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RECOIL IONS

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X RAYS AND AUGER ELECTRONS FROM FEW-ELECTRON RECOIL IONS

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ABSTRACT

A summary is given of recent experiments in which highly ionized atoms of low laboratory velocities are created by distant collisions with highly-charged very heavy projectiles in the MeV/amu specific-energy range. Emphasis is put on very-high recoil-ion charges and on excited states carrying K vacancies. The potential of x-ray and Auger-electron emission studies is illustrated in view of both the primary multiple ionization process and the selective electron capture observed in a secondary collision. The relevance of the latter process for the population of specific few-electron states is outlined. Briefly discussed are also a few aspects of electron-rearrangement processes following molecular-target ionization.

INTRODUCTION

There is presently a great interest in collision and radiation processes involving highly ionized atoms. X-ray transitions of such ions are observed in solar spectra ¹ and in fusion plasmas ² where they play an important role as they significantly contribute to plasma cooling and serve as plasma diagnostics. Similar states of excitation can be observed in ions of several MeV/amu specific energy traversing thin foils ³.

Another type of accelerator-based experiments ^{4,5} makes use of the observation of target atoms ionized in a single collision with fast heavy projectiles. Even though the total energy corresponding to the electronic excitation can easily reach several keV the kinetic energy of the recoil ion may be as low as a few eV.

Whereas other experiments ⁶ use such ions after they have returned to their ground states or do not discriminate against electronic states, we concentrated on *excited* states and the related radiation processes. In our studies slow recoil ions of atomic number $6 \leq Z_2 \leq 18$ were produced by bombarding monatomic and molecular target gases with fast heavy ions from the UNILAC. A wide range of projectiles with atomic number of $18 \leq Z_1 \leq 92$, ionic charges of $12 \leq q_1 \leq 70$ and specific energy between 1.4 and 9.0 MeV/amu was covered. The strong field suddenly introduced by the high charge of the projectile leads to electron removal already at impact parameters which are much larger than the electron-shell radii of the targets. For the collision regimes under discussion collision velocities approximately match orbital velocities of inner-shell electrons whereas they are large compared to those of outer-shell electrons. This mismatching can be compensated for by

a very high projectile charge which then leads to depletion of *outer* shells whenever the collision is close enough to remove an inner-shell electron of the target. The K x-ray and Auger-electron emission spectra, sensitive only for K-hole states, therefore, sample an impact-parameter range where high recoil charges are obtained. In the present article we will discuss the projectile dependence of high-charge state recoil-ion production in the *primary* single collision. Because the excited recoil ions move so slowly (typically 0.01 mm/ns) they can easily be observed until their electronic states are changed by *secondary* charge changing collisions with surrounding gas atoms. The importance of such processes for the population of few-electron excited states will be outlined. When *molecular* targets are used, a fast electronic relaxation limits the number of few-electron ions emerging from the dissociating molecule.

PROJECTILE DEPENDENCE OF MULTIPLE TARGET IONIZATION

The degree of multiple ionization can be obtained from both x-ray and Auger-electron satellite structure ^{7,8}. In this section we are discussing the results obtained on the two monatomic targets studied i.e. neon and argon. Figures 1 and 2 demonstrate the projectile velocity and charge-state dependence for a given projectile species.

Fig. 1. Neon-K Auger-electron spectra induced by krypton impact at various bombarding energies.

The Auger-electron spectra of figure 1 are taken at the fixed charge state 16+ (18+ in case of 1.4 MeV/amu). At high bombarding energy they reveal a complicated line structure due to simultaneous excitation of 3- to 5-electron states. When the bombarding energy decreases the structure more and more changes into a simplified pattern which in case of the lowest energy of 1.4 MeV/amu reflects the auto-ionization of a pure three-electron system. A simple relation between the number of L-shell vacancies and the centroid of the Auger-electron satellite distribution was found by Stolterfoht et al. ⁹ allowing to extract the degree of ionization from the measured data. The procedure starts to get inaccurate, however, when the spectra saturate at Li-like states as does the bottom spectrum of figure 1. A further increase of the multiple ioni-

zation does not change the spectra appreciably. The K α satellite structure shown in figure 2 reveals a strong charge-state effect as observed through the change in relative intensity between He-like and Li-like lines going from $q_1 = 30$ to $q_1 = 16$ at 5.9 MeV/amu. For comparison the 1.4 MeV/amu Kr $^{18+}$ spectrum is also displayed showing the increase of ionization when the velocity is lowered.

For characterizing the degree of multiple ionization we use the probability $p_L(0)$ for L-shell electron removal in small impact parameter i.e. K-shell ionizing collisions. An empirical scaling

Fig. 2. Neon-K α x-ray satellites induced by Kr q_1^+ impact.

to Ne $^{10+}$ and afterwards redressing it with one electron from the surrounding gas atmosphere. Those secondary-capture processes will be discussed in detail further below.

Similar results as for neon were obtained in case of the argon¹³ target for which we show representative spectra in figures 5 and 6. A strong increase in the degree of ionization can be observed in the K α satellite distribution of figure 5 when going from Kr $^{30+}$ to Pb $^{60+}$ impact. In case of the high projectile charge the spectrum reduces to essentially He- and Li-like states. Comparison with

of p_L is obtained when p_L is plotted as a function of the projectile velocity divided by the incoming charge state v_1/q_1 . The results are shown in figure 3 together with data for bare projectiles reported by Kauffman et al.¹⁰. Both, the bare and partially stripped ion data fit a common straight line. Taking into account the ionic rather than the nuclear charge seems to be justified - as we will see below - from the argument that the ionic radius of the highly charged heavy projectile is smaller than the mean impact parameter at which the recoil ion is created. Therefore, the projectile's inner-shell electrons will shield its nuclear charge during the collision i.e. the highly charged heavy ions behave like point charges. That can be quite different for less highly charged lighter ions where the inner¹¹ but not the outer¹² electrons shield the nuclear charge. Under the extreme condition of a very high projectile charge as in case of 5 MeV/amu U $^{65+}$ the neon K x-ray spectrum is dominated by the hydrogen-like line series as demonstrated in figure 4. Part of the observed intensity is already caused by first stripping the target atom completely

Fig. 3. L-shell ionization probability $p_L(0)$ of Ne in K-vacancy producing collisions.

satellite structure was studied for projectiles ranging from Kr to U in the specific-energy range of 2.5 - 9.0 MeV/amu. In Table I are listed the L-shell ionization probabilities p_L extracted from the $K\alpha$ satellite distribution.

theoretical wave-length positions of the individual satellites indicate that for the high degree of L-shell ionization, as observed in the present experiment, the M-shell is totally depleted. Figure 6 demonstrates the charge-state effect for 5.9 MeV/amu uranium ions. Only with the high charge state individual lines are discernable which then represent the three-electron Auger decay. The argon

Fig. 4. Neon x-ray lines produced by 5 MeV/amu U^{65+} .

For lighter projectiles ($Z_1 \leq 17$) Schmiedekamp et al. ¹⁴ found a scaling of p_L as a function of the collision velocity v_1 and the nuclear charge Z_1 employing the BEA model ¹⁵ on the basis of an increased binding effect ¹⁶. Not discussed so far has been the dependence on the ionic charge q_1 . This, however, plays an important role in the heavy-ion regime as demonstrated above. Our data suggest

Fig. 5. Argon $K\alpha$ satellite structure revealing the strong increase of the degree of ionization with projectile charge.

to use q_1 as the effective charge of the projectile. This is supported by the small ionic radii r_{proj} listed in Table I. The latter were estimated via the relation

$$r_{\text{proj}} = n_i (-2E)^{-1/2} \quad (1)$$

using the potential energies E of Carlson et al.¹⁷. n_i denotes the principal quantum number of the outermost shell of the ion. We applied the BEA model and a binding correction using q_1 instead of Z_1 to scale our data. In the BEA approximation the cross section for L-shell ionization then reads

$$\sigma_L = \pi N q_1^2 u_L^{-2} G(V) \quad (2)$$

where N is the number of electrons and u_L the binding energy of the L-shell. $G(V)$ denotes the BEA ionization curve as a function of the scaled velocity V which is the ratio of projectile and L-shell orbital velocity.

Fig. 6. Argon Auger-electron spectra showing the charge-state dependence for uranium projectiles.

Assuming the ionization probability to have the form

$$p_L(b) = \begin{cases} \sigma \cdot (\pi N R^2)^{-1} & b \leq R \\ 0 & b > R \end{cases} \quad (3)$$

yields

$$p_L = q_1^2 R^{-2} u_L^{-2} G(V) \quad (4)$$

The binding energy correction is taken into account by replacing u_L by $u_L \cdot \epsilon$ and V by $V \cdot \epsilon^{-1/2}$ arriving finally at

$$p_L = q_1^2 R^{-2} u_L^{-2} \epsilon^{-2} G(V \epsilon^{-1/2}) \quad (5)$$

The binding-energy correction factor ϵ , listed in Table I, was determined by equation (17) of Brandt and Lapicki ¹⁶. Figure 7 shows the data plotted in the BEA scaling according to equation (5). The only fit parameter used is the cut-off radius R which is determined to $R = 1.1$ au. Besides some scattering of the experimental data the BEA curve reproduces the dependence on q_1 and v_1 quite well.

Fig. 7. Scaled L-hole probability of argon according to equation (5) and Table I.

Table I Experimental L-hole probabilities p_L and L-shell binding-energy correction factors ϵ after Brandt and Lapicki ¹⁶ for various heavy ions colliding with argon.

ION	SPEZ. ENERGIE (MeV/amu)	V	q_1	$r_{\text{proj}}/\text{au}$	p_L	ϵ
Kr	2.5	2.35	26	0.14	0.53	2.82
	5.9	3.61	30	0.13	0.51	2.42
	8.0	4.20	31	0.12	0.40	2.27
Xe	2.6	2.39	36	0.22	0.73	3.48
	4.7	3.21	41	0.20	0.78	3.16
	9.0	4.46	45	0.09	0.75	2.74
Pb	5.9	3.61	60	0.14	0.83	3.83
	8.0	4.20	64	0.13	0.81	3.62
U	5.0	3.31	64	0.13	0.92	4.28

RECOIL-ENERGY DISTRIBUTION

Kinematical broadening of Auger-electron lines allows access to the velocity of the emitting ion provided other sources of broadening (natural width, instrumental) are small. This is the case for the lines observed in figure 6 where the instrumental width $\Delta E_i = 3.5$ eV due to the limited resolution of the electron-energy analyzer is substantially smaller than the one observed in the spectrum. In our case the recoil ions are produced by large-impact parameter collisions and, thus, are recoiling nearly perpendicular to the direction of the projectile. For a fixed kinetic energy E_R of the recoil ions the width ΔE_D of the Doppler profile, which can be approximated by a rectangular shape, is given by ¹⁸

$$\Delta E_D^2 = 16 \frac{m_e}{m} E_A \cdot E_R \cdot \sin^2 \alpha \quad (6)$$

where m_e and m denote the electron mass and the recoil-ion mass, and E_A and α denote the Auger-transition energy and the observation angle relative to the primary beam, respectively.

Because the recoil ions have a continuous energy distribution the experimental line profile $U(E)$ will be a convolution of the Doppler profile D with the transmission function G of the energy analyzer and with the recoil-energy distribution F :

$$U(E) = \iint D(E', E_R) \cdot G(E-E') \cdot F(E_R) dE_R dE' \quad (7)$$

The transmission function G can be approximated by a Gaussian. If the observed line $U(E)$ is Gaussian as well $F(E_R)$ can be easily deconvoluted analytically which results in a mean recoil energy of

$$\bar{E}_R = \frac{3}{8 \ln 2} \frac{\Delta E^2 - \Delta E_i^2}{16 m_e / m E_A \sin^2 \alpha} \quad (8)$$

where ΔE is the width of the observed line. If $U(E)$ has some arbitrary shape $F(E_R)$ can be deconvoluted numerically. In our case, the experimental line shapes follow quite well a superposition of two Gaussians separated by only 1 eV. This is demonstrated in figure 8 in case of the $1s2s2p \ ^4P^0$ line ¹³. From the smooth curve of figure 8a follows the recoil-energy distribution displayed in figure 8b. The distribution maximizes already at 7.5 eV whereas the centroid is at $\bar{E}_R = 21 \pm 3$ eV. These small recoil energies show that the recoil ions are created in very large-impact-parameter collisions. Provided the projectile-target interaction potential is known, the recoil energy distribution can be converted into an impact-parameter dependent ionization probability. In a simplified treatment one can assume the repulsion of the target to occur after the shielding target electrons are removed, i.e. in the second half of the collision one assumes Rutherford scattering of two point charges with the incoming and the final recoil charge state, respectively. In such a treatment, using the charge states 66 and 15, the curve of figure 8b would translate into an ionization probability which maximizes near an impact parameter of 0.3 au and which levels off at impact parameters larger than 6 au.

Fig. 8. (a) Experimental profile for the $1s2s2p\ 4P^0$ Auger-electron line of Ar^{15+} . (b) The deconvoluted recoil-energy distribution.

EXCITATION BY SECONDARY ELECTRON CAPTURE

The possibility of observing secondary electron capture by emission spectra of K-vacancy bearing states enters through the high fraction of metastable states present when the degree of target ionization is high. A recoil ion in a long-living K-hole state produced in the primary heavy-ion encounter survives until its electronic state is changed in a second collision with a neutral target gas atom. At practical gas pressures the second collision is observed typically after a few nanoseconds which corresponds to a travel distance of a few 10^{-2} mm. In that collision the electron-capture reaction

takes place, where an electron is transferred from a neutral atom B to an outer shell n of the highly stripped recoil ion. A simple one-electron model ^{7,19,20} assuming an over-barrier transition predicts the principal quantum number n as a function of the ionization potential J_B according to

$$n^2 \leq \frac{q^2}{2J_B[1+(q-1)/(1+2q^{1/2})]} \quad (10)$$

whereas the crossing distance is given by

$$R = \frac{q-1}{q^2/2n^2 - J_B} \quad (11)$$

In our experiments ^{7,20,21} we have studied

- (i) excited states distribution of the product ion $A^{(q-1)+}(n)$ by its Auger or x-ray decay,

- (ii) the exothermic energy defect E_{exo} by kinematic line broadening,
- (iii) capture rates by measuring the production rate of $A^{(q-1)+(n)}$ or the quenching rate of Aq^+ .

Because the transfer of the electron occurs selectively into mainly one shell of principal quantum number n specific 'capture lines' can be observed which sometimes dominate the spectra. In figure 4, for instance, the extraordinarily high intensity of the $6p \rightarrow 1s$ transition in NeX is due to the reaction $\text{Ne}^{10+} + \text{Ne} \rightarrow \text{Ne}^{9+(n=6)} + \text{Ne}^+$. A variety of gas mixtures was employed for investigating reaction (9) for a large number of different collector ions and donor atoms (of different ionization potentials). Furthermore, delayed Auger-electron spectra were measured making use of the pulsed primary beam. There the capture events occurring with several

Table II Predicted (equation (10)) and experimental principal quantum number for electron capture in various systems.

Ion	Neutral	Principal Quantum Number		Observed Radiation
		Calculated	Experimental	
C^{4+}	CH_4	3.2	3	Auger
N^{5+}	NH_3	4.3	4	Auger
"	CH_4	4.0	4	Auger
"	H_2	3.6	3(4)	Auger
"	N_2	3.4	3(4)	Auger
"	Ne	3.0	3	Auger
"	He	2.8	3	Auger
N^{6+}	N_2	4.0	4	Auger
O^{6+}	H_2O	4.6	4(5)	Auger
"	CO_2	4.4	4	Auger
"	O_2	4.7	5(4)	x ray
"	Ne	3.5	3(4)	x ray
"	He	3.3	3	Auger
O^{7+}	O_2	5.3	5	x ray
"	Ne	4.0	4	x ray
"	He	3.7	4	x ray
Ne^{8+}	NH_3	6.4	6	Auger, x ray
"	Xe	5.9	6	Auger
"	CH_4	5.8	6	Auger, x ray
"	H_2	5.2	5	Auger, x ray
"	Ar	5.2	5	x ray
"	Ne	4.4	4(5)	Auger, x ray
"	He	4.2	4	Auger, x ray
Ne^{10+}	CH_4	7.0	7	x ray
"	H_2	6.3	6	x ray
"	Ar	5.3	6	x ray
"	Ne	5.3	6(5)	x ray
"	He	5.0	5	x ray

Fig. 9. Total and delayed Ne-K Auger-electron spectra from different gas mixtures. The lines labelled $2S+1L_n$ arise from states with 2-electron cores ($1s2\ell$) $2S+1L_n$ and a captured electron in the outer shells n.

When monatomic gases are used the exothermic energy defect E_{exo} is substantially larger ²⁰ than the initial recoil energy. As the energy defect is shared as kinetic energy among the two repulsive product ions according to their mass ratio the energy defect is observed as an Auger-line broadening which is obtained analog to equation (6). The effect as observed on the $4P$ lines is demonstrated in Table III. In case of delayed observation where the lines are produced by capture they are systematically broader than for prompt observation where they are due to direct population. The crossing

ns delay time are separated from the prompt events. This is demonstrated in figure 9 showing the Li-like Auger-electron-spectra of Ne excited by 1.4 MeV/amu Kr^{18+} ions. The corresponding collector ions are in the metastable $1s2s\ ^3S$ or $1s2p\ ^3P_{0,2}$ states to which an electron is added into an outer shell producing the pronounced peaks observed at electron energies larger than about 840 eV. The selectivity and the dependence on the admixed gas and its ionization potential is clearly observed in agreement with equation (10). Part of the produced 3-electron product ions are in quartet states which do not directly decay to the K-shell but via cascades feed the low-lying $4p^0$ and $4p^e$ states found in the low-energy part of the spectra.

In Table II experimental results on the principal quantum numbers n are compared with the predictions of equation (10).

distances R derived via the relation

$$E_{\text{exo}} = \frac{q-1}{R} \quad (12)$$

are, within the experimental accuracy, in agreement with the prediction of equation (11).

Table III Experimental line widths in eV for Ne (KLL)⁴P lines in the prompt and in the delayed spectra for bombardment with 1.4 MeV/u Kr¹⁸⁺. The detector resolution was around 1.4 eV and the uncertainty for the widths ± 0.2 eV.

$$\Delta E_{\text{diss.}} = (\Delta E_{\text{del.}}^2 - \Delta E_{\text{prompt}}^2)^{1/2}$$

Target Pressure (mtorr)	Ne + Xe 25 + 25	Ne 20	Ne + CH ₄ 20 + 20	Ne + He 40 + 40	Ne + H ₂ 25 + 25
⁴ p ⁰ prompt	1.1	1.3	1.4	1.2	1.6
⁴ p ⁰ delayed	2.7	2.1	2.0	1.9	2.2
⁴ pe prompt	1.9	1.9	1.9	1.9	2.3
⁴ pe delayed	3.9	2.8	2.4	2.4	2.5
⁴ pe $\Delta E_{\text{diss.}}$	3.4	2.0	1.5	1.4	1.0

For the same Ne⁸⁺ recoil ions capture rates were measured employing the photon-quenching method which makes use of the fact that metastable states of proper radiative lifetime get collisionally depopulated by the capture process whereas prompt states keep unaffected²¹. Figure 10 shows the neon K α satellites measured at target pressures of 12 mbar and 93 mbar, respectively. The spectra are normalized to the ¹P intensity. At high pressure one notices a strong quenching of the ³P₁ state and of the Li-like ⁴P states whereas the intensity ratio of the prompt lines ¹P/²P remains practically constant. The ¹P/³P intensity ratio as a function of target density and target composition can be shown to be

$$I(^1P)/I(^3P) = R[1 + \tau(^3P)(k_{c1}N_1 + k_{c2}N_2)] \quad (13)$$

where R denotes the intensity ratio at zero density. N₁ and N₂ denote the density of the gas from which the recoil ions are studied and the density of a second admixed gas, respectively. k_{c1} and k_{c2} are the corresponding capture rates and $\tau(^3P)$ is the lifetime of the ³P₁ state which amounts to ²² 0.18 ns. Our experimental results are consistent with the linear pressure dependence predicted by equation (13). This is demonstrated in figure 11 for the pure Ne, the Ne+He, and the Ne+Xe mixture. From the slopes of the straight lines fitted to the data capture rates k_c are extracted which are in the range of $1 - 23 \cdot 10^{-9} \text{ cm}^3 \text{ s}^{-1}$. The corresponding cross sections $\sigma_c = k_c/\bar{v}_{\text{rec}}$ are obtained using the mean recoil velocity $\bar{v}_{\text{rec}} = 0.8 \cdot 10^6 \text{ cm s}^{-1}$ ($E_{\text{rec}} = 6.7 \text{ eV}$). In figure 12 the cross

Fig. 10. Neon $K\alpha$ satellite spectra induced by 3.6 MeV/amu krypton impact and taken at two different target pressures.

sections are compared to the geometrical cross section πR^2 predicted by equation (11). The oscillations are due to capture into different outer shells according to equation (10), where n has to be an integral value.

Fig. 11. Pressure dependence of the $1s2p$ $1P/3P$ intensity ratio in NeIX for different target compositions. In case of the mixed gases the neon partial pressure amounts to 27 mbar.

the line series extending approximately from 3.8 Å down to 2.9 Å are shown in a case of favourable conditions for a high degree of ionization. The H-like line series starting with the Lyman- α doublet extends up to principal quantum number $n = 5$, whereas the He-like series is observed up to $n = 6$. For the Li-like series the multiplet splitting of the He-like $1s2\ell$ core is observed and is indicated in brackets. The line labelled $1s2\ell 9p$ is due to secondary electron capture by Ar^{16+} ions into $n = 9$. There is, however, no indication of capture by bare or one-electron ions. The broad background observed in figure 13 is caused by uranium-M radiation of the projectile. As the experiments presented were not aimed at providing high wavelength precision the accuracy is limited to about ± 0.0008 Å. Experimental wavelengths of the line positions together with a comparison with theoretical transition wavelengths are given elsewhere ¹³.

MOLECULAR RELAXATION

The study of secondary electron capture as discussed above represents the first step towards tracing the slowly moving ion on its way back to charge neutrality. Once the K vacancy is refilled, however, further charge-exchange processes can not be detected in the spectral ranges under discussion. The situation gets much more complicated when heavy molecules are used. *Light*-ligand molecules reveal a similar behaviour ¹⁸ as monatomic targets, whereas the presence of *heavy* ligands with their many electrons results in fast charge-quenching processes which readily compete with the radiative deexcitation observed. Despite of the complexity of the process a few aspects may be delineated experimentally.

Because of the long-range nature of the target ionization by very highly charged projectiles the ligands get multiply ionized at least in their outer shells, in addition to the atom whose Auger or x-ray decay is observed. This molecular ionization leads to the 'Coulomb explosion' of the molecule which is observed by means of the kinematical broadening of metastable Auger-electron lines ¹⁸. The respective line width is, via the dissociation velocity, a measure for the degree of molecular ionization. Analogous to the monatomic-target results a drastic increase of molecular ionization with projectile charge was found.

The time history of the charge quenching may be diagnosed with the aid of x-ray and Auger transitions of various atomic lifetimes. Transitions from prompt states of typically 10^{-13} s lifetime occur when the electronic state is close to the one initially produced by the heavy ion encounter. At that instant many electrons (the number depending on the degree of ionization) are excited to the continuum or very high n states either by direct excitation or by very fast electron transitions from excited ligands. As time proceeds those electrons will redistribute and will fill the initial vacancies. Metastable states will experience this relaxation and the radiation emitted will be characteristic of the changed electronic state. Examples are given in figures 14 and 15 for fluorine ions emerging from SF_6 or CF_3Cl . Those molecules contain 60 or 40 electrons,

Fig. 14. Fluorine-K Auger-electron spectra of SF_6 bombarded with U^{66+} and U^{39+} .

respectively. Figure 14 shows the total and delayed (≥ 10 ns) fluorine Auger-electron spectra for SF_6 bombarded by U^{66+} and U^{39+} projectiles, respectively. No single lines can be observed in the total spectra because of the many-electron states produced. The delayed spectra show the fraction of metastable three-electron states directly produced which have survived electron refilling. In case of U^{39+} impact that fraction is close to zero, whereas for the high charge of U^{66+} it is much higher. This might be explained by the circumstances that in the latter case both the number of initially produced three-electron states and the number of ionized molecular electrons are higher. The large line width of 12 eV corresponds to a fragment energy of 560 eV.

As opposed to the total Auger-electron spectra of figure 14 a clear line structure is observed in the K x-ray spectra of figure 15. Even with the less violent projectile Kr^{18+} the structure is re-

Fig. 15. Fluorine-K x-ray produced by bombardment of SF_6 and CF_3Cl , respectively.

markably close to that of the monatomic Ne target. The extent of fluorine-fragment ionization represented by the K x-ray spectra is only marginally higher in case of CF_3Cl as compared to the heavier SF_6 molecule. Because most of the lines originate from states with lifetimes in the 10^{-13} s range the molecular electrons might not be fully redistributed at the time of x-ray emission. One might speculate about electrons occupying high-n states which lead to small satellite-wavelength shifts, even though existing data have not yet been analyzed with respect to that. An interesting finding is the

quenching of the $1s2p\ ^3P$ intensity relative to the 1P . Because of the low target pressure (~ 0.05 mbar) this effect is not explained by electron capture of a released F^{7+} ion colliding with a surrounding molecule. Due to the greater lifetime of the 3P_1 level of 1.6 ns the x-ray transition occurs at times when the relaxation is more advanced. The $^3P/{}^1P$ intensity ratio, therefore, is a diagnostic for the evolution of the molecular relaxation.

CONCLUSION

In summary we have tried to delineate the potential of x-ray and Auger-electron emission spectra as an effective probe for some of the interesting features of the recoil-ion light source. With the use of very heavy highly charged projectiles very high recoil charges can be produced. The corresponding x-ray and Auger-electron spectra of the few-electron systems reveal single-lines structure. For collision velocities much higher than the orbital velocity of target K-shell electrons the extent of multiple target ionization decreases. The simple BEA scaling used to explain the projectile dependence should not obscure the fact that further effort is necessary to elucidate the complex process of ionizing many electrons in a single collision. In applications where an outmost degree of ionization is required it might be advantageous to accelerate the projectiles, to strip them to a high equilibrium charge, and afterwards to decelerate them again. From the kinematical analysis a recoil-energy distribution follows which covers the few-eV range. From such measurements as well as from more direct determinations of recoil energies a deeper insight into excitation mechanisms is expected.

The analysis presented has also aimed to show the relevance of selective electron capture for the population of high- n states. Spectroscopic investigation of the capture process allows to use the recoil ions without acceleration. Thereby the collision regime of high charge states and ultimately low velocities is explored. The information extracted from the x-ray and Auger-electron measurements comprises final-state distribution, as well as capture rates and capture kinematics. Extension to other spectral ranges would allow to investigate those processes also for core ions without K-vacancies.

It should be emphasized that the recoil-ion light source can be regarded as stationary with regard to precision wavelength measurements and wavelength-calibration difficulties as known from the fast beam-foil source are missing. The study of molecular relaxation after introducing a fast disruption by a heavy-ion encounter may be relevant for tackling the even more complex situation of a very heavy ion interacting with matter of high density.

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