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Atomic quantum revivals produced by ultrashort laser pulses: the effect of energy discretization

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Synopsis We study atomic quantum revivals initiated by ultrashort laser pulses. The large energy spread of these pulses requires the use of atoms with high Z to limit the number of states excited. Yet the desired range of excitation energies must be accessible by state-of-the-art ultrashort laser pulses. This leads to $Z \sim 8$ and an interesting regime of a relatively small number $k$ of states in the wave packet in the range $2 < k < 6$. Under these circumstances the traditional harmonic expansion for the energy fails. We propose a method for calculating the periods of the system using the explicit values of the energies, with no harmonic expansion. Our method coincides in the limit of long pulses and high atomic number with the traditional one.

Quantum revivals appear when a wave packet spreads during a quasi-classical time evolution, only to reverse the spreading and reshape after a certain time called the revival time. This phenomenon arises in a large variety of physical systems, such as the orbital motion of atomic electrons in highly excited states [1], or rovibrational nuclear wave packets [2]. The study of quantum revivals in atoms has been traditionally focused on the excitation of Rydberg WPs, which contain a set of highly excited states centered on some principal quantum number $\pi$, with typical values of $30 < \pi < 85$. These Rydberg WPs are typically excited by laser pulses with a duration of the order of picoseconds [1].

A large amount of theoretical work has been devoted to study the quasi-classical evolution of these quantum WPs and to predict the periods of the orbital motion and the revivals. This is done through a Taylor expansion of the energy around the most populated level, where the different periods are obtained from the different terms in the expansion. For typical values of $\pi = 85$ and pulse widths FWHM=8 ps [1], the number of states that contribute significantly to the wave packet is $k \sim 12$. Under these circumstances the relative difference between the energies of the states is small, and the harmonic expansion provides good results.

With the appearance of ultrashort laser pulses (femtosecond or attosecond) this approach is no longer valid since these pulses have an energy spread of several eV, so they excite simultaneously a large number of discrete (and continuum) states. To reduce $k$ the atomic system must be excited at lower quantum numbers, but still relatively high energy of the ultrashort pulses. This is the case, e.g., in high-Z hydrogenic or He-like ions. However, for obtaining $k \sim 12$ with an ultrashort pulse of FWHM=2 fs, very high values of $Z$ have to be used, which require large excitation energies that are not accessible with state-of-the-art ultrashort pulses.

A compromise can be found for intermediate values of $Z \sim 8$ and $\pi \sim 15$, where $k \sim 3 - 5$. However, with such a small $k$ a harmonic expansion is not possible, since the relative difference between energies is much higher.

We propose an alternative way of calculating the periodicities of the quantum WP which takes explicitly into account the energies of the states, with no harmonic expansion. We predict accurately the periods of the autocorrelation function in the case of ultrashort pulses (FWHM≤2fs) interacting with hydrogenic ions ($Z\sim8$). In the limit of high $\pi$ and large pulse width, the periodicities coincide with those calculated with the harmonic expansion. Besides, we also explain the shifts in the peaks of the autocorrelation function that have been attributed to other causes in systems with high $\pi$ [3].

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