Angular correlation theory for double photoionization in a rare-gas atom: Ionization by polarized photons

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This is a sequel to an earlier article on the theory of angular correlation for double photoionization. Here we consider the two-step double photoionization of a rare-gas atom under the influence of a polarized photon beam described by appropriate Stokes parameters. Cylindrical mirror analyzers are used to detect the outgoing electrons. Theoretical values of the correlation function are obtained for linearly polarized light. Two different situations are handled. In the first, the value of the correlation function is obtained keeping the photoelectron in a fixed direction. In the other case, the direction of the Auger electron is kept fixed. Comparison with experiments on xenon shows excellent agreement for the case of $4d_{5/2}$ photoionization followed by a subsequent N_5-$O_{23}O_{23}{}^1S_0$ Auger decay for a linearly polarized incident photon of energy 94.5 eV [J. Phys. B, **26**, 1141 (1993)].

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I. INTRODUCTION

In an earlier paper [1], we considered the double photoionization (DPI) of a rare-gas atom under the influence of an unpolarized photon. The atom was taken to be in a randomly oriented $^1S_0$ state. We considered the angular correlation between the two successively emitted electrons, their emissions being adequately separated in time [2]. Using a statistical theory, we obtained good agreement with the experimental results of Kämmerling and Schmidt [3].

In the present paper, we take the incident photon beam to be polarized. The rare-gas atoms receiving the photon beam no longer remain randomly oriented, but become aligned. If a photon of adequate energy is absorbed by an atom, a photoelectron is emitted from one of its inner shells, leaving the atom singly ionized. This ion subsequently deexcites by emitting an Auger electron [4] from one of its outer shells. We are left with a doubly ionized atom and two electrons in the continuum. The double photoionization process described above therefore amounts to

$$h\nu + \mathrm{A} \rightarrow \mathrm{A}^+ + e_1^- \rightarrow \mathrm{A}^{2+} + e_1^- + e_2^- . \tag{1}$$

As in Ref. [1], we denote the initial state (photon+atom) by the set of quantum numbers $(J_a M_a \alpha_a)$, or by virtual quantum numbers $(J_a' M_a' \alpha_a')$, keeping in mind possible interaction with other atoms and electrons. (J_a, M_a) or $(J_a' M_a')$ are angular momentum quantum numbers, and α_a, α_a' stand for the set of remaining quantum numbers (similarly for the intermediate and final states). The polarization properties of the photon beam are described by appropriate Stokes parameters S_1, S_2, and S_3 [5].

II. DPI BY POLARIZED PHOTONS

We proceed by calculating the density matrix [6] and the angular correlation function, which is the expectation value of the efficiency operator for the detection of electrons. The density matrix of the initial state equals the product of the density matrix of the intermediate singly ionized atom and the density matrix of the photoelectron. Similarly, the density matrix of the singly ionized atom can be written as the product of the density matrices of the doubly ionized atom and the Auger electron.

Using the Wigner-Eckart theorem, the matrix element of the density operator for the initial atomic state can be expressed as [1]

$$\langle J_a M_a \alpha_a | \rho | J_a' M_a' \alpha_a' \rangle = \sum_{k_a \kappa_a} (-1)^{J_a' - M_a'} C^{J_a J_a' k_a}_{M_a M_a' \kappa_a} \rho_{k_a \kappa_a}(J_a \alpha_a, J_a' \alpha_a'). \tag{2}$$

Here the statistical tensor $\rho_{k_a \kappa_a}$ is an irreducible tensor of rank k_a, which transforms according to the $(2k_a+1)$-dimensional irreducible representation D^{k_a} of the rotation group. In Eq. (2), $C^{J_a J_a' k_a}_{M_a M_a \kappa_a}$ is a Clebsch-Gordan coefficient satisfying the triangle rule $\mathbf{k}_a = \mathbf{J}_a + \mathbf{J}_a'$ and κ_a is the projection of k_a. Using the unitarity property of Clebsch-Gordan coefficients, we get

$$\rho_{k_a \kappa_a}(J_a \alpha_a, J_a' \alpha_a') = \sum_{M_a M_a'} (-1)^{M_a - M_a'} C^{J_a J_a' k_a}_{M_a M_a \kappa_a} \langle J_a M_a \alpha_a | \rho | J_a' M_a' \alpha_a' \rangle. \tag{3}$$

We assume that the initial state is formed after the randomly oriented rare-gas atom absorbs a photon. Then the density matrix of the initial state becomes

$$\rho_{k_a \kappa_a}(J_a \alpha_a, J_a' \alpha_a') = 3(2J_0+1) \sum_{k_0 \kappa_0 k_\gamma \kappa_\gamma} \sqrt{2k_0+1}\sqrt{2k_\gamma+1} C^{k_0 k_\gamma k_a}_{\kappa_0 \kappa_\gamma \kappa_a} \times \begin{Bmatrix} J_0 & J_0' & k_0 \\ 1 & 1 & k_\gamma \\ J_a & J_a & k_a \end{Bmatrix} \rho_{k_0 \kappa_0}(J_0, J_0) \rho^\gamma_{k_\gamma \kappa_\gamma}(1,1). \tag{4}$$

This equation satisfies the triangle rule $\mathbf{k}_0=\mathbf{J}_0+\mathbf{J}_0'$, where J_0 and J_0' are the angular momentum quantum numbers of the randomly oriented atom before absorption of the photon and its virtual counterpart, respectively. Here $\rho_{k_0\kappa_0}(J_0,J_0)$ represents the density matrix of the randomly oriented atom and can be expressed as

$$\rho_{k_0\kappa_0}(J_0,J_0)=\frac{1}{\sqrt{2J_0+1}}\delta_{k_00}\delta_{\kappa_00}\langle J_b\|j_1\|J_a\rangle\langle J_b\|j_1'\|J_a\rangle^\star \times\langle J_c\|j_2\|J_b\rangle\langle J_c\|j_2'\|J_b\rangle^\star. \quad (5)$$

Here the symbol $\langle\|\,\|\rangle$ stands for a reduced matrix element.

In Eq. (4), the expression $\rho^\gamma_{k_\gamma\kappa_\gamma}(1,1)$ represents the density matrix of the photon with its polarization properties. Its elements are

$$\rho^\gamma_{00}=\frac{1}{\sqrt{3}},\quad \rho^\gamma_{10}=\frac{S_3}{\sqrt{2}},\quad \rho^\gamma_{20}=\frac{1}{\sqrt{6}}$$

$$\rho^\gamma_{1\pm1}=0,\quad \rho^\gamma_{2\pm1}=0,\quad \rho^\gamma_{2\pm2}=-\frac{1}{2}(S_1\mp iS_2). \quad (6)$$

S_1, S_2, and S_3 are the Stokes parameters [5] describing the polarization of the photon.

Then Eq. (4) yields

$$\rho_{k_a\kappa_a}(J_aJ_a')=3(-1)^{J_a+k_a+1}\begin{Bmatrix}J_a & 1 & 0\\ 1 & J_a & k_a\end{Bmatrix}\rho^\gamma_{k_a\kappa_a}(1,1)\langle J_b\|j_1\|J_a\rangle\langle J_b\|j_1'\|J_a\rangle^\star\langle J_c\|j_2\|J_b\rangle\langle J_c\|j_2'\|J_b\rangle^\star$$

$$=\frac{3(-1)^{J_a}}{\sqrt{2J_a+1}\sqrt{2J_a'+1}}\rho^\gamma_{k_a\kappa_a}(1,1)\langle J_b\|j_1\|J_a\rangle\langle J_b\|j_1'\|J_a\rangle^\star\langle J_c\|j_2\|J_b\rangle\langle J_c\|j_2'\|J_b\rangle^\star. \quad (7)$$

We define the angular correlation function as the expectation value of the efficiency operator [1]. Following the same notation as in Ref. [1], we can write it as

$$\bar{\varepsilon}=\sum_{J_aJ_a'\alpha_a\alpha_a'k_a\kappa_a}\rho_{k_a\kappa_a}(J_a\alpha_a,J_a'\alpha_a')\varepsilon^\star_{k_a\kappa_a}(J_a\alpha_a,J_a'\alpha_a'). \quad (8)$$

Some simplification gives

$$\bar{\varepsilon}=\sum\rho_{k_a\kappa_a}(J_a,J_a')\varepsilon^\star_{k_c\kappa_c}(J_c,J_c')\varepsilon^\star_{k_1\kappa_1}(J_1,J_1')\varepsilon^\star_{k_2\kappa_2}(J_2,J_2')C^{k_bk_1k_a}_{\kappa_b\kappa_1\kappa_a}C^{k_ck_2k_b}_{\kappa_c\kappa_2\kappa_b}\sqrt{2J_a+1}\sqrt{2J_a'+1}\sqrt{2k_b+1}\sqrt{2k_1+1}$$
$$\times\sqrt{2J_b+1}\sqrt{2J_b'+1}\sqrt{2k_c+1}\sqrt{2k_2+1}\times\begin{Bmatrix}J_c & j_2 & J_b\\ J_c' & j_2' & J_b'\\ k_c & k_2 & k_b\end{Bmatrix}\begin{Bmatrix}J_b & j_1 & J_a\\ J_b' & j_1' & J_a'\\ k_b & k_1 & k_a\end{Bmatrix}, \quad (9)$$

where the summation extends over $J_a,J_a',J_b,J_b',J_c,J_c',j_1,j_1',j_2,j_2',k_a,\kappa_a,k_c,\kappa_c,k_1,\kappa_1,k_2$, and κ_2.

In Eq. (9), $\varepsilon^\star_{k_i\kappa_i}(j_i,j_i')$ is the efficiency tensor component for detection of the ith electron. Here $i=1$ corresponds to the photoelectron and $i=2$ to the Auger electron. In DPI experiments, the detectors usually used are cylindrical mirror analyzers (CMA) [7] which have cylindrical symmetry with respect to the axis of the detector. Details of the choice of detectors are given in Ref. [8]. The efficiency tensor component now becomes

$$\varepsilon^\star_{k_i\kappa_i}(j_ij_i')=\sum_{\kappa_i'}z_{k_i}(i)c_{k_i\kappa_i'}(j_ij_i')D^{k_i}_{\kappa_i'\kappa_i}(\Re_i). \quad (10)$$

Since the residual doubly ionized state is unobserved, the corresponding quantum numbers are averaged over. This gives

$$\varepsilon^\star_{k_c\kappa_c}(J_cJ_c')=\sqrt{2J_c+1}\delta_{k_c0}\delta_{\kappa_c0}\delta_{J_cJ_c'}. \quad (11)$$

Then Eq. (9) becomes

$$\overline{\varepsilon}=\sum \rho_{k_a\kappa_a}(J_a,J_a')\sqrt{2J_c+1}C^{k_bk_1k_a}_{\kappa_b\kappa_1\kappa_a}C^{0k_2k_b}_{0\kappa_2\kappa_b}\sqrt{2J_a+1}\sqrt{2J_a'+1}\sqrt{2k_b+1}\sqrt{2k_1+1}\sqrt{2J_b+1}\sqrt{2J_b'+1}\sqrt{2k_c+1}\sqrt{2k_2+1}$$
$$\times\begin{Bmatrix} J_c & j_2 & J_b \\ J_c' & j_2' & J_b' \\ 0 & k_2 & k_b \end{Bmatrix}\begin{Bmatrix} J_b & j_1 & J_a \\ J_b' & j_1' & J_a' \\ k_b & k_1 & k_a \end{Bmatrix} z_{k_1}(1)c_{k_1\kappa_1'}(j_1j_1')z_{k_2}(2)c_{k_2\kappa_2'}(j_2j_2')D^{k_1}_{\kappa_1'\kappa_1}(\mathfrak{R}_1)D^{k_2}_{\kappa_2'\kappa_2}(\mathfrak{R}_2). \tag{12}$$

Here we have used the relation

$$D^{k_1}_{\kappa_1'\kappa_1}(\mathfrak{R}_1)D^{k_2}_{\kappa_2'\kappa_2}(\mathfrak{R}_2)=\sum_k C^{k_1k_2k}_{\kappa_1\kappa_2\kappa}C^{k_1k_2k}_{\kappa_1'\kappa_2'\kappa'}D^{k}_{\kappa\kappa'}(\mathfrak{R}) \tag{13}$$

to get the actual angular dependence of the angular correlation function. In Eq. (13), the Euler rotation $\mathfrak{R}=(\beta_1\theta\beta_2)$ [8]. This geometrical dependence of the tensor matrix element is separated out from the dynamics by using the Wigner-Eckart theorem. As a result, the dynamics of the DPI process resides in the reduced matrix elements and the geometric dependence is contained in the angular part.

We define

$$\zeta=\sqrt{2J_c+1}\sqrt{2k_1+1}\sqrt{2J_b+1}\sqrt{2J_b'+1}\sqrt{2k_2+1} \tag{14}$$

and

$$\xi=\langle J_b\|j_1\|J_a\rangle\langle J_b\|j_1'\|J_a\rangle^\star\langle J_c\|j_2\|J_b\rangle\langle J_c\|j_2'\|J_b\rangle^\star. \tag{15}$$

Then the expectation value of the efficiency operator in Eq. (12) becomes

$$\overline{\varepsilon}\sim\sum (-1)^{J_a}\zeta\xi\begin{Bmatrix} J_c & j_2 & J_b \\ J_c' & j_2' & J_b' \\ 0 & k_2 & k_2 \end{Bmatrix}\begin{Bmatrix} J_b' & j_1' & J_a' \\ J_b & j_1 & J_a \\ k_2 & k_1 & k \end{Bmatrix}$$
$$\times C^{k_2k_1k}_{\kappa_2\kappa_1\kappa}z_{k_1}(1)z_{k_2}(2)\rho^{\gamma}_{k\kappa}(1,1)c_{k_1\kappa_1'}(j_1j_1')$$
$$\times c_{k_2\kappa_2'}(j_2j_2')C^{k_1k_2k}_{\kappa_1\kappa_2\kappa}C^{k_1k_2k}_{\kappa_1'\kappa_2'\kappa'}D^{k}_{\kappa\kappa'}(\mathfrak{R}). \tag{16}$$

A. Attenuation corresponding to the polarization sensitivity of a detector

The electron detector may or may not be sensitive to the spin state of the incoming electron. The attenuation of the signal due to the detector will depend on this sensitivity. The factor $c_{k_i\kappa_i}(j_ij_i')$, $(i=1,2)$ describes this property [8]. We shall now consider two different cases.

1. Case I: Detectors insensitive to electron polarization

If the detectors (CMAs) are insensitive to the spin polarization of electrons, then the projection κ_i of the k_ith component of the angular momentum is effectively zero, i.e., the electrons are emitted symmetrically with respect to the axis of the detector. Hence the attenuation factor can be written as

$$c_{k_i0}(j_ij_i')=\frac{\sqrt{2j_i+1}\sqrt{2j_i'+1}}{4\pi}(-1)^{j_i-(1/2)+k_i}C^{j_ij_i'k_i}_{(1/2)-(1/2)0}. \tag{17}$$

2. Case II: Detectors sensitive to electron polarization

In Ref. [1], we defined $c_{k_i\kappa_i}(j_ij_i')$ as the attenuation factor due to the change in the state of polarization of an electron caused by the detector. When the detectors are insensitive to electron polarization, one takes the average over the electron spin and its projection. Now consider the case in which the detectors are sensitive to electron polarization. In this case, the spin sensitivity of the detectors is described by a tensor of the form $c_{k_{s_i}\kappa_{s_i}}(s_is_i)$. The attenuation factor then turns out to be

$$c_{k_i\kappa_i}(j_ij_i')=c_{k_{l_i}0}(l_il_i')c_{k_{s_i}\kappa_{s_i}}(s_is_i)\sqrt{2k_{l_i}+1}\sqrt{2k_{s_i}+1}$$
$$\times\sqrt{2j_i+1}\sqrt{2j_i'+1}\begin{Bmatrix} l_i & l_i' & k_{l_i} \\ s_i & s_i & k_{s_i} \\ j_i & j_i' & k_i \end{Bmatrix}C^{k_{l_i}k_{s_i}k_i}_{0\kappa_i\kappa_i}, \tag{18}$$

where

$$c_{k_{l_i}0}(l_il_i')=\frac{\sqrt{2l_i+1}\sqrt{2l_i'+1}}{4\pi}(-1)^{l_i'}C^{l_il_i'k_{l_i}}_{000}, \tag{19}$$

and $c_{k_{s_i}\kappa_{s_i}}(s_is_i)$ can be expressed in terms of the Stokes parameters describing the spin polarization of the electron to be detected [3]. The factor $c_{k_{s_i}\kappa_{s_i}}(s_is_i)$ picks out electrons with a particular spin projection and may be called a *Stern-Gerlach operator*. Its components are

$$c_{00}=\frac{1}{\sqrt{2}},\quad c_{10}=\frac{S_z^e}{\sqrt{2}},$$
$$c_{11}=-(S_x^e-iS_y^e),\quad c_{1-1}=-(S_x^e+iS_y^e). \tag{20}$$

Here S_x^e, S_y^e, and S_z^e are Stokes parameters describing the polarization of the electron. For polarization-insensitive detectors, one has $S_x^e=S_y^e=S_z^e=0$, and the attenuation factor reduces to Eq. (17).

The lifetime of the singly ionized state is very small. Depending on the photon energy, there may be a situation in

which it is impossible to differentiate between the photoelectrons and Auger electrons simply by energy analysis. Then, to distinguish between the two electrons it is necessary to measure the electron spin, i.e., their polarization. For spin analysis of the electrons, we have to use a Stern-Gerlach-type experimental setup. Here the factor $c_{k_{s_i}\kappa_{s_i}}(s_i s_i)$ serves exactly that purpose, i.e., it picks out electrons with a particular spin projection. This type of experiment is known as an "energy- and angle-resolved coincidence experiment" and is being done by Schmidt and his co-workers [9].

In general, for DPI of atoms using a polarized photon of sufficient energy, one can distinguish the photoelectrons and the Auger electrons by differential energy analysis. In that case, determination of electron spin is meaningless. Then, if the spin is unobserved, one can take the average over the spin projection. In that case, the projection κ_i of the k_ith component of the angular momentum is zero and the attenuation factor $c_{k_i\kappa_i}(j_i j_i')$ turns out to be $c_{k_i 0}(j_i j_i')$.

III. CALCULATION AND RESULTS

In Ref. [1], we treated DPI in the xenon atom due to unpolarized light. In this paper, we are concerned with the same xenon atom, with the difference being that DPI occurs due to a polarized light source. A randomly oriented xenon atom is irradiated with a polarized photon beam of energy 94.5 eV. As a result, the xenon atom no longer remains randomly oriented but acquires the polarization of the photon beam. This leads to photoionization in the $4d_{5/2}$ shell followed by a subsequent N_5-$O_{23}O_{23}{}^1S_0$ Auger decay. We use the dipole approximation, the letters e, f, and g, for the three possible photoionization channels [1]. These are characterized by (e) $4d_{5/2}\rightarrow\varepsilon_p f_{7/2}$, (f) $4d_{5/2}\rightarrow\varepsilon_p f_{5/2}$, and (g) $4d_{5/2}\rightarrow\varepsilon_p p_{3/2}$, respectively, and the Auger transition is characterized by the wave $\varepsilon_A d_{5/2}$. The same selection rules hold for photoionization and Auger transitions as in the case of unpolarized light.

In experiments for measuring angular correlation, one usually chooses detectors which are insensitive to the spin polarization of electrons. In such a case, $\kappa_1=\kappa_2=\kappa_1'=\kappa_2'=\kappa=\kappa'=0$ and $D^k_{00}(\beta_1\theta\beta_2)=P_k(\cos\theta)$. Then Eq. (16) becomes

$$\bar{\varepsilon}\sim\sum(-1)^{J_a}\zeta\xi\begin{Bmatrix} J_c & j_2 & J_b \\ J_c' & j_2' & J_b' \\ 0 & k_2 & k_2 \end{Bmatrix}\begin{Bmatrix} J_b & j_1 & J_a \\ J_b' & j_1' & J_a' \\ k_2 & k_1 & k \end{Bmatrix} \times z_{k_1}(1)z_{k_2}(2)\rho^{\gamma}_{k\kappa}(1,1) \times C^{k_2 k_1 k}_{000}c_{k_1 0}(j_1 j_1')c_{k_2 0}(j_2 j_2')P_k(\cos\theta). \quad (21)$$

The summation extends over k_1, k_2, and k.

In the limiting case of unpolarized photons, Eq. (21) reduces to a simple form. Using Eq. (17) and some properties of $9-j$ symbols and Racah coefficients [10], we get

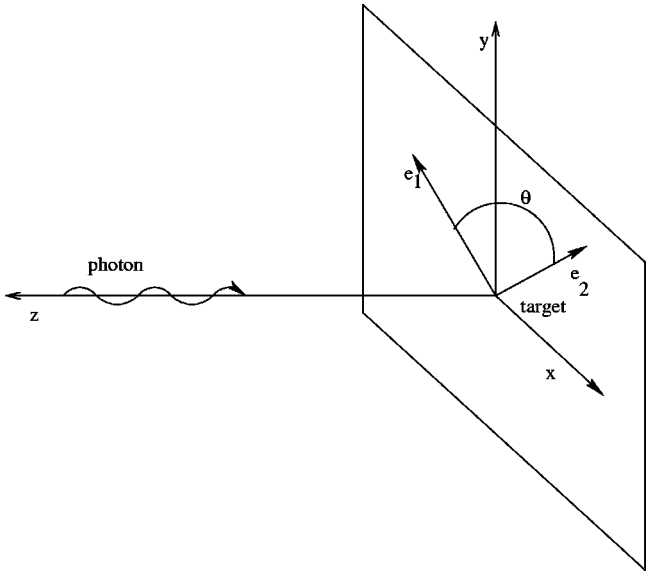

FIG. 1. Perpendicular plane geometry used in the experiments by Schmidt and his co-workers.

$$\bar{\varepsilon}=\sum_k z_k(1)z_k(2)(-1)^{j_1+j_2}c_{k0}(j_1 j_1')c^{\star}_{k0}(j_2 j_2') \times\langle J_c\|j_1\|J_b\rangle\langle J_c\|j_1'\|J_b\rangle^{\star}\langle J_b\|j_2\|J_a\rangle\langle J_b\|j_2'\|J_a\rangle^{\star} \times w(J_b J_b' j_1 j_1';kJ_a)w(J_b J_b' j_2 j_2';kJ_c)P_k(\cos\theta). \quad (22)$$

Note that this is identical to Eq. (25) of Ref. [1], as it should be.

Experiments on the xenon atom were carried out by Schmidt and his co-workers using 94.5 eV synchrotron radiation [3]. They used a perpendicular plane geometry to describe the process. The collision frame x,y,z is attached to the target where the z axis coincides with the direction of the photon beam. The arbitrary polarization of the incident beam from the synchrotron is described by the Stokes parameters S_1, S_2, and S_3. Both S_1 and S_2 refer to the same quantity,

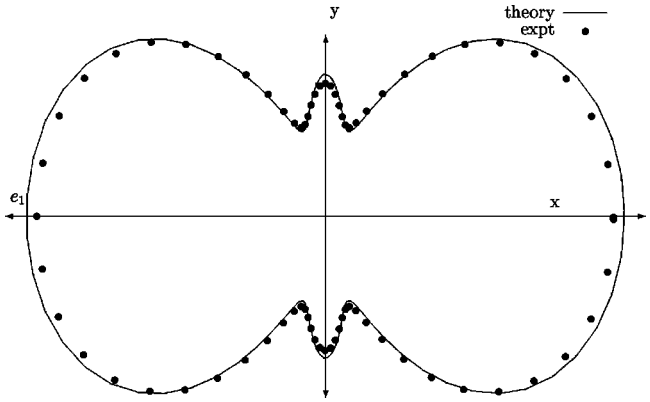

FIG. 2. Angular correlation pattern for xenon due to a linearly polarized photon beam ($S_1=1,S_2=0,S_3$ unknown) of 94.5 eV ($4d_{5/2}$ photoionization followed by N_5-$O_{23}O_{23}{}^1S_0$ Auger decay). The photoelectron is observed in a fixed direction [3].

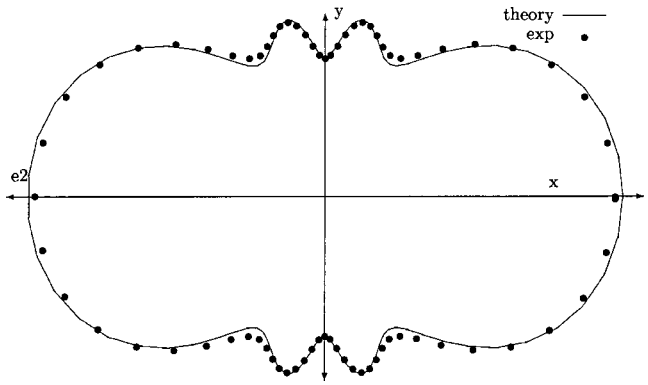

FIG. 3. Angular correlation pattern for xenon due to a linearly polarized photon beam ($S_1=1,S_2=0,S_3$ unknown) of 94.5 eV ($4d_{5/2}$ photoionization followed by N_5-$O_{23}O_{23}{}^1S_0$ Auger decay). The Auger electron is observed in a fixed direction [3].

but with differently oriented axes. One can make $S_2=0$ by choosing the x axis of the collision frame to coincide with the direction of maximum linear polarization, i.e., the major axis of the polarization ellipse. To compare our results with experimental values, we use the same polar and azimuthal angles in the perpendicular plane geometry. Figure 1 shows the perpendicular plane geometry described above, e_1 and e_2 being the directions of emission of the photoelectron and the Auger electron, respectively. θ is the angle between their directions of emission. We have calculated the theoretical value of the angular correlation function for the following two different cases.

(i) The photoelectron is observed in a fixed direction and the Auger electron spectrometer is turned around to get the angular distribution of the Auger electrons with respect to the photoelectron. Here the maximum allowed value of k is $2j_2$.

(ii) The second one is the complementary case, i.e., the Auger electron is observed in a fixed direction and the photoelectron spectrometer is turned around to get the angular distribution of the photoelectrons with respect to the Auger electron. Here the maximum allowed value of k is $2j_{1,\max}$; $j_{1,\max}$ is the maximum value of j_1 for the possible photoionization channels.

The value of k gives the highest order of the Legendre polynomials occurring in the correlation function. Interchannel interaction of the different photoelectron channels contributes to the angular correlation pattern by introducing the different terms, however the total intensity remains unchanged. This interchannel interaction is treated as in Ref. [1].

As in Ref. [1], we have defined the angular correlation function to be the angular part of the expectation value of the efficiency operator. Solid lines represent the theoretically calculated plot and the dots represent the experimental plot [3]. For a linearly polarized incident photon beam, the angular correlation function for our case turns out to be the following.

(i) Case 1: $S_1=1,S_2=0,S_3$ unknown. The photoelectron is observed in a fixed direction and the Auger electron spectrometer is turned around to get the angular distribution of the Auger electron with respect to the photoelectron,

$$W(\theta)\sim 1+1.314P_2(\cos\theta)+1.100P_4(\cos\theta). \quad (23)$$

(ii) Case 2: $S_1=1,S_2=0,S_3$ unknown. The Auger electron is observed in a fixed direction and the photoelectron spectrometer is turned around to get the angular distribution of the photoelectron with respect to the Auger electron,

$$W(\theta)\sim 1+0.817P_2(\cos\theta)+0.602P_4(\cos\theta)+0.570P_6(\cos\theta). \quad (24)$$

In both cases, one of the electron spectrometers is kept fixed along the direction of the electric-field vector (x axis). The index k in the general theoretical expression for $\overline{\varepsilon}$ depends on the angular momenta of the emitted electrons. Hence, the structure of the angular correlation pattern depends on this index. If higher-order angular momenta are involved, the angular correlation pattern has more structure. This is clear from Figs. 2 and 3. Since the distribution of the photoelectron with respect to the fixed Auger electron direction involves higher-order angular momenta, the angular correlation pattern has more structure.

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