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Photodetachment electron flux of H^- in combined electric and magnetic fields with arbitrary orientation

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ABSTRACT

On the basis of the semi-classical theory, we calculate the photodetachment electron flux of H^- in combined electric field and magnetic field with arbitrary orientation. Our results suggest that the electron flux distributions on the detector plane is not only related to the angle between the electric and magnetic fields, but also related to the electron energy. With the increase of the angle between the electric and magnetic field, the oscillating region in the electron flux distributions becomes smaller. In addition, we find with the increase of the detached electron's energy, the oscillating structure in the flux distributions becomes much more complicated. Therefore, the oscillation in the detached electron flux distributions can be controlled by adjusting the angle between the electric and magnetic field and the detached electron's energy. We hope that our studies may guide the future experimental researches in the photodetachment microscopy of negative ion in the presence of external fields.

1. Introduction

Experiments and theories have shown that oscillatory structure appears in the electron flux distribution of H^- in the presence of external fields. In 1989, Du had developed a semi-classical method to calculate the electron flux distributions in the photodetachment of H^- in an electric field [1]. His result suggests that the oscillation in the electron flux distribution was caused by the interference of waves traveling along two distinctive paths from the region of the bound state of H^- to the same point on the detector plane. His study can be considered as a primitive analysis for the photodetachment microscopy theoretically. As a powerful technique to investigate electron dynamics, the microscopy has been used to study the photodetachment of negative ions in external electric and magnetic fields for many years both theoretically and experimentally [2]. In early 1980s, Demo, Kondratovich and Ostrovsk first introduced the principle of photodetachment microscopy by studying the photodetachment process of negative ion in the presence of an electric field [3,4]. Ever since then, photodetachment microscopy opens a new way to measure electron affinities of neutral atoms by means of interference patterns with accuracy higher than any current *ab initio* calculations for multi-electron systems [5–8]. In the experimental aspect, Blondel et al. studied the photodetachment microscopy of Br^- and O^- in an electric field [9,10]. In the theoretical aspect, because Du's semi-classical theory provide a vivid physical picture description of the photodetachment process of negative ion in external fields [1], many researchers have used his semi-classical method to treat some more complicated systems. In 2006–2007, Bracher and Delos studied the detached electron dynamics in parallel electric and magnetic fields [11,12]; Gao et al. calculated the electron flux distribution of H^- in parallel electric and magnetic fields [13]. Recently, Tang and Wang studied the photodetachment microscopy of H^- in an electric field or in a magnetic field near a surface [14,15]; Bracher and Gonzalez studied the electron dynamics in a uniform magnetic field [16]. Unlike the case of the photodetachment of H^- in a uniform electric field, where only two detached electron's trajectories can arrive at a same point on the detector. When the magnetic field is added, due to the influence of the magnetic field forces, more than two trajectories of the detached electron can arrive at a given point on the detector, which lead to an intricate oscillatory structure in the electron flux distribution. In these early studies, they all studied the photodetachment electron flux of H^- in an electric field or in the presence of electric and magnetic field with a given orientation. As to the photodetachment electron flux of H^- in the electric and magnetic fields with arbitrary orientation, no reports have been given up to now. But it is necessary to study this problem, since in 1996, Liu et al. have studied the photodetachment cross section of H^- in the electric and magnetic fields with arbitrary orientation [17]. Their results suggest that oscillations appear in the photodetachment cross section and the oscillating structure is related to the orientation of the electric and magnetic fields. Since the photo-detachment cross section is proportional to the integrated outgoing electron flux across a large enclosure in which the bound negative ions sits, therefore it is

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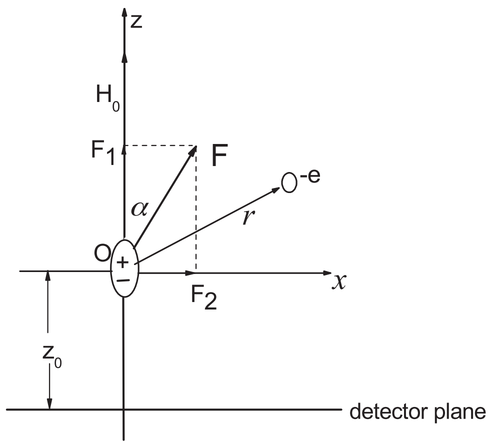

Fig. 1. The schematic plot of H^- in combined electric and magnetic filed. The magnetic field H_0 is along the +z axis. The electric field F lies in the x–z plane with the angle between the electric field and magnetic field is denoted as α. F_1 and F_2 are two components of the electric field F along the z-axis and x-axis respectively.

clear that the oscillation in the cross section reflects the oscillations in the electron flux distribution [1]. Inspired by their work, we study the photodetached electron flux distributions of hydrogen negative ion in the electric and magnetic fields with arbitrary orientation on the basis of the semiclassical theory. We pay special attention to the oscillatory structure in the flux distributions on the detector, and show how these oscillatory structures varies with the change of the angle between the electric and magnetic fields. As we all know, H^- is a simplified system. But the method we used in this work can be extended to other complex negative ions systems, such as O^-, Br^-, etc. [9,10]. By measuring the photodetachment microscopy interference patterns, people can obtain the electron affinities at the μeV level for Si and F atoms [5–8]. Using the photodetachment experiment, people managed to determine the ground state configuration of most atomic and some molecular negative ions. Many important biological processes and chemical reactions involve negative ions. For example, in order to model the ionic crystals, the binding energy of negative ions can be used as an input parameter. Besides, the photodetachment microscopy of negative ions is known to have a very significant impact on the properties of plasmas, in particular the conductivity. Negative ions are also astrophysical significance, being found in the atmosphere of stars in the intergalactic medium. Wildt, Chandrasekhar and Bethe have shown that hydrogen negative ion is an important prototype in atomic and astrophysics and is the main source of opacity in stellar atmospheres [18]. We hope that our studies may guide the future experiment research on the photodetachment microscopy of some more complex negative ions in the presence of external electric and magnetic fields. Atomic units are used throughout this work unless otherwise noted.

2. Hamiltonian and the classical motion

The schematic plot of the system is given in Fig. 1. Assuming the hydrogen negative ion sits at the origin with the detached electron loosely bound by a short-range, spherically symmetric potential $V_b(r)$. A z-polarized laser is used for the photodetachment and a position sensitive detector is placed at $z = z_0 < 0$ plane. External electric and magnetic fields are applied, with the magnetic field H_0 along the z-axis. The electric field F lies in the x–z plane, and the angle between the electric and magnetic field is denoted as α.

The physical picture of the photodetachment process of H^- in the combined electric and magnetic field can be described as follows: when the laser is on, the negative ion may absorb a photon of energy $E_{\rm ph}$ and the detached electron becomes an outgoing wave.

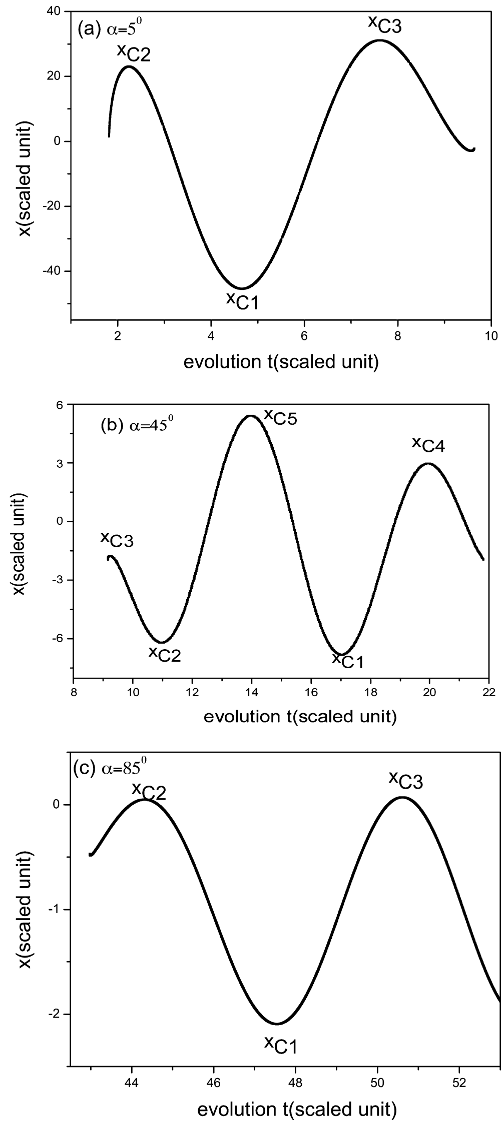

Fig. 2. The variation of the final position x with the evolution time t of the detached electron in combined electric and magnetic field. The detector is placed at $z_0 = -100$ (scaled unit) plane. The scaled energy and the angle between the electric and magnetic fields are as follows: (a) $E = 1000$ (scaled unit), $\alpha = 5°$; (b) $E = 20$ (scaled unit), $\alpha = 45°$; (c) $E = 0.1$ (scaled unit), $\alpha = 85°$.

According to the semiclassical theory, the wave propagates away from the hydrogen atom in all directions, following classical trajectories. Whenever two or more trajectories of the detached electron arrive at a given point on the detector, the corresponding waves interfere constructively or destructively, thus creating an oscillatory structure in the electron flux distributions on the detector. As the electron moves far away from the ions, the wave functions can be constructed using the semiclassical approximation. In order to calculate the electron flux distributions at a given point on the detector, we must find out all the trajectories of the detached electron that arrive at that point in great detail.

After the electron is photodetached and moved far away from the hydrogen atom, the short-range potential $V_b(r)$ can be neglected. Then the detached electron's Hamiltonian can be written as:

$$H = \frac{1}{2}P_x^2 + \frac{1}{2}P_z^2 + \frac{1}{2}\omega_L^2 x^2 + F_1 x + F_2 z \quad (1)$$

in which $\omega_L = H_0/2c$ is the electron's cyclotron frequency and c is the speed of light, $F_1 = F\sin\alpha$ and $F_2 = F\cos\alpha$.