Ne K Auger electron emission following high-energy Ne^{9+} and Ar^{9+} ion impact on Ne

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The production of Ne K Auger electrons is investigated in fast heavy-ion—atom collisions with the use of gas target and Ne^{9+} and Ar^{9+} ions ranging in energy from 3 MeV/amu to about 15 MeV/amu. In particular, the projectile energy dependence of multiple L-shell ionization in Ne is compared to previous results from heavy-ion—atom collisions covering a projectile energy range from 1.2 MeV/amu to about 3 MeV/amu with atomic numbers varying between 8 and 18. The proposed linear relationship between the mean number of multiple ionized outer-shell electrons and the centroid energy of the corresponding Auger spectra is confirmed. The scaling behavior of the multiple ionization in Ne as a function of projectile energy and atomic number is investigated. It is found that the degree of multiple outer-shell ionization can be represented by a universal curve over a wide range of projectile energy and species.

I. INTRODUCTION

The emission of K Auger electrons and K x rays from Ne gas targets has been studied extensively for a large variety of collision systems (e.g., see Ref. 1 and references quoted therein). Electron, protons,[2,3] and a variety of heavy ions[1,4–10] up to uranium[4] have been used as projectiles. It has been shown that measurements of Auger electron spectra[5,11,12] with high-resolution are useful if the collision system is chosen such that kinematic line-broadening effects and line blending are negligible. This is achievable for very heavy projectile ions at sufficiently high velocities. From those measurements detailed information regarding the atomic structure of highly excited and ionized atoms (few-electron systems) have been obtained.[8,11]

Furthermore it has been shown that the combination of high-resolution x-ray and Auger electron measurements yield quantitative results for the Ne K fluorescence yields as a function of the outer-shell charge state[12] which can be directly compared to theory.[13] In addition, information on the population of specific multiplets or on possible cascade feeding processes[14] can be obtained. These studies indicated the need for systematic investigations on multiple-ionization processes. Systematic studies based on measurements of satellite line intensities in high-resolution K x-ray spectra produced in various collision systems have been reported by several authors previously.[15–17] A universal scaling function based on the binary encounter approximation (BEA) and plane-wave Born approximation (PWBA)[15,18] was introduced and used to interpret the experimental data.

Figures 1(a)–1(d) represent a comparison between two previously measured[3,19] Ne K Auger electron spectra and present data from collisions with 85-MeV Ne^{5+} and 200-MeV Ne^{7+}. The intrinsic instrumental energy resolution was about 0.4% FWHM for all cases. In all four cases the broadening effects due to the collision kinematics[10] are small compared to the intrinsic resolution. It was shown that, for collisions with sufficiently fast heavy ions (tandem energies), it is possible to study the target Auger electron emission with high-energy resolution[5,8,12,14] such that spectroscopic assignments are possible. The peak structure in the various spectra consists, in general, of many overlapping satellites and diagram lines. Satellite lines are caused by the ionization of the outer shell (for the present case the Ne L shell), simultaneous with ionization of the inner shell. The outer-shell ionization is represented by the mean number of L vacancies $\bar{n}=8p$, where p is the one-electron probability for the removal of an L-shell electron by the projectile passing through the K-shell radius. It is possible to determine $\bar{n}$ by measuring the Auger spectra centroid energy $\bar{E}$.[1,2]

For fast light ion and electron impact [e.g., 4-MeV H^+, Fig. 1(a)] identical Ne K Auger spectra were reported.[3] Those spectra consisted mainly of diagram lines, hence the multiple ionization is very

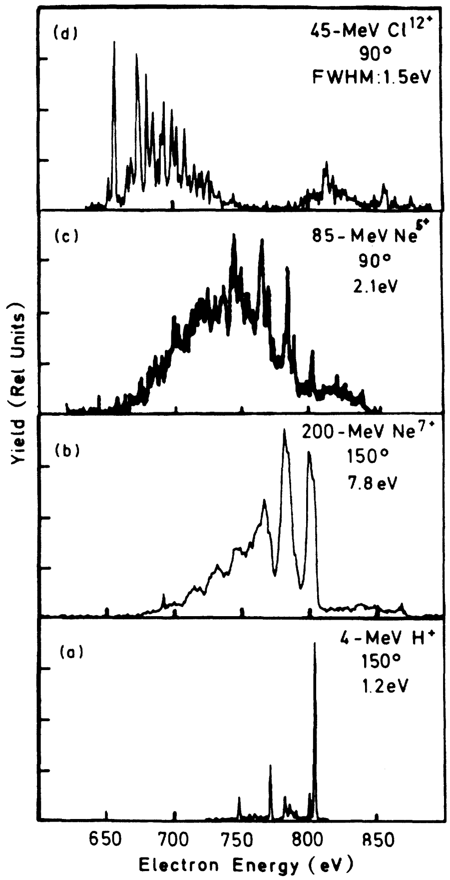

FIG. 1. Comparison of Ne K Auger electron spectra as produced in various collision systems. (a) 4-MeV H^+ on Ne, see Ref. 3; (b) 200-MeV Ne^{7+} on Ne (present data); (c) 85-MeV Ne^{5+} on Ne (present data); (d) 45-MeV Cl^{12+} on Ne, see Ref. 19. Spectra (c) and (d) have been measured with an electrostatic spherical electron analyzer (McPhearson Company) at 90° observation angle. Spectra (a) and (b) have been measured with an electrostatic parallel-plate analyzer at 150° observation angle.

small, about 0.2 (multiple ionization due to shake off) in this case.[3] However, for collisions with protons at energies below 600 keV,[20] an increase in multiple ionization causing many overlapping satellite lines is observed.

Collisions with very heavy projectiles with energies below 1.5 MeV/amu (e.g., Ar, Xe, or U) showed simplification of the spectral structures.[8,19] Only a few well-separated and identifiable lines remained in some spectra.[8] The spectrum in Fig. 1(d) is an example in which the target is highly ionized with only three to four electrons left[14] in the initially formed configurations and fewer Auger transitions are possible. Information concerning the atomic structure, as, e.g., the population of different multiplet terms, have been deduced and compared directly to theoretically predicted transition rates.[13]

We report measurements for Auger electron spectroscopy involving fast Ne^{9+} and Ar^{9+} projectile ions with energies between 3 and 15 MeV/amu. From the highly resolved Auger spectra, the degree of multiple ionization is obtained as a function of the projectile velocity; the previously suggested[1] linear dependence between $\bar{n}$ and $\bar{E}$ is examined and compared to previously reported scaling functions concerning the projectile energy and projectile Z dependence.

The experimental setup is described in Sec. II and the experimental results are presented in Sec. III. In Sec. IV the experimental results are discussed and compared to previous results and systematics concerning the multiple outer-shell ionization. In Sec. V summarizing conclusions are drawn.

II. EXPERIMENTAL

The 60–290-MeV Ne^{9+} and Ar^{9+} ion beams were produced in the new heavy-ion accelerator facility (VICKSI) at the Hahn-Meitner-Institut at Berlin. The accelerator is a combination of a 6-MV single-stage Van de Graaff accelerator as an injector for a four-sector split-pole-type cyclotron[21] with an energy gain of a factor of 17.

The incident ion beam of about 100-particle nA, focused to a 2-mm spot size, was crossed with an atomic neon-beam target, with a density times thickness product of approximately 5×10^{-3} Torr(3mm). The pressure a few centimeters away from the scattering center near the electron spectrometer was a few times 10^{-5} Torr. The pressure in the beam line was about 10^{-6} Torr during the experiment. Electrons emitted from the scattering region were measured by an electrostatic parallel plate analyzer having an intrinsic resolution of 7.8% FWHM that could be improved by using the analyzer in a deceleration mode.[10] Some of the high-resolution measurements have been performed with a McPhearson spherical electron analyzer (see Ref. 5) with higher transmission; the spectrometer was mounted at 90° observation angle. The crossed-beam apparatus has been described in more detail previously.[10,20,22] The electron observation angles were 150° and 90° in order to keep the continuous electron background small. In addition, care had to be taken[23] to avoid background caused by nuclear reactions since highly resolved Ne K Auger spectra in collisions with Ne^{9+} and Ar^{9+} projectile ions were measured at energies above 4 MeV/amu. Therefore, no beam skimming collimation system could be used at the entrance or exit of the target chamber and the beam stop had to be positioned several meters away from the target region. Quartz plates could be inserted in the scattering chamber and observed by TV cameras for aligning and focusing of the beam. In addition, a 2-mm diameter aperature could be inserted at the scattering center to control the beam size at the scattering center.

III. RESULTS AND DISCUSSION

Figures 1(b) and 1(c) show Ne K Auger spectra obtained in the present experiment as compared to previous work [Figs. 1(a) and 1(d)].[3,19] Large numbers of Auger transitions take place and make the spectra rather complex; most peaks in the spectra consist of many satellite lines. However, the present spectra still show some identifiable intensity from normal lines, as seen for 200-MeV Ne^{7+} on Ne. The peak at 780 eV is mainly due to satellite lines associated with a singly ionized L shell, while the peak at 805 eV is due to the well-known $KL_{23}L_{23}\,{}^1D_2$ diagram line. The peak structure extends to electron energies where lines from four electron systems would appear.[8,11,25,9] Intensities at those low electron energies have not been observed in Ne K Auger spectra produced by protons with comparable velocities. This indicates a more effective outer-shell ionization if a projectile with higher Z is used. Figure 1(c) shows a highly resolved spectrum from 85-MeV Ne^{5+} on Ne. There the satellite line intensities are even more enhanced, indicating an even higher degree for multiple ionization. The diagram line at 805 eV is still visible.

A previously introduced method has been applied to deduce the degree of outer-shell ionization ($\bar{n}$) from the centroid energy of the measured Ne K Auger spectra. The method is based on the assumption that the probability q_n for the production of n L-shell vacancies is given by a binomial distribution

$$q_n = \binom{8}{n} p^n (1-p)^{8-n} , \qquad (1)$$

where p is the one-electron-ionization probability. The parameter p can be calculated if one of the quantities q_n is known. Using the resolved diagram line at 805 eV and, independently, the first satellite group at 780 eV in the present spectra almost identical p values were determined. Then the mean number of ionized outer-shell electrons is given as $\bar{n}=8p$. Similarly, $\bar{n}$ values for 30-MeV O^{5+} and 4.2-MeV H^+ on Ne have been obtained as given in Ref. 1. Also, for 45-MeV Cl^{12+} the intensity of the Auger lines (e.g., $1s\,2s\,2p\,4p$) from Li-like Ne have been used to determine q_6 and, thus, $\bar{n}$. These $\bar{n}$ values are compared to the mean Auger electron energy $\bar{E}$ which is defined as

$$\bar{E} = \frac{\int E I(E) dE}{\int I(E) dE} , \qquad (2)$$

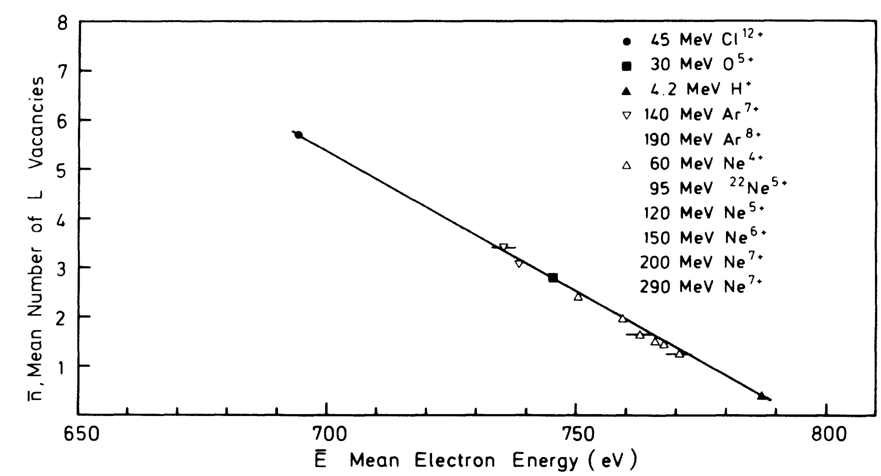

FIG. 2. Mean number $\bar{n}$ of L vacancies as a function of Auger centroid energy $\bar{E}_c^{0.1}$. The data are based on the Auger spectra which have been reported in Refs. 1, 3, 12, and 19.

where $I(E)$ is the intensity in the electron spectrum at the electron energy E. Figure 2 shows the mean number $\bar{n}$ of L-shell vacancies (also tabulated in Table I) as a function of the mean electron energy $\bar{E}$ for the present collision systems together with three points of Ref. 1. Within experimental errors all data points confirm the linear dependence between $\bar{n}$ and E.

Recently three systematic studies[15–17] concerning the probability for multiple ionization of L- and M-shell electrons in various collision systems have been performed by studing satellite line intensities in high-resolution x-ray spectra. As a result, universal scaling functions for multiple outer-shell ionization have been introduced. Schmiedekamp *et al.*[15] have investigated the Ar K x-rays with respect to the projectile species (Z_p) in a range of $1-17$ with energies betwen about 0.8 and 5 MeV/amu. They used a universal scaling function for the mean number of multiply ionized L-shell electrons ($\bar{n}$) based on the BEA and PWBA. According to their work[15] the relationship for the multiple L-shell ionization in Ne is

$$\bar{n}=\frac{4Z_p^2}{I_L^2 R_L^2 \epsilon^2} G(V\epsilon^{-1/2}) \,, \tag{3}$$

where Z_p is the atomic number of the projectile and I_L and R_L are the binding energy and radius for target L-shell electrons. $G(V\epsilon^{-1/2})$ is a universal function of the scaled projectile velocity $V=v_p/v_L$, where v_L is the orbital velocity of the L-shell target electrons. $G(V\epsilon^{-1/2})$ already includes the variation of the orbital velocity due to the increased binding and is tabulated in Ref. 18. ϵ is a velocity-dependent correction term that accounts for a change in the binding energies of the target electrons due to the projectile charge. Schmiedekamp *et al.*[15] determined ϵ from $\epsilon=1+(aZ_p+bZ_p^2)\,G(V)$, where a,b are parameters which were deduced from comparison to the experimental data. $G(V)$ is taken from Brandt and Lapicki[24]; it is also function of the scaled projectile velocity. It should be pointed out that Schmiedekamp *et al.*[15] used the bare nuclear charge for the projectile (Z_p).

A very similar analysis to that of Schmiedekamp *et al.*[15] was recently reported by Awaya *et al.*[17] They investigated systems using He, C, N, and O as projectiles with energies varying between 6 and 8 MeV/amu. A variety of solid targets ($Z<22$) and Ar as a gas target were used. Agreement between experimental data and a calculated universal curve without binding corrections was found. Watson *et al.*[16] performed systematic studies for light-ion bombardment with H^+, He^{2+}, and Li^{3+} ranging in energy from about 0.8 to 5 MeV/amu. They used various solid targets with Z's from 13 to 25 and also Si, S, Cl, and Ar gaseous targets.

The present experiment used comparably thin targets so that the charge state of the incoming projectile ions was more defined. Thus we had to take screening effects on the nuclear charge of the projectile ions into account in our analysis.

The screening of the nuclear charge of the pro-

TABLE I. Impact parameters (Massey criterion), mean charge states $\bar{n}$ in the target, effective nuclear charges $Z_{\rm eff}^p$, and binding corrections for various collision systems.

Projectile (energy MeV)	V_p Projectile velocity (a.u.)	$\bar{b}$ Impact[a] parameter (a.u.)	$Z_{\rm eff}^p$ Effective proj. (large)	ϵ Binding correction	$\bar{n}$ Mean charge state
O^{5+}(30)	8.66	0.15	7.24	1.16	2.9
F^{7+}(25)	7.27	0.14	8.17	1.22	4.15
Ne^{4+}(60)	10.9	0.16	8.89	1.17	2.4
Ne^{5+}(85)	13.72	0.19	8.69	1.14	1.92
Ne^{5+}(120)	15.42	0.20	8.53	1.12	1.48
Ne^{5+}(150)	17.24	0.22	8.39	1.10	1.48
Ne^{7+}(200)	19.91	0.25	8.28	1.09	1.44
Ne^{+}(290)	23.97	0.3	8.12	1.07	1.24
Ar^{12+}(56)	7.49	0.14	16.11	1.66	5.8
Ar^{7+}(140)	12.65	0.17	15.87	1.42	3.44
Ar^{8+}(190)	13.8	0.19	15.64	1.35	3.04

[a](Massey criterion: $\bar{b}=V_p/E_A$, E_A is excitation energy.)

jectile ions depends sensitivity on the impact parameter which can be estimated from the Massey criterion[25] ($\bar{b}=V_p/E_A$). The average kinetic energy E_A transferred to a K-shell electron has been estimated from calculations based on the bindary encounter approximation (BEA) from singly differential cross sections. $\bar{b}$ values for the different collision systems are given in Table I. Using these mean impact parameters the screening effect on the projectile ions and hence Z_{eff}^{p} could be deduced (Table I). This was done by applying a model which has recently been introduced by Toburen *et al.*[26] In this model an integration of the electron density up to a certain atomic radius R is performed, which gives the total charge inside a sphere with the radius R. This total charge $S_i(R)$ was subtracted from the bare nuclear charge Z_p to obtain a Z_{eff}^{p}. For hydrogenic wave functions the $S_i(R)$ are analytic functions. The relationship for evaluating Z_{eff}^{p} for individual shells is given as

$$Z_{\text{eff}}^{p}=Z_p-\sum_i N_i S_i(R)\ , \tag{4}$$

where N_i is the number of electrons in that shell. The obtained Z_{eff}^{p} are given in Table I and used to compare the experimental data on the multiple ionization in Ne (Fig. 3) to a modified scaling function given as

$$\bar{n}=\frac{4Z_{\text{eff}}^{2p}}{I_L^2 R_L^2}G(V\epsilon^{-1/2})\ . \tag{5}$$

I_L and R_L are the L-shell binding energy and radius. The experimental data and the universal curve are plotted in Fig. 3 versus projectile velocities. The graph shows good agreement for collisions with 150- and 190-MeV Ar^{n+} and 60–95-MeV Ne^{+} on Ne. Discrepancies are found in general for very fast projectile ions.

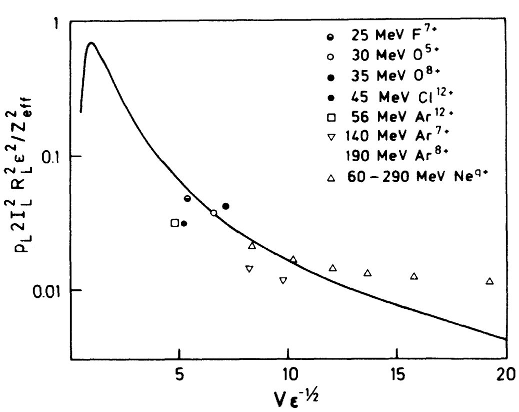

FIG. 3. Scaled probability for multiple L-shell ionization plotted vs a scaled projectile velocity. The solid line is the universal BEA function for ionization $G(V\epsilon^{-1/2})$.

V. CONCLUSION

In this publication the projectile species, charge state, and energy dependence of previous and new experimental data on Ne K Auger electron emission is investigated. The study covers a projectile energy range varying from 1.2 to 15 MeV/amu with atomic numbers ranging from 8 to 18. It is confirmed that there is a linear dependence between the mean number $\bar{n}$ of L-shell vacancies and the centroid energy $\bar{E}$ of Auger electron spectra for the case of Ne.

Previously Schmiedekamp *et al.*[15] have shown that up to energies of 2.5 MeV/amu a scaling of the multiple outer-shell ionization probability can be fairly well described within the BEA. For the collision systems investigated here, the introduced scaling function is used to predict the degree of multiple inner-shell ionization as a function of projectile atomic number and velocity. Evidence was found that binding corrections for the target electrons as suggested by Schmiedekamp *et al.*[15] are necessary and effective nuclear charge for the projectile charge should be used in the scaling function. The experimentally determined and scaled probability for the multiple outer-shell ionization roughly follow a universal curve. The present work shows that up to 6 MeV/amu the scaling function based on the BEA is still valid even for projectiles which are slightly heavier than the target.

For energies higher than 6 MeV/amu the agreement between the universal curve and the experimental data scaling breaks down. The reason for the discrepancies is unknown. Here it should be noted that at these high velocities the mean impact parameter becomes increasingly larger than the K-shell radius. Thus, it may be that the assumptions underlying the scaling function are no longer valid.

In summary, we would say that further theoretical and experimental studies on the mechanism responsible for the creation of highly ionized atoms in fast heavy-ion atom collisions are necessary, e.g., by studying some other target atoms systematically and by investigating the projectile charge-state dependence.

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