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Ionization rate for circularly polarized laser fields with modified ionization potential included

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Abstract
During the ionization of atoms with low-frequency laser fields, tunneling ionization occurs when the Keldysh parameter $\gamma \ll 1$. One of the most widely used theories is the Ammosov–Delone–Krainov (ADK) theory, which was developed for both linearly and circularly polarized laser fields. This paper studies the influence of modified ionization potential on ionization rate in the ADK theory for the case of a circularly polarized laser field. The studied atoms are K, Na, Li and Cs; they are ionized by CO_2 laser in the intensity regime between 10^{14} and 10^{16} W cm^{-2}. It is found that ionization rates of atoms with similar values of ionization potential behave in a similar manner; also, the influence of modified ionization potential on ionization rates is much stronger at higher laser intensities.

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(Some figures may appear in colour only in the online journal)

1. Introduction

The process of tunneling ionization of atoms by strong low-frequency laser fields—which are both linearly [1, 2] and circularly [3] polarized—has been successfully studied in recent years [4]. It has been shown [5] that as the strength of the external field F rises, the ionization rate increases in the range $F < F_{at}$ and decreases in the range $F > F_{at}$. The maximum ionization rate corresponds to an atomic field strength $F \sim F_{at}$. Because the laser field strength is proportional to the laser field intensity, i.e. $F \sim \sqrt{I}$, the fact that the fields are strong means that applied intensities are increasing toward 10^{16} W cm^{-2}. The theoretical approach to the tunneling problem is based on a single-active-electron approximation, where the idea is that only one electron is involved in the ionization process. The Ammosov–Delone–Krainov (ADK) theory is one of the most widely used theories in this area, and one of its main accomplishments is the resulting formula for ionization rate (in its correct form, obtained in [6] by including the influence of non-zero initial momentum of the ejected electron), in the case of linearly polarized light:

$$W_{\mathrm{ADK}}^{\mathrm{lin}} = \left(\frac{4\mathrm{e}Z^3}{Fn^{*4}}\right)^{2n^*-1} \exp\left(-\frac{2Z^3}{3Fn^{*3}} - \frac{p^2\gamma^3}{3\omega}\right), \tag{1}$$

and in the case of linearly polarized light:

$$W_{\mathrm{ADK}}^{\mathrm{cir}} = \sqrt{\frac{3FZ^3}{\pi n^{*3}}} \left(\frac{4\mathrm{e}Z^3}{Fn^{*4}}\right)^{2n^*-1} \exp\left(-\frac{2Z^3}{3Fn^{*3}} - \frac{p^2\gamma^3}{3\omega}\right), \tag{2}$$

where F is strength of the laser field, Z is the charge number, n^* is the effective principal quantum number, ω is the angular laser frequency and γ is the Keldysh parameter of adiabaticity, defined as $\gamma = \omega\sqrt{2E_{\mathrm{i}}}/F$. It divides the laser–atom interactions into two regimes: multiphoton and tunneling. It is obvious that the difference between formulae (1) and (2) lies in the expression under the square root.

The above formulae are expressed in the atomic unit system $\hbar = m_{\mathrm{e}} = e = 1$, which will be used throughout this paper.

The formula for momentum has been obtained in [7–9] in the following form:

$$p = \frac{1}{2}\left(\sqrt{F\eta - 1} + \frac{1}{\eta\sqrt{F\eta - 1}}\right). \qquad (3)$$

Now we try to further develop the observations in our previous work [10], by examining to what extent the modified ionization potential [11] influences the ionization rates with non-zero momentum included.

The transition rate formula for circularly polarized field (2) is transformed by replacing the effective quantum number n^* with its equivalent expression $Z/\sqrt{2E_{\mathrm{i}}}$:

$$W_{\mathrm{ADK}}^{\mathrm{cir}} = \left[\frac{3F}{\pi}(2E_{\mathrm{i}})^{3/2}\right]^{1/2}\left[\frac{4\,\mathrm{e}}{FZ}(2E_{\mathrm{i}})^2\right]^{\frac{2Z}{\sqrt{2E_{\mathrm{i}}}}-1} \times \exp\left[-\frac{2(2E_{\mathrm{i}})^{3/2}}{3F} - \frac{p^2\gamma^3}{3\omega}\right]. \qquad (4)$$

Also, the atomic ionization potential E_{i} that manifests itself in (4) will be modified under the influence of an external laser field, which causes ionization; this will lead to the following expression for modified ionization potential:

$$E_{\mathrm{i\,mod}} = E_{\mathrm{i}} + F^2 Z\,(2E_{\mathrm{i}})^{3/2}. \qquad (5)$$

Consequently, the formula for the ionization rate (2) assumes the following form:

$$W_{\mathrm{mod}}^{\mathrm{cir}} = \sqrt{\frac{3F}{\pi}(2E_{\mathrm{i\,mod}})^{3/2}}\left[\frac{4\mathrm{e}}{FZ}(2E_{\mathrm{i\,mod}})^2\right]^{\frac{2Z}{\sqrt{2E_{\mathrm{i\,mod}}}}-1} \times \exp\left[-\frac{2(2E_{\mathrm{i\,mod}})^{3/2}}{3F} - \frac{p^2\gamma_{\mathrm{mod}}^3}{3\omega}\right], \qquad (6)$$

where $\gamma_{\mathrm{mod}} = \omega\sqrt{2E_{\mathrm{i\,mod}}}/F$ represents the Keldysh parameter with the modified ionization potential included. Checking the values of γ_{mod} for the intensity range 10^{14}–$10^{16}\,\mathrm{W\,cm^{-2}}$, the condition for tunnel ionization is fulfilled since $0.02 < \gamma_{\mathrm{mod}} < 0.07$.

Since all the required relation and formulae are introduced, we shall now present the new results obtained.

2. Influence of modified ionization potential on ionization rate for circularly polarized laser fields

We studied the influence of modified ionization potential (5) on ionization rate ((4) and (6)) in the ADK theory for the case of a circularly polarized laser field [12, 13]. The studied atoms are K, Na, Li and Cs; they are ionized by CO_2 laser in the intensity regime between 10^{14} and $10^{16}\,\mathrm{W\,cm^{-2}}$.

In figure 1 the ionization rates for Li and Na are given, separately and together. There are two lines: one line with ionization potentials without any corrections to the ionization potential and the other line where the modified ionization potential is included. From this figure, it is obvious that for the intensity $10^{14}\,\mathrm{W\,cm^{-2}}$ the influence of $E_{\mathrm{i\,mod}}$ on ionization rate can be neglected. For values higher than $2\times10^{15}\,\mathrm{W\,cm^{-2}}$, its influence increases the values of ionization

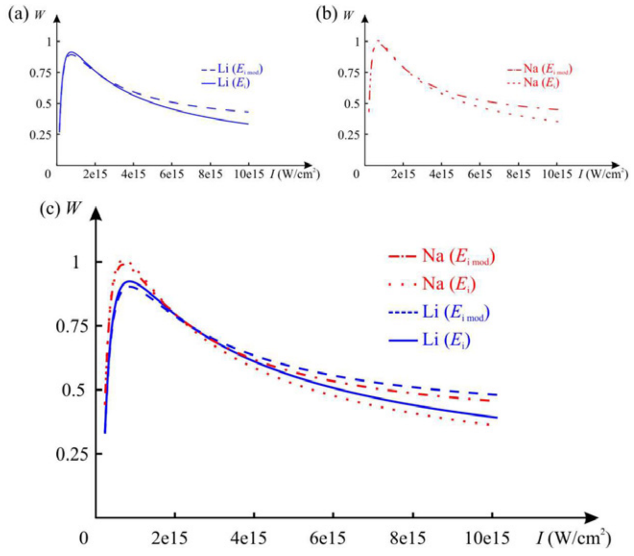

Figure 1. Ionization rates for (a) the Li atom, (b) the Na atom and (c) both atoms. One set of lines shows the influence of modified ionization potential $E_{\mathrm{i\,mod}}$, while the other shows the influence of unmodified ionization potential E_{i}.

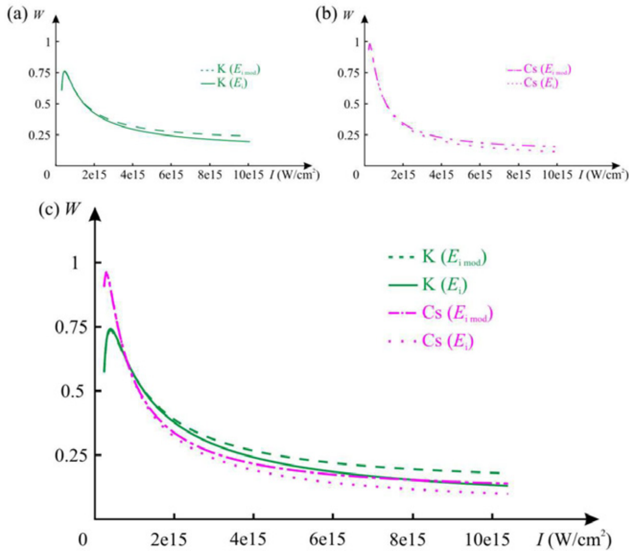

Figure 2. Ionization rates for (a) the K atom, (b) the Cs atom and (c) both atoms. One set of lines shows the influence of modified ionization potential $E_{\mathrm{i\,mod}}$, while the other shows the influence of unmodified ionization potential E_{i}.

rate (dashed for lithium and dash-dotted line for sodium). Since Na and Li have similar values of ionization potentials, $E_{\mathrm{i}}^{\mathrm{Li}} = 5.392\,\mathrm{eV}$ and $E_{\mathrm{i}}^{\mathrm{Na}} = 5.139\,\mathrm{eV}$, respectively, their ionization rates behave in similar manners, although the ionization rate for sodium has a larger maximum than lithium, because sodium atoms are easier to ionize.

Next was analyzed the behavior of ionization rate in the case of K and Cs atoms (figure 2). One of the two lines represents the ionization rate with unmodified ionization potential, while the other shows how modified ionization potential influences the same quantity for both elements. For intensities lower than $10^{15}\,\mathrm{W\,cm^{-2}}$, the influence of $E_{\mathrm{i\,mod}}$ on ionization rate can be neglected for both atoms. But for higher values of intensity, the influence of $E_{\mathrm{i\,mod}}$ leads to an increase in the values of ionization rate (dashed line for potassium and dash-dotted line for cesium). K and Cs atoms have rather different values of ionization potential, $E_i^K = 4.341\,\text{eV}$ and $E_i^{Cs} = 3.894\,\text{eV}$, but their ionization rates behave in similar manners. Still, the ionization rate for cesium has a much larger maximum than potassium, because E_i^K is much larger than E_i^{Cs} and therefore Cs atoms can be more readily ionized.

3. Conclusion

We have shown that modified ionization potential has a much greater influence on tunneling ionization rate than was suspected earlier. This is seen from figures 1 and 2, where the introduction of a modified ionization potential $E_{i\,mod}$ resulted in a strong influence at higher laser intensities, in the range 10^{15}–$10^{16}\,\text{W cm}^{-2}$.

Also it was found that the ionization rates of atoms with similar values of ionization potential behave in an analogous manner; we have compared lithium and sodium atoms in figure 1, and potassium and cesium atoms in figure 2. The ionization rate for sodium has a larger maximum than lithium; hence, the Na atom is more easily ionized than the Li atom, see figure 1. Nevertheless, the ionization rate for cesium has a much larger maximum than that for potassium, because E_i^{Cs} is much smaller than E_i^K, which leads to more rapid ionization (figure 2).

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