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MEASUREMENTS OF Q VALUES FOR Al^+, P^+, S^+, Cl^+, K^+, AND Mn^+ ON ARGON AT keV ENERGIES

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Inelastic-energy-loss distributions for single collisions of Al^+, P^+, S^+, Cl^+, K^+, and Mn^+ with argon at keV energies have a triple-peaked structure in a limited range of r_0 similar to that observed earlier for the homonuclear case Ar^+ on Ar. In contrast to the homonuclear case, however, the inner-shell excitation for the asymmetric cases takes place almost exclusively in the one of the collision partners with lowest atomic number Z.

Extensive experimental studies by Everhart and Kessel[1] and Afrosimov et al.[2] on $Ar^+ - Ar$ collisions have shown that the average inelastic energy loss $\bar{Q}$, in a narrow range of distances of closest approach r_0, exhibits a sudden increase. For the homonuclear case Ar^+ on Ar, the energy-loss distributions have a triple-peaked structure in the "active" r_0 region attributed to L-shell excitations in one or both collision partners.[3] The three Q values observed correspond to M-shell excitation ($\bar{Q}_{\text{I}}$), M-shell excitation plus an $L_{2,3}$ vacancy in one of the colliding particles ($\bar{Q}_{\text{II}}$), and M-shell excitation plus two $L_{2,3}$ vacancies, one in each particle ($\bar{Q}_{\text{III}}$). The results are consistent with the Fano-Lichten model[4] which, by applying the one-electron molecular-orbital approximation on a colliding homonuclear ion-atom system, predicts a promotion of one or two L-shell electrons to higher states for r_0 smaller than a critical value. The inner-shell vacancies decay preferentially via an Auger process–probably after the colliding particles have separated –resulting in the ejection of one fast electron per excited ion. Rudd, Joergensen, Jr., and Volz[5] have experimentally confirmed that the fast electrons in Ar^+ on Ar are due to LMM Auger processes. The asymmetric case Ne^+ on Ar, studied by Kessel,[6] turned out to have a single-peaked Q distribution over the whole range of measured r_0 values. Recent cross-section data by Loftager and Hermann,[7] however, point to a Q structure for the cases P^+, Cl^+, and K^+ on Ar.

The work to be reported here was undertaken in order to study experimentally various asymmetric collisions on Ar in more detail. The data show triple-peaked Q structures–in a narrow range of r_0 values–indicating that L-shell excitation also occurs in asymmetric systems. Excitation of two L electrons in the low-Z collision partner is highly probable for r_0 smaller than a critical value and is responsible for $\bar{Q}_{\text{III}}$.

The 80-keV isotope separator of the Insitute of Physics, University of Aarhus, equipped with a universal ion source, was used to perform the collision measurements of Al^+, P^+, S^+, Cl^+, K^+, and Mn^+ on Ar. The experimental apparatus consists of a collision chamber with a differentially pumped gas cell and a turnable exit port with an electrostatic analyzer. The energy distribution of the scattered incident particles, from which the Q distribution is easily obtained, was measured as a function of the scattering angle for various charge states m of the scattered particles, exluding neutrals. The angular divergence

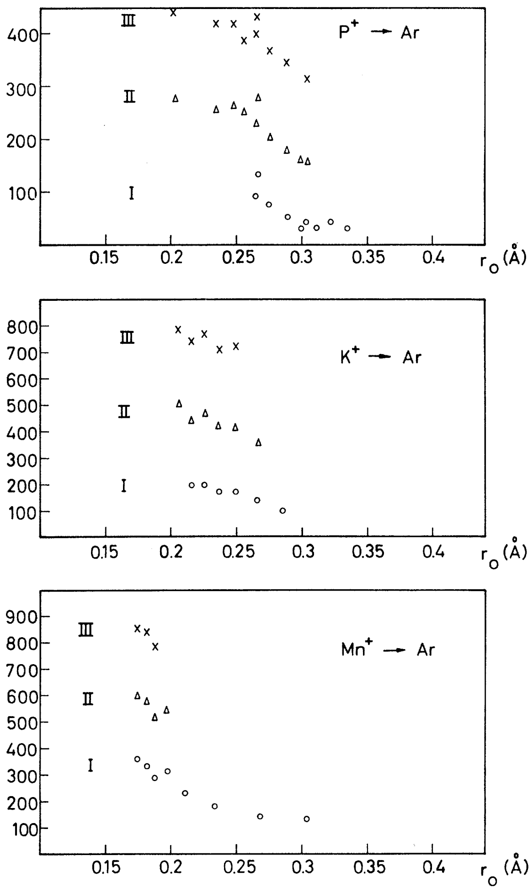

FIG. 1. The weighted inelastic energy loss $\bar{Q}_j$ as a function of r_0, the distance of closest approach. Open circles: j = I; open triangles: j = II; and crosses: j = III.

of the incident beam is maximally one third of a degree and the energy resolution of the electrostatic analyzer is approximately 0.3 %. The pressure in the target gas was less than 3×10^{-4} Torr in order to secure that single-collision conditions were fulfilled. The scattering angles ranged from 4° to 18°, and the energy of the incident particles was 20, 30, 40, 50, or 60 keV.

The resulting energy loss spectra of the scattered incident particles in all cases show three peaks in a localized region of r_0. Q distributions were resolved by fitting the sum of three Gaussian curves to the observed distribution.

The following quantities were derived from the data: The weighted mean Q value corresponding to peak j is

$$\bar{Q}_j = \sum_m \bar{Q}_j{}^m N_j{}^m / \sum_m N_j{}^m \quad (j = \mathrm{I}, \mathrm{II}, \mathrm{III}),$$

where $N_j{}^m$ is the number of scattered incident particles with charge state m in peak j, and $\bar{Q}_j{}^m$ is the corresponding mean energy loss. The excitation probability P_j of peak j is defined as

$$P_j = \sum_m N_j{}^m / \sum_{m,j} N_j{}^m \quad (j = \mathrm{I}, \mathrm{II}, \mathrm{III}).$$

The weighted mean charge $\bar{m}_j$ of the scattered incident particles in peak j is

$$\bar{m}_j = \sum_m m N_j{}^m / \sum_m N_j{}^m \quad (j = \mathrm{I}, \mathrm{II}, \mathrm{III}).$$

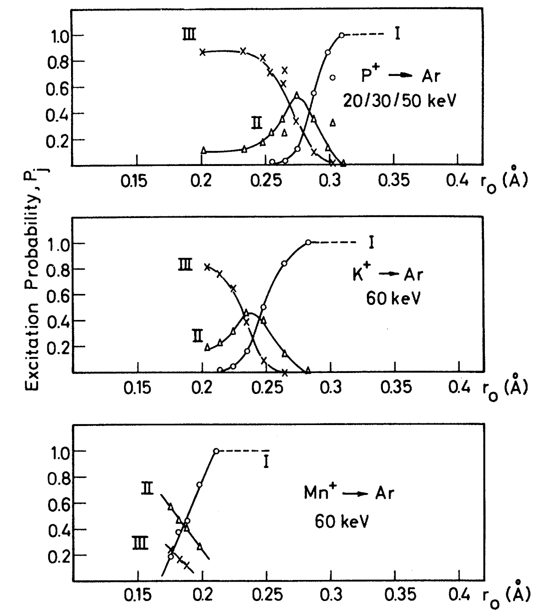

FIG. 2. The excitation probability P_j as a function of r_0. Open circles: j = I; open triangles: j = II; and crosses: j = III.

Figure 1 shows $\bar{Q}_j$ as a function of r_0 for three cases: P^+ on Ar, K^+ on Ar, and Mn^+ on Ar. r_0 was calculated on the basis of an exponentially screened interaction potential. Q is double or triple peaked inside the "active" region. $\bar{Q}_{\mathrm{III}} - \bar{Q}_{\mathrm{II}}$ and $\bar{Q}_{\mathrm{II}} - \bar{Q}_{\mathrm{I}}$ are almost independent of r_0. $\bar{Q}_{\mathrm{I}}$, $\bar{Q}_{\mathrm{II}}$, and $\bar{Q}_{\mathrm{III}}$ decrease with r_0 in contrast to the $Ar^+ \rightarrow Ar$ case where they are almost constant.

Figure 2 shows the excitation probability P_j as a function of r_0 for the same three cases as in Fig. 1. Here it is noted that for large r_0, only $\bar{Q}_{\mathrm{I}}$ prevails. In the intermediate region, all three $\bar{Q}_j$ exist. For small r_0 values and $Z_1 < 18$ (Z_2 is held fixed at 18), both $\bar{Q}_{\mathrm{II}}$ and $\bar{Q}_{\mathrm{III}}$ exist with P_{II} and P_{III} substantially different from zero. The data for Al^+, P^+, S^+, and Cl^+ on Ar for small r_0 values indicate that P_{II} becomes larger with decreasing Z_1. P_{III}, being 1 in the homonuclear case at low r_0 values, is accordingly smaller. Unfortunately, it was not possible to pursue the manganese data down to r_0 small enough to obtain a more complete set of excitation curves.

A summary of the results is shown in Table I.

Table I. Various $\bar{Q}_j$ differences for Z_1-on-Ar collisions. T_0 is the kinetic energy of the incident particles and $B_{L_{2,3}}(Z_1)$ the average binding energy of an L_2 or L_3 electron in the neutral Z_1 atom.

Z_1	T_0 (keV)	"Active" region r_0 (Å)	$\bar{Q}_{II}-\bar{Q}_I$ (eV)	$\bar{Q}_{III}-\bar{Q}_{II}$ (eV)	$\bar{Q}_{III}-\bar{Q}_I$ (eV)	$B_{L_{2,3}}(Z_1)$ (eV)
13	20/30	0.27–0.34	70 ± 10	90 ± 10	160 ± 10	80
15	20/30/50	0.24–0.30	127 ± 10	168 ± 10	295 ± 10	137
16	40	0.25–0.30	160 ± 10	200 ± 10	360 ± 10	167
17	60	0.24–0.28	189 ± 15	238 ± 15	427 ± 15	203
18	60	0.21–0.26	254 ± 20	254 ± 20	508 ± 20	250
19	60	0.21–0.25	246 ± 20	294 ± 20	540 ± 20	300
25	60	–0.21	233 ± 30	267 ± 30	500 ± 30	650

$\bar{Q}_{III}-\bar{Q}_{II}$ is seen to be some 15-25% larger than $\bar{Q}_{II}-\bar{Q}_I$. $\bar{Q}_{II}-\bar{Q}_I$ agrees well with the binding energy of an L_2 or L_3 electron in the low-Z collision partner, i.e., for Al^+, P^+, and S^+ on Ar, the L-shell excitation takes place in the projectile only, whereas for Mn^+ on Ar, the excitation takes place in the target atom. Cl^+, Ar^+, and K^+ on Ar are transition cases with Z_1 and Z_2 at the most differing by one unit. Except for these cases, none of the values $\bar{Q}_{III}-\bar{Q}_{II}$ or $\bar{Q}_{III}-\bar{Q}_I$ correspond to the binding energy of an L electron in the high-Z collision partner. For instance in the case of Al^+ on Ar it is seen from the table that $\bar{Q}_{III}-\bar{Q}_{II}$ and $\bar{Q}_{III}-\bar{Q}_I$ are 90 and 160 eV, respectively, whereas the binding energy of an $L_{2,3}$ electron in Ar is 250 eV. For the Mn^+-Ar case, $\bar{Q}_{III}-\bar{Q}_{II}$ and $\bar{Q}_{III}-\bar{Q}_I$ are 267 and 500 eV, respectively. The binding energy of an $L_{2,3}$ electron in Mn is 650 eV. Therefore the data suggest that $\bar{Q}_{III}$ corresponds to a promotion of two L electrons in the low-Z partner to higher M states. This hypothesis is supported by the fact that the value of $\bar{Q}_{III}-\bar{Q}_I$ equals the binding energy of two L_2 or L_3 electrons in the low-Z atom. The charge-state analysis also strongly supports this hypothesis. As exemplified in the Mn^+-on-Ar case, the mean charges $\bar{m}_I$, $\bar{m}_{II}$, and $\bar{m}_{III}$ are almost equal, indicating that no L-shell excitation has taken place in the high-Z ion. For Al^+, P^+, and S^+ on Ar, it was found that $\bar{m}_{III}\simeq\bar{m}_{II}+1\simeq\bar{m}_I+2$, which means that in average, the promotion of two L electrons results in the ejection of two electrons from the low-Z ion. It is then concluded that the M-shell excitations in the colliding atoms are roughly equal in the three Q peaks. For Al^+, P^+, S^+, and Cl^+, the mean charges $\bar{m}_j$ are almost independent of r_0 in the "active" region, whereas for K^+ and Mn^+ they show a significant r_0 dependence.

In the three cases, Cl^+, Ar^+, and K^+ on Ar, L-shell excitation takes place in one or both collision partners, i.e., $\bar{Q}_{III}$ corresponds to L-shell excitations in both atoms and $\bar{Q}_{II}$ corresponds to excitation in the low-Z atom only. However, the possibility of double electron promotions in the cases of Cl^+ and K^+ on Ar cannot be ruled out.

Electron-spectra measurements and Doppler-shift analysis carried out parallel to the Q measurements gave further support to the excitation model outlined here.

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