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# The influence of a parallel magnetic field on the ionization of a hydrogen atom in an electric field

Dehua Wang[a,*], Kaiyun Huang[a], Hui Zhou[b], Shenglu Lin[b]

[a] College of Physics and Electronic Engineering, Ludong University, Yantai 264025, China
[b] College of Physics and Electronics, Shandong Normal University, Jinan 250014, China

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ABSTRACT

The ionization of a hydrogen atom in an electric field plus a variable magnetic field has been examined. The dynamic motion of the electron is generated by exciting the hydrogen atom from its ground state using a short laser pulse. The results show that the atom ionizes by emitting a train of electron pulses. As the magnetic field is very weak, the ionization process of the hydrogen atom is nearly the same as the case of hydrogen atom in an electric field. With the increase of the magnetic field, a series of electron pulses appear in the ionization process. Not only the trajectories launched with large angles can pass through the saddle point and escape, but also those orbits with small initial outgoing angles can escape. The escape–time plot and the ionization rate curve become much more complicated. This is caused by classical chaos, which occurs for strong magnetic fields. Our theoretical analysis will be useful for guiding experimental studies of the ionization of atoms in the external fields, under chaotic conditions.


## 1. Introduction

With the development of the atomic streak camera, the escape dynamics of the Rydberg atoms in external static fields have attracted much attention in recent years [1–6]. If the energy of the Rydberg electron is above the saddle point of the combined Coulomb and static field potential, it escapes on a picoseconds time scale. In 1996, Lankhuijizen and Noordam measured the ionization rate for a rubidium atom excited by a short laser pulse in a constant applied electric field [1,2]. The ionization of the Rydberg atom occurred via a train of electron pulses. This observation has been qualitatively explained by the semiclassical theory [3,4]. Motivated by this experiment, Mitchell et al. predicted that a hydrogen atom can also ionize through emission of an electron pulse train when placed in combined electric and magnetic fields [6]. Unlike the case of the rubidium atom, the pulses are not created through core scattering. They are caused by the classical chaos due to the magnetic fields. In Ref. [7], Mitchell et al. gave a detailed analysis of chaos-induced pulse trains in the ionization of hydrogen. But in their work, they only discussed the ionization of hydrogen in a given scaled magnetic field. In this paper, by using the semiclassical theory, we calculate the ionization of hydrogen atom in an electric filed plus a variable magnetic field and analyze how the ionization rate varies with the magnetic field. The results show, as the magnetic field is very weak, the influence of the electric field dominates. There is a single pulse of electrons, with an exponentially decaying tail. But with the increase of the magnetic field, its influence becomes significant. The escape–time plot and the ionization rate curve become much more complicated. There are many electron pulses appearing in the ionization process. This is a consequence of the classical chaos, which occurs for strong magnetic fields. Our theoretical study is intended to stimulate experimental efforts to observe the influence of the magnetic field to the ionization of hydrogen atom. Besides, our theoretical method can also provide a convenient laboratory tool for studying chaotic transport and escape [8–10].

This paper is organized as follows. In the second part, we give the semiclassical theory of the ionization process of the Rydberg hydrogen atom in the presence of an electric field plus a parallel magnetic field. In particular, we explain how to find the ionizing trajectories by using the semiclassical method. In Section 3, we calculate the ionization rate of the hydrogen atom at a given scaled energy larger than the saddle energy but with different scaled magnetic fields. Besides, the escape–time plots and the relation between the icicles in the escape curves and the pulses in the ionization rate curves are also given. Some discussions on the influence of the magnetic filed to the ionization of hydrogen atom are also made in this part. Section 4 is some conclusions of this paper.

## 2. Theory and quantitative formula

The qualitative description of the ionization process of this system can be described as follows. The hydrogen atom is firstly placed

* Corresponding author.
*E-mail address:* jnwdh@sohu.com (D. Wang).

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in parallel electric and magnetic fields, after the electron absorbs a photon from the laser pulse, it is promoted from a low-energy bound state into an outgoing wave, which can be modeled semiclassically as an ensemble of trajectories propagating away from the nucleus in all directions and with a narrow range of energies. Some trajectories head directly downhill, and are accelerated by the external field toward a detector, creating an initial prompt pulse of electrons. Other trajectories initially head uphill, are turned around by the external electric and magnetic fields. As time evolves, some of the trajectories find their way over a saddle point in the potential energy surface that separates the Coulomb center from the ionization channel. These trajectories are subsequently accelerated toward the detector, striking it in a series of pulses. The behavior of a trajectory moving away from the nucleus depends intricately upon its initial outgoing angle $\theta$. Nevertheless, over certain interval of $\theta$, all trajectories have similar qualitative behavior, and most strike the detector within a short interval of time. Thus the family of trajectories within each escape segment gives rise to a single electron pulse. The pulse train becomes more and more complicated as time progresses.

### *2.1. Hamiltonian and scaled variables*

We consider the classical dynamics of the electron in a hydrogen atom that is placed in parallel electric and magnetic fields. The Hamiltonian of this system in cylindrical coordinates $(\rho, z)$ and atomic units is given by

$$H = \frac{1}{2}(p_\rho^2 + p_z^2) - \frac{1}{\sqrt{\rho^2 + z^2}} + \frac{1}{8}B^2\rho^2 + Fz \quad (1)$$

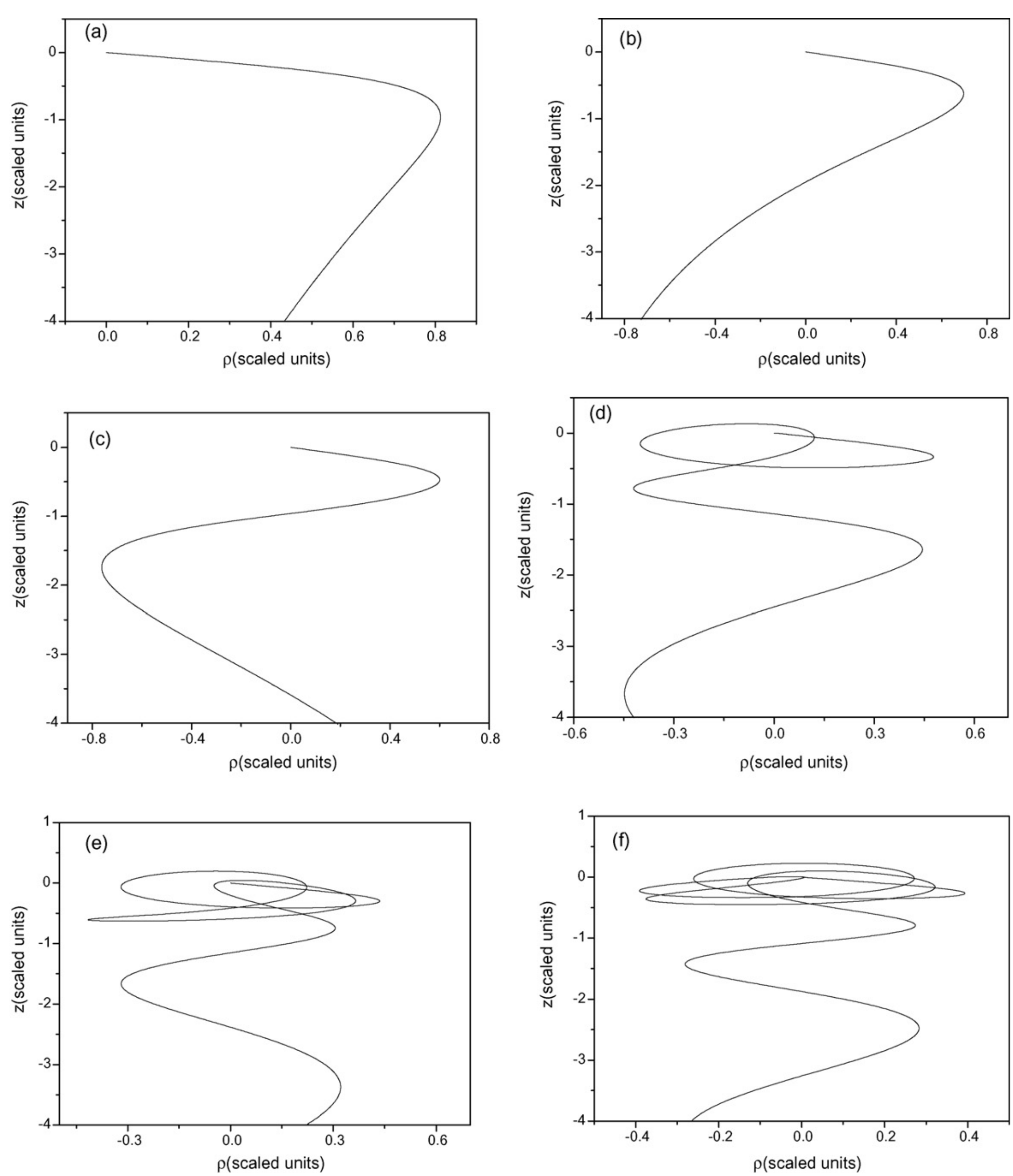


**Fig. 1.** The evolution of the ionizing trajectory with the magnetic field. These trajectories are emitted with the same initial angle $\theta = 126.60^\circ$, the detector locates at $z = -4.0$. The scaled energy $\varepsilon = -1.3$, the scaled magnetic fields are as follows: (a) $B = 0.5$, (b) $B = 1.5$, (c) $B = 2.5$, (d) $B = 4.5$, (e) $B = 5.5$ and (f) $B = 6.8$.