Angular distribution measurements of the xenon $N_{4,5}O_{2,3}O_{2,3}$ Auger electrons: Determination of alignment and intrinsic parameters

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In the framework of the two-step model of Auger decay the alignment of the xenon $4d^{-1}$ primary hole states has been derived as a function of photon energy. This quantity was obtained from angular distribution measurements of the $N_{4,5}O_{2,3}O_{2,3}$ Auger lines after ionization of free atoms by monochromatized synchrotron radiation of 80–250 eV photon energy. The data show a minimum of the alignment parameter in the Cooper minimum of the $4d$ photoionization cross section, which proves the vanishing of the outgoing ϵf electron wave. Furthermore, the intrinsic parameters for all lines in this Auger group were determined and are compared with previous experiments and calculations.

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I. INTRODUCTION

The investigation of Auger processes beyond relative yield measurements can give information about the dynamics of the underlying processes. In particular, angular distribution and spin polarization measurements of Auger electrons give valuable insight into the primary photoionization process, which is governed by the dipole interaction, and the successive nonradiative decay process governed by the Coulomb interaction.

The transition from a single-hole to a double-hole state is described by the scalar Coulomb operator. This means that Auger electrons from an isotropic initial state can only have an isotropic angular distribution and no spin polarization. The photoionization process usually leaves the singly charged photoion in a polarized state, i.e., with an uneven population of the magnetic sublevels. Thus, decay of a polarized photoion may lead to an anisotropic angular distribution and also to spin polarization of the Auger electrons [1,2].

The Xe $4d$ photoionization process, which leads to the emission of the $N_{4,5}O_{2,3}O_{2,3}$ Auger electrons, has been very well examined in a broad photon energy range. The cross section [3,4], branching ratio [5,6], and angular distribution parameter [3,7] are well known from threshold (67.5 eV) up to 250–280 eV. This energy range incorporates characteristic features of the cross section: the broad maximum of the shape resonance which peaks at approximately 100 eV (22 Mb) and the Cooper minimum around 185 eV (0.3 Mb). At specific photon energies all the dipole matrix elements have been determined (“complete experiments”) using spin-resolved electron spectroscopy [8] and coincidence techniques [9,10].

In contrast, a thorough investigation of the angular distribution of the Auger decay process, which follows the $4d$ photoionization, has been done only up to 142 eV photon

energy [11–14]. Between 150 and 190 eV four data points with large uncertainties exist [7]. The major difficulty in performing these measurements above 150 eV photon energy is the relatively low $4d$ photoionization cross section (<1 Mb). An additional problem is posed by the $4p$ photolines ($E_{\text{bind}} \approx 146$ eV), which overlap with the $N_{4,5}O_{2,3}O_{2,3}$ Auger group in the 175–188 eV photon energy range.

The aim of this paper is to present quantitative information about the alignment parameter of the Xe $4d^{-1}$ hole states using angular distribution measurements of the Xe $N_{4,5}O_{2,3}O_{2,3}$ Auger electrons in a broad photon energy range including the important region of the Cooper minimum. In addition, these measurements allow the determination of the Auger anisotropy parameters for all the lines of the $N_{4,5}O_{2,3}O_{2,3}$ Auger group.

II. EXPERIMENT

The experiment was carried out at the AMO undulator beamline 10.0.1 of the Advanced Light Source (ALS) storage ring at Lawrence Berkeley National Laboratory. Vacuum ultraviolet radiation from a 4.5-m-long 10-cm-period undulator was monochromatized with a spherical grating monochromator. Gratings with 925 lines/mm and 2100 lines/mm were used for operating at photon energies below and above 160 eV, respectively. High photon energy resolution was not required for the present measurements; photon bandwidths in the range of 40–150 meV were obtained using the 925 lines/mm grating in combination with entrance and exit slit widths of 100 and 100 μm . The 2100 lines/mm grating with entrance/exit slit settings of 100 and 800 μm provided photon bandwidths between 380 and 800 meV at photon energies from 160 to 250 eV.

A. HEA experiment

In a first experiment the electron spectra were measured using an end station designed for gas-phase angle-resolved studies and based on the Scienta SES-200 hemispherical electron analyzer (HEA) [15]. These measurements will be

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referred to as the HEA experiment throughout this paper. The analyzer is rotatable in a plane perpendicular to the propagation direction of the beam of linearly polarized photons (the degree of linear polarization is estimated to be higher than 99%), allowing electron angular distribution studies. We performed measurements at the angles of 0° , 54.7° , and 90° . The analyzer was operated at the constant pass energy of 40 eV with the electron energy resolution of 25–30 meV. The spectra were not corrected for the transmission of the analyzer, which was assumed to be independent of the measurement angle. The target gas was introduced into a differentially pumped gas cell, achieving about 10^{-3} mbar pressure in the interaction region.

B. TOF experiment

In the second experiment, which was solely carried out to measure the alignment parameter A_{20} , we used two time-of-flight (TOF) electron spectrometers [15,16] when the storage ring was operated in double-bunch mode. In the following this experiment is referred to as the TOF measurements. The TOF analyzers were mounted to a rotatable chamber so that we could record two spectra at different angles simultaneously. Hence, with four different chamber positions we took spectra at eight angles (-54.7° , -180° , 20.3° , -105° , 35.3° , -90° , -45.8° , -79.5°) with respect to the light polarization vector. The TOF analyzers were operated with -15.8 V and -18.3 V retarding voltages for the nose (for details see Ref. [15]) and the drift tube, respectively, resulting in an energy resolution of 160–200 meV for the Xe $N_{4,5}O_{2,3}O_{2,3}$ Auger group.

III. THEORETICAL BACKGROUND

The angle-dependent intensity of the emitted electrons is described by the differential cross section $d\sigma/d\Omega$. For completely linearly polarized light it is given by [17]

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{\sigma}{4\pi} [1 + \beta P_2(\cos \theta)], \quad (1)$$

where β is the angular distribution parameter, σ the partial cross section, and P_2 the Legendre polynomial of second degree: $P_2(x) := (3x^2 - 1)/2$. θ is the angle between the electric field vector $\mathbf{E}$ of the radiation (which lies in the horizontal plane in our case) and the direction of the outgoing electrons in a plane perpendicular to the light propagation vector. The above formula gives a convenient parametrization of the angle-dependent intensity and is identical for photo- and Auger electrons. In the case of photoionization the β parameter is directly related to the dipole matrix elements.

In the two-step model of Auger decay, where the photoionization and Auger decay processes are assumed to proceed subsequently and independently of each other, the angular anisotropy parameter can be factorized into a parameter describing the anisotropy of the primary hole state and into an “intrinsic” parameter α_2 describing the Auger decay itself [1]:

$$\beta = \alpha_2 A_{20}. \quad (2)$$

A_{20} is the alignment parameter of the primary hole state and is proportional to its electric quadrupole moment [18]. Whereas the Auger anisotropy parameter α_2 depends on the Coulomb matrix elements, A_{20} is connected to the dipole matrix elements.

To determine the amplitudes and phases of the Coulomb matrix elements (to perform a complete Auger experiment [19]) other intrinsic parameters also have to be measured. Snell *et al.* [20] measured the spin polarization of the Xe $N_{4,5}O_{2,3}O_{2,3}$ Auger electrons after excitation by circularly polarized radiation of 94 eV energy and could determine the intrinsic parameters of the transferred spin polarization and the orientation A_{10} of the primary hole state (i.e., its magnetic dipole moment).

A. Photoionization

The description of the photoionization process in the framework of the dipole approximation limits the possible values of the orbital angular momenta of the outgoing photoelectrons according to the selection rules. In the case of the $4d$ ionization, the electrons can leave the atom as ϵp or ϵf continuum waves. In the nonrelativistic approximation there is no further spin-orbit splitting of these waves in the continuum and the photoionization cross section is determined by the single-particle radial matrix elements $R_{4d,\epsilon p}$ and $R_{4d,\epsilon f}$ [21]. Using the density matrix and statistical tensor formalism, Berezhko *et al.* [22] showed that the alignment tensor of the $4d$ hole state depends only on the ratio of the dipole amplitudes,

$$A_{20}^{5/2} = -\frac{1}{5} \left(\frac{2}{7} \right)^{1/2} \frac{2 + 7\lambda^2}{1 + \lambda^2},$$

$$A_{20}^{3/2} = -\frac{1}{10} \frac{2 + 7\lambda^2}{1 + \lambda^2} \quad \text{with} \quad \lambda = \left(\frac{2}{3} \right)^{1/2} \frac{R_{4d,\epsilon p}}{R_{4d,\epsilon f}}. \quad (3)$$

In Ref. [22] the alignment parameter is defined with respect to the propagation direction of the photon beam, whereas in the present paper A_{20} is given with respect to the direction of the electric field vector $\mathbf{E}$. The expression for A_{20} in Ref. [22] [Eq. (8)] must be divided by a factor of -2 to obtain the above equations. In the nonrelativistic approximation the ratio of the alignments for the two spin-orbit components is fixed to the value [22]

$$A_{20}^{5/2}/A_{20}^{3/2} = \sqrt{8/7}. \quad (4)$$

The extrema of the alignment are reached when either the ϵp or the ϵf wave completely vanishes. In the case of $A_{20}^{5/2}$ these extrema are -0.214 and -0.748 for $R_{4d,\epsilon p} = 0$ and $R_{4d,\epsilon f} = 0$, respectively [22].

Theoretical A_{20} values as a function of photon energy have been published by several authors. Hartree-Fock calculations were performed by Kennedy and Manson [21] and by Berezhko *et al.* [22]. Cherepkov [23] carried out calculations using the random-phase approximation with exchange (RPAE). All these authors treated the photoionization process in the nonrelativistic approximation. Relativistic calcu-

lations were performed up to a photon energy of 160 eV [24,25]. Since they do not cover the range of the Cooper minimum they will not be discussed in the present report.

B. Auger decay

A convenient way for treating the Auger intrinsic parameters is to classify the Auger transitions into three different categories with respect to their dependence on particular coupling schemes [11]. (i) Transitions where only one partial wave can be emitted in any coupling scheme. The α_2 values are independent of the dynamical properties of the Auger decay in this case. (ii) Transitions where only one partial wave can be emitted in LS coupling but not in intermediate coupling. (iii) Transitions with several contributing partial waves in any coupling scheme.

Transitions to $J=0$ final states fall into the first category and the anisotropy parameters are fixed geometrical factors, $\alpha_2 = -1$ for N_4 holes and $\alpha_2 = -1.07$ for N_5 holes [26]. Using this property, e.g., 1S_0 Auger lines can be used to determine the photoion alignment directly from their angular distribution using Eq. (2). This method was used in Ref. [11]. In the present work, as described in the next section, we use a somewhat different approach.

The 3P_1 and 3P_2 lines belong to the second category. It is interesting to note that due to the high spectral purity of the 3P_1 lines (98% [27]) the theoretical predictions using LSJ coupling are very good ($\alpha_2 = -0.8$ for the N_4 and $\alpha_2 = -0.748$ for the N_5 3P_1 line [28,26]). Although the 3P_2 lines have also a relatively high spectral purity (86% [27]), the α_2 values are very sensitive to the inclusion of the spin-orbit coupling [28]. The 1D_2 lines, which belong to category (iii), can be significantly affected by the spin-orbit interaction and are sensitive to the choice of atomic model [28].

Theoretical angular distribution parameters α_2 have been published by several authors: Kabachnik and Sazhina [26], Kabachnik *et al.* [29], Chen [28], and Tulkki *et al.* [30]. Tulkki *et al.* use the most advanced calculational methods, the exchange interaction with continuum channels, and relaxation effects and continuum channel coupling were taken into account on the basis of a multiconfiguration Dirac-Fock (MCDF) method. In the present paper only intermediate coupling results will be discussed.

IV. ANALYSIS

Typically, in order to determine the anisotropy parameters from electron spectra taken at several emission angles, the spectra must be normalized either by taking into account numerous relevant parameters of the experiment or by using a spectral line, for which the β value is accurately known. No such line exists within the $\text{Xe } N_{4,5}O_{2,3}O_{2,3}$ group, and the change in the geometry of the experiment at different angles makes the normalization based on photon flux, gas pressure, and other experimental parameters unreliable.

A. HEA experiment

Alternatively, a method described by Kivimäki *et al.* [31] can be employed. The method makes use of the intensity

FIG. 1. $\text{Xe } N_{4,5}O_{2,3}O_{2,3}$ Auger group after excitation by 160.4 eV photons taken at three different angles, after subtracting a linear background. The resolution of the electron spectrometer was approximately 30 meV. The solid lines represent a fit with Voigt profiles. All three spectra are normalized to the same scale. The assignment of the lines is given in Table I.

ratios of different lines within the spectrum at each measured angle. If the emission anisotropy is sufficiently different for any pair of lines, then the β parameter of the second line, for example, can be determined using the following formula:

$$\beta_2 = 3 \frac{R(54.7^\circ) - R(90^\circ)}{R(0^\circ) - R(90^\circ)} - 1, \quad (5)$$

where $R(\theta)$ is the ratio $I_1(\theta)/I_2(\theta)$ of the intensities of the two lines in the spectrum at the emission angle θ . The accuracy of the anisotropy parameter obtained from Eq. (5) is considerably reduced if the two lines have similar angular distributions, and in the case of equal β parameters, Eq. (5) cannot be used at all.

The $\text{Xe } N_{4,5}O_{2,3}O_{2,3}$ Auger electron spectra were fitted with Voigt profiles as shown in Fig. 1. The same Gaussian contribution to the line profile was used for all Auger lines. The Lorentzian widths were allowed to differ for the two spin-orbit split groups—the N_4 and N_5 lines—but were kept equal within these groups. In all spectra the background was approximated by a linear fit. The spectra taken at 80.7 eV photon energy were fitted with an analytical postcollision interaction (PCI) line shape [32]. The areas of the fitted Auger lines were used to determine the anisotropy parameters and Eq. (5) was applied to all possible pairs of lines to construct a matrix of β values. The anisotropy parameter of each line was then calculated as a weighted average over all β values obtained for that line. The weight factors were determined from the error limits of the β values in the matrix, which depend on the line intensities and especially on how much the branching ratio of the two lines changes at different emission angles. The uncertainties of the line areas were calculated from the errors of the fit parameters.

The $4d$ photoelectron lines fall into the proximity of the $N_{4,5}O_{2,3}O_{2,3}$ Auger group at some photon energies and their intensities were then also included in constructing the matrix

of β values. On the other hand, near 180 eV photon energy the $4p$ photolines overlap with the Auger group; thus, not all Auger electron lines could be used.

As shown in Eq. (2), an observed β value can be expressed as a product of the Auger anisotropy parameter α_2 and the alignment parameter A_{20} . The α_2 values differ for each Auger line, but are photon energy independent, whereas the A_{20} values are common for all lines but depend on the photon energy. A single set of α_2 values can be established for the Auger lines, which can be used for determining the alignment values from the spectra measured at different photon energies. We applied a least-squares optimization procedure to determine the intrinsic parameters for the Auger lines and the alignment parameters at each photon energy. The differences between the products $A_{20}\alpha_2$ and the observed β values of individual lines at all photon energies were added up and the result minimized in order to arrive at a combination of the α_2 and A_{20} parameters best describing the complete experimental data set.

Several constraints were set to improve the reliability of the optimization procedure. The α_2 parameters for the $N_4O_{2,3}O_{2,3}(^1S_0)$ and $N_5O_{2,3}O_{2,3}(^1S_0)$ lines were fixed to their theoretical values of -1.000 and -1.069 , respectively.

The optimization process was repeated under different conditions. In one approach the ratio of the alignment parameters for the N_4 and N_5 groups was set to the constant value of 1.069 [cf. Eq. (4)] at each photon energy, in accordance with the nonrelativistic approximation. In another approach this ratio was optimized along with A_{20} and α_2 , and a value of 1.043 was obtained. In a third approach no relation between the alignment parameters of the two spin-orbit components was established. In all three cases the set of α_2 values remained remarkably stable. We used the small variations occurring to assign error bars to α_2 . The uncertainties of the alignment parameters were determined from the error bars of the α_2 and β values.

B. TOF experiment

In order to determine the Auger intensities, the TOF spectra had to be background corrected and converted from time to energy scale using known Auger peak positions [11]. The Auger lines were fitted with Voigt profiles. In contrast to the HEA experiment, the energy resolution of the TOF analyzers is dependent on the kinetic energy. Therefore, the Gaussian widths of lines 1 and 8 (in Fig. 1) were determined first and for the other Auger lines these widths were interpolated according to their kinetic energies. The Lorentzian widths of all lines were kept equal.

Using Eqs. (1) and (2), the intensities I of the Auger lines can be described by

$$I(h\nu, \theta, n) = I_0(h\nu, \theta) I_{\text{rel}}(n) [1 + \alpha_2(n) A_{20}(h\nu) P_2(\cos \theta)], \quad (6)$$

where $h\nu$ is the photon energy, θ is the emission angle with respect to the light polarization, and n is the Auger line number as shown in Fig. 1. I_0 is the total intensity of a spectrum (determined by the photon energy and the angle), which contains information about the photon flux, the gas flow, and the

spectrometer transmission in a certain direction. $I_{\text{rel}}(n)$ is the relative intensity of the n th Auger line, $\alpha_2(n)$ is the anisotropy parameter of the n th Auger line, A_{20} is the energy-dependent alignment parameter, and P_2 is the second-order Legendre polynomial.

For each photon energy $h\nu$ Eq. (6) describes a set of 72 equations (nine Auger lines at eight angles) with 27 variables (one for A_{20} , eight for I_0 , nine for I_{rel} , and nine for α_2). The number of variables is reduced to nine by using α_2 values from Ref. [11] and by fixing the relative intensities I_{rel} to the average values obtained from the TOF spectra taken at the magic angle (-54.7°) where the measured intensities are independent of the angular distribution parameters. We used a least-squares fit to determine the remaining nine parameters, particularly the alignment parameter A_{20} . As described above, this method also works best when the angular distribution parameters α_2 are maximally different and it does not work at all when the α_2 values are all equal. For the alignment parameter A_{20} the largest contribution to the errors is introduced by the uncertainty of the α_2 values. Hence, for each photon energy we performed 1000 least-squares fits by varying the α_2 values from Kämmerling *et al.* [11] according to their stated error bars. As a result we obtained a Gaussian distribution of A_{20} values. The mean values and widths of those distributions are shown in Fig. 2 as data points and error bars, respectively.

V. RESULTS AND DISCUSSION

In this section, we discuss the photoionization and Auger decay processes separately. We do not present the measured angular distribution parameters β , which can be easily calculated from A_{20} and α_2 using Eq. (2).

A. Photoion alignment A_{20}

Figure 2 shows the alignment A_{20} of the $\text{Xe} 4d^{-1} 2D_{5/2}$ hole state together with other experimental data and a theoretical curve. Our values are obtained from the optimization process where Eq. (4) was applied, i.e., the validity of the nonrelativistic approximation was assumed. The relatively large error bars at lower photon energies are due to the fact that our method does not give accurate anisotropy parameters if all lines in the spectrum have similar β values. The exception is at 108.5 eV where the inclusion of the $4d$ lines [$\beta_{3/2} = 0.73(2)$, $\beta_{5/2} = 0.78(2)$] significantly increases the accuracy. At higher energies the limiting factor is the low count rate. At 173.5 and 176.1 eV a partial overlap of the $N_{4,5}O_{2,3}O_{2,3}$ Auger group with the $4p$ photolines increases the uncertainties.

The agreement between all the experimental data is very good up to 142 eV photon energy. At higher energies a considerable discrepancy between our results and those of Southworth *et al.* [7] can be seen. The latter have large uncertainties and do not show a minimum, while our data show a strong dip.

The overall shape of the theoretical curve of Ref. [23] is similar to the experimental data, giving the position of the minimum at 6 eV lower energy than the experiment. To get

FIG. 2. Alignment A_{20} of the Xe $4d^{-1}2D_{5/2}$ hole state. The stars show the extreme values of A_{20} in LS coupling for a vanishing f wave (at threshold and in the Cooper minimum) and vanishing p wave in the cross section maximum [cf. Eq. (3) and text]. The error bars correspond to single standard deviations. The dashed curve was obtained by stretching the calculation of Cherepkov to match the A_{20} minimum.

a better idea about the course of A_{20} over photon energy, we modified this curve by stretching it toward higher energies in order to match the minimum in the experimental data. In this way we obtain a good overall agreement with a slight deviation around 145 eV. This deviation might be due to the fact that the $4p$ threshold is approximately at 146 eV photon energy and this was not taken into account during the calculations. The Hartree-Slater model of Ref. [22] places the position of the minimum at 30 eV lower energy, whereas Ref. [21] and the Hartree-Fock model of Ref. [22] place it at 30 eV higher energy than experiment. These theoretical curves are not shown in Fig. 2.

As described above, A_{20} can reach two extrema for vanishing p or f waves. [cf. Eq. (3)]. Due to the potential barrier for f electrons near threshold [$E_{\text{bind}}(4d_{5/2}) = 67.54$ eV], the outgoing p wave dominates the photoionization. At increasing energies, the f electrons overcome the barrier and carry almost all the cross section in the maximum of the shape resonance (~ 100 eV). In the Cooper minimum $R_{4d,ef}$ goes through zero, i.e., only the p wave is present at ~ 176 eV. Whereas the first two extrema were confirmed by the previous experiments, the present data prove the existence of the alignment minimum in the Cooper minimum of the cross section.

B. Auger anisotropy parameter α_2

Our results for the anisotropy parameters are given in Table I together with values from a previous experiment and three sets of calculations. Due to our method of analysis, where all the Auger spectra taken at different photon energies were used to determine α_2 , the uncertainties are rather small. The comparison with the results of Kämmerling *et al.* shows a very good agreement for all but one line, the $N_5\ ^3P_2$ line, which was not completely resolved in the previous experiment.

The results corresponding to the three categories introduced above (Sec. III B) are discussed below.

(i) In both experimental data sets α_2 values of the 1S_0 Auger lines were fixed to the theoretical values. The 3P_0 line should have the same anisotropy parameter as the 1S_0 line, and indeed both experiments give the proper value.

(ii) The 3P_1 lines show a good agreement between all experimental and theoretical values. This is due to the high spectral purity of these final states as mentioned above. The discrepancy for line 7 between the two experimental values is most likely due to the different spectrometer resolutions; in Ref. [11] lines 6 and 7 were not well resolved and thus the angular distribution of the weaker line 7 was harder to determine. Our result for the $N_5\ ^3P_2$ line supports the intermediate-coupling Dirac-Fock (ICDF) [29] and MCDF [28] calculations, whereas Kämmerling *et al.* are closer to the multichannel MCDF (MMCDF) [30] calculation. For the $N_4\ ^3P_2$ line a serious discrepancy between experiment and all theoretical models remains.

(iii) The MCDF calculation agrees very well with measurements of the $N_5\ ^1D_2$ Auger line and the ICDF calculation agrees very well for the $N_4\ ^1D_2$ Auger line.

To estimate the overall agreement between the experimental and theoretical values, we calculated the root mean squares of their differences, which are shown at the end of Table I. It can be clearly seen that the MCDF calculation of Chen [28] agrees best with both experimental data sets. Tulkki *et al.* also published α_2 values where the exchange interaction, relaxation, and interchannel interaction are neglected [30]. This approach is equivalent to that of Chen and gives the same values.

VI. SUMMARY

We measured the angular distribution of the Xe $N_{4,5}O_{2,3}O_{2,3}$ Auger electrons over a wide photon energy

TABLE I. Experimental and calculated anisotropy parameters α_2 of the Xe $N_{4,5}O_{2,3}O_{2,3}$ Auger lines.

Line	Final state	Experiment		Theory		
		This work	Ref. [11]	ICDF ^a	MCDF ^b	MMCDF ^c
2	$N_4O_{2,3}O_{2,3}^1S_0$	-1.000 ^d	-1.000 ^d	-1.000 ^e	-1.000 ^e	-1.000 ^e
6	$N_4O_{2,3}O_{2,3}^1D_2$	0.02(2)	0.05(6)	0.055	0.086	-0.116
8	$N_4O_{2,3}O_{2,3}^3P_1$	-0.69(5)	-0.73(1)	-0.835	-0.831	-0.837
9	$N_4O_{2,3}O_{2,3}^3P_2$	0.74(3)	0.72(13)	0.156	0.250	0.231
1	$N_5O_{2,3}O_{2,3}^1S_0$	-1.069 ^d	-1.069 ^d	-1.069 ^e	-1.069 ^e	-1.069 ^e
3	$N_5O_{2,3}O_{2,3}^1D_2$	0.24(2)	0.24(10)	0.139	0.238	0.094
5	$N_5O_{2,3}O_{2,3}^3P_0$	-1.07(9)	-1.07(10)	-1.069 ^e	-1.069 ^e	-1.069 ^e
4	$N_5O_{2,3}O_{2,3}^3P_1$	-0.73(3)	-0.77(17)	-0.734	-0.736	-0.743
7	$N_5O_{2,3}O_{2,3}^3P_2$	-0.16(2)	-0.47(13)	-0.227	-0.257	-0.385
RMS this work—theory ^f				0.23	0.20	0.23
RMS Kämmerling <i>et al.</i> —theory ^f				0.24	0.20	0.21

^aIntermediate-coupling Dirac-Fock final ionic state [29].^bMulticonfiguration Dirac-Fock final ionic state [28].^cMultichannel multiconfiguration Dirac-Fock final ionic state [30].^dFixed to their theoretical values.^eValue independent of matrix elements [26].^fRoot mean square of the differences between the experimental and theoretical values of all lines.

range, covering the Cooper minimum of the $4d$ ionization. Using the framework of the two-step model of Auger decay, we made the following determinations.

(i) The alignment A_{20} of the $4d^{-1}^2D_{3/2}$ and $^2D_{5/2}$ ionic states was determined at different excitation energies including the region of the $4d$ photoionization Cooper minimum around 180 eV.

The pronounced minimum in our data experimentally proves the vanishing of the ϵf component of the outgoing electron wave. This is in good agreement with theoretical predictions of a RPAE calculation [23], taking into account a small deviation in the position of the predicted minimum. An important implication of the present result is that with $R_{4d,\epsilon f}=0$ at 176 eV all the dynamical parameters of photoionization have fixed values (e.g., $\beta=0.2$ [8]) at this energy.

(ii) The Auger anisotropy parameter α_2 for all lines of the $N_{4,5}O_{2,3}O_{2,3}$ Auger group was determined. A very good agreement with a previous experiment was found for all but one line. The calculations of Chen [28] agree well with the

experimental data with the exception of the $N_4^3P_2$ line, for which all existing theories fail to predict the correct α_2 value. Interestingly, the inclusion of the exchange interaction and relaxation effects in the MMCDF calculation of Tulkki *et al.* does not improve the agreement with experiment.

For future photoionization and Auger complete experiments both the alignment and Auger anisotropy parameters will play important roles.

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