

This moving coordinate frame is generally called the Kramers-Henneberger (KH) frame.

An atomic electron must move in a more complicated way than the free electron of the zero-order scenario, but it is basically stationary in the KH frame, whereas the nucleus oscillates along the polarization axis in step with the laser field with amplitude $\pm\alpha_0$. Thus, the nucleus bumps the electron every time it goes past. The effect of these bumps is eventually to produce ionization, but at an anomalously slow pace if the laser intensity and frequency are both high enough. The high intensity is needed to induce a displacement of the oscillating nucleus that is wide enough to hold it away from the electron most of the time. The high frequency then guarantees that the velocity of swinging back and forth is high, making the rare electron-nucleus collisions extremely brief and ionization events improbable.

We are using classical language here, speaking of trajectories and not probability packets. In fact, it is useful to make a fully classical analysis of the same situation by dealing with the electron through Newton's classical equations of motion (*22–24*). A classical electron follows a definite trajectory, which is a quick way to visualize the electron's response to the fields. A typical trajectory of a classical electron in the KH frame (Fig. 5) shows the electron-proton bumps clearly as brief, sharp discontinuities in an otherwise slow, smooth drift. The trajectory also shows a gradual increase in the momentum of the electron. Its displacement eventually grows beyond the two-sided, almost stable orbit (that is, it eventually exhibits classical ionization).

A typical encounter between electron and nucleus has practically no net effect on the trajectory (Fig. 5). The motion of a quantum electron under these conditions is given by a weighted superposition of such trajectories. As a result, to a good approximation, the quantum electron actually responds only to an effective, time-averaged potential. This effective interaction is called the KH potential, given by

$$V_{KH}(\mathbf{r}) = -e^2 \int_0^{\frac{2\pi}{\omega}} \frac{dt}{|\mathbf{r} - \alpha_0 z \cos\omega t|} \quad (3)$$

the average over one cycle of the oscillating field, which is dominated by the nearly stationary nuclear charge at its two turning points at $\pm\alpha_0$, resulting in a double-well potential (Fig. 6).

Note that the laser frequency and intensity are both involved in the definition of the coordinate transformation (Eq. 2) to the KH frame, and thus of V_{KH}, but only through the combination that defines α_0 (Eq. 1). Our discussion above suggests that electronic wave functions calculated in the KH potential, which also must depend only on α_0, are a good starting point for a quantum-mechanical discussion of stabilization. A calculation illustrating the strongly distorted and symmetrically bi-local ("dichotomic") form of stabilized hydrogen was reported by Gavrila's group in 1988 (*6*).

An important consequence of the shallow bi-local KH potential is a dramatic decline of the electron's binding energy with intensity. This latter fact ameliorates somewhat the need for very high laser frequencies in order to achieve stabilization. Gavrila and his colleagues (*25*) showed that the relevant measure for high frequency is the KH binding energy (that is, the ionization energy of the distorted state in the presence of the field). A lower frequency leads to an enormous reduction in the intensity needed to obtain the same α_0 (recall Eq. 1). This was also pointed out by Law *et al.* (*26*) in connection with their demonstration of stabilization in three-photon ionization (*27*). For example, a frequency smaller by an order of magnitude leads to a four orders of magnitude reduction in the required intensity. This fact has led to an expectation that stabilization could be observed with existing lasers at optical or ultraviolet frequencies.

We have emphasized that our simulations support a picture of ionization that is based, in zero order, on classical free electron oscillations. We should also emphasize that this picture is not just an alternative to an older and more familiar picture but is in many ways a necessary replacement. Stabilization represents behavior that is plainly incompatible with conventional ways of thinking about atoms undergoing laser excitation. Let us illustrate this by returning to the data shown in Fig. 3, but this time, we analyze that data not with space-time wave packets but in a more traditional way. Ionization is traditionally recognized as the conversion of a bound electron into a positive-energy electron. Using the exact time-dependent atomic wave functions obtained by our numerical methods, we can identify ionization in this way by calculating the fraction of the electron probability associated with positive-energy atomic states. Before the laser pulse reaches the atom, this probability is zero, and it grows smoothly larger as the laser intensity grows during the pulse.

A graph of the atom's time-dependent ionization probability (Fig. 7) for a pulse whose maximum reaches the super-intense regime is confusing at first sight. The ionization probability exhibits dramatically large variations that are evidently periodic in time, with variations that reach unity many times in succession. Unit probability represents certainty of ionization, but ionization is generally regarded as a one-way process, so it is novel, to say the least, to see that an atom evidently has the ability to become completely ionized and then almost completely reverse itself, twice in every cycle of a strong laser field. These wide variations that repeatedly signal full ioniza-

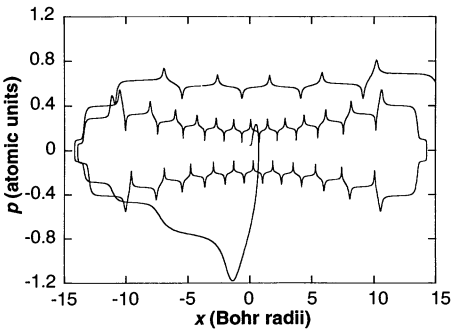

Fig. 5. The gradual drift of an electron's phase-space trajectory is shown in the KH frame, where the proton is widely oscillating. After an initial impulse downward, the electron drifts back and forth three times between the widely separated turning points of the classical motion, located at ±12 Bohr radii (*34*) in this example. During its drifting motion, the electron is repeatedly bumped by the proton, causing the scallops in the electron's trajectory, the bumps coming one-half cycle apart. The scallops are further apart in the last part of the electron's drift, showing that the electron has begun to move faster, in preparation for its departure from the atom. This trajectory is for a fully classical electron, not a quantum-mechanical electron wave packet. It has been shown that a classical electron cannot be fully stabilized (*22*). [Adapted with permission from (*23*)]

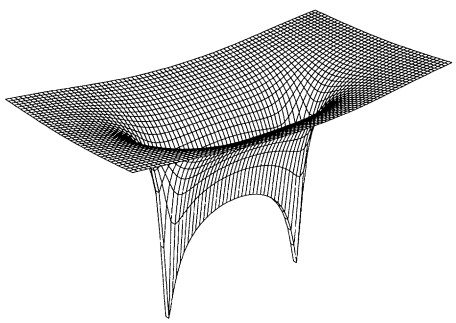

Fig. 6. The KH potential defined in Eq. 3 for α_0 = 13.5 Bohr radii. Shown is the cycle-averaged nuclear attraction seen by an electron in a strong, high-frequency laser field. The origin of the coordinate system used in the definition of this potential is fixed to the orbit of a classical electron, oscillating in response to the field. If the frequency is high enough, the electron can respond only to this averaged potential.

tion must call into question the traditional definition of ionization. However, these variations are not at all surprising when seen as part of the new picture we have sketched. On that basis, we actually expect the anomalous response (Fig. 7) because we expect the electron to be localized in a widely swinging linear "orbit" centered on the nucleus. We conclude that the curve in Fig. 7, which gives the probability that the electron has positive energy, is associated only with the forced motion attributable to the laser field, not to a high escape velocity. The true ionization probability is the probability of eventual escape, and this must be obtained by calculation of the one-way flux of electrons through a distant surface that surrounds the atom. This is precisely how ionization is detected experimentally. From this flux calculation, we find that the ionization of the atom slows down enormously after the super-intense regime has been reached. In a pulsed laser, stabilization does occur.

Summary and Prospects for Laboratory Observation

Our calculations (*4*, *5*) have shown that a substantial fraction of the atoms survives to peak intensities of 2 to 5 atomic units and exhibits stabilization; increasing the intensity further reduces the ionization rate of the stabilized state even further. Time-dependent snapshots of the electron probability distribution show that the wave packets are confined to a region of width on the order of $2\alpha_0$ near the nucleus, as predicted by Gavrila and co-workers (*6*, *25*). Its shape is not precisely that of the lowest KH eigenstate with two maxima separated by $2\alpha_0$ but often exhibits additional structure. This is because the rather rapid turn-on of the laser field allows some nonadiabatic mixing of higher KH eigenstates, so that the final stabilized orbital is a wave packet of several KH states, as emphasized by Reed *et al.* (*28*). This mixing is responsible for the asymmetry in the two peaks of the stabilized state shown in Fig. 1. Another consequence of the nonadiabatic effects is that the creation of a wave packet also significantly reduces the expected loss during the pulse rise, leading to a larger stabilized fraction than was predicted from the fixed-intensity rates. In subsequent simulations at higher intensity, as many as three quarters of the atoms were found in the localized state, and stabilization was demonstrated even for reasonably low frequency fields [requiring three photons for ionization in the weak field limit (*26*)] because of the dramatic decrease in the effective binding energy at the peak intensity.

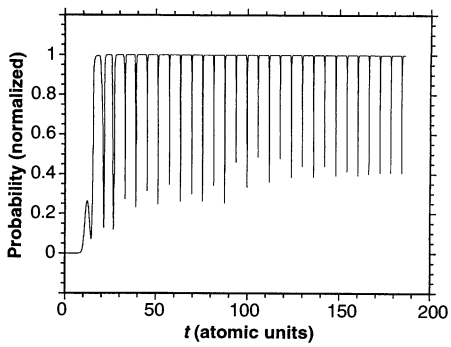

Fig. 7. The probability that the electron has positive total energy (has become "ionized") versus time during the course of the same laser pulse described in Fig. 3. The duration of an optical cycle at this frequency is 12.57 atomic units (*34*).

To observe stabilization, one can consider, for example, using atoms with lower ionization potentials than hydrogen, thus ameliorating the high-frequency requirement even further. With this in mind, we carried out calculations on atomic lithium (*29*). They confirm an earlier prediction (*30*), based on calculations with the one-dimensional "atom," that the onset of the low-frequency (two-photon) stabilization of lithium can occur for a wavelength and peak intensity appropriate to a KrF laser (248 nm and intensities above 10^{15} W/cm^2), as long as the peak intensity is reached in 10 to 20 optical cycles. The pulse rise needs to be fast only for intensities between 10^{14} and 10^{15} W/cm^2, which is the range where the ionization rate is large.

Other approaches to stabilization have been proposed. Up to this point, we have discussed only the evolution of atoms initially in their ground states. Fedorov (*31*) has reviewed theories for stabilization of atoms prepared in excited states, the prospects for which are reasonably favorable. The threshold for such stabilization is even less severe (*32*, *33*) if the excited states are those with nonzero projection of orbital angular momentum on the polarization axis. The significance of orbital angular momentum comes from the ability of the atomic centrifugal barrier to hold the electron away from the nucleus so that photoabsorption is greatly reduced. However, this approach would require the initial establishment of a volume of excited state atoms.

On the basis of our predictions as well as those of other workers, it appears likely that the laboratory observation of a recognizable version of theoretically ideal stabilization can be expected. The development of short-pulse, high-intensity lasers has been rapid in the past decade. As one consequence, several surprising discoveries have been made in atomic physics, and others will follow as the available laser pulses become shorter and more powerful. Surely, one of the most interesting and exciting will be the confirmation that atoms can become resistant to ionization as a result of an enormous distortion of their charge distributions in the super-intense regime.

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34. In the system of atomic units, the charge and mass of the electron and Planck's constant divided by 2π ($\hbar$) all equal unity. Subsequently, for distance, 1 atomic unit (au) is the Bohr radii (a_0); for energy, 1 au = 27.21 eV (twice the binding energy of a hydrogen atom); for velocity, 1 au = 2.19×10^8 cm/s (velocity of an electron with 1 au of energy); for time, 1 au = 2.42×10^{-17} s; and 1/2 au of intensity is described in the text.

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