# Short-Pulse Above-Threshold–Ionization "Multiplet" Effects

In a recent Letter, Freeman *et al.*[1] presented new photoelectron energy spectra obtained in the multiphoton ionization of xenon atoms with subpicosecond laser pulses. Their observations of a "multiplet" structure in the photopeaks at short enough pulse lengths are notable because (1) they show a clear non-free-electron phenomenon and (2) they represent a valuable step toward the realization of intrapeak information in above-threshold-ionization[2] (ATI) spectra in general.

To date, at least the gross features of ATI spectra have compared well with the predictions of a combination of free-electron and ponderomotive-potential model theories,[3] and no calculations published so far describe ATI effects similar to those of Ref. 1. Our purpose here is to describe very briefly the results of *ab initio* theoretical calculations that do predict effects similar to the recent observations.

To address ATI questions theoretically, in as clean an environment as possible, we have been analyzing the wave function of a one-dimensional one-electron atom with the symmetric binding potential $V(x)=-1/(1+x^2)^{1/2}$. In the presence of the laser-atom interaction $H_I=-xE(t)\sin\omega t$, the electron undergoes multiphoton ionization and its spectrum $P(W)=|\langle W|\psi(t)\rangle|^2$ can be computed. Here $|W\rangle$ and $|\psi(t)\rangle$ are the bare and interacting state vectors, computed with the standard Crank-Nicholson partial differential equation algorithm[4] on a spatial grid between $x=\pm 1146.81$. The initial state is taken to be the ground state with energy $W=-0.670$. All expressions are in atomic units.

In Fig. 1 we show results obtained from nominal two-photon ionization ($\omega\approx 0.52$) with an intense ($E_0=0.05$, $I\approx 10^{14}$ W/cm$^2$) smooth subpicosecond pulse 96 optical cycles long with the envelope $E(t)=E_0\sin^2(\pi t/T)$. In each spectral peak it is clear that there is "multiplet" substructure similar to the experimental data.[1] Also, subpeaks appearing in the first ATI peak are replicated in the higher peaks. This feature is also present in the experimental data, but less clearly.

Ponderomotive effects do not play the dominant role in the creation of our subpeaks. Because *none* of the allowed bound-bound transitions in our model atom is close to resonance, there is little or no level shifting even at the peak of the pulse, and no dynamic resonances occur. However, direct analysis of the atom's wave function during the ionization process reveals that each of the low-lying excited states that is dipole connected to the ground state is very weakly and transiently excited (or photon dressed with a portion of the ground-state amplitude). It is then susceptible to one-photon ionization. Thus in our case, as in the case of Freeman *et al.*, the subpeaks in each ATI peak are exact replicas of known bound states.

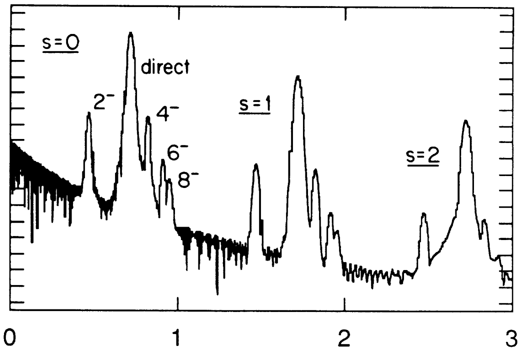

FIG. 1. ATI electron spectrum $P(W)$ showing the $S=0,1,2$ peaks and their intrapeak multiplets. The strongest line represents direct two-photon ionization from the ground level, and the other lines come from one-photon ionization of the lowest odd-parity levels, as labeled. The vertical scale is logarithmic, and the horizontal scale is in units of laser photon energy.

The results presented here are sensitive to numerical error at roughly the 10% level or below. Details of our method and an extended series of spectra for three-, five-, and ten-photon ionization will be published elsewhere.

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J. H. Eberly and J. Javanainen[(a)]
Department of Physics and Astronomy
University of Rochester
Rochester, New York 14627

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[(a)] Present address: Department of Physics, University of Connecticut, Storrs, CT 06268.

[1] R. R. Freeman, P. H. Bucksbaum, H. Milchberg, S. Darack, D. Schumacher, and M. E. Geusic, Phys. Rev. Lett. **59**, 1092 (1987).

[2] See P. Agostini, F. Fabre, G. Mainfray, G. Petite, and N. K. Rahman, Phys. Rev. Lett. **42**, 1127 (1979), and P. Kruit, J. Kimman, H. G. Muller, and M. J. van der Wiel, Phys. Rev. A **28**, 248 (1983), for early experimental observations of ATI phenomena.

[3] See J. Opt. Soc. Am. B **4** (1987), a special issue edited by W. E. Cooke and T. J. McIlrath, for a number of recent interpretations of ATI observations.

[4] A. Goldberg, H. M. Schey, and J. L. Schwartz, Am. J. Phys. **35**, 177 (1967).