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Optical threshold excitation functions of Xe 5s,5p photoionization satellites near the $5s^{-1}$ Cooper minimum

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Excitation spectra of undispersed vuv and uv emissions from photoionized Xe, 5s,5p satellites have been observed in the region between the $5s^{-1}$ threshold and the $5s^{-1}$ Cooper-minimum region. A vuv spectrum shows a number of resonance-enhanced satellites due to an interchannel coupling with doubly excited Rydberg states. Peculiar threshold enhancement in a uv spectrum around the Xe^{2+} $^3P_2$ limit is explained by an initial-ionic-state correlation and a post-threshold enhancement (shakedown) after the Xe^{2+} $^3P_0$ and ^1D limits by inelastic scattering.

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Photoionization of valence s-shell electrons of rare-gas atoms gives evidence of electron correlation by the production of accompanying ionic excited states, namely, satellites, or photoelectron satellites in photoelectron spectroscopy (PES). Studies of Xe satellites as a fascinating showcase of electron correlation were made of the inner-4d-shell ionization [1-4]. However, because of a photoionization cross section of the Xe 5s shell around the double-ionization limit in its Cooper-minimum region [5], intensity ratios of satellites to the principal s^{-1} state in this region [6,7] were remarkably large in comparison with those well above the threshold [8]. This was also the case for Ar 3s satellites [9]. It was proposed that the phenomenon originated from a borrowing of oscillator-strength intensities from the outer p-shell electron transition as a result of a strong initial ionic s^{-1} and p^{-1} state correlation [9,10]. Detailed investigations of Xe 5s,5p correlation satellites in their threshold region were initiated by Schartner *et al.* [11] with the detection of dispersed and undispersed vacuum-ultraviolet (vuv) fluorescences. Threshold structures in fluorescence intensities from $5s^{-1}$ and a few satellites were observed, but in a narrow photon energy region (23.4–25.8 eV). Using a PES method, Wills, Cafolla, and Comer [12] obtained excitation spectra for the $5s^{-1}$ and nine satellites up to 28 eV. Hall *et al.* [13] also observed resonance structures using a constant-ionic-state PES. These two PES studies did not provide information about the $5s^{-1}$ threshold behavior of satellites. Furthermore, satellite excitation functions at the Xe^{2+} limits were not obtained. In conclusion, detailed studies on Xe 5s,5p satellites near the $5s^{-1}$ Cooper minimum region are greatly needed.

Two types of double-electron transitions are involved in the production of satellites between the $5s^{-1}$ threshold and the direct double-ionization limit. One is the discrete excitation to doubly excited Rydberg states [14] followed by autoionization. The other is the direct ionization into the $nl\epsilon\lambda$ continua of satellites. An interchannel coupling between the two types of two-electron transitions was shown to result in a strong resonance enhancement of satellites [11,15,16]. An enhancement of satellites is expected due to a screening change below and above the double-ionization limit, i.e., shakeup and shakedown [17]. Here, inelastic scattering of the outgoing electron in the final state is underlined to determine whether the other of the two promoting electrons does or does not achieve a positive kinetic energy. This also implies that a complementary aspect of the double ionization is offered by a threshold enhancement of satellites at the double-ionization limits.

In this paper we present a measurement of fluorescence excitation spectra (FES) of undispersed vuv and ultraviolet (uv) emissions of Xe satellites between the $5s^{-1}$ threshold at 23.4 and 36.5 eV. The purpose of the present investigation is to clarify the general behavior of Xe satellites near the $5s^{-1}$ Cooper minimum, especially around the double-ionization limits. At the ionization thresholds of satellites, optical emission measurements are more advantageous than PES. Samson, Lee, and Chung [18] and Schartner *et al.* [19] obtained FES from some specified satellites. Concerning the present purpose, however, the total intensity is not necessary to be resolved into individual final states. We display a vuv FES rich with resonance-enhanced structures of doubly excited states. The observation of peculiar enhancements of Xe 5s,5p satellites is shown in a uv FES at around the first Xe^{2+} limit and after the second and fourth limits. This type of simple observation, together with complementary results of dispersed-emission measurements should give important information on the behavior of double-electron excitation processes.

The experiment was performed using an extreme uv synchrotron radiation (SR) from a 2.5-GeV positron storage ring at the Photon Factory. A monochromatized radiation enters a gas cell through two collimating diaphragms. Undispersed vuv (105–180 nm) emissions involving Xe^+ $5s^{-1} \rightarrow 5p^{-1}$ and some optical lines from satellites are detected by a CsI coated microchannel plate [20] (MCP) through a LiF window. Ultraviolet emissions are extracted to outside the vacuum chamber and detected by a uv-sensitive (160–320 nm) photomultiplier (PMT).

The shorter limit was, however, determined to be 200 nm by the atmospheric absorption. Signal intensities were not corrected for the optical responses. Optical emissions in an isolated condition were ascribed purely to photoionized satellites in the present photon-energy region. It is unlikely that emissions from doubly excited Rydberg states are detected because of much smaller rates of fluorescence decays of these states in comparison with their autoionization rates. However, special care was taken to eliminate secondary-photoelectron-impact emissions of neutral species, which showed quadratic pressure dependence. A gas pressure was maintained below a few mTorr to achieve linear pressure dependence of emission intensities. A linear pressure dependence of uv intensity was, however, obtained up to 40 mTorr because of the insensitivity of the PMT to neutral emission lines [21] and negligible collisional quenching of detected species. A polarization effect of emissions extracted parallel to a polarization axis of an almost linearly polarized SR was diluted because of a relatively large solid angles for detection. Data sampling was made by a 9.6-meV step with a 38-meV band pass and by a 19-meV step with a 96-meV band pass for vuv and uv FES, respectively.

Figure 1 presents an excitation spectrum (FES) of vuv emission in the 23.4–31 eV region. The aim of this investigation is to obtain a detailed excitation spectrum of Xe valence satellites. The FES shows a sharp onset at 23.4 eV corresponding to the Xe^+ $5s^{-1}$ threshold. The origin of emission is the $5s^{-1} \rightarrow 5p^{-1}$ resonance lines at the threshold. With the increase in the photon energy a variety of satellites are produced [13,22]. Lablanquie [22] observed the production of 52 satellites in this region by a threshold PES. It is likely that at least ten emission lines are included in consideration of compiled data by Striganov and Sventiskii [21] and Hansen and Persson [23]. A general appearance of the FES is in good agreement with undispersed results by Schartner *et al.* in the 23.4–25.8 eV region [11]. A slightly better resolution in this experiment allows us to resolve more detailed structures. The present FES in Fig. 1 further displays sharp oscillations on a decreasing continuum cross section with increasing photon energy toward 31 eV. Energy positions of oscillating peaks correspond well to absorption lines by Codling and Madden recorded in high-resolution absorption spectra [14]. They are identified with doubly excited Rydberg series which converge to respective satellites. Comparing with their absorption spectra, our results are assigned partly as indicated in Fig. 1. These resonance-enhanced features of satellites by a strong interchannel coupling with doubly excited Rydberg states were also seen in Ar 3*s* satellites [18,19]. According to PES results [6,9], the intensity of vuv emissions involves optical emissions from satellites with the amount of at least several times as large as the intensity of $5s^{-1} \rightarrow 5p^{-1}$ lines. It is clear that the strong resonance enhancement appears in Xe satellites as well as $5s^{-1}$ principal ionization.

The uv spectrum in Fig. 2 shows a first onset at 28.25 eV, which corresponds to the threshold of $(^1D)6p\,^2F_{7/2}$ satellite. With a reference of uv emission line data by Hansen and Persson [23] other steplike onsets are identified: $(^1D)6p\,^2D_{3/2}$, $(^1D)6p\,^2P_{1/2}$, $(^3P_2)7p\,^2P_{3/2}$, $(^3P_2)4f\,^2D_{3/2}$, $(^1S)6p\,^2P_{1/2}$, $(^1S)6p\,^2P_{3/2}$, and $(^1D)6d\,^2P_{1/2}$ satellites as indicated in Fig. 2 at 28.49, 28.59, 29.39, 29.43, 30.51, 30.63, and 31.5 eV, respectively. There still remain unidentified onsets. It is clear that the behavior of the uv FES gives dynamic aspects of these satellites. The most

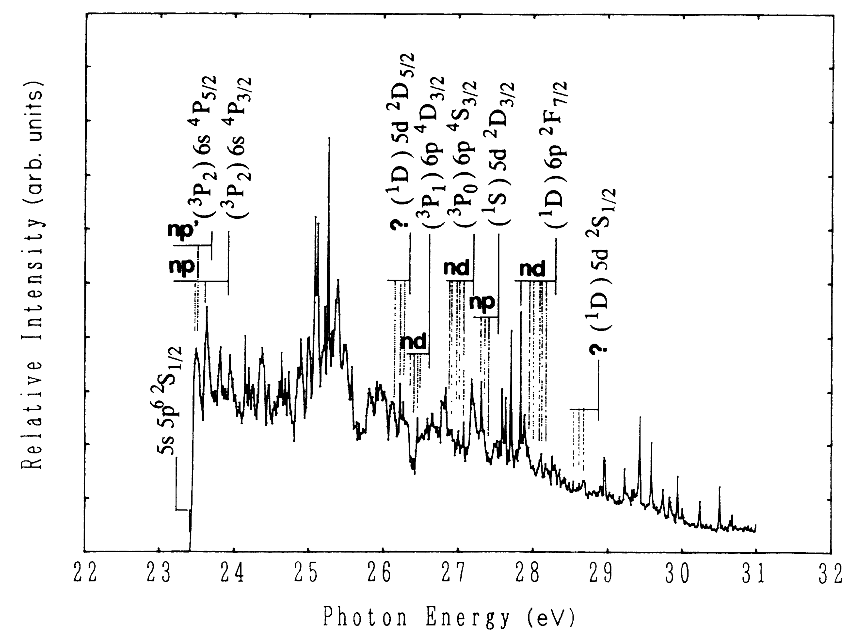

FIG. 1. Vacuum-ultraviolet fluorescence excitation spectrum in the 23.4–31 eV region. Data points are normalized for photon flux. Positions of doubly excited Rydberg states (dotted lines) and their series limits (solid lines) in Ref. [14] are indicated by vertical lines. Reassigned series limits of $(^1D)5d\,^2D_{5/2}$ at 26.37 eV (unassigned in Ref. [14]) and $(^1D)5d\,^2S_{1/2}$ at 28.87 eV [$(^3P)7s\,^4P_{1/2}$ in Ref. [14]] are employed from Ref. [23].

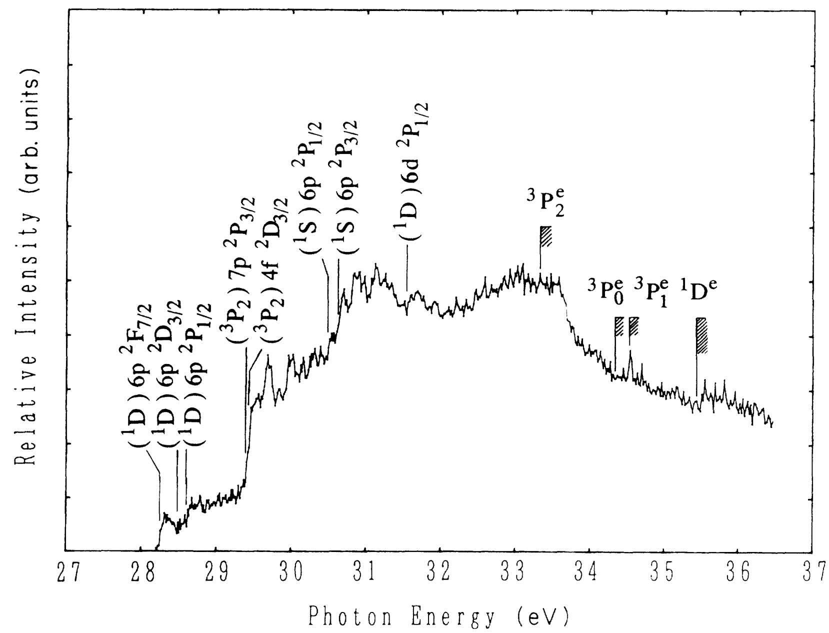

FIG. 2. Ultraviolet fluorescence excitation spectrum in the 28.2–36.5 eV region. Vertical lines indicate observed satellite thresholds. Four Xe^{2+} limits are also shown. After the $^3P_0$ and ^1D limits small enhancements are seen.

pronounced increase is recorded at the onset of the $(^3P_2)7p\,^2P_{3/2}$ satellite (29.39 eV). An increasing feature of FES above this onset appears to obey an asymptotic feature of shakeup processes [24,25] whereas the behavior above onsets of other satellites seems rather similar to that of neon conjugate states [15]. A maximum intensity is obtained at around the first double-ionization limit (Xe^{2+} $^3P^e_2$) at 33.3 eV, and then decreases gradually. This maximum, however, appears as an affected enhancement. After the second ($^3P^e_0$) and fourth ($^1D^e_2$) limits small post-threshold enhancements are recognized.

Considering a general similarity of Ar and Xe valence s^{-1} cross sections in their Cooper minima [5], it is interesting to compare cross sections of Ar satellites with the present Xe FES. Optical measurements of Ar $3p^4(^1D)4p(^2F_{7/2})$ and $3p^4(^1D)4p(^2P_{1/2})$ satellites by Samson, Lee, and Chung [18] suggest that fractions in the present uv FES of Xe $5p^4(^1D)6p(^2F_{7/2})$ and $5p^4(^1D)6p(^2P_{1/2})$ satellites with the same symmetry are very small and decrease with increasing photon energy. Wijesundera and Kelly calculated cross sections of Ar valence satellites with many-body perturbations [26]. Different natures of normal and conjugate satellites, i.e., a dipole transition to a continuum coupled with monopole shakeup and a dipole excitation combined with monopole shakeoff [27], show up in rather different behavior of cross sections between these two kinds of shakeup satellites. Post-threshold enhancement of satellites above the second and fourth Xe^{2+} limits are shown. These phenomena are not identical to increasing behavior of Ar $3p^4(^1D)nd(^2S)$ ($n=3$–5) cross sections above the first Ar^{2+} limit [26] because this increase was derived from a coupling with $3s3p^6\epsilon p$ channel in the coincident Ar^+ $3s^{-1}$ Cooper minimum. However, these enhancements of Xe satellites are explained by an inelastic scattering of outgoing electrons in the final state [16] to result in partitioned double-ionization into shakedown satellites. The minima, however, were not obtained in Ar $3p^4(^3P,\ ^1D,$ and $^1S)4p\,^2P$ satellites cross sections [26]. Among these, the Ar $3p^4(^3P)4p(^2P)$ satellite cross section was most striking; a maximum was at this first Ar^{2+} threshold. This can be understood as a strong initial-ionic-state correlation between $3s^{-1}$ and $3p^{-1}$ states. This supplies an interpretation of the affected maximum at around the first Xe^{2+} threshold. Ultraviolet FES above the $5p^4(^3P_2)7p\,^2P_{3/2}$ threshold is mainly ascribed to uv emissions from this satellite. The similarity of the maximum leads to a conclusion that the $5p^4(^3P_2)7p\,^2P_{3/2}$ satellite reveals an initial $5s^{-1},5p^{-1}$ ionic-state correlation. Considering theoretical Ar satellites cross sections in the same symmetries, a more gentle decrease of Xe FES from the maximum than the $3p^4(^3P)4p(^2P)$ satellite cross section is explained by gradually decreasing cross sections of $5p^4(^1S)6p\,^2P_{3/2},{}^2P_{1/2}$ satellites and an increasing one of $5p^4(^1D)6d\,^2P_{1/2}$. The uv FES, as a resultant of accumulated manifold cross sections of several kinds of satellites above, thus, reasonably exhibits its general feature.

In summary, from the observation of undispersed optical emissions from Xe $5s,5p$ satellites we have shown that resonance satellite enhancements due to an interchannel coupling with doubly excited Rydberg states are important, even in much higher photon energy region than the previous measurements [11]. We have shown an observation of peculiar threshold enhancements of satellites as a result of an initial-ionic-state correlation. A post-threshold shakedown enhancement due to inelastic scattering has also been demonstrated for Xe satellites. In order to discuss a more general production behavior of satellites, we remark on the importance of the following three investigations. (i) Detection of visible and, possibly, ultraviolet emissions to achieve more continuous distribution of satellites. (ii) FES of dispersed emissions [11, 18,19] to construct an integrated "total" FES from satellites. (iii) Determination of electron kinetic-energy spectrum [28,29] to understand energy partitioning processes at thresholds.

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