Post-Collision Interaction in the Xenon $N_{4,5}$-OO Auger Spectrum Excited by Photon Impact*†

V. Schmidt, N. Sandner, and W. Mehlhorn
Fakultät für Physik, Universität Freiburg, D 7800 Freiburg, Germany

and

M. Y. Adam and F. Wuilleumier
Equipe de Recherche "Spectroscopie Atomique et Ionique" du Centre National de la Recherche Scientifique and Laboratoire pour l'Utilisation de Rayonnement Electromagnétique, Université Paris-Sud, 91405 Orsay, France

(Received 28 October 1976)

The N_5-$O_{2,3}O_{2,3}$ $^1S_0$ Auger peak of xenon following ionization in the N_5 shell by photons of different energy has been investigated. When the photon energy is lowered close to threshold a shift of the position of the peak maximum to higher energies and a characteristic asymmetric intensity distribution of the Auger line are observed. The observed shifts agree well with values calculated with the classical Berker-Berry model modified because of the velocity change of the slow photoelectron in the Coulomb field of the inner-shell ionized atom.

Post-collision interaction (PCI) is a particular manifestation of electron correlation in the final state: a "slow" electron receding from the atom and a "fast" electron emitted in the decay of that atom. PCI has been studied widely in electron (or ion) scattering experiments.[1-9] In contrast to this, PCI occurring in inner-shell ionization processes had made progress only recently.[10-12] One of the most nearly ideal cases for studying PCI in inner shells is the ejection of an Auger electron following photoionization with photon energies close to the threshold. In this Letter, for the first time, we will present results of PCI in such an experiment. These results are in good agreement with the model of Barker and Berry[1] modified by Niehaus.[13]

In this work the synchrotron radiation emitted by the Orsay colliding-beam storage ring was used.[14] The continuum radiation was monochromatized by means of a 1-m grazing-incidence monochromator[15] (one grating with 576 lines/mm). The photon beam was limited to a diameter of about 4 mm and monitored by measuring the current of photoelectrons emitted from a gold foil. Xenon was used as target gas at a pressure of about 1×10^{-4} Torr. Electrons ejected at a mean angle of 54°44′ with respect to the photon beam direction were accepted by the electron energy analyzer (cylindrical mirror type) and energy analyzed. The instrumental resolution was set at 0.85%. The transmitted electrons were detected by a Channeltron and the detector pulses were registered using a multiscaling procedure. A detailed description will be given elsewhere.[16]

The present investigation concerns the $N_{4,5}$-OO Auger electrons of xenon. Figure 1 shows the $N_{4,5}$-$O_{2,3}O_{2,3}$ part of the whole Auger spectrum taken at 93 eV photon energy with a bandpass of ±1 eV; background subtraction and dispersion correction have been applied (for a complete electron spectrum with kinetic energies between 0 and 90 eV see Wuilleumier *et al.*[17]). The solid curve has been obtained in the following manner: The absolute energies and relative intensities of Auger lines have been taken from the experimental data of Ohtani *et al.*[12] and of Werme, Bergmark, and Siegbahn,[18] respectively. For each individual Auger line a Voigt profile was used, corresponding to a natural linewidth $\Gamma = 100$ meV due to preliminary results of Breuckmann *et al.*[19]; the theoretical calculation by McGuire[20] gives 82 meV. The solid line has then been fitted to the

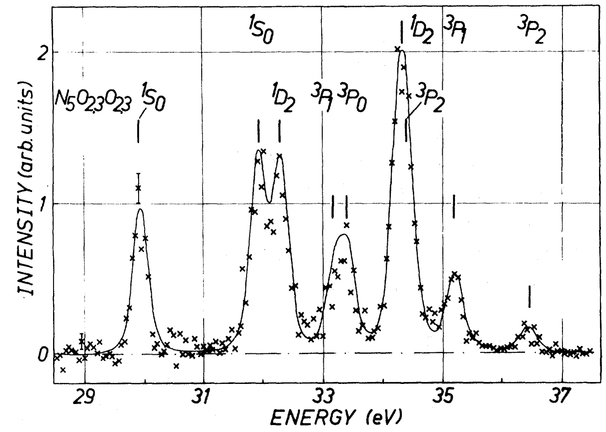

FIG. 1. $N_{4,5}$-$O_{2,3}O_{2,3}$ Auger spectrum of Xe following the ionization by photons of 93 eV.

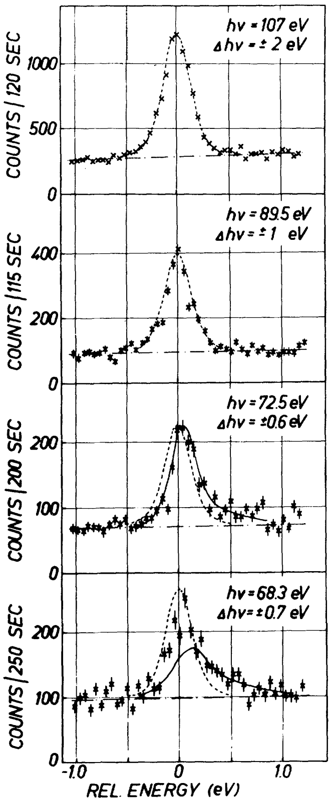

FIG. 2. N_5-$O_{2,3}O_{2,3}\,^1S_0$ Auger peak of Xe following the ionization by photons of different energies $h\nu$ with bandpass $\Delta h\nu$. Further explanation is given in the text.

maximum of the line at 34.2 eV. Figure 1 shows that the solid line agrees well with the intensity distribution.

Because of the low counting rates, for the investigation of PCI in the Xe Auger spectrum the interest was concentrated on the single Auger transition N_5-$O_{2,3}O_{2,3}\,^1S_0$ at 29.91 eV, the binding energy of an electron in the N_5 ($4d_{5/2}$) shell being 67.5 eV.[21] Figure 2 shows this Auger peak for several energies of the ionizing photons. In order to detect the small shifts of the energetic position of this Auger peak, it must be insured that no instrumental influences disturb the true effect. Therefore each individual experiment (which was carried out on different days) with the Xe target was framed by measurements of the decay electrons of the $2s2p\,^1P$ autoionizing state in He, which have a fixed and well-known energy of 35.34 eV (Fig. 3). For these additional experiments, the Xe target was replaced by He and the position of the monochromator grating was changed to zero-order diffraction in the He experiment. For the Xe runs at different photon energies equal target-gas pressures have been used. The Xe N_5-$O_{2,3}O_{2,3}\,^1S_0$ Auger electrons have been calibrated relative to the position of the resonance electrons from the decay of $2s2p\,^1P$ in He. As reference energy we used the crossing of the extrapolated "background" (dashed curve in Fig. 3) with the high-energy side of the resonance profile. This calibration allows us to determine the position of the Xe Auger peak with an accuracy of about ±0.5 channels which corresponds to about ±25 meV.

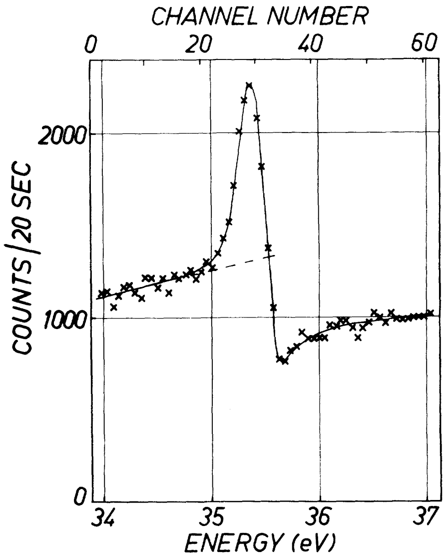

FIG. 3. Spectrum of electrons ejected in the decay of the $2s2p\,^1P$ autoionizing state in He excited by the synchrotron light in zero order of the monochromator.

In Fig. 2 the dotted curve represents the unshifted peak position where the shape is equal to the Voigt profile used in the predicted spectrum of Fig. 1. At a photon energy of 107 eV the theoretical curve fits the experimental data very well, and at 89.5-eV photon energy the experimental points are still compatible with this shape. At 72.5-eV photon energy (bandpass ±0.6 eV), i.e., 5.0 eV above threshold, the solid line through the experimental points indicates a shift of the maximum position of 55±25 meV relative to that taken at 197-eV photon energy and a slightly asymmetric shape. In spite of the low counting rates, i.e., the large statistical error, this tendency becomes even more pronounced at a mean photon energy of 68.3 eV (bandpass ±0.7 eV), i.e., about 0.8 eV above threshold. Here the solid curve represents the PCI Auger line; its maximum is shifted by 135±40 meV relative to the maximum found for 107-eV photon energy. In or-

TABLE I. Experimental and theoretical energy shifts of the N_5-$O_{2,3}O_{2,3}$ $^1S_0$ Auger peak of xenon.

Photon energy ± bandpass (eV)	Mean photoelectron energy ΔE (eV)	Energy shift ϵ_W (meV) Experiment	Theory[a] (Γ = 100 meV)	(Γ = 82 meV)
72.5 ± 0.6	5.0	55 ± 25	82	68
68.3 ± 0.7	0.8	135 ± 40	178	149

[a] See Ref. 13.

der to get this solid curve, the experimental data had to be corrected for the contribution of photons with 136.6 eV energy which passed the monochromator in second order of diffraction. These photons produce Auger electrons with energies and peak shape as given by the Auger peak at 107-eV photon energy in Fig. 2. The amount of these non-PCI Auger electrons has been determined to be about 35% of the total Auger peak by measuring the intensity of $4d$ photoelectrons at $136.6 - E(4d) = 68.3$ eV and using the intensity ratios between the N_5-$O_{2,3}O_{2,3}$ $^1S_0$ Auger peak and the $4d_{5/2}$ and $4d_{3/2}$ photoelectron peaks measured at 93-eV photon energy. At 72.5-eV photon energy the contribution of second-order diffracted photons is much smaller; the corresponding $4d$ photopeak has not been found.

Our experimental data clearly demonstrate a PCI effect in the N_5-$O_{2,3}O_{2,3}$ $^1S_0$ Auger peak, namely, an asymmetric peak profile with more electrons at higher energies and a shift of the maximum position. For a comparison of our data with theoretical models one must take into account that in the case of PCI in Auger decay the receding slow electron (photoelectron) is under the influence of the Coulomb field resulting from the ionization process. Therefore, the velocity of the slow ejected photoelectron changes according to this Coulomb potential. With this change of velocity included in the classical model of Barker and Berry,[1] the shift of the peak position, ϵ_W, has been calculated by Niehaus[13] and is given by (all quantities are in atomic units)

$$\tau^{-1}[2(\Delta E+\epsilon_W)]^{1/2} - 4(\Delta E+\epsilon_W)\epsilon_W - (\epsilon_W)^2 = 0, \qquad (1)$$

where $\Delta E = h\nu - I$ is the energy of the photoelectron without PCI at infinite separation from the ion and $\tau = 1/\Gamma$ is the lifetime of the inner-shell vacancy. For $\epsilon_W \ll \Delta E$ Eq. (1) reduces to the Barker-Berry formula $\epsilon_W = (2\tau)^{-1}(2\Delta E)^{-1/2}$. In our case this occurs already for $\Delta E \gtrsim 2$ eV. Table I shows the results of Eq. (1) together with our experimental values; the agreement is good, espeically for $\Gamma = 82$ meV.

The shift of the maximum position of the N_5-$O_{2,3}O_{2,3}$ $^1S_0$ Auger line observed by Ohtani *et al.*[12] in their electron-impact experiment (at an impact energy of 78 eV, i.e., 10.5 eV above threshold) was 170 meV. This value is somewhat larger than that found in our experiment for photons with mean energy of 0.8 eV above threshold. This difference can be attributed to the fact that in the case of electron impact with energies close to the threshold two electrons, the scattered and the ejected inner-shell electron, recede from the atom. If both electrons have equal energy, $\Delta E_1 = \Delta E_2 = 5.25$ eV, this gives a lower limit for the shift: $\epsilon_{\min} = 2\epsilon_W(\Delta E = 5.25\text{ eV}) = 132$ meV ($\Gamma = 82$ meV) or 166 meV ($\Gamma = 100$ meV). The upper limit $\epsilon_{\max}$ is reached when one electron has energy $\Delta E = 0$ and the other $\Delta E = 10.5$ eV and is approximately given by $\epsilon_{\max} \cong \epsilon_W(\Delta E = 0) + \epsilon_W(\Delta E = 10.5\text{ eV}) = 292$ meV ($\Gamma = 82$ meV) or 336 meV ($\Gamma = 100$ meV). The observed shift of 170 meV is compatible with the limits.

Further work with improved experimental conditions (reduction fo second-order diffraction, improved photon flux through the monochromator, and better signal-to-noise ratio) is planned.

The authors gratefully acknowledge the contribution of Dr. P. Dhez to this experiment by setting the monochromator. They also thank Dr. P. Jaeglé for his constant support and the members of the Laboratoire de l'Accélérateur Linéaire for their help in operating the storage ring.

---

*Work carried out in Orsay at Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, laboratory jointly created by the Centre National de la Recherche Scientifique and the Université Paris-Sud.

†Research supported by the Deutsche Forschungsgemeinschaft, Germany, and the Centre National de la Recherche Scientifique, France.

[1] R. B. Barker and H. W. Berry, Phys. Rev. 151, 14

(1966).

[2] G. Gerber, R. Morgenstern, and A. Niehaus, J. Phys. B 5, 1396 (1972).

[3] P. J. Hicks, S. Cvejanović, J. Comer, F. H. Read, and J. M. Sharp, Vacuum 24, 573 (1974).

[4] A. J. Smith, P. J. Hicks, F. H. Read, S. Cvejanović, G. C. M. King, J. Comer, and J. M. Sharp, J. Phys. B 7, L496 (1974).

[5] A. Nienhuis and H. G. M. Heideman, J. Phys. B 8, 2225 (1975).

[6] F. H. Read, Radiat. Res. 64, 23 (1975).

[7] D. Spence, Phys. Rev. A 12, 2353 (1975).

[8] R. Morgenstern, A. Niehaus, and U. Thielmann, to be published.

[9] R. Morgenstern, A. Niehaus, and U. Thielmann, to be published.

[10] M. J. Van der Wiel, G. R. Wight, and R. R. Tol, J. Phys. B 9, L5 (1976).

[11] M. J. Van der Wiel, in *Proceedings of the International Conference on Inner Shell Ionization Phenomena Freiburg, 1976*, edited by W. Mehlhorn and R. Brenn (University of Freiburg, Freiburg, Germany, 1976), p. 209.

[12] S. Ohtani, H. Nishimura, H. Suzuki, and K. Wakiya, Phys. Rev. Lett. 36, 863 (1976).

[13] A. Niehaus, private communication, and to be published.

[14] P. Dagneaux, C. Depautex, P. Dhez, J. Durup, Y. Farge, R. Fourme, P. M. Guyon, P. Jaeglé, S. Leach, R. Lopez-Delgado, P. Morel, R. Pinchaux, P. Thiry, C. Vermeil, and F. Wuilleumier, Ann. Phys. (Paris) 9, 9 (1975).

[15] P. Jaeglé, P. Dhez, and F. Wuilleumier, in *Proceedings of the Fourth International Conference on Vacuum Ultraviolet Radiation Physics, Hamburg, 1974,* edited by E. E. Koch, R. Haensel, and C. Kunz (Pergamon, New York, 1974), p. 788.

[16] M. Y. Adam, F. Wuilleumier, N. Sandner, V. Schmidt, and W. Mehlhorn, to be published.

[17] F. Wuilleumier, M. Y. Adam, V. Schmidt, N. Sandner, and W. Mehlhorn, in Extended Abstracts of the International Conference on the Physics of X-Ray Spectra, Gaithersburg, Maryland, 1976 (unpublished), p. 329.

[18] L. O. Werme, T. Bergmark, and K. Siegbahn, Phys. Scr. 6, 141 (1972).

[19] B. Breuckmann *et al.*, to be published.

[20] E. J. McGuire, Phys. Rev. A 9, 1840 (1974).

[21] K. Codling and R. P. Madden, Phys. Rev. Lett. 12, 106 (1964).