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Photoelectron Angular Distributions of Positronium in Intense Laser Field *

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When positronium is generated in super intense laser fields irradiated by an intense laser field, it breaks up into an electron and a positron. The momentum of the electron as well as that of the positron depends on the relative direction with respect to the laser propagation. Thus, the photoelectron angular distributions show inversion asymmetry. The inversion asymmetry becomes notable for higher kinetic energy of electrons.

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Positron's theoretical prediction by Dirac[1] and experimental observation by Anderson[2] were one of the most surprising physical discoveries of last century. Positronium consists of an electron and a positron bound together in a configuration resembling a hydrogen atom. It is the lightest known atom physicists have been interested in for a long time. A great deal of attention has been paid to its basic properties, including decay lift time, decay modes, spectroscopy, etc. Although the positronium's decay has been observed experimentally in different gases by Deutsch[3] fifty years ago, the creation of positronium in vacuum is still a challenge in experiment. The electron-positron pairs creation in collision of laser photons have been observed by Burke *et al.*,[4] where the photons were backscattered to GeV energies by a 46.6 GeV electron beam. It is the first laboratory evidence for inelastic light-by-light scattering only involving real photons. However, the pairs creations only by collision of two laser pulses are still lacking in experiment. It acquires the electric field strength up to the order of the QED critical value[5] $E_c = m^2c^3/e\hbar = 1.32 \times 10^{16}\,\mathrm{V/cm}$, which corresponds to the laser intensity as high as $I_c = 4.6 \times 10^{29}\,\mathrm{W/cm^2}$. Fortunately, Tajima and Mourou[6] suggested a way to increase the intensity up to 10^{26}–$10^{28}\,\mathrm{W/cm^2}$, which makes it possible to create electron-positron pairs in vacuum. As the rapid developments of laser technology to create the positron continue, further studies on positronium are becoming more and more urgent.

When irradiated by the intense laser field, atoms will absorb multiple photons, and then be ionized. The kinetic energy of photoelectrons satisfies ($\hbar = c = 1$)

$$\boldsymbol{P}^2/2m_e = n\omega - E_b - u_p\omega,$$

where $\boldsymbol{P}$ is the momentum of electron, m_e is the electron rest mass, n is the number of absorbed photon for ionization, ω is the laser frequency, E_b is the binding energy, u_p is ponderomotive energy U_p in units of ω, i.e. $u_p = U_p/\omega$. If the kinetic energy of photoelectrons is less than ω, this phenomenon is termed as the multiphoton ionization (MPI). When the laser field is intense enough, the atoms will absorb more photons than the minimum required, and the energy of photoelectrons may be far greater than that of photons, which is called above-threshold ionization (ATI). The kinetic energy of the electron satisfies

$$\boldsymbol{P}^2/2m_e = (n+s)\omega - E_b - u_p\omega,$$

where s is the excessive photon number and denotes the ATI order. Photoelectron angular distributions (PADs) is one important topic in ATI and MPI. It has been extensively investigated by experimental and theoretical physicists. The PADs were directly measured in experiments, which forms the base to other significant data, such as the photoelectron spectrum and the ionization rate. Meanwhile, the study on PADs is crucial in understanding the relevant physical processes. Due to the development of experimental techniques, various phenomena in PADs have been observed in the last twenty years, such as the broadening effect,[7,8] "ring structure" in high-energy ATI peaks,[9] and jet-like structure in low-energy ATI peaks.[10,11] Companying the experimental developments, theoretical studies are also developed quickly, among which the most famous one is the Keldysh–Faisal–Reiss theory.[12–14] Based on this theory, many extended treatments were proposed recently.[15–17]

Photoionization of positronium shows many new features. When the positronium interacts with intense laser pulses, it will absorb multiple photons to overcome the binding energy E_b, then the electron and the positron are detached from each other and immersed in the laser field independently, each with ponderomotive energy U_p. Thus the number of absorbed photons

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must satisfy

$$n_{ps} > (E_b + 2U_p)/\omega. \tag{1}$$

While for the atoms, the ponderomotive energy due to the quiver motion of the heavy parent ion is of a negligible size. Thus the number of absorbed photons should satisfy

$$n_{at} > (E_b + U_p)/\omega. \tag{2}$$

This difference enhances the ionization threshold for the positronium. For example, for atoms with binding energy 6.8 eV irradiated by laser intensity $I = 7.6 \times 10^{13}\,\mathrm{W/cm^2}$ and the wavelength $\lambda = 780\,\mathrm{nm}$, seven photons are enough to ionize the bound electron of hydrogen, while at least ten photons are needed to ionize the positronium. The PADs for positroniums are also different from that for atoms. For atoms, the PADs exhibit strict four-fold symmetry in linearly polarized laser fields,[18] i.e. the PADs are symmetric with respect to the two axes with one axis along the laser polarization direction and the other perpendicular to the polarization direction. However, the PADs for positroniums are not the same as those of atoms. For positroniums, as the mass of positron equals to that of electron, the two particles will share the absorbed energy. When they break up, the energy they obtained depends on their motion direction. Thus the momentum of the electron depends on the ejection direction, which brings many new characters on the PADs.

Our study on PADs is based on a nonperturbative scattering theory of ATI developed by Guo, Åberg and Crasemann (GAC).[19,20] In the GAC theory, the Volkov state acts as an intermediate state, while an electron-photon plane wave acts as the final state. Both energy and momentum keep conservation in each step of the ionization process. This theory has had a notable success in an explanation of the strong-field phenomena, such as the angular distribution splitting observed by Bucksbaum *et al.*,[21,22] and the recent observation of the jet-like structure in PADs by Nandor *et al.*[10,18]

When the positroniums are irradiated by an intense laser field, they will absorb multiple photons to overcome the binding force, then be detached to an electron and a positron. The two particles move in the laser filed, both oscillating with the ponderomotive energy and ponderomotive momentum.[23] According to energy-momentum conservation, we have

$$\boldsymbol{P}_+ + \boldsymbol{P}_- = j\boldsymbol{k}, \tag{3}$$

$$(|\boldsymbol{P}_+|^2 + |\boldsymbol{P}_-|^2) = 2m_e\omega(j - \varepsilon_b - 2u_p), \tag{4}$$

where $\boldsymbol{P}_+$ and $\boldsymbol{P}_-$ are the momentum of the electron and the positron, respectively, j is the number of absorbed photons during ionization, $\varepsilon_b = E_b/\omega$ is the binding energy E_b in the unit of ω. By means of the energy-momentum conservations, we find the relation

$$P(\theta) = \frac{1}{2}\left[j\omega\cos\theta + \sqrt{4m_eE' - j^2\omega^2(1+\sin^2\theta)}\right], \tag{5}$$

$$E' = (j - \varepsilon_b - 2u_p)\omega, \tag{6}$$

where E' is the total kinetic energy shared by electron and positron, $P(\theta)$ is the norm of $\boldsymbol{P}_-$, and the scattering angle θ is the angle between the electron momentum $\boldsymbol{P}_-$ and the wave vector $\boldsymbol{k}$, such that $\theta = 0$ means the electron ejected along the laser propagation direction. This relation means that the magnitude of the electron momentum depends on the electron emission direction. Especially,

$$P(\theta)_{\max} = P(\theta)|_{\theta=0} = \frac{1}{2}\left(j\omega + \sqrt{4m_eE' - j^2\omega^2}\right), \tag{7}$$

$$P(\theta)_{\min} = P(\theta)|_{\theta=\pi} = \frac{1}{2}\left(-j\omega + \sqrt{4m_eE' - j^2\omega^2}\right), \tag{8}$$

i.e., when the electron moves along the laser propagation after ionization, it has the maximal momentum, while as the electron moves against the laser propagation, it has the minimal momentum.

An important difference between the atoms and the positroniums is that in the positronium the two particles have the same mass while in the atom the mass of the electron could be neglected comparing with that of the nuclear ion. When the intense laser field irradiates the atoms, the nucleus can be treated as rest. By means of the energy conservation, we find the magnitude of the photoelectrons' momentum satisfies

$$P = \sqrt{2m_e(j - \varepsilon_b - u_p)\omega},$$

which does not depend on the emission direction. This difference directly affects the PADs in many aspects as we will show.

The differential ionization rate formula for photoelectrons with given energy from positronium is given by[22]

$$\begin{aligned}\frac{d^2W}{d^2\Omega_{P_f}} = {} & \frac{2^{1/2}e^2\omega^{9/2}}{m_e^{1/2}(2\pi)^4}(j - \epsilon_b - 2u_p)^{1/2}(j - u_p)^2 \\ & \times \sum \int_q |\Phi_i(|\boldsymbol{P}_f(\theta)|)|^2(u_p - j + q)| \\ & \cdot \mathcal{X}_q(\boldsymbol{P}_f(\theta), \boldsymbol{k}')|^2 d^2\Omega_{k'},\end{aligned} \tag{9}$$

where $\Phi_i(|\boldsymbol{P}_f(\theta)|)$ is the Fourier transform of the initial wave function, $d^2\Omega = \sin\theta d\theta d\varphi$ is the differential solid angle and φ is the azimuthal angle of $\boldsymbol{P}_f$. The quantity $\mathcal{X}_q(\boldsymbol{P}_f(\theta), \boldsymbol{k}')$ is defined as

$$\begin{aligned}\mathcal{X}_q(\boldsymbol{P}_f(\theta), \boldsymbol{k}') \equiv {} & \frac{1}{\omega}\mathcal{X}_{-j}(Z,\eta)\sum_{j'}\frac{1}{u_p - j'}\mathcal{X}_{-j'}(Z_f,\eta) \\ & \times \big[-(\boldsymbol{P}_f(\theta) + (j - q - u_p)\boldsymbol{k}) \\ & \cdot \boldsymbol{\epsilon}'^* X_{q-j+j'}(Z_{k'}) \\ & + e\Lambda\boldsymbol{\epsilon}^* \cdot \boldsymbol{\epsilon}'^* X_{q-j+j'+1}(Z_{k'}) \\ & + e\Lambda\boldsymbol{\epsilon} \cdot \boldsymbol{\epsilon}'^* X_{q-j+j'-1}(Z_{k'})\big].\end{aligned} \tag{10}$$

In the above equation, the generalized phased Bessel (GPB) function $\mathcal{X}_j(Z,\eta)$ is defined as

$$\mathcal{X}_j(Z,\eta) = \sum_s X_{j-2s}(Z)X_s(\eta), \tag{11}$$

where the phased Bessel function $X_n(z)$ of a complex variable z.[24] The arguments in Eq. (10) are defined as

$$Z_f = 2\frac{|e|\Lambda}{m_e\omega}\boldsymbol{P}_f(\theta)\cdot\boldsymbol{\epsilon}, \quad Z_{k'} = 2\frac{|e|\Lambda}{m_e\omega}\boldsymbol{k}'\cdot\boldsymbol{\epsilon},$$
$$Z = Z_f + Z_{k'}, \qquad \eta = \frac{1}{2}u_p,$$

where 2Λ is the amplitude of the classical field. In Eq. (9) the quantity u_p is replaced by $2u_p$ by considering the addiational quiver motion of the positron. The positronium is irradiated in the linearly polarized laser light, with the laser wavelength $\lambda = 780\,\text{nm}$, the binding energy of the positronium $E_b = 6.8\,\text{eV}$. We calculate the PADs of positronium on a plane configurated by the polarization vector ϵ and the wave vector $\boldsymbol{k}$, i.e. $\varphi = 0$. Integrating the solid angle of the spontaneously emitted mode $d^2\Omega_{k'}$ with different scattering angles of θ, we obtain the PADs of positronium irradiated by linearly laser field.

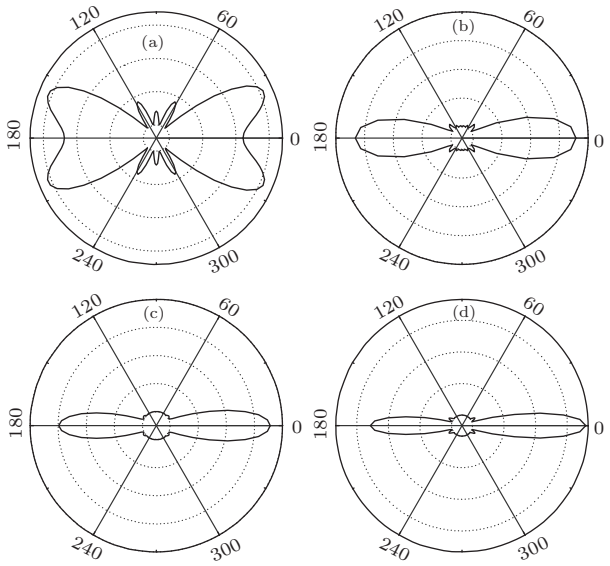

Fig. 1. Polar plots of the PADs at the laser intensities $I = 1.1\times10^{13}\,\text{W/cm}^2$ and for different ATI peaks: (a) $s = 2$, (b) $s = 5$, (c) $s = 7$, (d) $s = 9$. The laser field is linearly polarized and of wavelength 780 nm.

In general, the PADs present two main lobes along the laser propagation, and several jets struck out from the waist of the main lobes. The main lobes may be larger or smaller than jets. Figure 1 depicts the PADs for the 2nd, 5th, 7th and 9th ATI peaks. In our calculations, the laser intensity is chosen as $1.1\times10^{13}\,\text{W/cm}^2$ ($u_p = 0.39$), at least six photons are needed to overcome the binding energy and the ponderomotive shift. In plot of even ATI peaks (see Fig. 1(a)), a central jet exists perpendicular to the polarization direction of the field. In each plot of odd ATI peaks, (see Figs. 1(b)–1(d)), only the main lobes are notable while the jets between the two main lobes are too small to be seen clearly. The main lobes along and against the laser propagation are of different lengths, denoting the unequal ionization rate in these two directions. This is termed as the inversion asymmetry of the PADs. An important feature is that the inversion asymmetry increases as the energy of photoelectrons increases. As shown in Fig. 1, when the ATI order increases, the main lobes along the laser propagation are about 6%, 7%, 20%, and 40% longer than that against the laser propagation. This indicates that the asymmetry becomes more evident with a higher ATI order.

The inversion asymmetry of PADs stems from the dependence of the photoelectron kinetic energy on the emission direction. It has shown that the structure of PADs is mainly determined by the GPB function $\mathcal{X}_{-j}(Z,\eta)$ in Eq. (9), and the others approach a constant and do not contribute to the PADs structure.[20] The argument η of the GPB function $\mathcal{X}_{-j}(Z,\eta)$ is uniquely determined by the laser field, while $Z \approx Z_f \propto P_f(\theta)\cos\theta$ varies with θ. In atomic case, the momentum of electron does not vary with the scattering angle θ, which ensures the arguments Z_f and the absolute value of the GPB function symmetric about the axis $\theta = 0$ and $\theta = \pi/2$, i.e.

$$||\mathcal{X}_{-j}(Z(\theta),\eta)| = |\mathcal{X}_{-j}(Z(\pi-\theta),\eta)|, \tag{12}$$
$$|\mathcal{X}_{-j}(Z(\theta),\eta)| = |\mathcal{X}_{-j}(Z(-\theta),\eta)|. \tag{13}$$

Thus the PADs present four-fold symmetry. However, for the positronium, according to Eq. (5), the momentum of electron $\boldsymbol{P}_f$ depends on the scattering angle θ, and Z_f has the expression as

$$Z_f = \frac{|e|\Lambda}{m_e\omega}\cos\theta\Big[j\omega\cos\theta + \sqrt{4m_eE' - j^2\omega^2(1+\sin^2\theta)}\,\Big]. \tag{14}$$

Thus Eq. (13) is still kept, which brings on the up-down symmetry about the axis $\theta = 0$, while

$$|\mathcal{X}_{-j}(Z(\theta),\eta)| \neq |\mathcal{X}_{-j}(Z(\pi-\theta),\eta)|,$$

which induces the PADs asymmetry between forward and backward directions. The variable Z_f has a maximum as electron ejects along the laser propagation

$$Z_{f\,\max} = Z_f|_{\theta=0} \propto \big\{j\omega + \big[-j^2\omega^2 + 4m_ej\omega - 4m_e(\varepsilon_b + 2u_p)\omega\big]^{1/2}\big\}, \tag{15}$$

and a minimum as electron ejects against the laser propagation

$$Z_{f\,\min} = Z_f|_{\theta=\pi} \propto \big\{-j\omega + \big[-j^2\omega^2 + 4m_ej\omega - 4m_e(\varepsilon_b + 2u_p)\omega\big]^{1/2}\big\}, \tag{16}$$

which induces the asymmetry of PADs. For higher order ATI peaks, the value of the square-root term increases with the value of j, which leads to Z_f varying

in a larger range, thus the asymmetry of PADs become notable, as shown in Fig. 1. Moreover, when the variable $Z = Z_f|_{\theta=0}$ (or $Z = Z_f|_{\theta=\pi}$) is just around the node of $|\mathcal{X}_{-j}(Z,\eta)|$, where $|\mathcal{X}_{-j}(Z,\eta)|$ changes rapidly, i.e. $|\mathcal{X}_{-j}(Z|_{\theta=0},\eta)| \gg |\mathcal{X}_{-j}(Z|_{\theta=\pi},\eta)|$ or $|\mathcal{X}_{-j}(Z|_{\theta=0},\eta)| \ll |\mathcal{X}_{-j}(Z|_{\theta=\pi},\eta)|$, the asymmetry will be clearly presented.

Based on the above discussion, we begin to search the special PADs through the absolute value of the GPB function. We vary the laser intensity and observe the absolute value of the GPB function $|\mathcal{X}_{-j}(Z,\eta)|$. We find that when the laser intensity is around $8 \times 10^{13}\,\mathrm{W/cm^2}$, along the forward direction, the value of $|\mathcal{X}_{-j}(Z|_{\theta=0},\eta)|$ has overcome a node of the GPB function and stuck up, while along the backward direction, the value of $|\mathcal{X}_{-j}(Z|_{\theta=0},\eta)|$ still drops to the node of the GPB function and has a negligible value. Thus we obtain the relation $|\mathcal{X}_{-j}(Z|_{\theta=0},\eta)| \gg |\mathcal{X}_{-j}(Z|_{\theta=\pi},\eta)|$, as shown in Fig. 2.

Corresponding to the absolute value of the GPB function $\mathcal{X}_{-j}(Z,\eta)$ shown in Fig. 2, a new type of PADs is presented in Fig. 3.

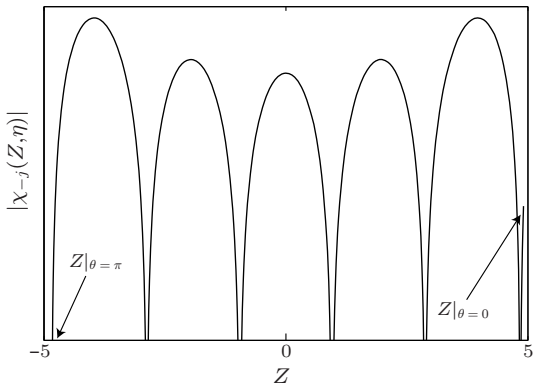

Fig. 2. Variation of the absolute value of the GPB function $|\mathcal{X}_{-j}(Z,\eta)|$ with Z for $j = 12$. The laser intensity is $7.84 \times 10^{13}\,\mathrm{W/cm^2}$, and is of wavelength 780 nm.

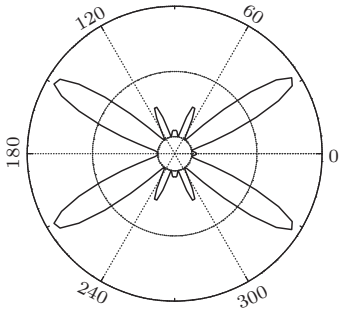

Fig. 3. Ploar plot of the PADs of the second ATI peak for laser intensity $7.84 \times 10^{13}\,\mathrm{W/cm^2}$. One important feature of the PAD is that it has only one lobe along the laser propagation.

The electron needs to absorb ten photons at least for ionization, and the exceed photon number is two. In the plot, five jets exist on the each side. The most vagarious phenomenon is that along the polarization direction the main lobe exists, while against the polarization direction the main lobe completely splits. It could be regarded as an extreme asymmetry. The characters of PADs in Fig. 3 agree with those of the variable $|\mathcal{X}_{-j}(Z,\eta)|$ in Fig. 2. In Fig. 2, there is a peak on $\theta = 0$, which is smaller than the other peaks, and no peak exists on $\theta = \pi$. Corresponding to Fig. 3, on the direction of $\theta = 0$, a main lobe exists, which is smaller than the jets, and no main lobe on the direction of $\theta = \pi$.

In summary, we have investigated the PADs of positronium irradiated by an intense laser field. The positronium can be generated in super intense laser fields. When irradiated by a weak laser beam, the positronium breaks up into an electron and a positron. The momentum of the electron as well as that of the positron depends on the relative direction with respect to the laser propagation. Thus, the ionization rate along the laser propagation is not equal to that against the laser propagation, i.e. the PADs are inversion asymmetric. The inversion asymmetry becomes notable for higher kinetic energy of electrons. The distinct asymmetry PADs structure will present when the laser intensity makes the $|\mathcal{X}_{-j}(Z,\eta)|$ approach to zero. Higher order ATI peaks are helpful when enhancing the inversion asymmetry of PADs.

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