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Abstract We theoretically improved the relativistic ADK formula for a linearly polarized laser field. We have taken into account the influence of the magnetic component of laser field on the transition rate, in near relativistic field intensity. It was shown that the magnetic component results in a decrease of the transition rate in comparison to the results obtained by the original relativistic expression. We gave considered noble and alkali atoms. The obtained results show that this influence is larger (more significant) for alkali atoms.

Keywords Tunneling ionization · Lorentz ionization

1 Introduction

Much interest has been directed towards understanding collision processes of atoms and molecules in a strong laser field [1–3]. There are many reasons for that: collisions are an important probe of the structure and properties of matter, they challenge current experimental and theoretical capabilities and demand the development of new techniques [4].

In this paper, we investigated the influence of the magnetic component of laser field on the tunneling transition rate of atoms in near relativistic intensity region.

It is known that an atom can be ionized through different mechanisms, which are distinguished by the Keldysh parameter [5], γ, defined as the ratio of the "tunneling time" and laser period, or, expressed in frequency as the ration of the tunneling frequency, ω_t and the field frequency, ω, $\gamma = \frac{\omega}{\omega_t}$. The tunneling frequency is estimated by $\omega_t = F/\sqrt{2I_p}$ where F is the laser field strength created by a laser and I_p is the field free ionization potential. In atomic units [6], $\mathrm{e} = \mathrm{m} = \hbar = 4\pi\varepsilon_0 = 1$, which are used throughout this paper, the

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Keldysh parameter becomes $\gamma = \frac{\omega}{\omega_t} = \sqrt{\frac{I_p}{2U_p}} = \omega\frac{\sqrt{2I_p}}{F}$ where U_p is the ponderomotive potential defined as $U_p = \frac{F^2}{4\omega^2}\frac{1-\epsilon^2}{1+\epsilon^2}$ where ϵ is ellipticity [7]. For a linearly polarized laser field ellipticity is $\epsilon = 0$, and U_p became $U_p = \frac{F^2}{4\omega^2}$. With increasing laser field intensity, the influence of ponderomotive potential on the field free ionization potential becomes larger and more significant and must be taken into account [8]. The ponderomotive energy is the mean energy stored in the quiver motion of a free electron in an external alternating electric field. The tunneling ionization dominates if $\gamma << 1$, while multiphoton ionization prevails when $\gamma >> 1$ [5].

Relativistic and nonrelativistic phenomena are present in strong field laser interactions with atoms [9]. Increase of the laser field intensity leads to a relativistic domain and appearance of relativistic effects [8, 10]. When the intensity increases indefinitely, $I_p \to \infty$ the limit leads to a relativistic domain, so electric and magnetic fields become equally important [11].

2 Influence of the Magnetic Field Component on the Transition Rate

As already mentioned, we investigated the contribution of the magnetic field component on the tunneling transition rate, in near relativistic domain. By increasing the laser‘s intensity height of the tunneling barrier decreases and the shape of barrier changes qualitatively [17]. Additionally, according to [12], such strong lasers can no longer be treated as pure electric fields and the laser‘s magnetic field component has to be taken into account, too. The magnetic component of the linearly polarized laser field induces a drift of the electron in laser propagation direction. It was shown that relativistic effects result in decrease of the transition rate in comparison to nonrelativistic expressions [13]. For a laser with a wavelength of $\lambda = 800nm$, the onset of magnetic field effects can occur at about $10^{15}W/cm^2$, whereas true relativistic effects do not set in before about $10^{17}W/cm^2$ [14–16].

The appearance of magnetic effects sets a lower limit on γ where tunneling theories can be applied [18]. It is widely believed that a zero frequency limit of laser-induced ionization is a tunneling limit, but it is shown that the $\gamma \to 0$ limit is an extreme relativistic limit. In that case, the relativistic Keldysh parameter must be introduced [19]:

$$\gamma_{rel} = \frac{\omega c}{F}\sqrt{1 - \left(\left(c^2 - \frac{Z^2}{2}\right)/c^2\right)^2}, \tag{1}$$

where ω is the field frequency, Z is the ion charge and c is the speed of light.

For intensities that require relativistic treatment, the ponderomotive potential has relativistic form [20]:

$$U_p^{rel} = \sqrt{c^4 + 2c^2U_p} - c^2, \tag{2}$$

where U_p is, nonrelativistic ponderomotive potential which is already defined. Based on this the relativistic ionization potential, I_p^{rel} can be written as:

$$I_{p,eff}^{rel} = I_p^{rel} + U_p^{rel}. \tag{3}$$

where $I_p^{rel} = c^2 - \sqrt{c^4 - Z^2c^2}$ is the potential that will affect the total ionization probability [21].

For the purpose of incorporating the magnetic field component in the transition rate we started with nonrelativistic transition rate, W_{nonrel} in the frame of widely used ADK theory including the correction for non zero initial momentum of the photoelectron [21]:

$$W_{nonrel} = \left(\frac{4z^3 e}{Fn^{*4}}\right)^{n^*} \mathrm{Exp}\left[-\frac{2Z^3}{3Fn^{*3}} - \frac{p^2\gamma^3}{3\omega}\right]. \tag{4}$$

Here, p denotes the longitudinal component of the initial momentum, and n^* is the effective principal quantum number, $n^* = \frac{Z}{\sqrt{2I_p}}$ [22].

The relativistic transition rate is given by Krainov's expression [23] obtained based on the Landau-Dykhne approach (with exponential accuracy):

$$W_{rel} = W_{nonrel}\mathrm{Exp}\left[-\frac{2E_e\gamma^3}{3\omega} - \frac{E_e^2\gamma}{c^2\omega}\right] \tag{5}$$

where E_e is kinetic energy of ejected photoelectrons, $E_e = \sqrt{p^2c^2 + c^4} - c^2$ [13].

In this paper our goal (idea) was to see how the magnetic component of laser field influences the relativistic transition rate, i.e. how it contributes to the transition rate. This process is called the Lorentz ionization, and corresponding transition rate has the form [12]:

$$W_L = \left(1 - \nu^2\right)^{1/2} SW(F) \tag{6}$$

where, W (F) is the transition rate of the atom under the influence of an electric field only [21] v is the electron velocity and S is the stabilization factor [12]. In order to express v, we focused on the momentum of ejected photoelectrons in the form [24]:

$$p = -\frac{2I^{rel}_{p,eff}}{3c} = -\frac{2}{3c}\left(I_p^{rel} + U_p^{rel}\right) = -\frac{2}{3c}\left(I_p^{rel} + \sqrt{c^4 + 2c^2\frac{F^2}{4\omega^2}} - c^2\right). \tag{7}$$

The relativistically corrected definition of the momentum also can be expressed through the following expression:

$$p = m\nu\gamma_L = (m = 1) = \frac{\nu}{\left(1 - \frac{\nu^2}{c^2}\right)^{1/2}} \tag{8}$$

where γ_L is the Lorentz factor. Combining the expression for momentum of the ejected photoelectron, (7), and electron momentum definition, (8), we obtained $\nu/\sqrt{1 - \left(\nu^2/c^2\right)} = -2I_p^{rel}/3c$, resulting in:

$$\nu^2 = \left[4\left(I_p + \sqrt{c^4 + 2c^2\frac{F^2}{4\omega^2}} - c^2\right)^2\right] \Big/ \left[9c^2 + 4\frac{\left(I_p + \sqrt{c^4 + 2c^2\frac{F^2}{4\omega^2}} - c^2\right)}{c^2}\right]. \tag{9}$$

Finally, substituting (9) and (5) into (6) the following expression is obtained:

$$
\begin{aligned}
W_L \;=\; & \left(1-\frac{4\left(I_p+\sqrt{c^4+2c^2\frac{F^2}{4\omega^2}}-c^2\right)^2}{9c^2+4\left(I_p+\sqrt{c^4+2c^2\frac{F^2}{4\omega^2}}-c^2\right)/c^2}\right)^{1/2}\\
& \times S\times\left(\frac{4z^3e}{Fn^{*4}}\right)^{n^*}\\
& \times Exp\left[-\frac{2Z^3}{3Fn^{*3}}-\frac{\left(p^2+2\sqrt{p^2c^2+c^4}-c^2\right)\gamma^3}{3\omega}-\frac{\left(\sqrt{p^2c^2+c^4}-c^2\right)^2\gamma}{c^2\omega}\right]
\end{aligned}
\tag{10}
$$

From the form of expression (10) we concluded that the tunneling rate, W_L depends exponentially on the field intensity, F the initial momentum, p and also the field free ionization potential, I_p. Hence any applications where these parameters can change will result in large changes in the tunneling signal.

3 Discussion

A number of theoretical investigations of the atomic transition rate have been performed without inclusion of the effect of the magnetic component of laser field. But, as we already mentioned, increase of laser field intensity leads to relativistic domain, in which electric and magnetic fields become equally important. Magnetic component contributes to the transition rate through Lorentz ionization, and in this work, we have included the magnetic component in performed analysis of the relativistic transition rate. The obtained expression (10), for rate, W_L, depends exponentially on the field intensity, F the initial momentum, p and the field free ionization potential, I_p, where momentum and ionization potential are relativistically corrected.

For this purpose, the laser field intensity varied within the range $I = 10^{15}-10^{17}\,Wcm^{-2}$. According to Reiss, onset of the influence of the magnetic field effects becomes noticeable already at significantly smaller intensities and higher frequencies [25, 26].

We considered the cases of argon, Ar, and potassium, K atoms. In the regime of a very low Keldysh parameter $\gamma << 1$ and wavelength of the incident light $\lambda = 800nm$ ($\omega = 0.05696$ a.u) ionization in a strong field can be successfully described as a tunneling process. Short pulses were assumed.

In Fig. 1, based on (5) and (10), we presented relativistic transition rates, without, W_{rel} and included the effects of the magnetic component of laser field, W_L for single, $Z = 1$, and triple ionized, $Z = 3$ Argon atom, Ag.

Figure 1a and b, show that for lower laser field intensities both curves, W_{rel} and W_L, have almost the same shape, but for values larger than, approximately $I \sim 2\times10^{16}\,Wcm^{-2}$ for single, and $I \sim 1,5\times10^{16}\,Wcm^{-2}$ for triple ionized Argon atom, the curve behavior is significantly different. One can observe that in both cases the curves first rise together until the mentioned values, but with increasing of the laser field intensity of curve that represents (1) decreases significantly faster than the other curve representing rates without considering the magnetic component It is obvious that the transition rate is affected by

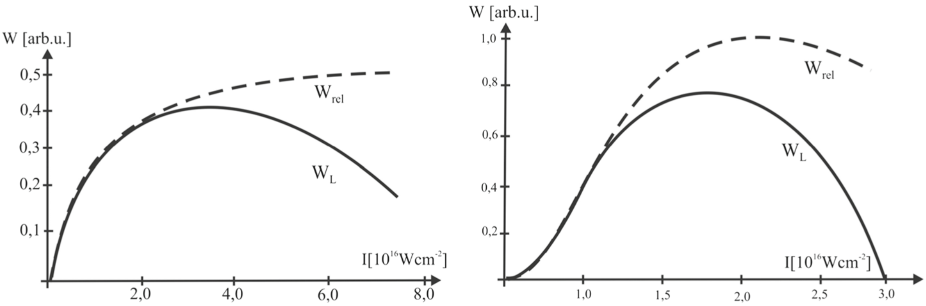

Fig. 1 Relativistic W_{rel} (dotted line) and Lorentz W_L (solid line) transition rates as a function of the laser filed intensity, I, for argon atom Ar. Intensity varies within the range: $I = 10^{15} - 8 \times 10^{16} Wcm^{-2}$ **a** $Z = 1$, **b** $Z = 3$

the magnetic component of laser field. Graph shows simply that the dependence of the magnetic component is not significant for lower field intensities and, on the other hand is significant for higher regions [27, 28]. Similar results were obtained for other noble gas atoms (He, Ne, Kr, Xe). Also, from Fig. 1b it is obvious that for a double ionized argon atom, $Z = 2$, the influence of the magnetic component is more significant. Under the same conditions it is clear that increasing of the ion charge increases the transition rate value for the corresponding curves. Also the curve that corresponds to W_L approaches the axis faster then W_{rel}. This rate's behavior is in accordance with [29–31]. Thus, the transition rate in near relativistic domain is very sensitive to the considered magnetic component of laser field. The absolute rate's magnitude in cases with and without inclusion of the magnetic fields component differs very strongly.

The 3D graphical presentation of ionization occurring through the tunneling mechanism involving a magnetic component of laser field is presented in Fig. 2:

Figure 2 shows dependence of the relativistic Lorentz transition rate, W_L, on field intensity, for different values of the stabilization factor S (0, 1) for the single ion charge $Z = 1$

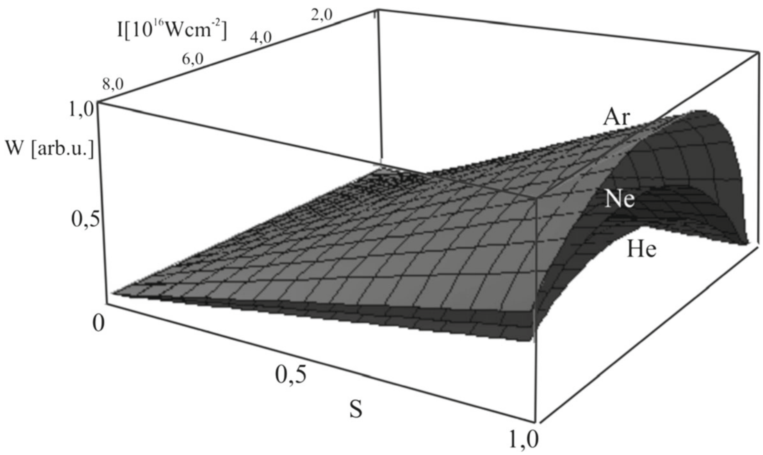

Fig. 2 3D graph for W_L as a function of the field intensity I and the stabilization factor S for noble single ionized, $Z = 1$ argon, neon and helium atoms. Intensity varies within the range $I = 10^{14} - 8 \times 10^{16} Wcm^{-2}$ and the stabilization factor $0 \leq S \leq 1$

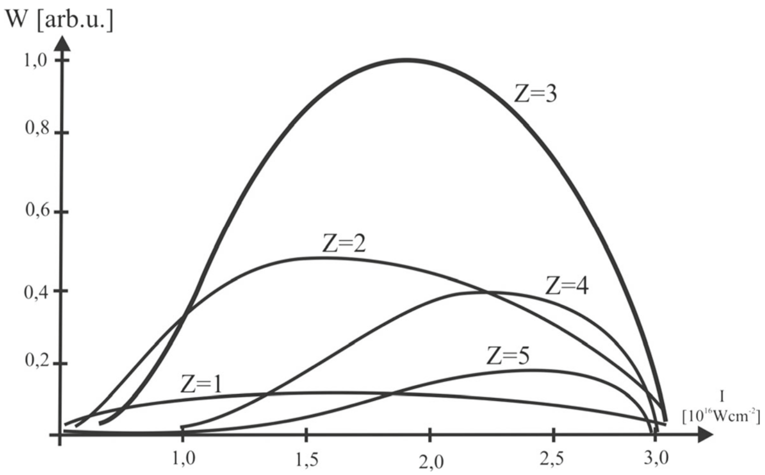

Fig. 3 The relativistic Lorentz transition rate, W_L, as a function of field intensity, I, for the ion charge $Z = 1, 2, 3, 4, 5$, for the argon atom Ar. Intensity varies within the range $I = 10^{15} - 10^{17} Wcm^{-2}$, and the stabilization factor $0 \leq S \leq 1$

and for He, Ne, Ar atoms respectively. As can be seen, all graphs show similar behavior, but some asymmetry exists. In fact, the graph's slope is larger for higher field intensities. The graphs reached the maximal values on lower field intensities for He, Ne, Ar, respectively. Also, intensity of the transition rate increases going from He to Ar

Next, in Fig. 3, we presented the Lorentz transition rate, W_L for values of the ion charges $Z = 1, 2, 3, 4, 5$, with a fixed stabilization factor $S = 1$. We wanted to see how the ion charge influences the Lorentz transition rate. Accordingly [8, 32] with Z increasing, it should be expected that the rate increases.

All curves generally express, more or less, similar behavior. They do not have prominent peaks, but have maxima and all are asymmetric. Increasing of the ion charge shifts the curve's maxima toward (to) higher field intensities. This peak intensity position is completely expected, because with higher value of Z, it needs larger amounts of energy for atom ionization. After reaching maximal intensities, curves decrease and approach the intensity axis.

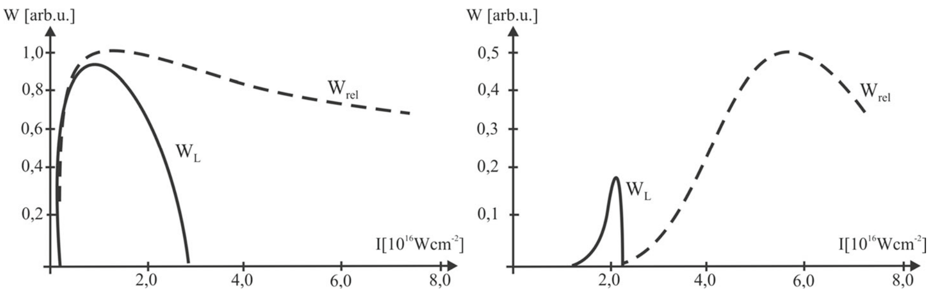

Fig. 4 Relativistic W_{rel} (dotted line) and Lorentz W_L (solid line) transition rates as a function of the laser filed intensity, I, for potassium atom, K. Intensity varies within the range $I = 10^{15} - 8 \times 10^{16} Wcm^{-2}$ **a** $Z = 2$ **b** $Z = 3$

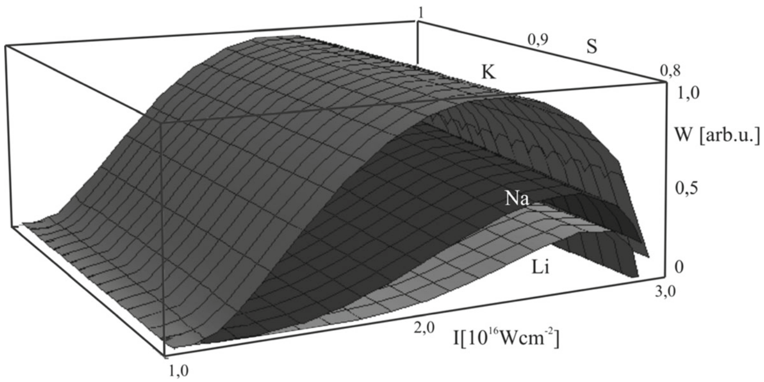

Fig. 5 3D graph for W_L as a function of the field intensity, I and the stabilization factor S, for alkali, double ionized, $Z = 2K, Li, Na$. Intensity varies within the range $I = 10^{15} - 8 \times 10^{16} Wcm^{-2}$ and the stabilization factor $0.8 \leq S \leq 1$

Additionally, we considered the influence of the magnetic component of laser field on transition rate for alkali atoms. For this purpose we observed the potassium atom, K, for$Z = 2$ and $Z = 3$. As a result the following graphs were obtained:

In Fig. 4, we presented the relativistic transition rates, without, W_{rel} (see 5, dashed lines) and with inclusion of the effect of the magnetic component of laser field, W_L (see 10, solid lines) for double, $Z = 2$ (a) and triple ionized, $Z = 3$ (b) atom Potassium, K. Obviously the curves behave differently. For the double ionized K atom, on lower field intensities, both curves W_{rel} and W_L, increase exponentially, but after intensity of approximately $I \sim 2 \times 10^{16} Wcm^{-2}$ the curve which represents W_{rel} decreases significantly slower than the W_L curve. For $Z = 3$, for same intensity range, compared to $Z = 1$, Fig. 4 shows the presence of a significant reduction of the rate's level. From all aforementioned, we concluded that inclusion of the magnetic component of laser field strongly diminishes the value of the transition rate with increasing field intensity. Also, it occurs on the shorter range of the field intensity.

Finally, the 3D graph for double ionized K, Li, Na atoms is given in Fig. 5:

Taking into account the presented graph a similar behavior for all atoms is found. The potassium atom, K has the highest level rate, W_L, while, Li has the lowest one. This ordering implies a significantly larger amount of energy for lithium, which is completely expected, as well as the shift of field intensity, on which the rate achieves the maximal values, to higher field intensity.

4 Conclusion

In conclusion it should be noted that the relativistic transition rate has been discussed in frame of the ADK theory with inclusion of the influence of the magnetic component of laser field. For the same parameters inclusion of this component changes the shape of the aforementioned rate and leads to significant decreasing of the maximal rate's value. In spite of the fact that it is commonly neglected it is obvious that the effect of included corrections is significant and must be taken into account at higher field intensities. We applied it to ionization of noble and alkali atoms.

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References

1. Meuren, S., Keitel, C.H., Di Piazza, A.: Phys. Rev. D **93**, 085028 (2016)
2. Song, X., Lin, C., Sheng, Z., Liu, P., Chen, Z., Yang, W., Hu, S., Lin, C.D., Chen, J.: Sci. Rep. **6**, 28392 (2016)
3. Zimmermann, H., Eichmann, U.: PhysicaScripta **91**, 104002 (2016)
4. Fléchard, X., Adoui, L., Ban, G., Boduch, P., Cassimi, A., Chesnel, J.Y., Durand, D., Frémont, F., Guillous, S., Grandin, J.P., Hennecart, D., Jacquet, E., Jardin, P., Lamour, E., Liénard, E., Lelièvre, D., Maunoury, L., Méry, A., Naviliat-Cuncic, O., Prigent, C., Ramillon, J.M., Rangama, J., Rozet, J.P., Steydli, S., Trassinelli, M., Vernhet, D.J.: Phys.: Conf. Ser. 629 (2015)
5. Keldysh, L.V.: Sov. Phys. JETP **20**, 1307 (1965)
6. McWeeny, R.: Nature **243**, 196 (1973)
7. Miladinović, T.B., Petrović, V.M.: Pramana **86**, 565 (2016)
8. Miladinović, T.B., Petrović, V.M.: Rev. Mex. Fis. **60**, 290 (2014)
9. Grochmalicki, J., Lewenstein, M., Rzaewski, K.: vol. 66 (1991)
10. Milosevic, N., Krainov, V.P., Brabec, T.: J. Phys. B: At. Mol. Opt. Phys. **35**, 3515 (2002)
11. Reiss, H.R.: Phys. Rev. Lett. **101**, 043002 (2008)
12. Zhakenovich, A.E., Valentina, Y., Nessipbay, T., Tatyana, S., Zhadyra, Y.: J. Chem. Chem. Eng. **9**, 299 (2015)
13. Krainov, V.P.: Opt. Express. **2**, 268 (1998)
14. Reiss, H.R.: Phys. Rev. A **63**, 013409 (2000)
15. Reiss, H.R.: Opt. Express **8**, 99 (2001)
16. Krainov, V.P., Sofronov, A.V.: Phys. Rev. A **77**, 063418 (2008)
17. Landsman, A.S., Weger, M., Maurer, J., Boge, R., Ludwig, A., Heuser, S., Cirelli, C., Gallmann, L., Keller, U.: Optica **1**, 343 (2014)
18. Reiss, H.R.: Phys. Rev. A **82**, 023418 (2010)
19. Miladinović, T.B., Petrović, V.M.: Braz J Phys **45**, 251 (2015)
20. Ghebregziabher, I.: Radiation and photoelectron dynamics in ultra strong laser fields ProQuest 36 (2008)
21. Yakaboylu, E., Klaiber, M., Bauke, H., Hatsagortsyan, K.Z., Keitel, C.H.: Phys. Rev. A **88**, 063421 (2013)
22. Ammosov, M.V., Golovinsky, P.A., Kiyan, I.Y., Krainov, V.P., Ristic, V.M.: JOSA B. **9**(8), 1225 (1992)
23. Delone, N.B., Kiyan, I.Y.u., Krainov, V.P.: Laser Phys. **3**, 312 (1993)
24. Krainov, V.P.: Opt. Express **2**, 268 (1998)
25. Klaiber, M., Yakaboylu, E., Bauke, H., Hatsagortsyan, K.Z., Keitel, C.H.: Phys. Rev. Lett. **110**, 153004 (2013)
26. Reiss, H.R.: J. Phys. B: At. Mol. Opt. Phys. **47**, 20 (2015)
27. Reiss, H.R.: Phys. Rev. A **87**, 033421 (2013)
28. Ludwig, A., Maurer, J., Mayer, B.W., Phillips, C.R., Gallmann, L., Keller, U.: Phys. Rev. Lett. **113**, 243001 (2014)
29. Eichmann, U., Dörr, M., Maeda, H., Becker, W., Sandner, W.: Phys. Rev. Lett. **84**, 3550 (2000)
30. Kornev, A.S., Tulenko, E.B., Zon, B.A.: Phys. Rev. A **68**, 0434141 (2003)
31. Smeenk, C.T.L., Arissian, L., Zhou, B., Mysyrowicz, A., Villeneuve, D.M., Staudte, A., Corkum, P.B.: Phys. Rev. Lett. **106**, 193002 (2011)
32. Shemi, A.M.: Turk J Phys **28**, 229 (2004)