PRODUCTION AND LOSS OF Kr^{n+} (n = 1,2,3,4) AND Kr_2^+ IN A LOW PRESSURE KRYPTON DISCHARGE

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ABSTRACT

The spatial distribution of ions in a cylindrical krypton hollow cathode discharge is determined by the production (electron impact ionization, associative ionization) and loss processes (single and double electron transfer, volume recombination). An evaluation of the steady-state equation for each ion gives the loss rate constants, considering the ambipolar diffusion and taking into account the different energy thresholds for the effective ionization of Kr to Kr^+, Kr^{2+}, Kr^{3+} and Kr^{4+}. For the molecular ion Kr_2^+, the volume recombination coefficient provides a check on the plasma parameters used in the evaluation. The energy distribution of the fast ionizing electrons manifests itself in the radial density distribution of the ions which is different for the individual charge states.

INTRODUCTION

The formation of the ions Kr^{n+} (n = 1,2,3,4) and Kr_2^+ and their losses are studied in a low pressure krypton hollow cathode discharge. The primary atomic ions Kr^{n+} are produced within the negative glow by electron impact ionization. The production processes are as follows:

$$e_f + Kr \xrightarrow{k_n} Kr^{n+} + (n+1)e \qquad (1)$$

n = 1,2,3,4; e_f denotes the fast cathode-sheath electrons, k_n being the rate constant of process (1) in cm^3s^{-1}.

These fast electrons gain energy in the cathode fall and their maximum as well as average energy is determined by the maintenance voltage.

Thus the ratio k_n/k_1 can be calculated from the maintenance voltage and the cross sections obtained from the literature.

We have measured the total loss rates for the atomic ions which include single and double electron transfer:

$$Kr^{n+} + Kr \xrightarrow{k_x} \begin{cases} Kr^{(n-1)+} + Kr^{+} \\ Kr^{(n-2)+} + Kr^{2+} \end{cases} \qquad (2)$$

n = 2,3,4; x = 6,7,8.

The following loss rate coefficients are obtained:

Kr^{2+} ($k_6 < 5\cdot 10^{-13}$ cm^3s^{-1}), Kr^{3+} ($k_7 = (1,9 \pm 0,7)\cdot 10^{-11}$ cm^3s^{-1}), Kr^{4+} ($k_8 \approx (1 \pm 0,7)\cdot 10^{-10}$ cm^3s^{-1}).

The experimental setup and the method of evaluation has already been described /1/.

ION PRODUCTION BY ELECTRON IMPACT

The production of the primary ions by electron impact is described by process (1). The maximum energy available to the electron is given by the maintainance voltage U_e of the discharge (355-480 V). The voltage is high enough to provide the necessary energy of all the charge states observed in the low pressure region. A significant production of ions is only to be expected by electrons having energies where the ionization cross section, σ_n, for the production of Kr^{n+} is significantly high. This is the case for Kr^+ above 45 eV, Kr^{2+} above 100 eV, Kr^{3+} above 270 eV and Kr^{4+} above 340 eV.

Figure 1 shows the currents of the ions extracted on the axis of the negative glow as dependent on the discharge pressure.

Figure 2 shows the radial distribution of the ion densities of Kr^+, Kr^{2+}, Kr^{3+}, Kr^{4+}, and Kr_2^+ at a pressure of 0.046 torr and a current of 6 mA. The distributions are remarkably different. While the ions Kr^+ and Kr_2^+ show the normal diffusion-determined density distribution across the negative glow of the discharge, the distributions of the higher charge states get more and more pointed on the axis. These distributions (most remarkably for Kr_3^{3+} and Kr^{4+}) consist actually of two distributions, a wide one which is due to fast electrons that fill the space uniformly (elastically and inelastically scattered electrons) and a narrow distribution around the discharge axis which is due to very fast electrons which have traveled through the sheath and the entire negative glow without attenuation or deflection by collisions. Here, the ion density actually reflects the geometrical effect of the 1/r density increase of these electrons in the cylindrical geometry. The effective thresholds for a quantitative production of the individual charge states of the Kr^{n+} ions together with their radial distribution allows a qualitative estimate on the contribution of unscattered electrons to the total production of the Kr^+, Kr^{2+} and Kr^{3+} ions. Table 1 shows the percentage of the ion densities of these ions produced by the unscattered electrons at different discharge pressures. The density of Kr^{4+} is too low for a quantitative evaluation.

Table 1. Contribution of unscattered high-energy electrons to the production of Kr^+, Kr^{2+} and Kr^{3+} in the negative glow of the hollow cathode discharge at various pressures.

p (Torr)	Kr^+	Kr^{2+}	Kr^{3+}
0,027	3,2 %	8,1 %	40,0 %
0,04	1,8 %	4,5 %	33,7 %
0,06	1,2 %	2,9 %	30,8 %
0,07	0,9 %	2,2 %	27,4 %

PRODUCTION AND LOSS OF Kr_2^+

Formation and loss processes are studied for the molecular ion Kr_2^+, too. Kr_2^+ is produced by associative ionization

$$Kr' + Kr \xrightarrow{k_o} Kr_2^+ + e \qquad (3)$$

and by termolecular collision of Kr^+

$$Kr^+ + 2\,Kr \xrightarrow{k_5} Kr_2^+ + Kr \qquad (4)$$

Kr_2^+ is lost by dissociative volume recombination

$$Kr_2^+ + e_s \xrightarrow{\alpha} 2\,Kr \qquad (5)$$

e_s denotes the slow plasma electrons having a temperature of T_e = 1200°K /2/. The recombination coefficient α turns out to be α = $(5{,}5 \pm 3{,}5) \cdot 10^{-7}$ $cm^3 s^{-1}$ for T_e = 1200°K, in good agreement with Oskam and Mittelstadt's value of $1{,}2 \cdot 10^{-6}$ $cm^3 s^{-1}$ for 300°K /3/ if the reduction is made on a $T_e^{-0,5}$ basis.

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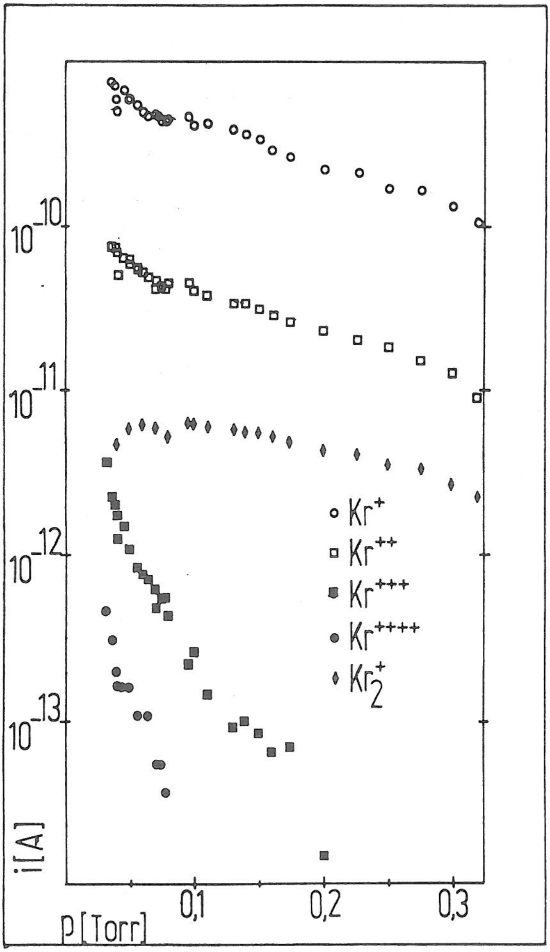

Fig.1 Ion currents of Kr^{+}, Kr^{2+}, Kr^{3+}, Kr^{4+}, and Kr_2^{+} extracted at space potential from the axis of the negative glow as dependent on discharge pressure.

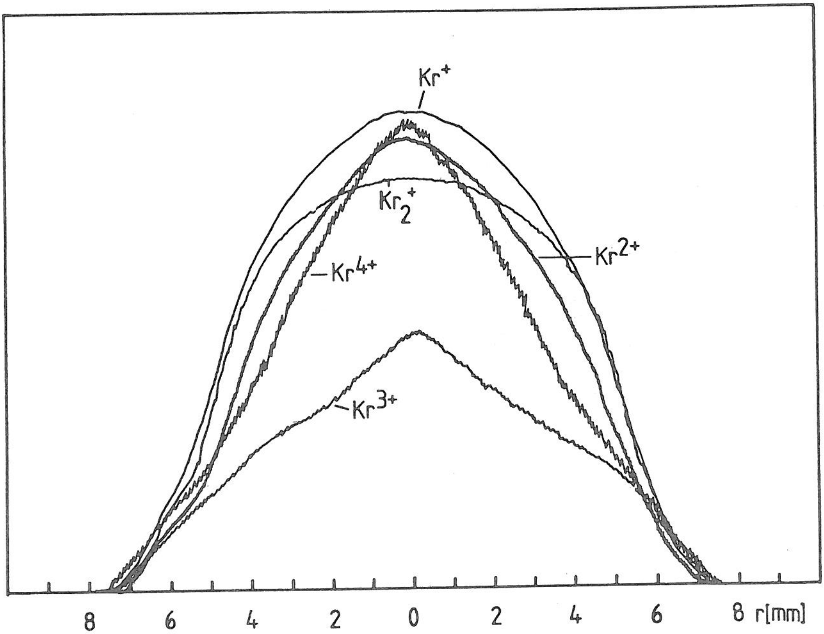

Fig. 2. Radial density distributions of the individual ions in the negative glow of the hollow cathode discharge (r = 10 mm). The densities are not drawn to scale. Discharge pressure 0,046 Torr, discharge current 6 mA.