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Single electron loss of Kr^+ ions in gaseous media

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Abstract. Differential and total cross sections for single electron loss were measured for Kr^+ ions on gaseous media in the energy range of 1.0 to 5.0 keV. The single electron loss cross sections for all the targets studied are found to be in the order of magnitude between 10^{-22} and 10^{-20} cm^2, and show a rapid monotonically increasing behaviour as a function of the incident energy; no remarkable differences in the energy dependence of σ_{12} were found for any atom studied. The single electron loss cross sections show a weaker Z_t dependence in the large Z_t region than that given by the Bohr formula. A striking feature of the results is the experimental evidence of saturation in the single electron loss cross section as the nuclear charge of the target increases.

1. Introduction

The loss of electrons by fast ions when they collide with the atoms of a medium is in essence an ionization process of atomic particles. Because of its fundamental nature, the knowledge of the cross section for this process is essential in many applied areas, such as atomic physics (Datz *et al* 1999), plasma physics (Janev 1995), chemical physics (Herschbach 1999), material science (Möller 1999), radiotherapy and radiation research (Möller 1999) and energy loss information in organic material, such as human tissue. To date, there are few systems dealing with projectiles carrying more than one electron, for which experimental data and theoretical calculations are known. To understand the electron dynamics in moderate-energy collisions a detailed molecular description is required, in which the crossings between molecular states and the coupling of these states with the continuum play a fundamental role (Delos 1981, Barat and Lichten 1972, Sidis 1973, Brenot *et al* 1975a, Sidis *et al* 1975, Brenot *et al* 1975b, Barat *et al* 1970, Gerber *et al* 1973). In the analysis of the measured data of inelastic processes in symmetric atom–atom collisions for rare-gas atoms, Brenot (1975a) concluded that, in a first approximation, these processes seem to occur through the same basic mechanism in the atom–atom and ion–atom cases. In the Kr–Kr case they reported, for 3 keV, the differential ionization cross sections for the projectile and ionization of the projectile with excitation of the target. They considered that the promotion of one electron from the $6h\sigma_u$ MO was the main mechanism. Müller *et al* (1976) reported the one-electron stripping process of Ar^+ ions colliding with Ar atoms at 6 and 36 keV. Many of the experiments and calculations have been restricted to the simplest case of He^+ colliding with Ne, Ar, Kr and Xe atoms and even these are often restricted to the high-velocity regime (Voitkiv *et al* 1999). Recently, theoretical calculations of the cross sections for the loss of an electron by fast He^+ and C^{3+} particles colliding with H and H_2 in the $0.5 \leqslant E \leqslant 3.5$ MeV energy range (Sant'Anna *et al*

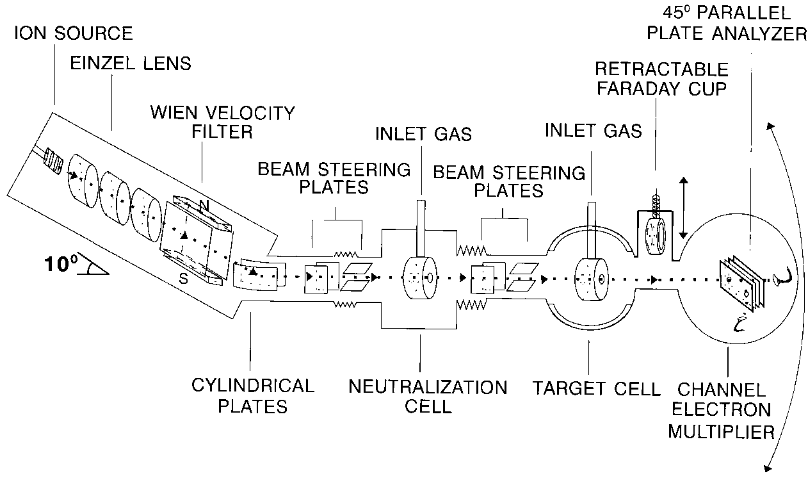

Figure 1. Schematic diagram of the apparatus.

1998, Montenegro *et al* 1994), were made in a wide range of velocities for two very simple cases: loss of an electron by a simple charged helium ion colliding with heavy atomic targets (Voitkiv *et al* 1999, Kaneko 1985, 1986), and loss of an electron by hydrogenlike ions with atomic number Z_1 ($2 \leqslant Z_1 \leqslant 7$) and with velocity v ($0.3v_0 \leqslant v/Z_1 \leqslant 6v_0$; v_0 is the Bohr velocity) colliding with N_2, O_2, Ne and Ar (Wu *et al* 1997, Kaneko 1986). In a previous paper (Martínez 1999), the energy dependence of the electron loss cross section for Kr^+ ion colliding with Kr was measured. As an extension of those measurements, this paper aims to acquire knowledge of the dependence of the single electron loss (SEL) cross sections of Kr^+ on the physical parameters E (incident energy) and Z_t (target atomic number). Data were measured for 1.0–5.0 keV and for $2 \leqslant Z_t \leqslant 54$.

2. Experiment

The experimental apparatus and technique needed to generate the fast ion beam were recently reported (Martínez 1999, Martínez and Reyes 1999) and are displayed in figure 1. Briefly, the Kr^+ ions formed in an arc discharge source containing Kr gas (99.99% purity) at ion source pressures of 0.04–0.07 mTorr were accelerated to 1.0–5.0 keV and selected by a Wien velocity filter. The Kr^+ ions were then allowed to pass through a series of collimators before entering the gas target cell, which was a cylinder of 2.5 cm in length and diameter, with a 1 mm entrance aperture, and a 2 mm wide, 6 mm long exit aperture. The target cell was located at the centre of a rotatable, computer-controlled vacuum chamber that moved the whole detector assembly which was located 47 cm away from the target cell. A precision stepping motor ensured a high repeatability in the positioning of the chamber over a large series of measurements. The detector assembly consisted of a Harrower-type parallel-plate analyser and two channel-electron multipliers (CEMs) attached to its exit ends. The Kr^0 atoms passed straight through the analyser. Separation of charged particles occurred inside the analyser, which was set to detect the Kr^{2+} ions ($I_f(\theta)$) particles per unit solid angle per second detected at a laboratory angle θ with respect to the incident beam direction (typically $\sim 2.2 \times 10^8$ particles s^{-1}) with the lateral CEM. The CEM was calibrated *in situ* with a low-intensity Kr^{2+} beam, which was measured as a current in a Faraday cup by a sensitive electrometer. The uncertainty in the detector calibration was estimated to be less than 3%. A retractable Faraday cup was located 33 cm away from the target cell, allowing the measurement of the incoming Kr^+ ion-beam current (I_0 is the number of Kr^+ ions incident per second on the target, typically $\sim 6.6 \times 10^{10}$ particles s^{-1}).

Under the thin target conditions used in this experiment, the differential cross sections for the Kr^{2+} formation were evaluated from the measured quantities by the expression

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{I_f(\theta)}{I_0 n l} \tag{1}$$

where n is the number of target atoms per unit volume (typically 1.2×10^{13} atoms cm^{-3}) and l is the length of the scattering chamber ($l = 2.5$ cm).

The estimated rms error is 15%, while the total cross sections were reproducible to within 10% from day to day.

The total cross section σ for the production of the Kr^{2+} particles was obtained by the numerical integration of $d\sigma/d\Omega$ over all angles measured; this is

$$\sigma = 2\pi \int_0^{\theta_m} \frac{d\sigma}{d\Omega} \sin(\theta)\, d\theta. \tag{2}$$

For $\theta > \theta_m$ the differential cross sections vanish.

Extreme care was taken when the absolute differential cross section was measured. The reported value of the angular distribution was obtained by measuring it with and without gas in the target cell with the same steady beam in order to eliminate the counting rate due to ionization of the Kr^+ beam on the slits and those arising from background distributions.

In the present work, changes were not observed in the absolute values with respect to the ion source conditions. Also, no variation in the distributions was detected over a target pressure range of 0.2–0.6 mTorr.

Several sources of systematic errors are present and have been discussed in a previous paper (Martínez 1998). The absolute error of the reported cross sections is believed to be less than ±15%. This estimate represents both random and systematic errors.

3. Results and discussion

Measurements of differential cross sections (DCSs) were performed at laboratory angles of $\theta \leqslant |3^0|$ and collision energies E from 1.0 to 5.0 keV. As an example, we show in figure 2 our DCSs for SEL of Kr^+ in He at 1.0, 2.0, 3.0, 4.0 and 5.0 keV laboratory energies (the vertical error is of the order of the size of the symbols used in the figure). The behaviour of the DCSs is qualitatively identical for all the targets studied in this work as shown in figure 3. All curves plotted in figure 2 show that the differential cross section tends to decrease with increasing angle. The SEL data show slight structures in the DCSs which tend to disappear as the incident energy decreases. All data represent the average of at least ten scans, made on no less than five separate occasions over a period of several months. This gives us the confidence in the reproducibility of the slight DCSs structures.

The measured DCSs have been integrated numerically over the observed angular range ($0^0 \leqslant \theta \leqslant 3^0$) to yield the total cross sections σ_{12}. The energy dependence of the cross section for a Kr^+ ion colliding with Kr (taken from Martínez (1999)) and He, Ne, Ar and Xe atoms are listed in table 1 and shown in figure 4. The error bars are a measure of the reproducibility of the data (15%). The cross sections obtained for each colliding system exhibit an increasing behaviour as a function of the incident energy. The energy dependence observed previously by Martínez (1999) for Kr^+ on Kr in the same energy range and in He^+–atom systems at high energies by Kaneko (1985) is $\sigma_{12} \sim E^c$, where c is the power index of the energy E.

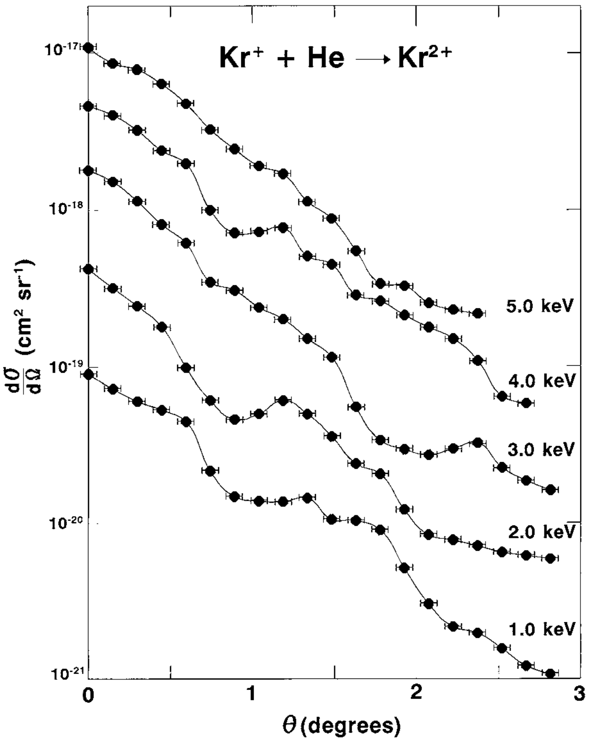

Figure 2. Measured absolute DCSs for single electron loss of Kr^+ ions in He.

Table 1. Total SEL cross sections $\sigma_{12}(10^{-20}\ cm^2)$ as a function of Z_t and the incident energy.

Energy (keV)	Target He	Ne	Ar	Kr[a]	Xe
1.0	0.01	0.07	0.08	0.12	0.13
1.5	0.02	0.15	0.15	0.22	0.28
2.0	0.04	0.30	0.38	0.43	0.53
2.5	0.09	0.48	0.53	0.80	0.90
3.0	0.15	0.78	1.05	1.38	1.65
3.5	0.26	1.48	1.85	2.50	3.00
4.0	0.43	2.29	2.73	3.84	4.53
4.5	0.64	3.48	4.15	5.80	6.80
5.0	1.02	5.59	6.73	9.25	11.03

[a] From Martínez (1999).

Considering that the SEL cross sections have the form $\sigma_{12} = A + B * E^c$, where E is the energy in keV, and optimizing it through a least-squares fit to our data, yields to the parameters and correlation coefficients listed in table 2, and shown in figure 4 as solid curves. From the least-squares fit, we find that $\sigma_{12} \sim E^4$ in the present energy range, for all the targets used in this work. For SEL cross section measurements of Ar^+ ions colliding with He, Martínez (1998) found that $\sigma_{12} \sim E^2$ in the same energy range. The difference in the energy dependence of the cross sections of the present data and Martínez's (1998) may be explained by considering that in ion–atom collisions the interaction probabilities are strongly influenced by the projectile

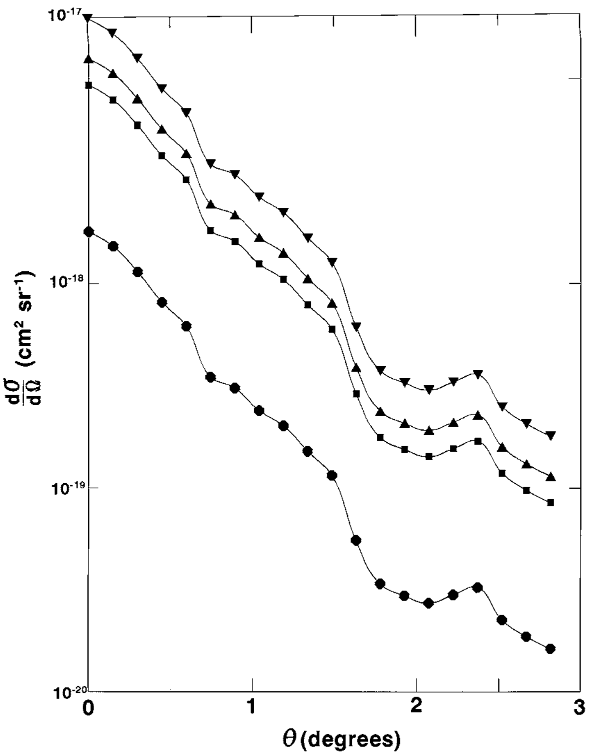

Figure 3. Measured absolute DCSs for SEL of Kr^+ ions at 3 keV in ●, He; ■, Ne; ▼, Ar and ▲, Xe.

Table 2. Total SEL cross sections parameters. SEL cross section form: $\sigma_{12}(E) = A + B * E^c$.

Parameter	Kr^+ + He	Kr^+ + Ne	Kr^+ + Ar	Kr^+ + Kr[a]	Kr^+ + Xe
$A(10^{-20}$ cm$^2)$	0.0165	0.1330	0.1527	0.1889	0.2342
$B(10^{-20}$ cm^2 keV$^{-c})$	0.0016	0.0072	0.0096	0.0143	0.0159
C	3.9998	4.1091	4.0446	4.0009	4.0414
Correlation coefficients	0.99873	0.99838	0.99717	0.99846	0.99766

[a] From Martínez (1999).

electronic structures, which in turn changes the quasimolecular model of the systems (Delos 1981, Sidis *et al* 1975, Brenot *et al* 1975, Sidis 1973, Barat and Lichten 1972). Kaneko (1985), using the unitarized impact parameter method to calculate the SEL cross section for He^+ ions colliding with He, Ne, Ar and Kr, found that the energy dependence was $\sigma_{12} \sim E^{2.8}$ in the energy range $30 \leqslant E \leqslant 150$ keV. We know that these are different collision systems and energy ranges but this relation can be used to make a comparison of the behaviour of the cross sections as a function of the impact energy. From these results it may be inferred that there is not a clear relation between the exponent of the energy dependence of the cross section and the ionization potential as was found by Bohr (1948) from the free-collision approximation at high energies. Figure 5 shows the dependence with Z_t of the SEL cross section for 1.0–5.0 keV Kr^+ ions colliding with various gases. SEL shows an increasing behaviour as a function of Z_t, which is slower for higher Z_t values, and displays a slight structure at low energies which

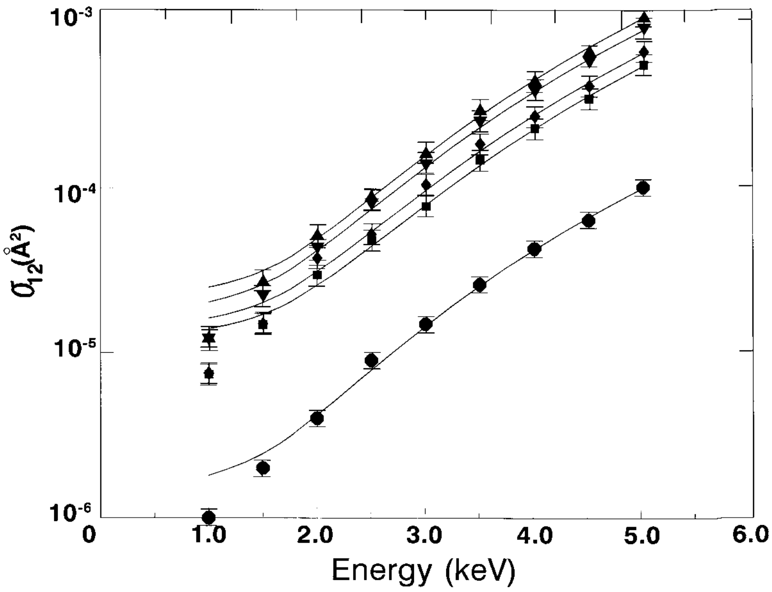

Figure 4. Calculated total cross sections for SEL of Kr^+ ions in atoms. ●, He; ◆, Ar; ▲, Xe; ■, Ne; ▼, Kr (from Martínez (1999)). The solid curves are the fitting functions listed in table 2.

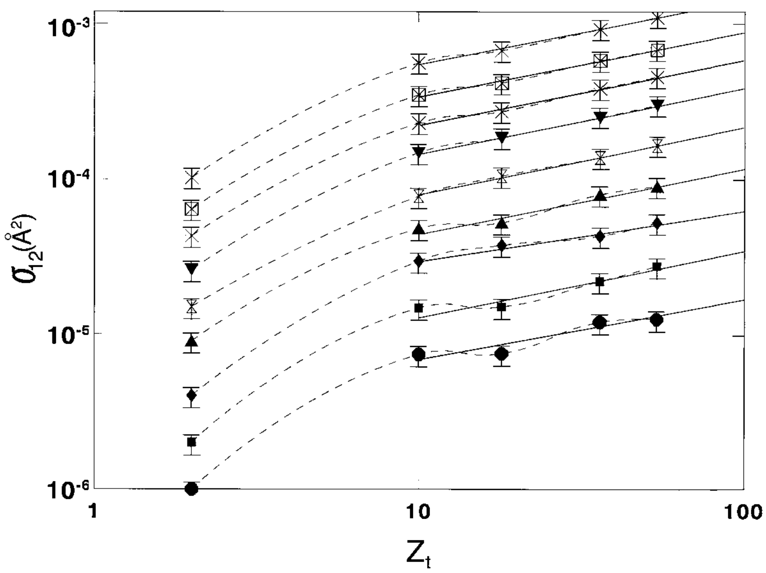

Figure 5. Total cross sections for SEL of Kr^+ ions in atoms as a function of the target atomic number Z_t. ●, 1.0 keV; ■, 1.5 keV; ◆, 2.0 keV; ▲, 2.5 keV; ⧖, 3.0 keV; ▼, 3.5 keV; ⋆, 4.0 keV; ⊠, 4.5 keV and ×, 5.0 keV. The dashed curves are an interpolation to show the behaviour and the solid curves represent the fitting functions listed in table 3.

Table 3. Total SEL cross sections of Kr^+ on gases as a function of the target atomic number Z_t at several incident energies considering $\sigma = D * Z_t^m$.

Energy (keV)	D (10^{-20} cm^2)	m	Correlation coefficient
1.0	0.0271	0.3990	0.9637
1.5	0.0486	0.4310	0.9278
2.0	0.1459	0.3173	0.9636
2.5	0.1750	0.4131	0.9678
3.0	0.2946	0.4321	0.9981
3.5	0.5466	0.4257	0.9990
4.0	0.8321	0.4246	0.9940
4.5	1.2943	0.4159	0.9943
5.0	2.0660	0.4187	0.9960

becomes less important as the energy increases. A similar saturation of the SEL cross section for high Z_t and high energies was observed for He^+ as projectile (Santa'Anna *et al* 1995, Kaneko 1985) and in the excitation channel of highly charged projectiles on neutral targets (Kaneko 1985, Wohrer *et al* 1986). During the loss process, the target electrons can either stay in the ground state screening the target nucleus, or be the active ionizing agents of the projectile electron, increasing the electron loss cross section through the so-called antiscreening process (Kaneko 1985, Montenegro *et al* 1992). In the first case, the expected dependence of the SEL cross section with the target atomic number varies with Z_t^2, within first-order theories; but it is well known that a saturation effect occurs for high values of Z_t (Santa'Anna *et al* 1995, Voitkiv *et al* 1999, Wohrer *et al* 1986). In the antiscreening mode, the expected dependence would be approximately linear with Z_t. Fitting the expression $\sigma_{12} \approx D * Z_t^m$ to our data (ranging from 10 to 54) gives the results shown in table 3 and displayed in figure 5 by a straight line to high-Z_t. Our results present a weak Z_t dependence when compared with Bohr's results of $\sigma_{12} \approx \pi a_0 Z_t^{2/3} Z_p^{-1}(v_0/v)$ for intermediate Z_t, where a_0 is the Bohr radius, v_0 the Bohr velocity, Z_p is the atomic number of the projectile and v is the projectile velocity. A similar behaviour was observed by Dimitriev *et al* (1962) and Kaneko (1985) using He^+ as the projectile.

From a least-squares fit, combining the results $\sigma_{12} \approx E^4$ and $\sigma_{12} \approx Z_t^{0.4}$ we find

$$\sigma_{12} = Z^{0.4}[0.044 \pm 0.001 + (0.0034 \pm 0.0001) * E^4] \qquad (3)$$

in the present energy range, for the targets Ne, Ar, Kr and Xe; for the He target there is a difference of a factor of around three on the linear parameters.

It thus appears desirable that a detailed theoretical analysis be carried out to understand the basic mechanisms responsible for the behaviour shown in this paper.

4. Summary

The results of this work can be summarized as follows.

(a) Differential and total cross sections for SEL in Kr^+–atom collisions were obtained at laboratory energies between 1.0 to 5.0 keV.
(b) The SEL cross sections for all the targets studied are found to be of the order of magnitude between 10^{-22} and 10^{-20} cm^2, and show a rapid monotonically increasing behaviour as a function of the incident energy.
(c) For the targets studied we found that $\sigma_{12} \sim E^4$ in the present energy range, with no remarkable differences in the energy dependence of σ_{12} for any of the targets studied.

(d) The SEL cross section shows a weaker Z_t dependence in the large Z_t region compared with that given by the Bohr formula.
(e) A striking feature of the results is the experimental evidence of a saturation in the SEL cross section as the nuclear charge of the target increases.
(f) In the present energy range a Z_t and E dependence given by $\sigma_{12} = Z^{0.4}[(0.044 \pm 0.001) + (0.0034 \pm 0.0001)E^4]$ was found for the targets Ne, Ar, Kr and Xe.

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