Photoelectron angular distributions from photodetachment of negative ions in strong laser fields

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Abstract. Using a nonperturbative scattering theory, the photoelectron angular distributions (PADs) of negative ions irradiated by intense laser fields are studied. Various PADs are obtained. Similar to that of atoms, PADs of negative ions show main lobes and jet-like structures. Here, the main lobe means the formation of the detached photoelectrons around the direction of laser polarization, while the jet-like structure means a peaked-out formation of photoelectrons emitted from the waist between the two main lobes. For a set of above-threshold-detachment peaks, with one-more-photon absorption, the number of the jet-like structures is not always increased by one, which verifies that the jet-like structures are irrelevant to photoelectron angular momentum.

1. Introduction
Photoionization of atoms in intense laser fields is an important nonlinear effect in the domain of strong field physics. Recently, more and more interests have been arisen in the study of photoionization, among which the study of photoelectron angular distributions (PADs) is a hot topic. Both in experimental researches and in the comparison of experimental observations with theoretical studies, PADs are an important tool. With rapid developments in experimental techniques, it is possible to measure photoelectron kinetic-energy spectra with highly resolved angles [1-5]. Nandor et al. [1] and Schyja et al. [5] observed a jet structure sticking out from the main lobes in the PADs of low-energy above-threshold ionization peaks of xenon atoms. Here, the main lobes in PADs are the formations of photoelectrons emitted in and around the direction of laser polarization, while the jets are the formations of photoelectrons emitted from the waist between the two main lobes. It was revealed that when the number of absorbed photons increases by one, the number of jets (we denote the jet number throughout this paper, here the jet number denotes the number of jets on one side of PADs) also increases by one. Since in traditional perturbation theory, a photon absorption will alter the electron angular momentum state, it is likely to attribute the number of jets in PADs to the quantum number of the electron angular momentum state. Recently, we have studied the PADs of a hydrogen atom irradiated by linearly polarized laser light [6] by using a nonperturbative quantum scattering theory proposed by Guo et al. [7]. Our previous study [6] has shown that the calculated PADs show main lobes and jet-like structures. Our study has confirmed the experimental observation that when the
absorbed-photon number increases by one, the jet number also increases by one. And has further predicted that in some cases three or other odd-number more jets may appear with just one-more-photon absorption. The jet-like structure of PADs is due to the maxima of generalized phased Bessel functions, not an indication of the quantum number of photoelectron angular momentum states.

Then do the predicted phenomena be confirmed by other strong field theories? Do the predicted phenomena only exist in photoionization of atoms? These questions will be answered in this paper. If the predicted phenomena are confirmed by other strong field theories, if the predicted phenomena exist in ionization of other matters with laser fields, they will provide a strong support to our statement. In this paper we investigate the PADs of negative ion H irradiated by linearly polarized laser light by using a nonperturbative scattering theory proposed by Reiss [8]. Our study shows that the calculated PADs from above-threshold detachment of H also show main lobes and jet-like structures. Similar to that of atoms, our study confirms the experimental observation [1] that when the absorbed-photon number increases by one, the jet number also increases by one. And our study also verifies the predicted phenomena that in the PADs of a set of above-threshold detachment peaks, three more jets may appear with just one-more-photon absorption. This study shows that the jet-like structures have no relation with the angular momentum of photoelectrons and provides a strong support to the prediction and the nonperturbative quantum scattering theory used in our previous study [7].

2. Theory

The vector potential for a monochromatic linearly polarized plane wave in long-wavelength approximation is \( \mathbf{A}(t) = a \mathbf{E} \cos \mathbf{r}_0 \), where \( \mathbf{E} \) is the polarization vector, \( \mathbf{E} \) is real and normalized (\( \mathbf{E} \cdot \mathbf{E} = 1 \)).

The total transition probability per unit time for photodetachment arising from monochromatic linearly polarized electromagnetic fields is given by [8]:

\[
\frac{dW}{d\Omega} = \frac{(2m \omega)}{2} \sum (n-z)^j \epsilon (n-z) \left( \epsilon (n) - \epsilon (n+z) \right) \left| \phi (\mathbf{r}) \right|^2 r_{n+\frac{1}{2}} \left( \alpha, z \right)/2
\]

where \( n \) is bounded from below, since \( n \geq z + \epsilon \), in terms of integer relationships, \( n \geq n_\epsilon, n_\epsilon = z + \epsilon \), \( \epsilon \) is the initial binding energy of the electron. Since \( n_\epsilon \) is the smallest index in the sum over \( n \), the range of \( n \) is now confined to \( n_\epsilon \leq n < \infty \), \( z \) is a fundamental intensity parameter defined by \( z = e^2 a/4m \omega \) [9], where \( a \) is the amplitude of the radiation-gauge vector potential of the applied plane-wave field of linear frequency \( \omega \). Energy of the photodetached electron is given by the energy contributed by an nth order interaction with the field, less the energy which must be invested in overcoming \( E_\epsilon \). In the general case, where \( z \neq 0 \), the energy \( z \omega \) is a minimal interaction energy of the charged particle with the electromagnetic field. \( \phi (\mathbf{r}) \) is the Fourier transform of \( \phi (\mathbf{r}) \), \( \phi (\mathbf{r}) = e^{i \alpha \cdot \mathbf{r}} \int \phi (\mathbf{r}) e^{-i \alpha \cdot \mathbf{r}} d^3 \mathbf{r} \), the initial-state wave function \( \phi (\mathbf{r}, t) = \phi (\mathbf{r}) e^{-i \alpha \cdot \mathbf{r}} \). \( J_n(u, v) \) is a generalized Bessel function

\[
J_n(u, v) = J_n(u) J_{\alpha}(v) + \sum J_n(u) \left[ J_{\alpha}^2(v) + J_{\alpha + 1}^2(v) \right],
\]

where \( \alpha = 8^{(n-z)^j \cos \theta} \), the angle \( \theta \) is the polar angle in spherical polar coordinates, but in linear polarization case, the polar axis is taken to be along the polarization vector, \( \mathbf{E} \).

3. Results and analysis

In this paper, by using the nonperturbative scattering theory [8], PADs of negative ion H irradiated by linearly polarized intense laser fields are studied. PADs for odd values of \( n \) and even values of \( n \) are obtained. Similar to that of atoms, PADs of negative ion H show main lobes and jet-like structures. We find that for odd-\( n \) PADs, a maximum locates at the direction of laser polarization, and a zero is at the direction perpendicular to the laser polarized direction. We also find that for even-\( n \) PADs, a peak exists in the direction perpendicular to the laser polarization, which is in consistent with the conclusion of Reiss [8]. We further find that for a set of above-threshold detachment peaks, when one-more-photon is absorbed, the number of the jet-like structures in PADs is increased by one and three. It verifies the prediction that the jet-like structures are irrelevant to photoelectron angular momentum.

According to equation (1), PADs of above-threshold detachment for negative ion H in linearly polarized laser fields are obtained. In our calculations, the binding energy of H is chosen as 0.75421 eV [10] and the initial momentum-space wave function of a negative ion H in its ground state is given.
as \[ \phi_i(p) = 2f(2\pi\beta)^{1/2}(\beta^2 + p^2)^{1/2}, \]
where \( \beta = (2mE)^{1/2} \), and \( f \) is an empirical constant with the value \( f = 2.65 \).

In this paper, we investigate PADs with shorter laser wavelength comparing to the study of Reiss [8], and different character of PADs are found. For longer laser wavelength and lower laser intensity [8], when the absorbed-photon number increases by one, the jet number also increases by one, as shown in figure 4 of reference [8]. Our calculation shows that for shorter laser wavelength and higher laser intensity, when one-more-photon is absorbed, the number of the jet-like structures in PADs is increased by one and three.

For shorter laser wavelength and lower laser intensity, when one-more-photon is absorbed, the number of the jet-like structures in PADs is increased by one, which is in good agreement with the study of Reiss [8].

We first calculate the PADs of H irradiated by the laser light of wavelength 2100 nm and the laser light of intensity \( 1 \times 10^{12} \) W/cm\(^2\), the threshold order is \( n_0 = 2 \). PADs for \( n = 2, 3, 4 \) are depicted in figure 1. We can see from figure 1 that each plot shows the main lobes along the direction of laser polarization and several jets sticking out from the waist between the main lobes. For PADs of \( n = 2 \), there are two jets, and for PADs of \( n = 3 \) and \( n = 4 \), there are three and four jets, respectively. Figure 1 shows that when the absorbed-photon number increases by one, the jet number also increases by one, which is in agreement with the observation of Nandor et al. [1] and the study of Reiss for PADs with shorter laser wavelength and lower laser intensity [8]. We also find that for odd-\( n \) PADs, as shown in plot (b) for three photons absorbed, the maximum locates at the direction of laser polarization and zero in the direction perpendicular to the laser polarization, which is in agreement with the study of Reiss [8]. In plot (a), more detached electrons are emitted to the direction perpendicular to the direction of laser polarization, which is the so-called threshold effect, which has been studied experimentally and theoretically [11, 12]. In plot (c) for four photons absorbed, we also find a peak in the direction perpendicular to the laser polarization. For even-\( n \) PADs, there is always a peak in the direction perpendicular to the laser polarization, as shown in plot (a) and plot (c). For odd-\( n \) PADs, no peak appears in the direction perpendicular to the laser polarization, as shown in plot (b), which is in agreement with the study of Zhang et al. [13].

We then calculate the PADs of H irradiated by laser fields with much higher laser intensity. Figure 2 depicts the PADs of H irradiated by laser fields with laser intensity at \( 1 \times 10^{13} \) W/cm\(^2\) and laser wavelength at 1600 nm, the threshold order is \( n_0 = 5 \). Plots (a)-(c) depict PADs for \( n = 5, 6, 7 \), respectively. For odd-\( n \) PADs, as shown in plot (a) and plot (c), there are almost no photons emitted along the direction perpendicular to the laser polarization. For even-\( n \) PADs, as shown in plot (b), there is a peak in the PAD along the direction perpendicular to the laser polarized direction, which is in agreement with the study of Zhang et al. [13]. For PADs of \( n = 5 \), there are two jets, and for PADs of \( n = 6 \) and \( n = 7 \), there are five and six jets, respectively. By comparing an \( n \)-photon PAD with its neighboring \((n+1)\)-photon PAD, figure 2 shows that the jet number increases by three and one, when the absorbed-photon number increases by one, the jet number is not always increase by one.
Figure 1. PADs of H by intense linearly polarized laser fields with laser wavelength at 2100 nm and laser intensity at $1 \times 10^{12}$ W/cm$^2$. Plot (a) is the contribution from the lowest order $n_0=2$. Plot (b) and plot (c) are for the PADs from orders $n=3$ and $n=4$, respectively.

Figure 2. PADs of H by intense linearly polarized laser fields with laser wavelength at 1600 nm and laser intensity at $1 \times 10^{13}$ W/cm$^2$. Plot (a) is the contribution from the lowest order $n_0=5$. Plot (b) and plot (c) are for the PADs from orders $n=6$ and $n=7$, respectively.

Similar feature is also found in figure 3. Figure 3 depicts PADs for $n=6, 7, 8$ with laser intensity at $1 \times 10^{13}$ W/cm$^2$ and laser wavelength at 1800 nm, the threshold order is $n_0=6$. For PADs of $n=6$, there are three jets, and for PADs of $n=7$ and $n=8$, there are four and seven jets, respectively. We also find that for odd-$n$ PADs, as shown in plot (b), the maximum locates at the direction of laser polarization, for even-$n$ PADs, as shown in plot (a) and plot (c), there is a maximum in the direction perpendicular to the laser polarization. By comparing an $n$-photon PAD with its neighboring $(n+1)$-photon PAD, figure 3 shows that the jet number increases by one and three.
From the above calculation, we see that one more jet may not indicate one-more-photon absorption. The three-more-jet case shows that the number of jets does not indicate the angular momentum change: the jet-like structures are irrelevant to photoelectron angular momentum.

4. Conclusion
In conclusion, using a nonperturbative scattering theory, PADs from above-threshold photodetachment of negative ion H\(^-\) in linearly polarized laser fields are investigated. Similar to that of atoms, PADs of negative ions show main lobes and jet-like structures. For a set of above-threshold-detachment peaks, with one-more-photon absorption, the number of the jet-like structures is not always increased by one, which verifies that the jet-like structures are irrelevant to photoelectron angular momentum. For odd-\(n\) PADs, a maximum locates at the direction of laser polarization, and a zero is at the direction perpendicular to the laser polarization. We also find that for even-\(n\) PADs, a peak exists in the direction perpendicular to the laser polarization, which is in consistent with the investigation of Reiss [8].

In our previous study [7], based on the nonperturbative quantum scattering theory of photoionization, we have predicted that for PADs of above-threshold ionization of atoms in intense linearly polarized laser fields, the jet number may increase by one, three, or other odd numbers when one-more-photon is absorbed, which is confirmed by the nonperturbative scattering theory proposed by Reiss [8]. Good agreement is obtained by these two quite different treatments. And we find our prediction exists in above-threshold detachment of intense laser fields with negative ions, which provides a strong support to our prediction.

Acknowledgments
The authors acknowledge the National Natural Science Foundation of China for support under grants 60908006, 10804067, and 60407007.

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