High-Resolution K-Auger Spectra for Multiply Ionized Neon*

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K-Auger transitions of neon produced by 33-MeV O^{5+} bombardment are clearly resolved above a broad peaked background. Besides the 5 normal transitions, we observe 58 satellite lines stemming from initial configurations having single K-shell, multiple L-shell vacancies. Transition energies and relative intensities are measured and compared with those obtained with 1.5-keV electron bombardment. Calculated energies for Auger satellite transitions are used to give possible identifications for observed lines.

The subject of multiple inner-shell ionization produced by heavy-ion–atom collisions has received a great deal of attention in recent years. Summaries of measurements of Auger electrons produced by heavy-ion bombardment are given in review articles.[1-5] With the exception of the O + Ne data of Burch *et al.*,[6] almost all of the previous heavy-ion work has used low-energy bombardment (less than 1 MeV). However, since the data by Burch *et al.*[6] are of low energy resolution, little detail has been obtained about the Auger decay of these exotic multiply ionized atoms. In fact, based on these previous experiments, it had been thought that the increased complexity of the Auger spectrum produced by heavy-ion bombardment would prevent the separation and classification of single Auger lines. Bhalla and co-workers[7,8] have calculated the average energies, absolute transition rates, and fluorescence yields for both K- and L-shell defect configurations of multiply ionized Ne and have stressed the need for experimental verification. Kauffman *et al.*[9] have recently provided the K x-ray energies and relative intensities for O+Ne collisions.

In this Letter we report the first high-resolution measurements of the K-Auger electrons produced by high-energy heavy-ion bombardment of neon. With 33-MeV O^{5+} bombardment, we observed clearly a K-Auger electron spectrum dominated by satellite lines with energies as low as 666 eV. These lines are more than 60 eV lower than any observed in high-resolution e+Ne spectra obtained in our work or in that of Krause, Carlson, and Moddeman.[10] A Hartree-Fock computer program[11] was used to calculate the energies of Auger satellite transitions from initial configurations having single K-shell, multiple L-shell defects. Comparison of measured line energies with these calculated energies enabled us to attribute all of the observed lines to the Auger decay of multiply ionized Ne. Despite the complexity of the spectral features, we measured relative intensities for most of the 63 observed lines.

This experiment was performed using the University of Texas model EN tandem Van de Graaff accelerator. A 33-MeV O^{5+} ion beam at an intensity of 1 μA was directed through a differentially pumped scattering cell having 2-mm-diam entrance and exit apertures. The 10-cm^3 volume of the cell sustained a flowing Ne target gas at a constant pressure (~ 10 mTorr) as monitored by a thermocouple gauge (attached directly to the scattering cell). The thermocouple gauge was carefully calibrated for Ne against a McLeod gauge. A liquid-N_2–trapped, high-speed diffusion pump maintained pressures outside the cell of less than 1×10^{-6} Torr. A double-focusing electrostatic energy analyzer[12] having a mean radius of 36 cm and instrumental resolution of 0.02% full width at half-maximum (FWHM) was used to accumulate Auger spectra at a lab angle of 90°. The 10.2-mm×0.25-mm entrance slit of the spectrometer was mounted directly into one side of the scattering cell. Spectrometer acceptance angles of 0.93° and 28.13° enabled the Channeltron electron multiplier to see 0.40-mm (horizontal) and 6.25-mm (vertical) segments of the beam-target interaction path. Electron-induced spectra were also accumulated using this same geometry, but with an electron gun replacing the Van de Graaff accelerator. An automatic data collection system produced the Auger spectra in a stepwise fashion, a typical step size being 0.011 eV per channel of computer memory. Each step corresponded to a 4.8-mV increment of ΔV across the spheres of the spectrometer. Accumulation time between steps was normalized to integrated beam current and was typically 7–8 sec.

The degree of multiple inner-shell ionization caused by oxygen bombardment of Ne has been observed to vary with the charge state of the in-

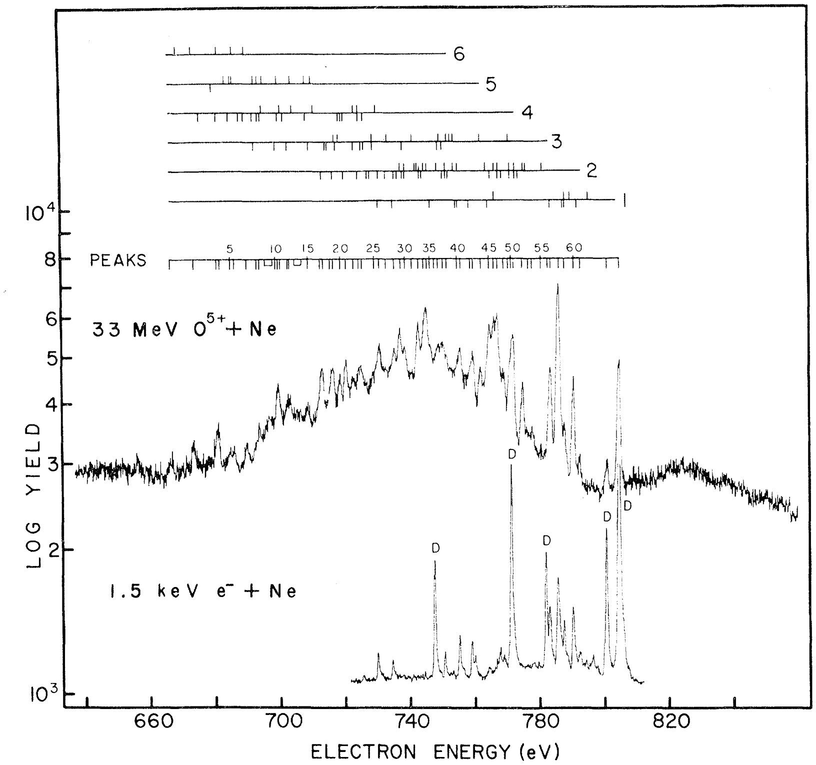

FIG. 1. Comparison of Ne K-Auger spectra produced by heavy-ion and electron bombardment. In the $e^- + \mathrm{Ne}$ spectrum normal or diagram Auger lines are marked "D." The "peaks" number line identifies all transitions resolved in the O + Ne spectrum. The calculated Auger satellite transition energies are shown on the axes which label the number of L-shell vacancies. The placement of energy tick marks *above* a particular L-shell vacancy line denotes a transition from an initial configuration having both $2s$ and $2p$ vacancies. A tick mark *below* signifies that only $2p$ vacancies are present. Note the number of calculated transitions from different configurations which have nearly the same energy as an observed peak. The $e^- + \mathrm{Ne}$ spectrum is plotted on arbitrary log scale. No background was subtracted from either of the displayed spectra.

cident projectile.[9] Charge-changing effects associated with target thickness are therefore important collision parameters. For oxygen bombardment a low pressure (~ 10 mTorr) was used to ensure single collisions in the target. This assumption was verified by a measured linear dependence of electron yield with target gas pressure (1 to 50 mTorr). An over-estimated electron capture cross section of 10^{-16} cm^2 then implies that at most 4% of the beam underwent charge exchange in the target. The gas pressure of ~ 10 mTorr also minimized corrections for characteristic electron energy loss.

Figure 1 presents the basic results of this experiment. It demonstrates that discrete Auger transitions can be observed in energetic heavy-ion–atom collisions. The $e^- + \mathrm{Ne}$ spectrum is included to demonstrate the striking enhancement of satellite production for oxygen as compared to electron bombardment of Ne. As an aid in comparing the two spectra, diagram lines corresponding to $KL_1L_1(^1S_0)$, $KL_1L_{2,3}(^{1,3}P)$, and $KL_{2,3}L_{2,3}(^1S, ^1D)$ transitions are marked "D." The unmarked strong transitions in the $e^- + \mathrm{Ne}$ spectrum are mostly due to single-$2p$-vacancy satellite lines and have been discussed in detail by Krause, Carlson, and Moddeman.[10] The broader energy range of observed transitions for oxygen bombardment is attributable to increased multiple inner-shell vacancy production. High-energy (33 MeV) oxygen bombardment was used to diminish target-atom recoil broadening[1] and Stark broadening[13] effects on the measured peak widths. The natural linewidths of observed peaks could not be extracted because of difficulties in determining the proper spectrometer function.[14] The uncorrected peak width of the $KL_{2,3}L_{2,3}(^1D_2)$ transition was, however, measured to be 0.45-eV

FWHM for electron and 1.03-eV FWHM for oxygen bombardment. In addition to the individual Auger electron peaks observed in Fig. 1, two broad "humps" centered about 750 and 825 eV are evident. The first of these "humps" is tentatively attributed to a superposition of many weak Auger transition lines stemming from single or double K-shell, multiple L-shell ionization. Auger hypersatellites (double K-shell ionization[8]) and K-LX electrons (produced in the population of of $n = 3$ or higher levels by shakeup or K-shell excitation[10]) are possibly responsible for the second "hump."

Figure 1 also demonstrates that classification of Auger satellite lines according to the charge state of the ion (number of L-shell vacancies) is not as simple as in the corresponding x-ray measurements.[9] Since Auger selection rules allow many transitions from the same initial configurations, calculations for the energies of Auger satellite lines are much more complex than corresponding x-ray satellite calculations. Therefore, calculations of average transition energies[8] cannot be used to identify the large number of individual lines observed. However, by computing the electrostatic integrals F^k and G^k (using Slater's scheme[15]), we have extended the calculations of Ref. 8 to give energies for satellite transitions between particular terms of a given initial and final configuration. In this manner we obtained about 150 satellite lines from the initial configurations $1s^1 2s^2 2p^n$ ($n = 1-6$) and over 190 satellites from initial configurations $1s^1 2s^m 2p^n$ ($m = 0, 1$; $n = 1-6$). Calculated transitions whose energies lie near an observed peak are plotted as a function of energy on the corresponding L-shell vacancy line graph. This profusion of calculated lines makes it difficult to identify observed peaks unambiguously. The line graphs clearly demonstrate that there is a considerable degree of overlap among calculated satellite lines from different initial configurations. There is yet a further complication when energy calculations of this type are compared with experimental results. Kauffman *et al.*[9] have reported that the calculated x-ray line energies are consistently

TABLE I. Auger lines for multiply ionized neon.

No.	Energy (eV)	Assignments	I/I_0 (a) (%)	No.	Energy (eV)	Assignments	I/I_0 (a) (%)
1	666.1	111pp	-	33	744.6		41
2	673.3		17	34	745.1		-
3	680.4		17	35	746.3		34
4	680.7		19	36D	747.9	126ss($^1S_0$)	-
5	684.6		10	37	748.6		39
6	686.0		10	38	749.9		-
7	689.7		18	39	751.2		27
8	692.3		11	40	754.4		20
9	693.6		19	41	755.2		40
10	698.7		24	42	758.6		22
11	699.5		34	43	759.2		37
12	699.9		22	44	761.6	114pp	36
13	702.0	123ss	23	45	764.4		108
14	703.1		29	46	765.9		113
15	708.4		15	47	766.8		118
16	712.5		16	48	768.8		50
17	713.0		35	49	770.7	124pp	-
18	715.6		13	50D	771.3	126sp($^1P_1$)	-
19	716.2		34	51	771.7	115pp	-
20	718.4		22	52	774.5	124pp	47
21	720.4	124ss	41	53	776.3		15
22	722.4		15	54	777.6		19
23	724.3		16	55	780.3	115pp	11
24	725.1		22	56D	782.1	126sp($^3P_{012}$)	11
25	729.0		11	57	783.1	125pp	106
26	730.6	125ss	56	58	785.5	125pp	193
27	732.3		17	59	787.5	125pp	40
28	735.1	125ss	40	60	790.3	125pp	74
29	736.9	124sp	75	61	792.1		21
30	738.3		42	62D	800.6	126pp($^1S_0$)	22
31	740.5		-				
32	742.5		73	63D	804.2	126pp($^1D_2$)	100

[a]Peak 63 is I_0. As an example of the notation, $126ss\,(^1S_0)$ implies the configuration $1s^1 2s^2 2p^6$ undergoes a $2s2s$ (KL_1L_1) transition to a $^1S_0$ final state.

smaller than measured values with the discrepancy becoming larger (up to 5 eV) for increasing values of multiple ionization. Calculation of the Auger transition strengths for various L-shell defect configurations (not attempted because of the serious problems discussed by Schmidt[16]) will certainly be necessary to identify these peaks uniquely. Tabulation of our energy calculations will appear in a forthcoming article.

Further results of the experiment are given in Table I. The tabulated energies and relative intensities for O^{5+} + Ne are accurate to within ± 0.15 eV and 10% for strong lines and to within ± 0.5 eV and 100% for lines which are weak or imbedded in complex spectral features. Line identification is given where possible. From the quoted relative intensities the ratio of total Auger satellite yield to total Auger yield is determined to be 0.94. As expected this measure of multiple-ionization probability is considerably higher than the value of 0.21 obtained for electron bombardment[10] and 0.52 obtained for 0.3-MeV H^+ bombardment.[13]

This experiment presents the need for detailed calculation of Auger satellite line energies and intensities. If unique line assignments can be accomplished, the measurement of K-shell fluorescence yields as a function of ion charge state will then be possible.

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