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COMMENT

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COMMENT

A comment on the stabilization of a one-dimensional short-range model atom in intense laser fields

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Abstract. The behaviour of an electron in a one-dimensional short-range potential subject to high-intensity short laser pulses was modelled numerically, by Su *et al* (1996 *J. Phys. B: At. Mol. Opt. Phys.* **29** 5755) who claimed that stabilization against ionization increases as the frequency is increased for a given intensity. Interpretation of these results as stabilization was challenged in a comment by Geltman (1999 *J. Phys. B: At. Mol. Opt. Phys.* **32** 853). We argue that dynamical stabilization is more easily interpreted if comparisons between different frequencies are made for the same quiver amplitudes and pulse shapes.

Since the early predictions of atomic stabilization [1, 2], there has been significant progress towards understanding the suppression of ionization resulting from an atom exposed to high-intensity laser fields. Gavrila and co-workers [12] initiated the development of the theoretical basis which accounts for 'adiabatic' (steady-state) stabilization. The question arises as to whether such stabilization can occur for the non-steady-state case, with a laser pulse possessing a rise and a fall time. The first investigations using such pulses [3, 4] did see evidence of stabilization. Su *et al* [5] conducted a numerical study to model 'dynamic' (non-steady-state) stabilization. In [10], a different type of calculation did not find signs for dynamic stabilization. However, the authors did note that the new results by Geltman [7] agree with those of Su *et al* [5] in the sense that suppression was observed, whereas their attempt failed to produce any suppression at all. Geltman [7] has argued that the non-monotonic variation of the ionization probability with the laser intensity is a normal expectation in any strongly coupled quantum system.

In this comment, we will describe a framework with which it is possible to discuss dynamic stabilization in a well defined manner. The new calculations reported here are initially in full agreement with the numerical results of both Su *et al* [5] and Geltman [7]. Based on the same parameters and method used in Su *et al* [5], we were able to replicate all of the results in that paper. However, the calculations in figure 7 of [5], describing the stabilization behaviour at different frequencies, were done with only one intensity. Confusion derived from this data is misleading: the full picture with multiple intensities cannot be deduced from a single intensity. In order to clarify the correct behaviour, several steps were performed. First, we transform the results of Su *et al* and Geltman into plots in which the quiver amplitude of the free electron $\alpha_0 = E_0/\omega^2$ is the independent parameter. Second, we show that preserving the number of cycles when altering the frequency (as in figure 7 of [5] and figure 1 of [7]) means that the electron is exposed to a smaller total energy when the frequency is raised so that it is no surprise that the ionization probability drops. Instead, one should preserve the time duration of the pulse which is physically significant. Third, we show why looking at dynamic stabilization as a residual Rabi oscillation [7] is oversimplistic and does not take into account the creation of a laser-induced state. Our results indicate that dynamic stabilization as reported in [5, 6] does exist and show the existence of a high-frequency limit recently predicted by Barash *et al* [11]. In the following we describe these three steps in detail.

Following [5], a comprehensive study was performed to investigate how dynamic stabilization of a short-range potential responds when different laser frequencies are applied

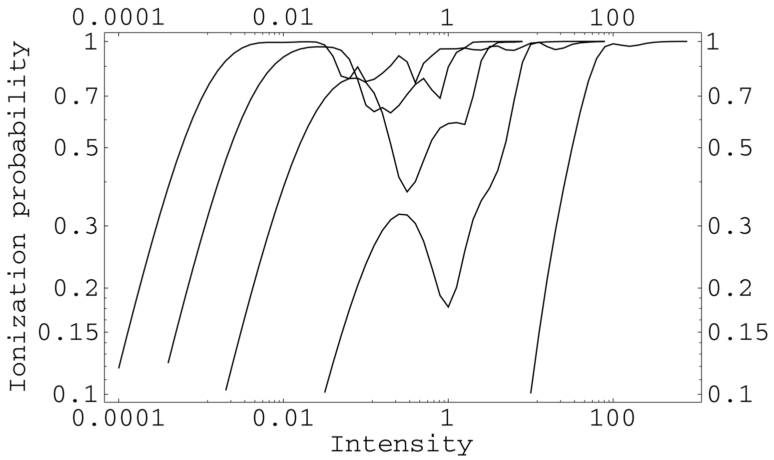

Figure 1. Ionization probability for several frequencies, where the independent variable is the intensity and holding the number of cycles in the laser pulse (3–8–3) fixed. The frequencies from top to bottom (in au) are: $w = 0.2, 0.25, 0.33, 0.5, 1.0$. The potential is a short-range potential with multiple points (see text).

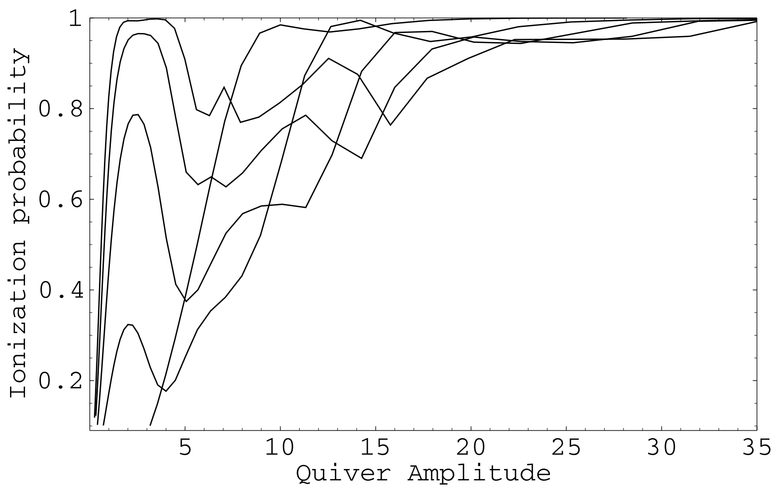

Figure 2. Ionization probability for several frequencies, where the independent variable is α_0 and holding the number of cycles in the laser pulse (3–8–3) fixed. The frequencies from top to bottom (with respect to the vertical line $\alpha_0 = 2.0$) are: $w = 0.2, 0.25, 0.33, 0.5, 1.0$. The potential is a short-range potential with multiple points (see text).

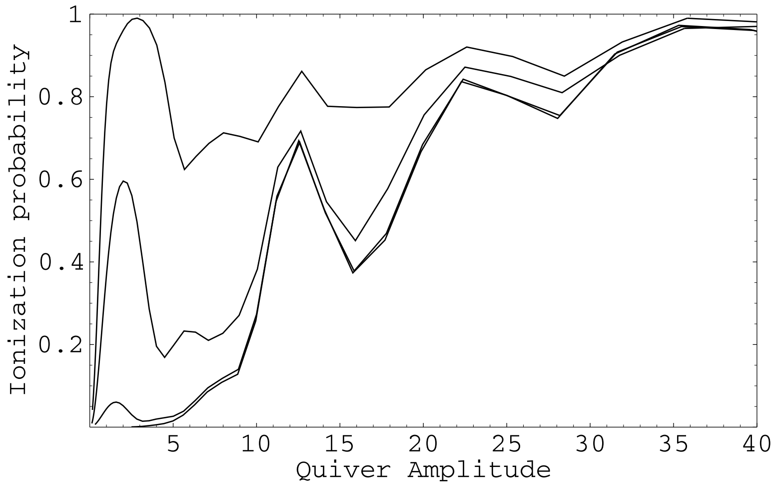

Figure 3. The ionization probability as a function of α_0 for several frequencies, holding the total time duration of the laser pulse ($T = 439.8$ au) fixed, for a short-range potential with multiple points. The frequencies from top to bottom (in au) are: $w = 0.25, 0.5, 1.0, 2.0$. The existence of a high-frequency limit is evident.

[8]. The following equation was solved numerically using the split-operator method with the same grid parameters as in [5]:

$$\mathrm{i}\frac{\partial\psi(x,t)}{\partial t} = \left[-\frac{1}{2}\frac{\partial^2}{\partial x^2} + xE_0 f(t)\sin(\omega t) + V(x)\right]\psi(x,t). \tag{1}$$

The one-point delta potential was used, as in [5, 7]

$$V(x) = -B\delta(x) \tag{2}$$

where $B = w \times D$, with w being the width of a square well and D its depth. In the limit $w \to 0$ the square well becomes a delta potential and the potential supports a single bound state energy given by $W_\mathrm{b} = -B^2/2$. Only one grid point is used to describe this delta potential. The same pulse shape $f(t)$ as in [5, 7] was chosen, switching the laser on and off smoothly, according to $f(t) = \sin^2((\pi/2) \times t/T_1)$ for $0 \leqslant t \leqslant T_1$, $f(t) = 1$ while the laser is on ($T_1 \leqslant t \leqslant T_2$) and switching off according to $f(t) = \cos^2((\pi/2) \times t/(T_3 - T_2))$ for $T_2 \leqslant t \leqslant T_3$. With these parameters, we achieved full agreement with figures 5 and 7 in [5] and figure 1 in [7]. However, with the one-point delta potential used by Su *et al* [5] and Geltman [7], a problem is encountered when checking for convergence by decreasing the spatial grid spacing dx from high to low, since the potential changes as the step size is modified. In order to address this issue, a multiple-point short-range potential of the form $V(x) = -V_0 \exp(-x^2/x_0^2)$ (as in [9]) was implemented instead of the one-point delta potential and an analogous calculation was performed. The potential parameters were set at $V_0 = 0.18$ and $x_0 = 7.0225$ so that the potential supports only a single bound state. The results we obtain using the short-range potential show the same behaviour as those using the delta function potential, but now the convergence of the results is ensured.

We first re-examine figure 7 in Su *et al* [5]. This figure seems to indicate that the suppression of ionization grows as the laser frequency is increased. However, when the calculations are repeated for all relevant intensities (instead of only a single intensity) the pattern shown in figure 1 is obtained. First, these results, in contrast to the assertion of Geltman

[7], show that stabilization does exist over a wide range of frequencies and intensities. Second, the trend seen by Su *et al* [5], that stabilization increases with increasing frequency, is only true for the limited intensities and frequencies studied in [5]. The true behaviour is much more complicated. It is difficult to draw conclusions about trends in the stabilization from the figure as displayed, however, if the quiver amplitude of the free electron $\alpha_0 = E_0/\omega^2$ is used as the independent variable rather than the intensity the underlying pattern becomes clearer. These results are shown in figure 2.

In Su *et al* [5] and Geltman [7], the frequency was increased keeping the number of laser cycles fixed. However, as mentioned above, this procedure reduces the total energy to which the electron is exposed and therefore artificially introduces a lowering of the ionization probability. Instead, the time duration of the pulse should be preserved. Figure 3 shows the results of calculations, using the short-range potential discussed above with the same parameters as used in obtaining the results displayed in figures 1 and 2, but keeping the pulse length fixed. This figure clearly shows the existence of a high-frequency limit and that beyond a certain frequency the stabilization structure remains fixed.

We can therefore conclude that the assertion by Geltman, claiming that dynamic stabilization is a residual Rabi oscillation, is oversimplistic because the bound–free Rabi oscillations he loosely refers to actually take place between a bound state and a resonance of the *dressed* atom [11, 12]. This means that it is only because of the high intensity of the field that a laser-induced state, between which such oscillations are possible, can be formed.

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