K-shell Auger-electron hypersatellites of Ne†

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The cross section for production of excited Ne ions with double K-shell vacancies is measured by observing the Auger electrons from the decay of these states. A Ne-gas target is bombarded by 1–2-MeV/amu N, O, and F projectiles in various incident charge states. The K-shell Auger hypersatellites are observed only for bare nuclear projectiles. The projectile charge-state dependence, projectile Z dependence, and energy dependence of the cross section suggest K-shell electron exchange as a production mechanism.

I. INTRODUCTION

Auger-electron emission from Ne gas targets bombarded by high-energy heavy-ion projectiles has recently been investigated.[1–4] The observed spectra generally exhibit many peaks at lower energies than the single K-shell vacancy diagram lines. These lines are due to multiple L-shell ionization. Many lines are also observed at higher energies than the diagram lines, and they correspond to Auger electrons from initial states with excited electrons. Even in the highest available energy resolution, the Auger emission lines cannot be completely resolved, because of the large density of closely spaced lines.

We have obtained Ne K-shell Auger spectra from a gaseous target of Ne bombarded by 1–2-MeV/amu N, O, and F projectiles in various incident-projectile charge states. Auger-electron-production cross sections have been deduced; the complete results will be presented in a forthcoming paper. In the present paper we wish to emphasize the observation of a new group of electron lines in the Auger spectra from Ne at approximately 110 eV above the ^1D diagram line. These Auger electrons are identified as coming from transitions involving Ne ions with double K-shell vacancies in the initial state (Auger hypersatellites). The cross section for producing these Auger hypersatellite electrons is presented. The projectile charge-state dependence of the cross section indicates that the double K-shell vacancy initial states are produced only with bare nuclear projectiles. The cross section for production of these states is also found to decrease with increasing energy in the energy range studied. The energy dependence of the cross section is the same as the energy dependence predicted for charge exchange.

II. EXPERIMENT

The ejected electrons are energy analyzed in a cylindrical-mirror analyzer with a 42° acceptance cone.[5] The axis of the cylinder is rotated 132° with respect to the beam axis so that electrons ejected from 90° to 174° in the lab frame are analyzed. This is done to reduce the background associated with collisionally produced electrons and beam Auger electrons which are forward peaked.[6] The energy-analyzed electrons are detected with a channel electron multiplier, and this signal gates a voltage which is proportional to the voltage between the cylinders of the analyzer. This voltage is then processed by a PDP-15 computer with a multichannel pulse-height interface. The voltage between the analyzer cylinders is varied between 200 and 700 V in a triangular wave pattern at a rate of 1 Hz, with typical runs consisting of approximately 4000 cycles. Calibration is accomplished by setting the voltage between the cylinder and then using a pulser to operate the gate. The conversion from voltage between the cylinders to energy of the electrons is determined by the geometry of the analyzer. In all the electron spectra a continuous electron background is present.

The gas pressure in the gas-cell region was monitored by a thermocouple gauge, and it was usually set at 20 mTorr. The absolute pressure does not need to be known accurately, since the cross sections are deduced by normalizing to the electron yield from proton bombardment. The pressure needs to be low enough so that no charge-changing collisions occur before the gas-cell region, and so that a beam ion suffers at most one collision in the gas cell. Doubling the 1-cm gas-cell region, and using a collision cross section of $\pi a_0^2 \cong 9\times10^{-17}$ cm^2, it is estimated that only 12% of the incident ions would suffer a collision in traversing the gas cell with a gas pressure of 20 mTorr. Tests were conducted on Ne using F^{+3} at 3 and 5 MeV, and the proton normalization and Ne K-shell Auger yield were linear, with the gas-cell pressure from 5 to 30 mTorr. The current measured at the Faraday cup for F^{+9} at 24 MeV was measured with the gas in the cell and with the gas pumped out of the cell. No current change could be detected, indicating that there were no large (> 10%) charge-changing effects occurring.

In order to obtain Auger-electron yields, it was necessary to perform a background subtraction. The background above and below the peaks could be fitted satisfactorily with a polynomial or an exponential of a polynomial in the electron energy. Cross sections are deduced by assuming isotropic emission of electrons and normalizing to the previously measured 1.0-MeV proton-induced cross section of Toburen.[7] Details of the apparatus and analysis will be presented in a forthcoming paper.

III. RESULTS

Figure 1 shows the spectra obtained for Ne bombarded by 25-MeV F^{+9} and 2-MeV H^{+}. The instrumental resolution is approximately 1%. The H^{+}-induced spectrum consists primarily of diagram lines,[8] as illustrated, and are similar to previously reported spectra.[9] Several interesting features are seen in the F^{+9}-induced spectrum. The main peak shifts from about 800 to 700 eV owing to multiple L-shell ionization. The lowest energy peak, at approximately 660 eV, is due to the highly ionized Li-like configuration (one K-shell and two L-shell electrons in the initial state), and is seen with a large intensity.[10] There are also intense peaks above the normal Auger lines at approximately 820 and 915 eV.

The variation of the spectra with charge state is depicted in Fig. 2, and shows clearly that the F^{+9}-induced spectrum differs substantially from the F^{+7}- and the F^{+8}-induced spectra. The latter two spectra are similar to previously reported low-resolution Ne Auger spectra produced by 50-MeV Cl bombardment[1] and high-resolution Ne Auger spectra produced by O bombardment.[2] The electron intensity near 820 eV mentioned above is due to single K-shell vacancies plus excitation, and has been observed in previous experiments.[1,4] The major differences that we wish to emphasize in the new data are the following: (1) a peak is present at 915 eV in the F^{+9} spectrum but not in the other spectra and (2) the F^{+9} spectrum shows greater intensity near 750 eV. We tentatively identify these structures as Ne K-shell Auger hypersatellites, which are Auger electrons emitted from initial states of Ne with double K-shell vacancies. Feature (1) is associated with a KLM type of Auger transition from excited Ne with double K-shell vacancies. Ne has no M electrons initially; therefore, the M electron required for the KLM transition must come from excitation during the collision. Feature (2) is associated with a KLL type of Auger transition from Ne with double K-shell vacancies. The spectra for F^{+q} bombardment with $q \leq 8$ do not exhibit these two features. The spectra for N^{+q} and O^{+q} are similar in that these features are present when and only when a bare nucleus is used for a projectile. The Li-like state at 660 eV is also more intense with the bare nuclear projectile. It is expected that initial states with three L-shell electrons and one M-shell electron and states with four L-shell electrons would cascade through the Li-like state by Auger emission. The enhancement of the Li-like state for bare nuclear projectiles is due to this cascading effect, as well as to an increase in multiple L-shell ionization with increasing projectile charge state. The lines in the upper part of the figure are Hartree-Fock[11] energies of the ejected electron from all the initial states with electron configurations $(2p)^n(3p)$ (a total of 114 transitions for $n = 1-6$) and $(2p)^n$ (a total of 20 transitions for $n = 2-6$). Multiplet splittings are included, and the solid bars indicate a large density of closely spaced initial spin states. Many more K-shell Auger hyper-

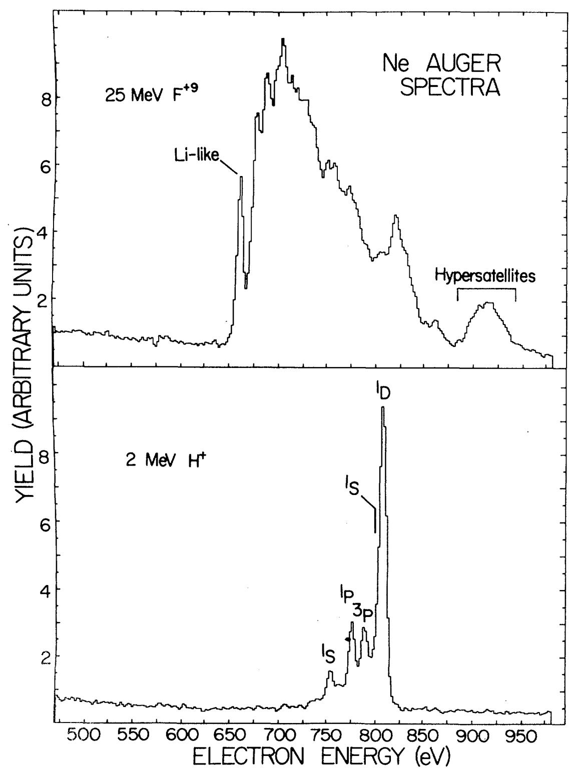

FIG. 1. The four peaks in the H^{+}-induced spectrum are the partially resolved diagram lines and indicate the experimental resolution. The peak labeled ^3P contains intensity from KL-L^3 transitions as well as the diagram line. The 25-MeV F^{+9}-induced spectrum indicates the excitation of Auger electrons at energies both above and below the diagram lines. The lowest energy peak, at approximately 660 eV, is due to the Li-like initial configurations $1s2s^2$ and $1s2s2p$. The Auger-electron group (hypersatellites) centered at 915 eV arises from double K-shell vacancies plus excitation.

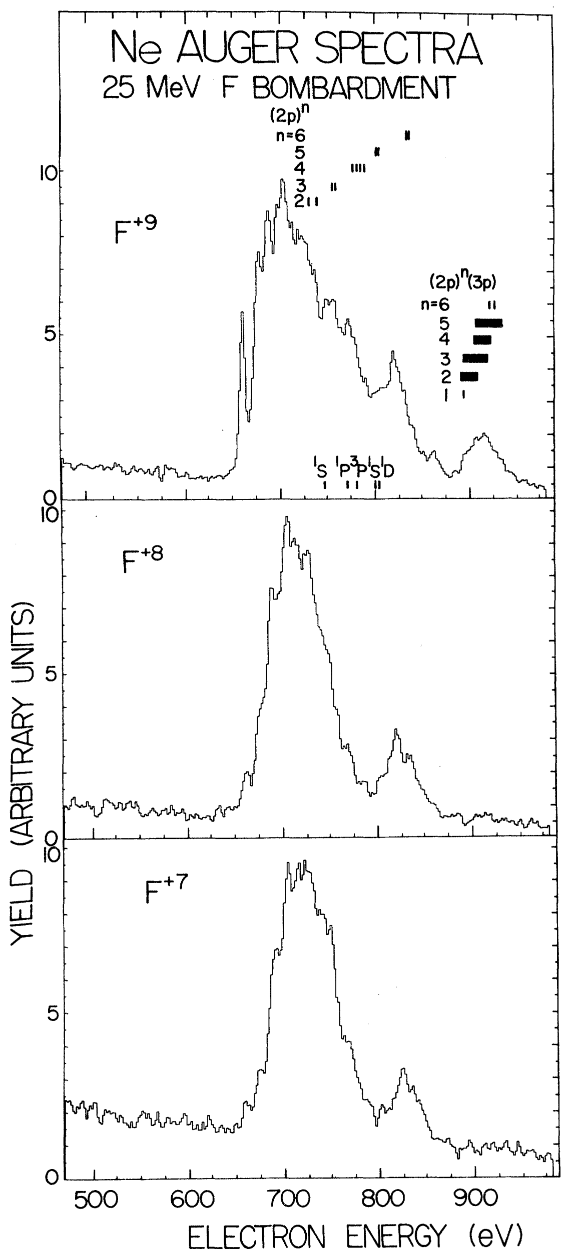

FIG. 2. Projectile charge-state dependence of Ne Auger electrons by F at 25 MeV. The hypersatellite peak at 915 eV is present only in the F^{+9} case. The calculated positions for $2p^n3p$ initial configurations are shown. The spectrum filling near 750 eV is attributed to hypersatellite Auger electrons from the initial configurations $(2p)^n$, as shown. The intensity of the Li-like configurations is also dramatically increased for the F^{+9} case.

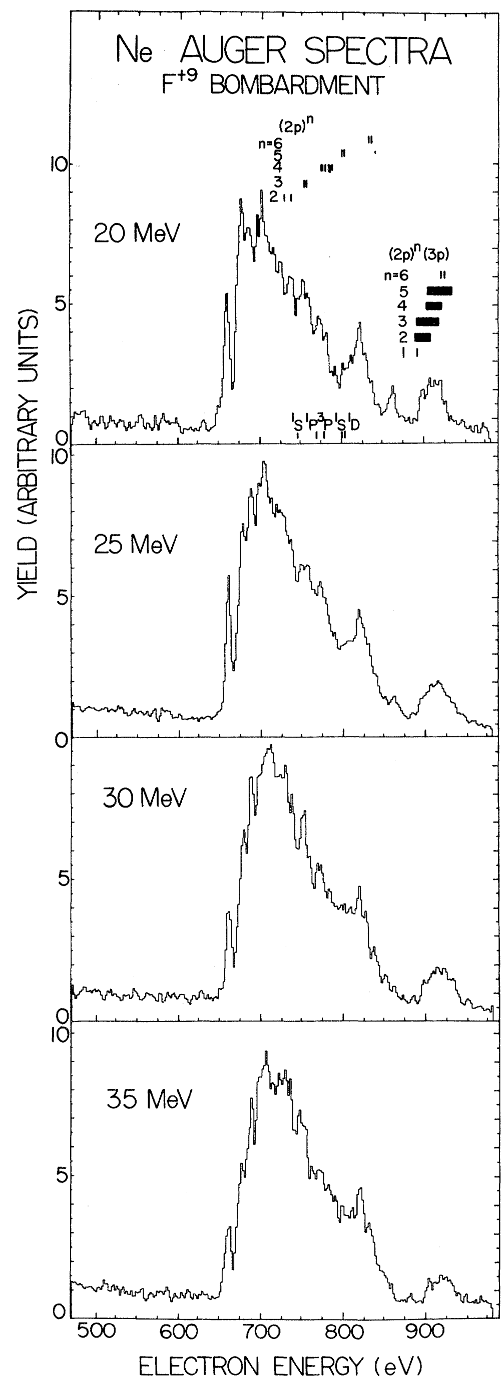

FIG. 3. Energy dependence of the Ne K-shell Auger-electron spectra for F^{+9}projectiles from 20 to 35 MeV. The calculated hypersatellite energies are depicted as in Fig. 2. The hypersatellite-plus-excitation peak at 915 eV is decreasing in intensity as the energy increases. The intensity of the Li-like peak at 660 eV is also decreasing as the energy increases.

satellites are possible for states with 2*s* electrons; however, it is expected that the energies will depend mainly on the number of *L*-shell electrons in the initial state. These are not illustrated in Fig. 2, but add tremendously to the density of allowed transitions.

Figure 3 shows the F^{+9}-induced Ne *K*-shell Auger spectra for various energies. It is clear that the peak centered at 915 eV is decreasing with increasing energy. It should also be noted that the Li-like peak is also decreasing with increasing energy. Figure 4 displays the measured *K*-Auger-electron-production cross section as a function of energy for F^{+9}-Ne collisions. The total Auger-production cross section in the energy range 20–35 MeV is constant, as indicated by the dashed line. The excitation cross section for the *K*-Auger hypersatellites decreases by a factor of 2 over this same energy range. The solid line represents a renormalized Brinkman-Kramer[12] energy-dependence prediction for electron capture into the projectile *K* shell from the target *K* shell. The ob-

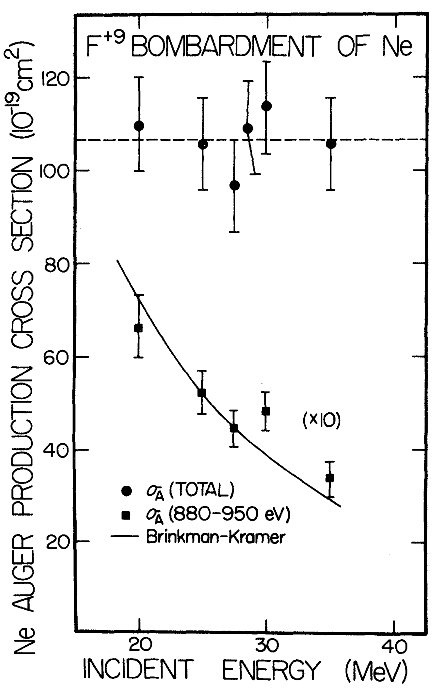

FIG. 4. Total *K*-shell Auger-electron cross section (●) and partial cross section for exciting the hypersatellites centered at 915 eV (■). The latter is multiplied by 10 in the figure for clarity. The absolute accuracy is about 30% and the energy dependence is accurate to 10%, as shown. The solid curve is the Brinkman-Kramer calculation for electron capture into the *K* shell of the projectile from the *K* shell of the target, normalized at 25 MeV. The dashed line indicates the trend of the total *K*-shell Auger-production cross section.

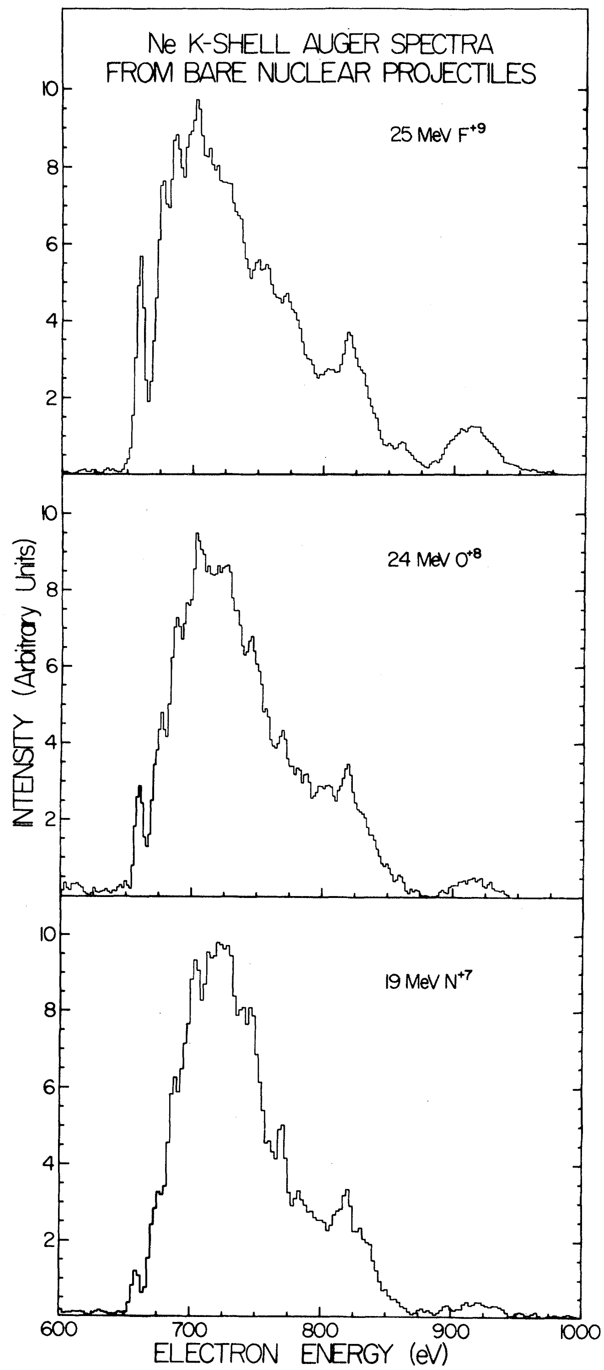

FIG. 5. Projectile dependence of the Ne *K*-shell Auger spectra for bare nuclear projectiles of N, O, and F. A background of the form of an exponential of a polynomial in electron energy has been subtracted from all three spectra.

served energy dependence closely follows the theoretical Brinkman-Kramer prediction for K-electronic exchange.

The Ne Auger spectra for bare nuclei of N, O, and F are given in Fig. 5. In these spectra, a continuous electron background of the exponential form, as discussed in Sec. II, has been subtracted.

Table I gives the measured Auger-electron-production cross sections by bare nuclear projectiles for the electron energy range of 850–950 eV. Also given is the Brinkman-Kramer[12] prediction for target K-shell to projectile K-shell electron exchange. The absolute theoretical cross section and values, normalized to the 880–950-eV cross section for F^{+9} at 25 MeV, are given. The F^{+9} energy dependence is predicted, as discussed previously. The observed N^{+7} and O^{+8} cross sections are approximately 50% lower than the F^{+9} cross section for matched velocities. The calculated cross sections also fall off, but less rapidly.

It is not possible to deduce the average fluorescence yield for the double-vacancy states reported here, since the x-ray yields have not been measured. Experiments have been performed in which Ne x-ray emission from heavy-ion bombardment is used as a measure of relative multiple-vacancy production by using curved-crystal spectrometers.[13-15] These x-ray spectrometers have enough resolution to separate the double K-shell vacancy hypersatellite x rays from the single K-shell vacancy satellite lines. F-projectile x rays overlap the Ne hypersatellite x rays, which prevents accurate determination of the x-ray hypersatellites for this case. For the case of N and O bombardment, the yield is relatively small, making it difficult to obtain enough intensity to do a detailed study. When Cl is used as a projectile,[15] the hypersatellite x rays are clearly observed; however, most of the hypersatellites x-ray intensity comes from H-like initial states. The KLM hypersatellite Auger-electron transitions are not observed in the electron spectra with Cl bombardment,[1, 16] though bare nuclear Cl^{+17} has not been used as a projectile.

IV. CONCLUSION

In conclusion, we observe a dramatic difference in the Auger spectra of Ne when bombarded with bare nuclear projectiles as compared to projectiles with one or more electrons. The difference is additional structure from KLM and KLL hypersatellites in the Ne Auger spectra with bare nuclear projectiles. The energy dependence of the hypersatellite production with F projectiles suggests a K-shell electron-exchange mechanism, since the observed cross section is decreasing with increasing projectile energy in the region studied. The charge-state dependence indicates that it is necessary to have two K-shell vacancies in the projectile in order to produce an appreciable amount of hypersatellite intensity. This also suggests that K-shell electron exchange is the mechanism for producing double K-shell vacancies in these collisions. We suggest that the excited states observed are produced by a capture mechanism that should be peaked about symmetric Z collisions with bare nuclear projectiles. A thorough analysis of fluorescence yields for ion-atom collisions involving bare nuclear projectiles should contain the consideration of Auger hypersatellites. Approximately 5% of the total Auger-electron production cross section of Ne by F^{+9} is in the KLM-

TABLE I. Cross sections for the production of Ne K-shell Auger hypersatellites in the 880–950-eV electron energy range.

Projectile	Energy (MeV)	σ_A (10^{-19} cm^2) [a] (observed)	σ_{BK} (10^{-17} cm^2) [b] (calculated)	σ_{BK} (10^{-19} cm^2) [c] (normalized)
F^{+9}	20.0	6.6	9.06	7.32
	25.0	5.2	6.49	5.24
	27.5	4.4	···	···
	30.0	4.8	4.83	3.90
	35.0	3.4	3.69	2.98
O^{+8}	24.0	2.2	4.71	3.80
N^{+7}	14.0	···	6.69	5.40
	19.0	2.4	4.10	3.31

[a] The absolute error in the cross section is about 30%, whereas the relative error is about 10%.

[b] Brinkman-Kramer prediction for K-shell-to-K-shell electron exchange.

[c] These are renormalized Brinkman-Kramer calculations to fit the 25-MeV F^{+9} hypersatellite cross section.

type hypersatellite production as given in Table I. In addition, the unresolved *KLL*-type hypersatellite production, which fills in the F^{+9} spectrum near 750 eV electron energy, is estimated to be 15% of the total Auger-electron-production cross section. The estimate is obtained by subtracting the F^{+8} spectrum from the F^{+9} spectrum.

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