Selective production of Li-, Be-, and B-like K vacancy states in fast Ne projectiles studied by zero-degree Auger spectroscopy

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High-resolution measurements of Ne K Auger electrons have been performed using multiply charged ^{20}Ne projectiles in collisions with He, CH_4, and Ar at impact energies of 70 and 100 MeV. Kinematic line-broadening effects were substantially reduced by observing the electrons at 0° with respect to the beam axis. For the He-gas target the outer-shell electronic configuration of the incident ions is essentially retained during K-shell ionization. Thus, B-, Be-, and Li-like electron configurations were selectively produced for incident ions of Ne^{4+}, Ne^{5+}, and Ne^{6+}, respectively. For target gases CH_4 and Ar, Li-like lines are found to be strongly excited, independent of the initial charge state of the projectiles.

I. INTRODUCTION

In collisions between heavy particles the ionization of an inner-shell electron is usually accompanied by the ejection of several electrons from the outer shells. Satellite lines resulting from various multivacancy states can be studied with high resolution to provide a better understanding of the excitation mechanisms involved. High-resolution Auger spectroscopy, extensively applied in recent years to the study of energetic ion-atom collisions, has been very successful in providing detailed information on the production of such multivacancy states in low-Z particles as described in previous review articles by Rudd and Macek,[1] Stolterfoht,[2] and Mann *et al.*[3] In particular, there has been great interest in the study of highly ionized target atoms, especially noble gases such as Ne, produced in heavy-ion—atom collisions.

However, most target Ne K Auger spectra previously measured have been complicated by line-blending effects as reported by Matthews *et al.*,[4] Woods *et al.*,[5] and Schneider *et al.*,[6,7] Auger energies are affected by the charge state of the excited atom and, if this cannot be selected, a blending of lines from different charge states will occur. It is possible to obtain spectra with distinct lines by using projectiles which are sufficiently heavy so that the target atom is stripped down to only a few electrons, as shown by Stolterfoht *et al.*[8] and Mann *et al.*[9] Then, however, one can only study systems of not more than three or four electrons.

Studies of Auger spectra from Ne projectiles excited by collisions with foils have been made by Schumann *et al.*[10] Electron-ion coincidence techniques were used to specify the charge state of the electron-emitting projectile. However, because of the possibility of multiple Auger or autoionization transitions, the correlation between the charge states of the projectile during the Auger decay and that of the ion subsequently analyzed is not always unique. Moreover, it is known that in beam-foil experiments high Rydberg states are readily populated as discussed in the work of Schneider *et al.*[11] and Bruch *et al.*[12] Transitions from such Rydberg states may repopulate the Auger states of interest. To avoid such problems it is desirable to perform experiments under single-collision conditions using gaseous targets.

Studies of projectile Auger electrons at higher beam energies are difficult, since the Auger lines are significantly broadened by kinematic effects.[1,12–14] The line broadening which is primarily due to the finite acceptance angle of the spectrometer increases rapidly with increasing ion velocity. Hence, high-resolution studies of projectile Auger electrons have been limited to rather low (a few hundreds of keV/amu) incident energies.[15,16]

We avoid such kinematic broadening effects by measuring electrons at 0° with respect to the beam direction.[17,18] The method has recently been described by Itoh *et al.*[19] For projectile electrons observed at 0° with respect to the beam, kinematic line-broadening effects are strongly reduced, permitting high-resolution measurements. In this work, fast projectiles of 70-MeV Ne^{4+} and 100-MeV Ne^{5+} and Ne^{6+} are used together with light target atoms such as He. The collision systems studied here are reversed from those previously investigated in target Auger spectroscopy studies where light projectiles were incident on Ne. Light projectiles (e.g., e^-, p, and He) have the well-known ability to act as a "needle" in selectively ionizing a single $1s$ target electron without disturbing outer-shell electrons. However, this type of target spectroscopy is limited to few-hole configurations.[20,21]

Here, light target atoms are chosen to needle ionize the projectile. The present method of projectile spectroscopy has access to a wider range of electronic configurations, since the charge state of the incident ion can be varied. Thus we studied selectively the electronic configurations of various projectile charge states. Moreover, in the present collision systems the population of Rydberg states is found to be small showing that cascade-free conditions can be secured. Such a cascade-free environment is important to lifetime measurements in beam-foil spectroscopy[22] as well as high-resolution x-ray work for the determination of Lamb shift.[23] Finally, we would like to point out the similarity of this method and the one recently reported by Dillingham *et al.*,[24] who studied individual

configurations of projectiles produced by capture of target electrons.

In Sec. II, the experimental method is described and the data are analyzed. Results and discussion follow in Sec. III. Conclusions are drawn in Sec. IV.

II. EXPERIMENT AND DATA ANALYSIS

The experimental apparatus used in these measurements has been described previously,[7,8] and is shown schematically in Fig. 1. Projectiles of 70-MeV $^{20}Ne^{4+}$ and 100-MeV $^{20}Ne^{5+}$ and $^{20}Ne^{6+}$ were provided by the accelerator facility VICKSI at the Hahn-Meitner-Institute in Berlin. The beam was carefully collimated to about 1 mm in diameter to avoid slit scattering. Typical beam currents of 50 nA were collected in the Faraday cup which was used for normalizing the spectra.

Measurements were performed under single-collision conditions using gaseous targets of He, CH_4, and Ar. The pressure of the beam line before the collision chamber was $\sim 10^{-7}$ Torr. Assuming an upper limit of 10^{-18} cm^2 for the charge-exchange cross sections,[25] it was calculated that less than 1% of the incident particles underwent a charge exchange in the beam line. The target cell had a length of 10 cm with an entrance and exit aperture of 3 mm in diameter. To test single-collision conditions in the target cell, a pressure dependence of the Auger spectra was carried out in the range 10^{-3}—10^{-2} Torr for each gas target. (During operation of the cell the pressure in the target scattering chamber was 10^{-5}—10^{-6} Torr and its effect could be neglected.) In this pressure range the intensities of all the peaks were found to have a linear dependence on pressure and no change in the spectral shape was observed.

Auger electrons were measured at the observation angle of 0° with respect to the beam direction by a spectrometer composed of two consecutive 90° parallel-plate electrostatic analyzers[13,26,27] connected together in a tandemlike arrangement[19] as shown in Fig. 1. The entrance analyzer was used as a deflector to steer the electrons out of the ion beam as well as to suppress background electrons produced along the beam within the spectrometer. The entrance slit of this deflector was 16 cm away from the center of the target cell. Inside the deflector a series of three relatively large apertures with a diameter between 3 and 4 mm ensured the unobstructed passage of the beam. The exit analyzer determined the electron energy with high resolution. Entrance and exit slits of this analyzer were separated by 50 mm and were 1.5 mm by 10 mm wide. To improve the electron-energy resolution the deflected electrons were decelerated in the region between the two analyzers to 70 eV by a retarding electric field.[13] The overall energy resolution of the spectrometer was about 2 eV.

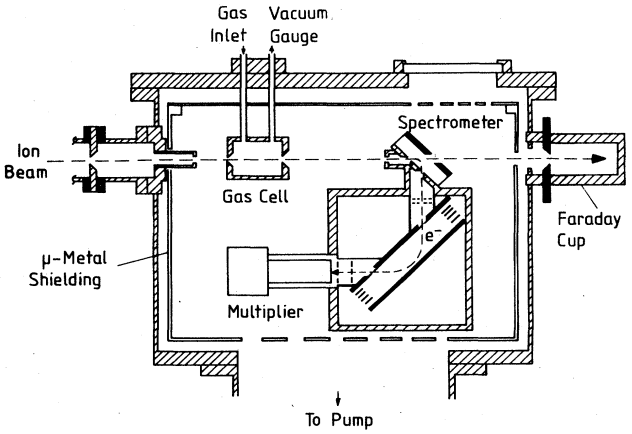

FIG. 1. Schematic drawing of the collision chamber including the target gas cell and the tandem-type electron spectrometer.

The electron acceptance (half-) angle of the tandemlike spectrometer was 1°, which was small enough to substantially reduce kinematic line-broadening effects in the present experiments. At the observation angle of 0° the kinematic broadening arises primarily from the second-order term,[19] since the first-order term being proportional to $\sin\theta$ vanishes.[13] Calculated broadenings for the present collision systems were less than 0.4 eV at full width at half maximum (FWHM). This broadening could be neglected in comparison with the spectrometer resolution mentioned previously.

In these experiments the velocity of the projectile is greater than that of the Auger electrons in the projectile frame. Therefore, electrons emitted with an energy E' in the projectile frame are observed at 0° in the laboratory frame at two different energies[19]

$$E_{H,L}=(t_p^{1/2}\pm E'^{1/2})^2 , \tag{1}$$

where the signs + and − correspond to emission angles of 0° and 180° in the projectile rest frame, respectively. The quantity $t_p=T_p m/M$ is the projectile energy T_p scaled by the electron-to-projectile mass ratio.

The Auger spectra observed in the laboratory frame were transformed to the projectile rest frame by using the following relation for the double differential cross section:[28]

$$\frac{d\sigma'}{dE'\,d\Omega'}=\left[\frac{E'}{E}\right]^{1/2}\frac{d\sigma}{dE\,d\Omega} . \tag{2}$$

In this work only the low-energy (E_L) Auger electrons were measured, corresponding to the ejection angle of 180° in the projectile rest frame [see Eq. (1)]. For 70- and 100-MeV Ne projectiles the electrons were observed in the energy range of 270—340 eV and of 620—730 eV, respectively, corresponding to a range of 640—750 eV in the projectile rest frame. The resolution in the laboratory and projectile frames was about the same (i.e., 2 eV) as the transformation of energies from the laboratory to the projectile rest frame [Eq. (1)] does not appreciably change the energy range.

III. RESULTS AND DISCUSSION

A. Ne^{q+} and He

In Fig. 2 experimental results are shown for 70-MeV Ne^{4+}, and 100-MeV Ne^{5+} and Ne^{6+} incident on a He-gas target. In order to distinguish the spectral components

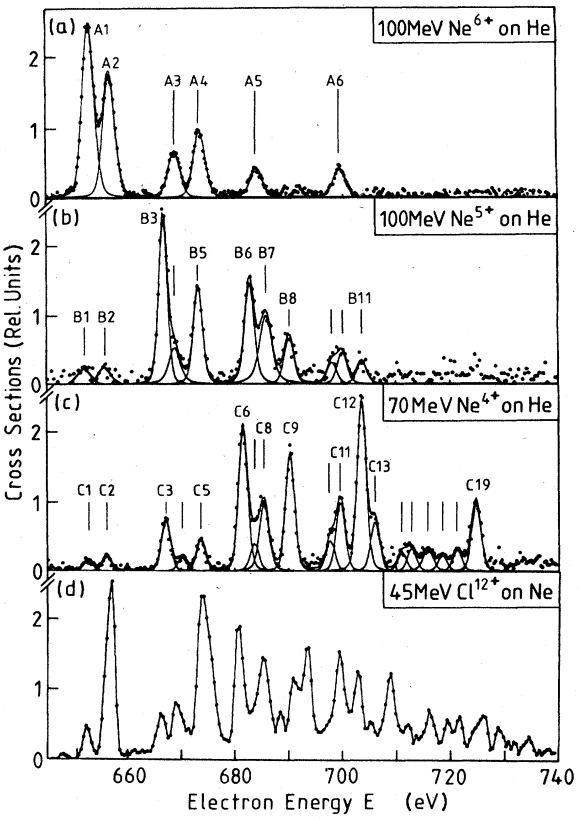

FIG. 2. Ne K Auger electron spectra after background subtraction produced in collisions of ^{20}Ne ions with He target atoms for selected incident charge states of the projectile; (a) 100-MeV Ne^{6+}, (b) 100-MeV Ne^{5+}, and (c) 70-MeV Ne^{4+}. The Ne target spectrum obtained by Schneider *et al.* (Ref. 6) using 45-MeV Cl^{12+} ions is shown in (d) for comparison. The electron energy refers to the emitter rest frame.

more clearly, most Auger peaks were fitted by a Lorentzian curve folded by a Gaussian-type spectrometer response function. The line identification was based on energy comparisons with previous experimental and theoretical studies by Matthews *et al.*[29] and Schumann *et al.*[10] The Auger energies obtained from the fit were presented in Table I together with the previous results.[10,29] It should be noted that the Auger energies for B-like Ne determined here constitute the first measurement of these lines with high resolution.

Before discussing the present results, we would like to point out some of the difficulties which arise in target Auger spectroscopy and which are essentially avoided by performing the present measurements at 0°. The Ne target Auger spectrum shown in Fig. 2(d) was previously obtained using 45-MeV Cl^{12+} ions by Schneider *et al.*[6] The strong Coulomb field induced by the highly charged Cl ion results in the removal of several electrons from the Ne L shell whenever a vacancy is produced in the K shell. This causes the simultaneous production of recoil atoms with different charge states which correspond to Li-, Be-, and C-like electron configurations. The decay of these states gives rise to the line blending observed in Fig. 2(d) at electron energies above 600 eV. In addition, violent collisions may readily populate Rydberg states that can feed metastable Auger states by cascade transitions.[22] Therefore, it is difficult to analyze the Auger states of target spectra. In the discussion that follows it is shown that the method of projectile Auger spectroscopy, which is possible to do with comparable energy resolution at an observation angle of 0°, avoids a great deal of the problems encountered by the Auger spectroscopy of recoil atoms.

1. $Ne^{6+}+He$

The spectrum obtained for Ne^{6+} impact shows relatively simple structures dominated by lines arising from three-electron (Li-like) states. Predominant formation of the Auger state $1s\,2s^{2}\,{}^{2}S$ is observed in this spectrum giving rise to the strongest peak $A1$ [see Fig. 2(a)]. This state is produced by the removal of a single $1s$ electron from the incident electronic configuration $1s^{2}2s^{2}$.

Further prominent lines refer to the Li-like configuration $1s\,2s\,2p$. The peak $A2$ can be attributed to the metastable state $1s\,2s\,2p\,{}^{4}P$. Peaks $A3$ and $A4$ refer to mixtures of the states $1s(2s\,2p\,{}^{3}P)\,{}^{2}P$ and $1s(2s\,2p\,{}^{1}P)\,{}^{2}P$. In principle the configuration $1s\,2s\,2p$ can be produced by different mechanisms. It may be created from the ground-state configuration $1s^{2}2s^{2}\,{}^{1}S$ by the removal of a $1s$ electron and the simultaneous transfer of a $2s$ electron to the $2p$ orbital. The $2s$-$2p$ transition without spin flip could account for the excitation of the $1s(2s\,2p\,{}^{1}P)\,{}^{2}P$ state, while the transition with spin flip for the excitation of the $1s\,2s\,2p\,{}^{4}P$ and $1s(2s\,2p\,{}^{3}P)\,{}^{2}P$ states. However, in the present collision system we expect the probability for such a $2s$-$2p$ transition to be small.

The main indication that the $2s$-$2p$ transition is weak comes from the absence of any line from the configuration $1s\,2p^{2}$. In the spectra of Fig. 2(a) there are no peaks at Auger energies corresponding to the states $1s\,2p^{2}\,{}^{2}D$ and $1s\,2p^{2}\,{}^{2}S$. These states appear rather strongly in foil-excited Ne spectra[10] or in recoil target spectra produced by high-energy heavy ions.[8,30] Therefore the two-electron transition $2s^{2}$-$2p^{2}$ in addition to the removal of the $1s$ electron forming the configuration $1s\,2p^{2}$ from the incident configuration $1s^{2}2s^{2}$ can be considered to be negligible in this collision system.

From the very low probability of the $2s^{2}$-$2p^{2}$ transition one may deduce that the probability for $2s$-$2p$ transitions is small. There is an additional argument; the configuration $1s\,2p^{2}$ may also be formed from the incident metastable state $1s^{2}2s\,2p\,{}^{3}P$ considered further below via ionization of a $1s$ electron and a $2s$-$2p$ transition. Again, the fact that the $1s\,2p^{2}$ configuration is missing shows that the $2s$-$2p$ excitation is small. The excitation of the states $1s(2s\,2p\,{}^{3}P)\,{}^{2}P$ and $1s(2s\,2p\,{}^{3}P)\,{}^{4}P$ from the ground state $1s^{2}2s^{2}\,{}^{1}S$ requires a spin-flip during the $2s$-$2p$ transition. In the excitation of projectiles by low-Z target atoms such as He we would expect such spin-flip processes to be negligible (see also the following). So the $2s$-$2p$ transition which requires a spin flip in addition becomes even more improbable.

Another possibility to create the $1s\,2s\,2p$ configuration

TABLE I. Energies of Ne K Auger lines shown in Figs. 2(a)–2(c). Relative energy uncertainty of this work is ±0.3 eV. The present data are calibrated in energy to the $1s2s^2\,^2S$ line calculated by Schumann *et al.* (Ref. 10).

System				Energy (eV)			
Peak label			Transition	Experiment		Theory	
A	B	C	final — initial	present[a]	a	a	b
Li-*like*							
1	1	1	$1s^2\,^1S$ — $1s2s^2\,^2S$	652.7	652	652.7	656.3
2	2	2	$1s^2\,^1S$ — $1s2s2p\,^4P$	656.5	656	656.3	655.6
3			$1s^2\,^1S$ — $1s2s2p\,^2P$	668.6	669	688.9	668.2
4			$1s^2\,^1S$ — $1s2s2p\,^2P$	673.4	674	673.1	672.3
			$1s^2\,^1S$ — $1s2p^2\,^4P$			673.5	672.6
			$1s^2\,^1S$ — $1s2p^2\,^2D$		682	681.8	681.5
			$1s^2\,^1S$ — $1s2p^2\,^2P$			682.2	682.2
			$1s^2\,^1S$ — $1s2p^2\,^2S$		693	693.3	688.5
Be-*like*							
	3	3	$1s^22p\,^2P$ — $1s2s^22p\,^3P$	667.3	665	667.8	662.4
	4	4	$1s^22p\,^2P$ — $1s2s2p^2\,^5P$	670.3	669	669.9	669.2
	5	5	$1s^22p\,^2P$ — $1s2s^22p\,^1P$	673.8	676	674.5	672.3
	6		$1s^22s\,^2S$ — $1s2s^22p\,^3P$	683.2	683	683.8	678.4
5			$1s^22p\,^2P$ — $1s2s2p^2\,^3D$	684.0		684.9	684.4
	7		$1s^22s\,^2S$ — $1s2s2p^2\,^5P$	684.4	687	686.0	685.1
			$1s^22p\,^2P$ — $1s2s2p^2\,^3P$			686.2	682.8
	8		$1s^22s\,^2S$ — $1s2s^22p\,^1P$	690.6		690.5	688.3
	9		$1s^22p\,^2P$ — $1s2s2p^2\,^3P$	698.6	696	695.8	696.5
6	10		$1s^22s\,^2S$ — $1s2s2p^2\,^3D$	700.5	702	700.9	700.3
			$1s^22p\,^2P$ — $1s2s2p^2\,^1P$			701.3	700.5
			$1s^22s\,^2S$ — $1s2s2p^2\,^1P$			701.6	701.1
	11		$1s^22s\,^2S$ — $1s2s2p^2\,^3P$	704.1		702.2	698.8
B-*like*							
			$1s^22p^2\,^1D$ — $1s2s^22p^2\,^4P$				679.1
		6	$1s^22p^2\,^1S$ — $1s2s^22p^2\,^2D$	681.7			680.0
			$1s^22p^2\,^1S$ — $1s2s^22p^2\,^2P$				681.5
		7	$1s^22p^2\,^3P$ — $1s2s^22p^2\,^4P$	683.8			683.6
		8	$1s^22p^2\,^1D$ — $1s2s^22p^2\,^2D$	685.6			686.7
			$1s^22p^2\,^1S$ — $1s2s^22p^2\,^2S$				686.8
		9	$1s^22p^2\,^3P$ — $1s2s^22p^2\,^2D$	690.4			691.1
			$1s^22s2p\,^1P$ — $1s2s^22p^2\,^4P$				691.4
		10	$1s^22p^2\,^3P$ — $1s2s^22p^2\,^2S$	697.9			697.9
			$1s^22s2p\,^3P$ — $1s2s^22p^2\,^4P$				698.5
		11	$1s^22s2p\,^1P$ — $1s2s^22p^2\,^2P$	699.8			700.4
		12	$1s^22s2p\,^1P$ — $1s2s^22p^2\,^2S$	703.7			705.7
		13	$1s^22s2p\,^3P$ — $1s2s^22p^2\,^2D$	706.2			706.0
			$1s^22s2p\,^3P$ — $1s2s^22p^2\,^2P$				707.5
		19	$1s^22s^2\,^1S$ — $1s2s^22p^2\,^2D$	732.9			723.8

[a]Schumann *et al.* (Ref. 10).
[b]Matthews *et al.* (Ref. 29).

is the simultaneous removal of electrons from the $1s$ and $2s$ orbitals and the capture of an electron from the He target atom into the $2p$ orbital. Thus, also quartet states could be produced. However, we feel that such a complicated three-electron process can be ruled out. This is primarily due to the fact that the probability for electron capture is small at the high incident energies used in these experiments.[25] Indeed, this is further confirmed by our Ne^{5+} + He data discussed in Sec. III A 2.

The formation of the $1s2s2p$ configuration can be partly explained by assuming that the incident beam is contaminated by ions in the metastable state $1s^22s2p\,^3P$. This state may be produced in the stripper foil located between the Van de Graaff injector and the cyclotron of the VICKSI accelerator. Since the $1s^22s2p\,^3P$ state has a long lifetime (the $^3P_0$ has a lifetime of seconds[31]), it sur-

vives the passage through a 20 m beam line and probably also the quenching field of the switching magnet and the cyclotron. The $1s\,2s\,2p$ configuration may easily be created from this metastable state through single $1s$ electron ionization. Intensity comparisons between lines $A\,1$—$A\,4$ in Fig. 2(a), based on the number of final spin states available, indicate that the fraction of metastable particles in the Ne^{6+} beam could be as high as 10%.

The Auger peaks $A\,5$ and $A\,6$ are tentatively assigned to the Be-like configuration $1s\,2s\,2p^2$ as indicated in Table I. This state may be created from the incident metastable state $1s^2 2s\,2p\,{}^3P$ via a $1s$-$2p$ transition. However, this possibility appears questionable; if such a $1s$ electron excitation process is important we would also expect the observation of the state $1s\,2s^2 2p\,{}^1P$ formed by $1s$-$2p$ transitions from the incident ground state $1s^2 2s^2\,{}^1S$. In Fig. 2(a) such a line is not observed [compare with peak $B\,8$ in Fig. 2(b)]. Also, Be-like Auger states may be created when electron capture accompanies the removal of the $1s$ electron. The lowest-lying Be-like excited state, $1s\,2s^2 2p\,{}^3P$, gives rise to the peak $B\,3$ in Fig. 2(b) and is expected to be predominantly populated in our collision system. However, no such peak is observed in Fig. 2(a) indicating that the electron-capture process does not play a substantial role. Hence, the origin of the lines $A\,5$ and $A\,6$ in the Ne^{6+} + He spectrum remains unclear.

2. Ne^{5+} + He.

The most striking feature of this spectrum is the weakness of the first two Li-like lines $B\,1$ and $B\,2$ which are the most prominent peaks in Fig. 2(a). From this feature we conclude that the Li-like contributions are weak and can be neglected in the line analysis of this spectrum. Similarly, there is no clear indication of B-like lines [see e.g., $C\,6$ in Fig. 2(c)] which could be created from the initial configuration $1s^2 2s^2 2p$ via $1s$-$2p$ excitation or the ionization of a $1s$ electron with an additional electron capture process. Again this shows that the process of electron capture into the projectile does not play an important role. Hence, in Ne^{5+} + He collisions Be-like states are produced nearly exclusively. In fact, all Auger lines $B\,3$—$B\,11$ can be attributed to Be-like Ne. Thus, in conflicting cases where Li- and Be-like states are close in energy (within the experimental resolution), the corresponding line is attributed to a Be-like configuration. For example, the peak $B\,5$ is assigned to the Be-like state $1s\,2s^2 2p\,{}^1P$ (decaying to $1s^2 2p\,{}^2P$) rather than to the Li-like state $1s\,2s\,2p\,{}^2P$, see also line $A\,4$ in Fig. 1(a).

In particular, it is noted that the most prominent lines such as $B\,3$, $B\,5$, $B\,6$, and $B\,8$ are found to originate from the configuration $1s\,2s^2 2p$ created by single ionization of a $1s$ electron from the initial state $1s^2 2s^2 2p$ of Ne^{5+}. The other Auger lines ($B\,4$, $B\,7$, and $B\,9$—$B\,11$) are attributed to the configuration $1s\,2s\,2p^2$ created by the ionization of a $1s$ electron accompanied by the excitation of a $2s$ electron into a $2p$ hole. These peaks except for $B\,4$ are probably composed of at least two lines as partly shown in Table I. It is seen that, the intensities of these lines are much weaker in comparison with those which originate from the configuration $1s\,2s^2 2p$. Again, this suggests that the probability for $2s$-$2p$ transitions is small.

Hence, the present results show that the Auger states produced in collisions of Ne^{5+} and He are predominantly created by ionization of a single $1s$ electron. In particular, the absence of B-like lines indicates that the K vacancy is preferentially produced by ionization instead of excitation of a $1s$ electron. The predominance of the ionization process over the excitation process is a well-known tendency in high-energy collisions.[32] Thus, we also expect that in collisions with He atoms, the Ne Auger states are produced under nearly cascade-free conditions.

3. Ne^{4+} + He.

Again, a spectrum is obtained characterized by the initial charge state of the projectiles. Most of the Auger lines observed at electron energies above 680 eV originate from the B-like initial configurations. The identification of each line is difficult, because in the present energy region there are many Auger lines expected from the B-like configurations (see the tables of Auger transition energies by Matthews *et al.*[29]). However, the line assignment is simplified, if one takes into consideration that the configuration of $1s\,2s^2 2p^2$ is expected to be predominantly produced. It is created via ionization of a single $1s$ electron in accordance with the results for Ne^{5+} and Ne^{6+} impact. Thus, in Table I we only show the Auger transitions for the configuration $1s\,2s^2 2p^2$. In particular, the most prominent lines $C\,6$, $C\,9$, $C\,12$, and $C\,19$ are clearly identified. The assignment of the other lines should be considered as being tentative.

In Fig. 2(c) the Li-like lines $C\,1$ and $C\,2$ are also observed. The intensity of these lines is relatively small, so that the influence of Li-like lines can be neglected in practice. Moreover, in Fig. 2(c) the Be-like lines $C\,3$—$C\,5$ are observed with noticeable intensity. Hence, the B-like Auger group especially in the energy range of 680—710 eV is probably mixed with some Be-like lines. By comparing the spectral intensities shown in Figs. 2(b) and (c) the contribution of the Be lines is estimated to be less than 10%, which may still be considered to be a small contribution.

The Be-like configuration $1s\,2s^2 2p$ is probably created by simultaneous ionization of a $1s$ and a $2p$ electron from the ground-state configuration $1s^2 2s^2 2p^2$ Ne^{4+}. This feature is qualitatively different from the result of Ne^{5+} + He where the additional ionization of a $2p$ electron forming Li-like states can be neglected. The origin of the differences observed in the Ne^{4+} + He and Ne^{5+} + He systems may be due to the fact that Ne^{4+} has two $2p$ electrons whereas Ne^{5+} has only one. Also, the binding energy of the $2p$ electrons of Ne^{4+} is smaller than the corresponding values[33] of Ne^{5+} by about 33 eV. Consequently, the additional ionization of the $2p$ level for Ne^{4+} projectiles is expected to be more probable than that for the Ne^{5+} ions.

B. Ne^{q+} + Ar

In Fig. 3 experimental results are shown for 70-MeV Ne^{4+} and 100-MeV Ne^{5+} and Ne^{6+} incident on the target Ar. For Ne^{4+} and Ne^{5+} impact, lines due to Be-like Ne

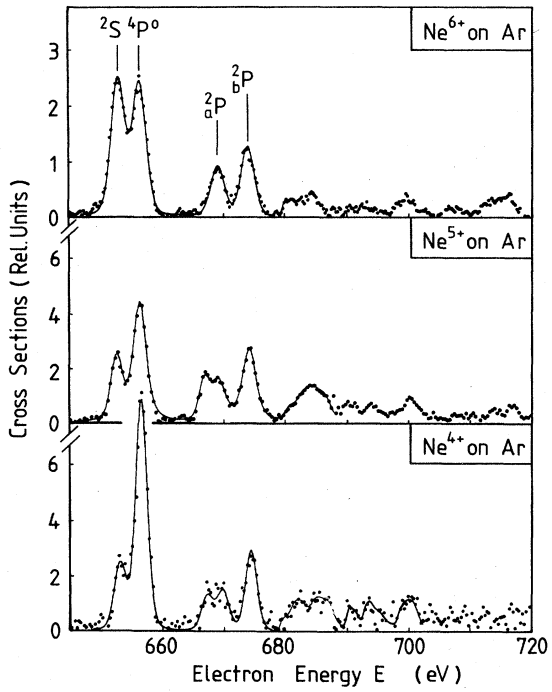

FIG. 3. Ne K Auger spectra after background subtraction produced with Ar target atoms for different incident charge states as indicated.

are observed in the spectra, whereas lines due to B-like Ne are not seen. All the spectra are dominated by the presence of Li-like lines which indicate that K-vacancy production by Ar atoms is accompanied by additional ionization of L-shell electrons. This is in agreement with previous experimental observations of K Auger electrons from Ne target atoms, where the Auger spectra approach the pure Li-like spectrum as the projectile mass increases.[6,8,9]

For Ne^{5+} and Ne^{4+} impact the relative intensities of the Auger lines are nearly the same except for the Li-like line $A2$ arising from the metastable $1s\,2s\,2p\,^4P$ state (see Fig. 2). The origin of the apparent enhancement of the line $A2$ observed in $Ne^4 + Ar$ collisions is not quite clear. In our 0° measurement the spectrometer accepts electrons which are emitted along the beam anywhere between the entrance slit of the target cell and the entrance slit of the spectrometer. Electrons ejected outside the target gas cell are detected more efficiently due to the increase of the solid angle accepted by the spectrometer. On the contrary, electrons ejected after they have gone by the spectrometer cannot be detected. Therefore, the number of detected electrons depends on the lifetime of the Auger state and the projectile velocity. In particular, lines originating from a long-living metastable state such as $A2$ could be affected in intensity. However, the difference in the velocities of 70 and 100 MeV Ne ions is only 15% and cannot account for the factor of 2 change observed in the intensity.

Another possible explanation for this intensity difference in the line $A2$ may be due to cascade transitions from higher excited states. As mentioned previously the high Rydberg states are readily populated in collisions with heavy target atoms such as Ar. We expect that the probability for the production of Rydberg states increases with increasing number of outer-shell electrons. Thus, the Ne^{4+} ions having two $2p$ electrons are expected to be more influenced by the population of Rydberg states than the Ne^{5+} ions which have only one $2p$ electron.

C. Ne^{6+} on He, CH_4, and Ar

Figure 4 compares Auger spectra obtained for Ne^{6+} incident on He, CH_4, and Ar. It is seen that the spectral structures do not vary substantially when the target atom is changed. For the Ar target the peaks at 669 and 673 eV ($A3$ and $A4$) referring to the Li-like states $1s\,2s\,2p\,^2_aP$ and $1s\,2d\,2p\,^2_bP$ are enhanced and additional peaks occur such as that at 681 eV which may be attributed to the Li-like state $1s\,2p^2\,^2D$ (see Table I). These observations show that $2s$-$2p$ transitions in addition to the removal of the $1s$ electron play an important role in collisions with the target atom Ar.

The second peak ($A2$) at 656 eV attributed to the metastable Li-like state $1s\,2s\,2p\,^4P$ increases slightly in intensity, as the atomic number of the target atom is increased. It is recalled that the metastable state $1s\,2s\,2p\,^4P$ could be created by $2s$-$2p$ transitions accompanied by spin-flip. Also, if spin flip would be possible, higher-lying Rydberg states of the $1s\,2snp\,^4P$ series could be populated from the ground-state configuration $1s^22s^2$ via ionization of a $1s$ electron accompanied by a $2s$-np transition and cascade

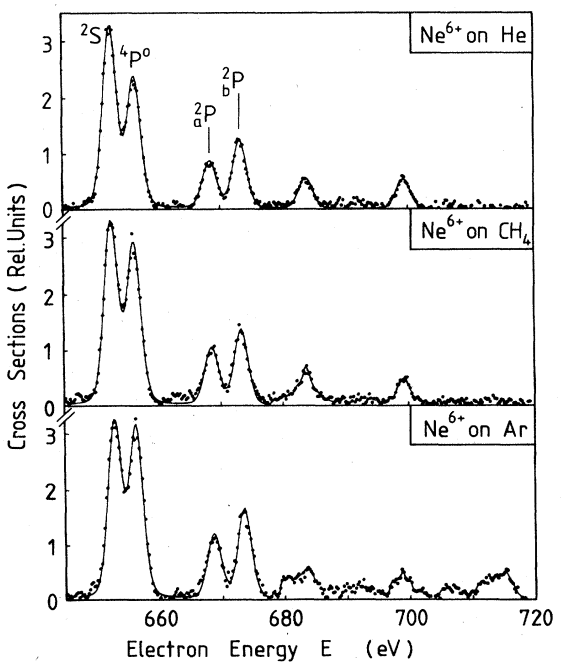

FIG. 4. Ne K Auger spectra after background subtraction produced in collisions of 100-MeV Ne^{6+} ions with He, CH_4, and Ar targets. The data are normalized to equal intensity of the most prominent peak ($A1$) at 653 eV assigned to the Li-like state $1s\,2s^2\,^2S$.

feeding of the state $1s\,2s\,2p\,^4P$ could occur. Then, we would expect a significant enhancement to the $1s\,2s\,2p\,^4P$ line for the heavier targets as already seen in Fig. 3. Such enhancement is not observed in Fig. 4.

Another possibility is that the series $1s\,2snp\,^4P$ may be populated from the metastable state $1s^2 2s\,2p\,^3P$ by removal of a $1s$ electron and an additional $2p$-np transition without spin flip. Since the contamination of the beam by ions in the $1s^2 2s\,2p\,^3P$ state is relatively small only a slight enhancement of the $1s\,2s\,2p\,^4P$ due to cascade feeding is expected. Thus, the increase in intensity of the $1s\,2s\,2p\,^4P$ line with increasing atomic number of the target may be explained.

IV. CONCLUSIONS

In this work, we studied projectile K Auger electrons from fast Ne^{4+}, Ne^{5+} and Ne^{6+} ions in collisions with He, CH_4, and Ar gas targets. High-resolution measurements were performed applying the method of 0° Auger spectroscopy. The measured spectra are composed of lines produced by the ionization of one $1s$ electron from the ground-state configuration of the incident ion. The observation of specific lines such as the Li-like state $1s\,2s\,2p\,^4P$ indicates a contamination of the incident beam by ions in the metastable state $1s^2 2s\,2p\,^3P$.

By using the light target atom He in the experiments, outer-shell ionization was reduced to negligible proportions and selective ionization of the $1s$ electron was achieved. Furthermore, by using relatively high incident energies electron-capture processes by the projectile were diminished. Thus, processes that could change the outer-shell configurations of the incident ions were avoided. Consequently, Li-, Be-, and B-like Auger lines were selectively produced by incident ions of Ne^{6+}, Ne^{5+}, and Ne^{4+}, respectively.

Moreover, the present collision systems favor not only a specific charge state but also a certain configuration which is equal to the incident configuration apart from the removal of the $1s$ electron. In particular the occupation of higher-lying Rydberg states is minimized so that Auger line intensities may be studied free of cascade transitions. The restriction to a certain configuration is important for the Ne^{4+} + He system where the production of numerous lines may obscure the analysis of the spectra. For the complete line identification of the B-like Ne spectrum further calculations of Auger transition energies are desirable.

The spectra obtained with heavier targets such as CH_4 and Ar show strong excitation of Li-like states independent of the initial projectile charge state. This indicates that the K-vacancy production by heavy particles is accompanied by additional outer-shell ionization, an observation consistent with results obtained in previous target spectroscopy studies. Hence, in collisions with Ar target atoms, Auger electron production loses the selectivity observed for He atoms.

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