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IMPACT-PARAMETER DEPENDENCE OF INNER-SHELL VACANCY PRODUCTION BY HEAVY-ION BOMBARDMENT

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30-MeV I ions were scattered by thin targets of Yb and Te. The differential and total cross sections for characteristic x-ray production were measured. The mechanism responsible for inner-shell ionization is suggested to be electron promotion by level crossing in the quasimolecule of the colliding atoms.

In collisions between energetic heavy particles, inner-shell vacancies may be produced in both atoms and characteristic x rays will be observed. A possible mechanism for vacancy production is direct ionization, which can be treated under certain conditions in first Born approximation.[1] Employing Born's approximation with the corrections given in Bang and Hansteen[2] and in Brandt, Laubert, and Sellin,[3] outside its range of validity ($Z_1 \approx Z_2 \gg 1$, ion velocity v less than orbital velocity u of the excited electron), the calculated cross sections are orders of magnitude smaller than experimentally determined.[4] Since this approximation outside its range of validity generally overestimates cross sections, the mechanism of direct ionization can be assumed to be negligible in these cases. As a result, other mechanisms have to be considered, e.g., multiple ionization or electron promotion.[4-6] To shed more light on this open question we measured the inner-shell excitation probability by heavy-ion bombardment as a function of impact parameter.

30-MeV I ions from the Heidelberg EN tandem accelerator were scattered by thin targets of Te and Yb. Characteristic x rays of both colliding particles were analyzed in a proportional counter and measured in coincidence with ions scattered through large angles. The deflection angles, $0.5° \lesssim \theta_{lab} \lesssim 7°$, were chosen such that the corresponding impact parameters p ranged approximately from 10^{-2} to 10^{-1} Å.[7] In addition, the total ionization cross section σ_{tot} was obtained by measuring the total number of characteristic x rays coincident with all ions transmitted through the target.

The experimentally determined quantity is the number of detected characteristic x rays per

Table I. Characteristic parameters involved in the collision between 30-MeV I ions and Te and Yb atoms.

Colliding particles	X rays	ω	σ_{tot} [10^5 b]	n	α	P_{max} [10^{-10} cm]	a_m [10^{-10} cm]
I→ Te	Te_L/I_L	0.14	6.4 ± 2	1.05 ± 0.15	0.5 ± 0.3	4 ± 2	~5
I→ Yb	I_L	0.14	2.0 ± 0.2	1.10 ± 0.15	0.5 ± 0.3	~4	~5
	Yb_M	0.04	55 ± 2.5	0.95 ± 0.10	>2	>4	~8

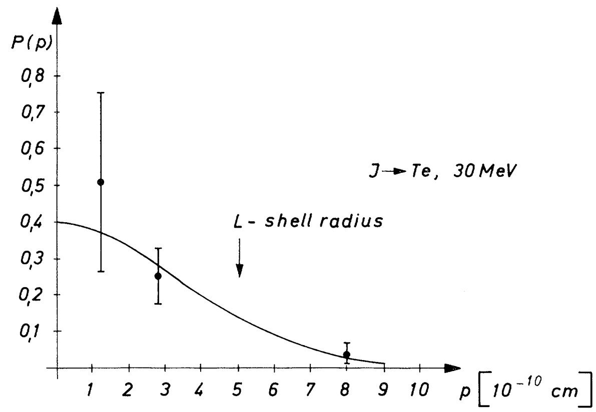

FIG. 1. Probability $P(p)$ for production of L-shell vacancies in I to Te as a function of impact parameter p.

scattered I ion, N_x/N_I. This ratio is a direct measure of the impact-parameter-dependent probability P for inner-shell vacancy production. The absolute value of P can be obtained by multiplying with a scale factor, depending on counter efficiency and solid angle, and x-ray fluorescence yield ω (cf. Table I).

In Fig. 1, $P(p)$ is plotted for the scattering of 30-MeV I ions on Te atoms. It is assumed that $P(p)$ is identical for both colliding particles ($Z_I \approx Z_{Te}$). The solid curve is a best-fitting Gaussian function. From this function we obtain the production probability for an inner shell vacancy in a head-on collision α and the impact parameter p_{max} which contributes most to the total cross section. p_{max} is located at the maximum of the function $pP(p)$. Besides α and p_{max}, we summarize in Table I our measured values for σ_{tot} and the exponent n of its energy dependence, $\sigma \propto E^n$ (for 30- to 40-MeV I ions). ω and the approximate shell radii a_m are given also.

In the case of a Gaussian function for $P(p)$ (Fig. 1), the total cross section is $2\alpha p_{max}^2$. Using this formula and our tabulated values for α and p_{max}, the resultant cross sections (5×10^5 b, I-Te) are consistent with the measured total cross sections.

Our values σ_{tot}, p_{max}, α, and n cannot be explained by the direct ionization mechanism, as shown in the following for the I-Te system: (1) From the calculations given,[2] we get $p_{max} \lesssim 9.5 \times 10^{-3}$ Å, which is too small if compared with the experimental result. (2) From the theory of direct ionization[1] we obtain $\sigma_{tot} \approx 3\times10^4$ b. This too small value is an upper limit from a theory which in this velocity range overestimates the cross sections. In addition, the corrections introduced by Brandt, Laubert, and Sellin[3] would reduce the calculated cross sections by orders of magnitude. (3) For direct ionization, we expect $n = 4$[1] instead of $n = 1$.

Our values are in agreement with an electron-promotion mechanism.[6] Inner-shell vacancies are produced by level crossings in the quasimolecules formed by the colliding particles. With our values of σ_{tot}, n, and p_{max}, and following the calculations in Fortner et al.,[8] we obtain an average level-crossing distance of 0.075 Å. This lies between the L-shell diameter and the L-shell radius. From our α, we conclude that several terms in the L shell are involved.

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[1] Cf. E. Merzbacher and H. W. Lewis, in Handbuch der Physik, edited by S. Flügge (Springer, Berlin, 1958), Vol. 34, p. 166.

[2] J. Bang and I. M. Hansteen, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 31, No. 13 (1959).

[3] W. Brandt, R. Laubert, and I. Sellin, Phys. Rev. 151, 56 (1966).

[4] H. J. Specht, Z. Physik 158, 301 (1965).

[5] N. F. Mott and H. S. W. Massey, The Theory of Atomic Collisions (Oxford Univ., Oxford, England, 1965).

[6] U. Fano and W. Lichten, Phys. Rev. Letters 14, 627 (1965).

[7] W. Everhart, G. Stone, and R. J. Carbone, Phys. Rev. 99, 1287 (1955).

[8] R. J. Fortner, B. P. Curry, R. C. Der, T. M. Kavanagh, and J. M. Khan, Phys. Rev. 185, 164 (1969).