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# Selective Electron Capture: A Dominant Production Process for Few-Electron States of Light Target Atoms after Heavy-Ion Impact

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The total and delayed $K$–Auger-electron emission of Ne, $N_2$, and $SF_6$ targets was investigated after 1.4-MeV/u $Kr^{18+}$ and $Ar^{12+}$ impact. The lines of promptly decaying $1s2lnl'$ ($n \geq 3$) states observed nanoseconds after projectile impact demonstrate that selective electron capture from neutral target atoms into outer-shell orbitals of slow recoils is an important production mechanism for certain states in highly stripped target atoms. Contributions of prompt and delayed excited states are observed as well as specific cascades to inner-shell states.

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Spectroscopic studies of highly stripped slow target recoil ions after heavy-ion impact are of interest both for atomic physics and for aspects of plasma physics[1] and astrophysics,[2] as they give information on interactions of the highly charged ions with the surroundings. The target $K$–x-ray and $K$-Auger-electron spectra reflect the states that are directly excited by the heavy-ion impact, and when the target ionization is very high, lines produced by electron capture from neutral target particles into the recoiling target ions may occur. Some evidence that electron capture in a second collision is responsible for specific lines in the observed $K$ spectra was already found.[3]

Here, we report on the first direct observation of target $K$ Auger electrons, which arise from capture collisions nanoseconds after the projectile impact. It is demonstrated that mainly lines from selective electron capture (SEC) dominate the spectra. A strong production of metastable $K$-hole configurations which survive capture collisions and populate specific outer-shell states is pointed out to be a main feature of multiple target ionization by very heavy projectiles.

In the experiments, pulsed (1 ns pulse width, 37 ns period) $Kr^{18+}$ and $Ar^{12+}$ beams of 1.4 MeV/u specific energy were passed through a gas cell containing Ne, $H_2O$, $N_2$, and $SF_6$ target gases at various pressures (1 mTorr $\leq p \leq 100$ mTorr) measured with a capacitance manometer. In order to demonstrate the selectivity of the electron capture associated with differences in the target ionization potential $I_p$, other gases were mixed with the target. The Auger electrons were observed at 135° with respect to the projectile direction and analyzed by an electrostatic analyzer[4] of 1.4 eV full width at half maximum (FWHM) resolution. A time-to-amplitude converter was started by the electron signal and stopped by the 27-MHz signal of the beam bunch. For each spectrum different time windows of 5-ns time resolution were set on the beam-bunch periods, allowing us to separate delayed and prompt electron emission from the total spectrum. Most Auger lines are identified by comparison with calculated transition energies.[3]

Figure 1 exhibits Ne $K$–Auger-electron spectra induced by $Kr^{18+}$ projectiles. A total spectrum of a pure 50-mTorr Ne target [Fig. 1(a)] is compared with a delayed spectrum ($t \geq 10 \pm 2$ ns) of a mixture of 40 mTorr Ne + 40 mTorr He [Fig. 1(b)]. The total spectrum is governed by few Auger lines in the energy range 650–680 eV and 845–880 eV, which are attributed[3] to the decay of Li-like one-$K$-hole configurations. The prominent lines $^4P^o$ and $^4P^e$, which denote $1s2s2p\,^4P^o$ and $1s2p^2\,^4P^e$ initial configurations, and the lines $^3P$-($n=4$) and $^3S$-($n=5$), which indicate $1s2p\,^3P$ and $1s2s\,^3S$ cores with an additional electron in the outer shells $n=4$ and 5, respectively, strongly arise in the delayed spectrum. This demonstrates the importance of a secondary production of $K$–Auger-electron lines of target atoms after heavy-ion impact.

The delayed spectrum presents the first direct observation of SEC from neutral target atoms into outer shells of slowly ($E_r \lesssim 5$ eV) recoiling target ions and its strong dependence on the ionization potentials $I_p$ of the neutrals as predicted by charge-transfer models.[3,5-7] For a pure Ne target [$I_p$(Ne) = 21.6 eV], SEC occurs into $n=4$ and $n=5$ shells of the metastable $^3P_{0,2}$ (lifetime $\tau \approx 9$ ns) and $^3S_1$ ($\tau = 91$ $\mu$s) core ions producing the lines $^3P$-($n=4$) and $^3S$-($n=5$). When $I_p$ increases by adding He to the target [$I_p$(He) = 24.5 eV], a line $^3S$-($n=4$) intensively appears in the

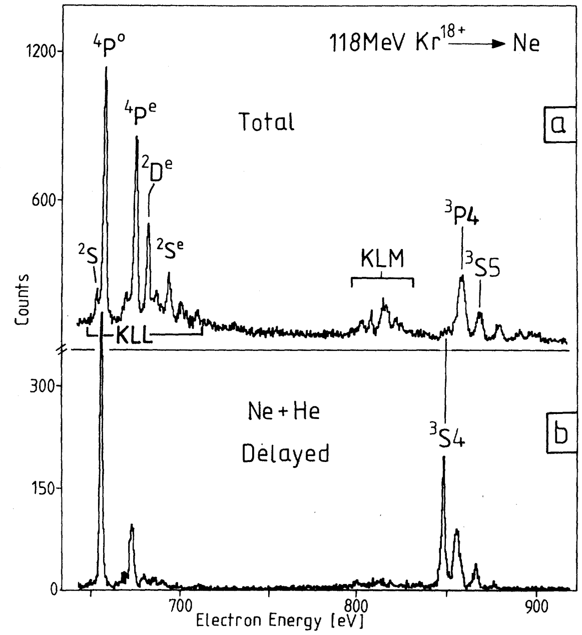


FIG. 1. Total and delayed ($t \geq 10$ ns) Ne $K$–Auger-electron spectra from 1.4-MeV/u $Kr^{18+}$ impact on (a) pure Ne and (b) Ne + He(50%) mixture. The lines $^3S$-($n=4$), $^3P$-($n=4$), and $^3S$-($n=5$) arise from selective electron capture in a second collision of $Ne^{8+}$ ($1s2s\,^3S$, $1s2p\,^3P_{0,2}$)-core recoils with target neutrals (He, Ne). The lines $^4P^e$ and $^4P^o$ in the delayed spectrum reflect a subsequent cascade feeding.

spectrum [Fig. 1(b)] which is explained to result from a capture of one electron from He into the $n=4$ shell of a $^3S_1$-core recoil ion. In this experiment, a population of different angular momenta ($l = 0, \ldots, n-1$) by SEC is not resolved from the capture lines because of the small energy splitting of the outer-shell multiplets.

In the total spectrum lines from $1s2s^2\,^2S$, $1s2p^2\,^2D^e$, $1s2p^2\,^2S^e \to 1s^2\,^1S^e + e^-$ transitions, from the $K$-$LM$ group of three-electron systems and a minor part from Be-like $1s(2s,2p)^3$ configurations around 700 eV are observed in addition, indicating states which are produced by the primary projectile impact. The metastable $1s2s2p$ $^4P_{5/2}{}^o$ term ($\tau \sim 8.4$ ns)[8] is the only one which may contribute to the $^4P^o$ line in the delayed spectrum although it arises from a primary collision.

According to a statistical population by the heavy-ion impact, the $^3S_1$ and $^3P_{0,2}$ terms of the metastable He-like recoils $1s2s\,^3S_1$, $1s2s\,^1S_0$, and $1s2p\,^3P_{0,2}$ dominate. From electron capture into outer shells of such recoil ions a ratio of 9:10 would result for the population of quartet and doublet terms if the capture cross sections are equal for both. The quartet states which cannot couple to the continuum via electron-electron Coulomb interaction preferentially decay by $E1$ cascades feeding the inner-shell states $1s2s2p\,^4P^o$ and $1s2p^2\,^4P^e$ ($\tau \approx 0.2$ ns). Indeed, these cascade contributions are observed in the delayed spectra in the $^4P^o$ and $^4P^e$ lines [Figs. 1(b) and 2(b)] having approximately the same intensity as the capture lines around 850 eV when the contribution of primary excitation was taken into account for the $^4P^o$ line.

From the exothermicity[5] of the electron-capture kinetic energy $E_K = |E_b| - |I_p|$ (where $E_b$ is the binding energy of the captured electron) is shared between the charge-exchanging partners. Consequently, kinematically broadened[4] Auger lines of widths

$$\Delta E_c = [(\Delta E_s)^2 + 16 E_A E_K m_2 m_e/(m_1 + m_2)m_1]^{1/2} \quad (1)$$

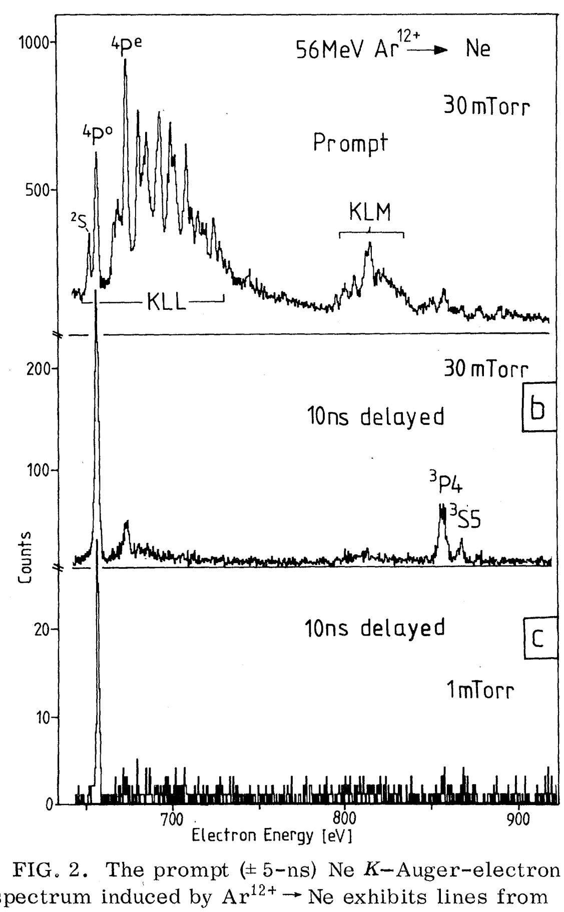


FIG. 2. The prompt (± 5-ns) Ne $K$–Auger-electron spectrum induced by $Ar^{12+} \rightarrow Ne$ exhibits lines from directly excited Li-like and Be-like states. The delayed spectra display contributions of specific capture and cascade lines from second collisions being suppressed at low target pressure.

are expected, neglecting the low recoil energy of the heavy-ion impact. $\Delta E_s$ is the spectrometer resolution, $E_A$ is the Auger electron energy, and $m_e$, $m_1$, and $m_2$ are the masses of electron, target ion, and the neutral, respectively. In fact, such a line broadening (Table I) is observed in the delayed spectra for the "cascade lines" $^4P^o$ and $^4P^e$ agreeing with the exothermic capture process. From the broadening of the $^4P^e$ line, a value $E_K \approx 30$ eV was estimated for $Ne^{8+} + Ne \rightarrow Ne^{7+} + Ne^{+}$, which is much larger than the mean recoil energy $E_r \lesssim 5$ eV due to the heavy-ion impact. $E_r$ is obtained from the small linewidth of the $^4P^o$ line in the prompt spectra which is close to the spectrometer resolution. In the framework of a classical model[3,6] we may estimate a capture cross section $\sigma_c \sim 0.5\pi R^2 = 1.8 \times 10^{-15}$ cm$^2$, where the crossing distance $R$ for electron capture is obtained from $E_K = (q-1)/R$.

For lighter projectiles ($Ar^{12+}$), the multiple ionization of Ne target atoms decreases and most lines are directly produced; in particular the $K$-$LL$ lines from Be-like configurations at 680–730 eV appear in the prompt spectrum [Fig. 2(a)]. A remaining contribution from the specific capture and cascade lines are observed in the delayed spectrum [Fig. 2(b)]. Their intensities (normalized to the intensity of the total spectrum) are reduced by a factor of 3, compared with $Kr^{18+}$ impact.

At low target pressure [Fig. 2(c)] the $^3P$-$(n=4)$, $^3S$-$(n=5)$, and $^4P^e$ lines are strongly suppressed, consistent with a pressure dependence of a population by a secondary capture collision. Only a residual contribution of the primary produced metastable $^4P_{5/2}{}^o$ term is found resulting in a smaller $^4P^o$ linewidth compared to a width at higher pressure (Table I), because a kinematic broadening due to electron capture and a cascade feeding is missing.

TABLE I. Measured ($\Delta E$) and calculated [$\Delta E_c$ from Eq. (1)] widths (FWHM) of Auger lines. The uncertainty is ± 0.2 eV.

| Line | $\Delta E^a$ | $\Delta E_c{}^a$ | $\Delta E^b$ | $\Delta E_c{}^b$ | $\Delta E$ | |
|---|---|---|---|---|---|---|
| $^4P^o$ total | 2.2 | ··· | ··· | ··· | ··· | |
| $^4P^o$ prompt | 1.7 | 1.6 | 1.2 | 1.6 | | |
| $^4P^o$ delayed | 2.4 | 2.5 | 1.9 | 1.9 | 2.5[c] | 1.9[d] |
| $^4P^e$ prompt | 2.2 | ··· | 1.9 | ··· | 3.2[c] | 3.0[d] |
| $^4P^e$ delayed | 3.3 | ··· | 2.4 | ··· | 3.7[c] | ··· |

[a]See Fig. 1(a).
[b]See Fig. 1(b).
[c]See Fig. 2(b).
[d]See Fig. 2(c).

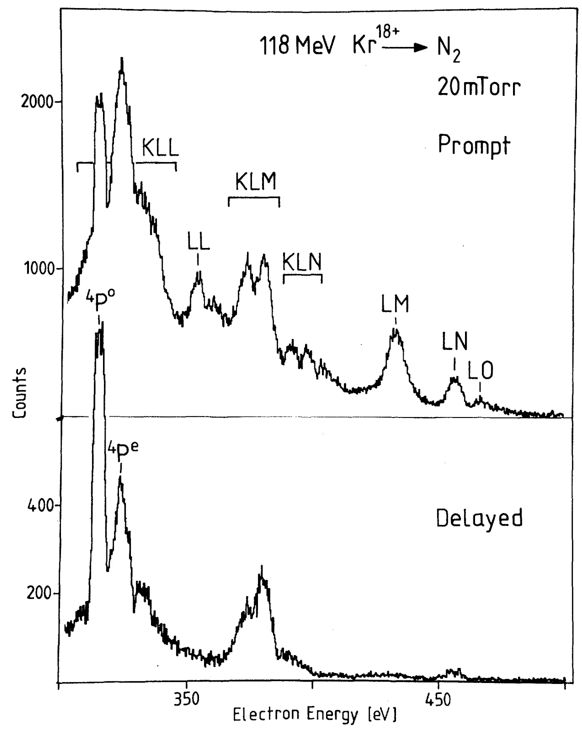


FIG. 3. Nitrogen $K$–Auger-electron spectra from $Kr^{18+}$ impact on $N_2$. A lower contribution from SEC in the delayed spectrum and a relative high intensity of He-like hypersatellites ($LL$, $LM$, $LN$, $LO$) in the prompt spectrum may indicate that a fast electron redistribution during molecular dissociation is important for targets of higher atomic numbers.

In Fig. 3, prompt and delayed Auger spectra from $Kr^{18+}$ impact on $N_2$ molecules are shown. The lines which are strongly broadened because of the molecular Coulomb explosion[4] are attributed to $K$-$LL$, $K$-$LM$, and $K$-$LN$ transitions from Li-like configurations and to He-like hypersatellites $LL$, $LM$, $LN$, and $LO$. The delayed spectrum is seen to arise from SEC into the $n=3$ shell of $N^{5+}$ ions bearing $1s2s\,^3S$ and $1s2p\,^3P_{0,2}$ core states. The $K$-$LL$ transitions may reflect an $L$-shell population by cascades, similar to the case of Ne. A weak contribution of the $LN$ hypersatellite above 450 eV may result from SEC into the $n=4$ shell of metastable H-like $2s\,^2S_{1/2}$ core ions. The SEC into the $n=4$ shell for $N^{6+}$ and the $n=3$ shell for $N^{5+}$ ions is in accord with a classical model.[3,6]

The intensity of the delayed spectrum amounts to 20% compared with the prompt emission which is less than in the case $Kr^{18+} \to Ne$ (~35%) for equal target pressures and time windows. This suggests that a fast electron redistribution during

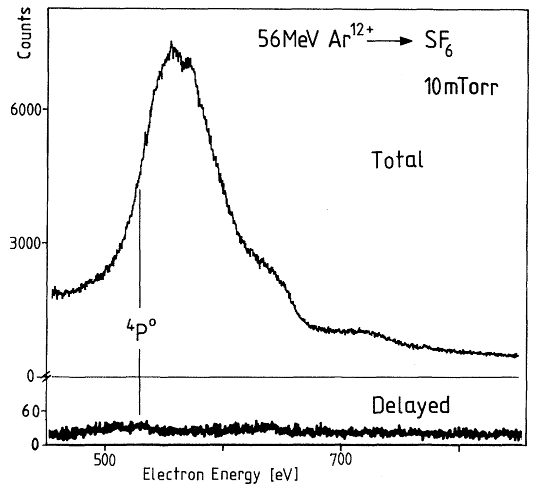


FIG. 4. A missing intensity in the delayed fluorine $K$–Auger-electron spectrum and many overlapping lines in the total spectrum from $Ar^{12+}$ impact on $SF_6$ molecules may demonstrate that recoils carrying metastable $K$-hole cores are totally quenched by prompt electronic rearrangement.

the molecular dissociation after the projectile impact populates promptly decaying states. It reduces the number of metastable $K$-hole configurations available for a second collision. The relatively high intensity of hypersatellites in the prompt spectrum which are not observed for Ne may support this conclusion.

When complex molecules containing many electrons are bombarded by heavy ions, a fast rearrangement[9] of molecular electrons into highly ionized atoms quenching out the metastables dominates the population of states. This is demonstrated by the total and delayed fluorine $K$–Auger-electron spectra from $Ar^{12+} \to SF_6$ in Fig. 4. Many overlapping lines from multiple-electron configurations govern the total spectrum, whereas in the delayed spectrum a significant contribution from SEC in a second collision is missing.

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