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Simultaneous Coulomb Ejection of K- and L-Shell Electrons by Heavy, Charged Projectiles*

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The recently observed multiple inner-shell Coulomb ionization induced by swift, heavy ions is treated by a semiclassical method. Impact-parameter dependences and multiple ionization probabilities as functions of the projectile energy are given and discussed in relation to experimental data.

It has recently been suggested that the phenomenon of multiple inner-shell ionization by swift, heavy ions can be partially described within the frame of existing theories for atomic Coulomb ionization.[1] The semiclassical approximation (the SCA model) in impact-parameter form for single Coulomb ionizations[2,3] might prove advantageous in this context. The following calculations are all performed in the straight-line projectile-path version of the SCA model.[2,3]

We consider one particular electron shell containing n electrons. These electrons are assumed to move independently of each other. An expression for the probability I_p for removing one arbitrary electron by Coulomb ionization induced by a heavy projectile with impact parameter p has been given in earlier work.[3] The probability corresponding to a fixed impact parameter for removing m electrons from that particular electron shell in this picture equals

$$\binom{n}{m}\left(\frac{1}{n}I_p\right)^m\left(1-\frac{1}{n}I_p\right)^{n-m}. \tag{1}$$

For simultaneous Coulomb ejection of one K electron and m arbitrary L-shell electrons we obtain the following probability,

$$I_p(KL^m)=I_p(K)\sum_{r,s,t}\binom{2}{r}\binom{2}{s}\binom{4}{t}\times[\tfrac{1}{2}I_p(L_{\rm I})]^r[\tfrac{1}{2}I_p(L_{\rm II})]^s[\tfrac{1}{4}I_p(L_{\rm III})]^t, \tag{2}$$

where $r+s+t=m$, and the reasonable assumption is made that the quantities $[1-\frac{1}{2}I_p(L_{\rm I})]^{2-r},\dots,$ etc. are equal to 1. In Eq. (2) $I_p(K),\dots,$ etc. denote the probabilities for ejection of one arbitrary electron from the respective shells and subshells.

For double and triple Coulomb ionization we obtain from Eq. (2)

$$I_p(KL)=I_p(K)I_p(L), \tag{3a}$$

$$I_p(KL^2)=\tfrac{1}{2}I_p(K)\{I_p(L^2)-[\tfrac{1}{2}I_p(L_{\rm I}^2)+I_p(L_{\rm II}^2)+\tfrac{1}{2}I_p(L_{\rm III}^2)]\}. \tag{3b}$$

The total cross section for direct Coulomb ejection of both K- and L-shell electrons in this picture is given by

$$\sigma_{KL^m}(E_1)=2\pi\int_0^\infty p\,dp\,I_p(KL^m), \tag{4}$$

with E_1 being the projectile energy.

The relative production rate may be defined as

$$R_0=\sigma_{KL}(E_1)/\sigma_K(E_1) \tag{5}$$

with protons as projectiles. For other heavy projectiles with equal velocities we obtain, in the straight-line approximation,[3] a relative production rate

$$R=Z_1^2R_0, \tag{6}$$

where Z_1e is the charge of the projectile. The projectile is here treated as a naked charge.

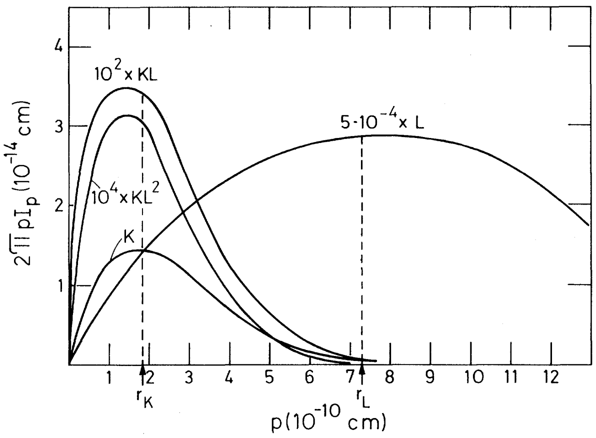

FIG. 1. Impact parameter dependences of the quantity $2\pi p I_p$ for single and multiple ionizations produced by 5-MeV protons on a copper target. The Bohr radii of the K and L shell are denoted r_K and r_L, respectively.

In Fig. 1 it is shown how the SCA model in impact parameter form makes possible a more detailed analysis of the multiple Coulomb ionization process than has been feasible with the plane-wave Bethe-Born approximation.[4,5] Thus, the curves in Fig. 1 confirm the suggestion by Saltmarsh, Van der Woude, and Ludeman[1] that the observed multiple K- and L-shell Coulomb ionizations originate from impact parameters deep inside the L electron shell.

The relative production rates for multiple inner-shell ionizations for Ti and Fe as targets have been obtained by Hansen, Li, and Watson.[6] For 13-MeV α particles as projectiles the estimated R values are given as 0.2 for Ti and 0.1 for Fe. These values appear to be consistent with the R_0 values given in Table I.

The changes in the R_0 values as a function of the projectile energy E_1 are exemplified by the predicted numbers in the last column of Table I. These changes apparently reflect the strongly varying positions of the peaks of the K- and L-shell ionization cross sections as functions of E_1 and of the impact parameter p.[2,3] The several possible Auger processes have not been taken into consideration in the calculation of the numbers given in Table I and Fig. 1.

TABLE I. Energy dependences of single and multiple Coulomb ionization cross sections and relative production rates for protons on a copper target.

E_1 (MeV)	σ_K (b)	σ_L (10^5 b)	σ_{KL} (10^{-2} b)	σ_{KL^2} (10^{-4} b)	$R_0\times10^2$
0.5	2.5	1.40	6.0	6.0	2.4
1.0	23	1.65	60	60	2.6
2	120	1.45	240	170	1.2
5	480	0.87	1200	930	2.5
10	740	0.25	160	16	0.2

It is noteworthy that the work of Saltmarsh, Van der Woude, and Ludeman[1] on multiple inner-shell ionizations by heavy ions gives no evidence for a molecular promotion mechanism.[7] From this and the outcome of the present calculations we have reason to believe that the atomic Coulomb excitation mechanism is somewhat more important in atomic and ionic collisions than hitherto presumed. It would be highly desirable to obtain further experimental tests for the validity of this assumption.

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