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REGULAR ARTICLE

The Velocity Gauge KFR Ionization Rates of H($2p_x$), H($2p_y$) and H($2p_z$) Atom in the Linear Polarized Laser Field

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Abstract We obtain the ionization rates of H($2p_x$), H($2p_y$) and H($2p_z$) from the so-called velocity gauge(VG) forms of the Keldysh-Faisal-Reiss(KFR) theory for a linear polarized laser field. Then the ionization rates of H($2p_x$), H($2p_y$) and H($2p_z$) were compared thoroughly. The result of ionization rates of H($2p_x$) and H($2p_y$) are totally equal , while different from that of H($2p_z$). We also numerically compare ionization rates of H($2p_x$), H($2p_y$) and H($2p_z$), the numerical study shows that the ionization rate of H($2p_z$) is a few orders underestimated compared with the ionization rate of H($2p_x$) and H H($2p_y$). Our ionization rates of H($2p_x$), H($2p_y$) and H($2p_z$) may provide more insight into the origin of the discrepancy between the different bound states for hydrogen atom.

AMS subject classifications: 37N20
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1. Introduction

With the rapid advancement of laser technology, the physics of strong-field photoionization has been extensively studied. Much of our knowledge of strong-field photoionization from the study of above-threshold ionization (ATI) [1]. Since then, ATI has been continuously advancing our understanding of strong-field physics. As in atom systems, a series of related strong-field processes occur including above-threshold ionization and dissociation [2,3], double and multiple ionization [4,5], and high-order harmonic generation [6,7]. Especially from the physical point of view using linear polarization of the laser field is more interesting,

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since one can experimentally observe such phenomena like rescattering. The hydrogen atom is the simplest atom and as such has been the favorite of theorists in investigations of atom effects in strong-field physics. To understand the physics of strong-field photoionization, we believe that detailed studies of hydrogen atom ionization rates of different bound states will provide additional insights into the dynamics of ionization processes in general. As we have already investigated on the ionization rate of H(1s) in intense laser field, the ionization rate of H($2p_x$), H($2p_y$) and H($2p_z$) in intense laser field is supposed to be obtained .Therefore, it is intensely important to explore the hydrogen atom photoionization in more detail.

Certainly, in the study of strong-field ionization the two model the velocity gauge(VG) and the length gauge(LG) forms of the Keldysh-Faisal-Reiss(KFR) theory [8-13] should been widely used. The KFR theory is based on the S-matrix theory; approximate wavefunctions have to be used in practice to evaluate the S-matrix elements [14] for bound-free transitions. It utilizes the S-matrix theory, which is in principle exact. However, since there is no general analytical solution to the Schrödinger equation for a charged particle interacting. Processing for numerically integrate the TDSE [15] (the time-dependent Schrödinger equation) is difficult and its approach has limitation. The strong-field approximation (SFA) in the VG and the LG differ and apparently constitute two distinct models. Various approximate theories may lead to different expressions for the ionization rate. All theories describe the same physical problem, and the main difference between them is in the form of the laser-atom interaction. It have caused an extensive controversy about which gauge is more appropriate for the SFA [16-21]. Meanwhile, the gauge invariant is theoretically proved still valid for photoionization amplitude [22-27]. However, which indicates similar or even more pronounced gauge dependencies. For example, within the same approximations both VG and LG KFR theories describe the same electromagnetic fields acting on bound electron, we found the VG and LG KFR [28,29] ionization rates of the H(1s) atom are different. Furthermore, the VG SFA predicts better well about phenomenon. To summarize, numerous controversial results obtained within different gauges and needs some revising and improving.

F.–C. Ma has derived a formula of atom ionization in an intense field using the VG [30,33] which provides a more insightful guidance to investigate the long standing discrepancy in the strong-field ionization theory. The formula is as simple as Keldysh's formula, and he draw a conclusion that the discrepancy of calculated ionization rate between the approximations in two gauges do not arise from algebraic method. Tang Z H also has obtained a formula of molecular ionization in an intense field [33]. The method which he used can date from Ma F C's formula and he changed conditions in VG forms of the KFR theory for a linear polarized laser field. He presented an appropriate example for strong-field ionization of N_2 molecules, which the corresponding approximate two centered