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Charge transfer cross section for K^{+}+ Ar collisions

F.B.Alarcón[1,2], J.Omaña[3], H.Martínez[1]*

[1]Laboratorio de Espectroscopia, Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, Apartado Postal 48-3, 62210, Cuernavaca, Morelos, (MÉXICO)
[2]Instituto Profesional de la Región Oriente (IPRO), Universidad Autónoma del Estado de Morelos, C.P. 62715, Xalostoc, Morelos, (MÉXICO)
[3]Universida Autónoma Metropolitana, Unidad Azcapotzalco, Distrito Federal, (MÉXICO)
E-mail : hm@fis.unam.mx
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*Corresponding author's Name & Address

H.Martínez
Laboratorio de Espectroscopia, Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, Apartado Postal 48-3, 62210, Cuernavaca, Morelos, (MÉXICO)
E-mail : hm@fis.unam.mx

Abstract

Measurements of charge transfer cross sections for the K^{+} - Ar system are reported. The measurements are performed at low incident energy (0.25 - 4.30 keV). We compare the experimental results with previous data and a semiempirical calculation. The present results show an overlap with existing measurements and extend down in energy to 0.25 keV. Good agreement in behavior has been found between the semiempirical calculations and the present experimental data.

Key Words

Single-electron capture; Cross section; Ion beam experiment; Potassium; Ar.

INTRODUCTION

Charge transfer (CT) is one of the most fundamental and important processes occurring in ion-atom collisions. Therefore, it has attracted a large number of experimental as well as theoretical investigations over the years, generating significant contributions to our basic understanding of atomic physics, since it provides fundamental information for many-body collision dynamics. Comparatively comprehensive studies involving a variety of atomic targets, a wide range of collision energies (meV to keV), and various charged projectiles have greatly improved our understanding of CT in ion-atom collisions. Specifically, processes involving potassium, such as ionization, CT and electronic excitations are crucial in many applied sciences, such as biomass fuels[1], heavy metal pollution[2], material science[3] and atmospheric chemistry[4,5]. The need to understand CT mechanisms and the associated collision dynamics stimulated systematic theoretical and experimental investigations of systems for which indirect processes tend to dominate CT cross sections. There are two experimental studies reporting the measurement of the total cross section of the K^+ + Ar system. Ogurtsov et al.[6] measured the charge exchange of the K^+ + Ar system in the energy range of 1 - 30 keV, while Lo and Fite[7] made a compilation of electron-capture cross section data in the energy range of 15 keV - 1.65 MeV for the same system. Although these experiments on K^+ + Ar were reported several years ago, no experimental or theoretical results at low energies have since been published. This was the motivation to investigate CT resulting from the collisions of K^+ ions with Ar atoms at low-keV energies, where the CT channel is dominant. In previous articles[8-10] we have reported CT cross section measurements on the K^+- CH_4[8], K^+- H_2[9], and K^+- N_2[10] systems, and in the present paper, we report the absolute total cross section of single electron capture for K^+ collisions with Ar atoms.

EXPERIMENTAL METHOD

A schematic diagram of the apparatus is shown in Figure 1. Part of the experimental system has been described previously[8-12]. Briefly, potassium ions were formed by surface ionization of KCl vapors on a hot tungsten surface. Thus, the projectile ions had a narrow energy spread (≤ 0.3 eV) and were all in the ground electronic state. Mass separation *in situ* was not employed, since the impurity ions contained in the beam were less than 0.1% of those of K^+; this fact was confirmed by employing a mass spectrometer separately integrated in our laboratory. After acceleration to the desired energy (0.25 - 4.30 keV), the K^+ beam passed through several collimating apertures. All apertures and slits were knife-edged. Subsequently, the ion beam was directed to a target cell where the CT took place. The target cell was filled with Ar gas of 99.99% purity. The angular spread of the K^+ ion beam was estimated to be smaller than 0.4° in the collision chamber. The K^+ ion beam intensity was measured with a Faraday cup (FC). The gas target cell pressure was measured with a MKS Baratron capacitance manometer. The K^+ ions were conducted to an FC with parallel plates (analyzing plates in Figure 1).

The FC had a diameter of 2.5 cm and the K^+ ion beam diameter was of 0.5 mm. To ensure the full acquisition of the K^+ ion signal, the K^+ beam was measured as a function of the applied voltage to the parallel plates. The experiment was conclusive when a plateau was observed.

The CT cross sections (σ_{10}) were obtained from thin-target data. To a good approximation, the cross section is the slope of the linear growth of the beam component curve (GR method),

$$\sigma_{10} = \frac{dF_0}{d\pi} \tag{1}$$

where the fraction F_0 is given by

$$F_0 = \frac{[I_+(0) - I_+(P))]}{I_+(0)} \tag{2}$$

where $I_+(0)$ is the projectile beam current when the pressure in the gas cell was zero, $I_+(P)$ is the K^+ beam current when the pressure in the gas cell was P and π was determined from the ideal gas equation

$$\pi = \frac{\ell P}{kT}, \tag{3}$$

where P is the pressure in the target gas cell, ℓ is the target cell effective length, T is the temperature, and k is Boltzman's constant.

The background pressure in the system was 1.0×10^{-6} Torr.

An important consideration in low-energy absolute cross-section measurements is to ensure the complete collection of the scattered beam. This was experimentally demonstrated by measuring the charge transfer of protons in collisions with Ar at 1.5 keV. A value of σ = 11.9 Å^2 was obtained, which compares well with the result of σ = 11.0 Å^2 measured by Johnson et al.[13].

The uncertainties in the measured cross sections result primarily from the following factors: (1) the effective path length of the collision cell, (2) the approximate corrections for deviations from "thin" target conditions, (3) the measurement of target-gas pressure, and (4) the measurement of the beam intensity.

The effective path length is greater than the physical path length because of gas streaming from the apertures, which results from differential pumping. This effective increase in path length was estimated to be approximately 3%. This value was deduced from a comparison of the measured cross sections with a simple calculation based on isotropic-molecular flow of gas from the apertures.

The random uncertainties due to the determination of the beam intensity and target gas pressure can best be evaluated by the uncertainties encountered in obtaining the slope of the straight line defined by the points of the plot of the intensity ratios versus pressure. When the cross section is calculated from this slope, the fluctuations for individual points are averaged. The slope of each set of points corresponding to a particular cross section was determined by a least-squares fit. The uncertainties in the slopes of the straight lines vary from 3 to 5%. The larger uncertainty is associated with intensity data obtained with the Faraday cup.

The combined effects of the uncertainties discussed above result in uncertainties of ±15% in the measured charge transfer cross section.

RESULTS AND DISCUSSION

The GR curves for the K^+ and Ar system at energies 0.50, 1.00, 2.00, 3.00, and 4.00 keV are shown in Figure 2.

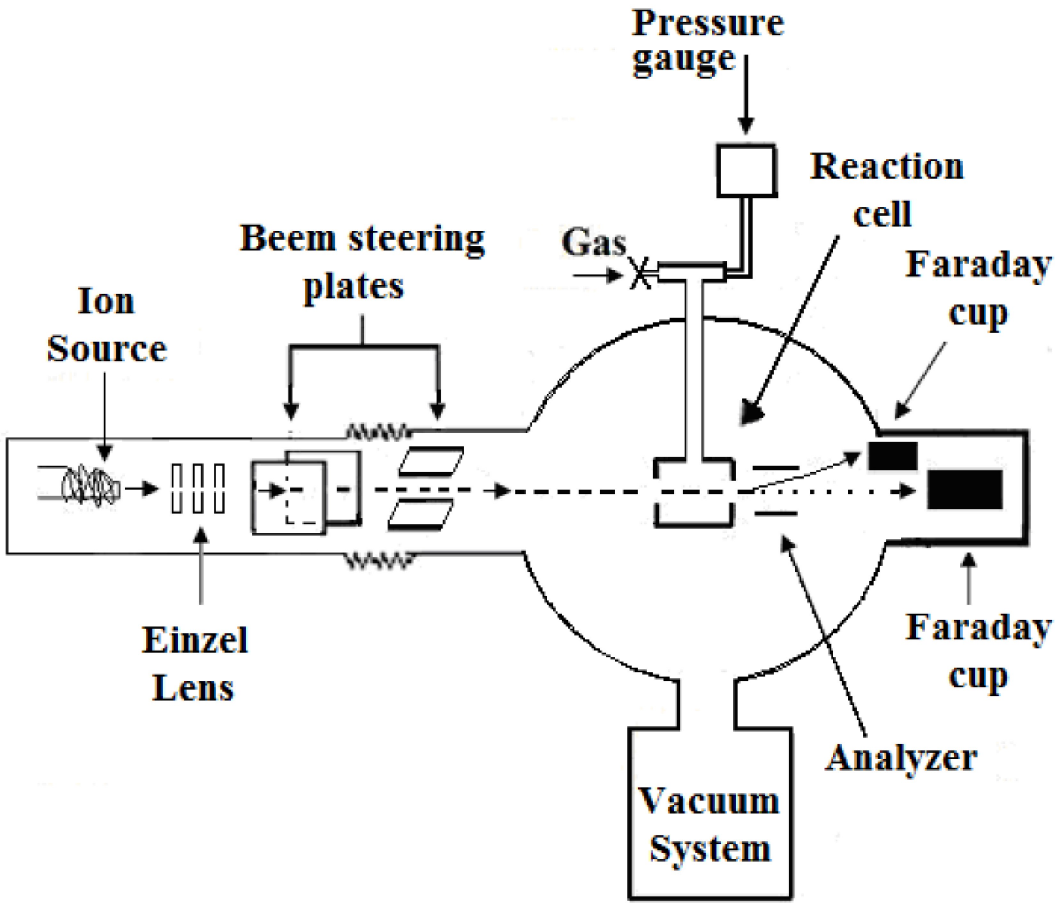

Figure 1 : Schematics of the experimental apparatus.

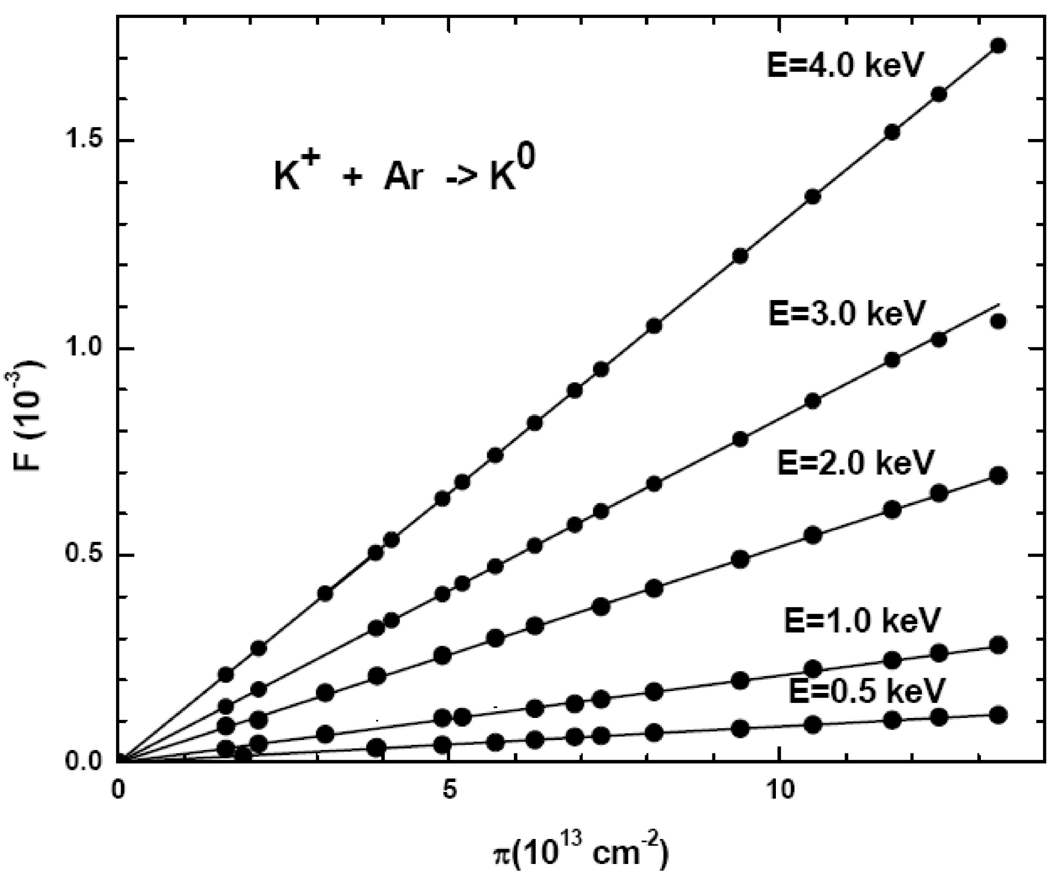

Figure 2 : Typical growth-rate curves of K^0 produced by charge transfer of K^+ on Ar.

With this method, it was possible to ensure single-collision conditions for each data point. The present data have been fitted using a least-square fit to obtain a linear function (full curves in Figure 2), obtained with a minimum correlation factor of 0.98. Figure 3 displays the present experimental results for the CT cross sections for K^+ on Ar within the energy range of 0.25 to 4.30 keV. The results of Ogurtsov et al.[6] for the energy range of 1 - 30 keV, and of Lo and Fite[7] for the energy range 15 - 1650 keV are also shown. In order to compare them with the present data, it is imperative that the uncertainties of the earlier data are available. Ogurtsov et al.[6] identified the absolute error associated with their measured cross sections to be 15%, resulting from the absolute measurements of the target gas concentration, and Lo and Fite[7] affirmed that the accuracy of their cross sections was 20%. The Ogurtsov et al.[6] results are in good agreement with the present experimental data within the experimental uncertainty. Additionally, the extrapolation of our data above 1.00 keV, and the results of Ogurtsov et al.[6] are consistent with the lower energy data of Lo and Fite[7]. The total cross sections illustrate a monotonic increasing behavior as a function of incident energy.

Until now, there have been no theoretical studies on the above process to compare with our experimental result. However, Lomsadze et al.[14] have recently measured the energy-loss spectrum for K^+ - Ar collisions at energy of 2 keV and scattering angle of 3.5°. They observed that a variety of inelastic processes (elastic scattering of K^+ions, single-electron excitation of the Ar atom to (4*s*), (4*p*), and (3*d*) states, excitation of K^+ions to the (4*s*) and (3*d*) states and, single and double autoionization states of Ar) are more efficiently in the 10 - 35 eV energy-loss interval. These results indicate that at low collision energies the CT process is small owing to the important contribution of these channels, as can be seen in Figure 3.

It is desirable to perform a simple theoretical analysis of the CT cross section in order to compare with the experimental data. For this purpose, we estimated the behavior of the electron transfer cross section using the semiempirical model of Olson[15,16] for the system

$$K^+(^1S_0) + Ar(3s^2p^6) \rightarrow K^0(4s^2S_{1/2}) + Ar^+(3s^2p^5) - 11.418\ eV, \quad (4)$$

The electron transfer was calculated employing the universal reduced cross section of Olson[8-10,15,16] using 15.759 eV as the effective ionization potential of the Ar target and 4.341 eV as the K ground-state electron affinity. The coupling matrix element H_{12}(2.01 eV), the inter nuclear separation at which CT occurs R_c($3.5a_0$) and the first derivatives of the potential energies of the two states $|\Delta V'(R_c)|$ ($3.70\ eV/a_0$) were fitted until the maximum cross section value was obtained, corresponding to the energy E_{max} = 756.665 keV, as predicted by the Massey adiabatic model[17]. The model brings about the experimental cross section at 2.0 keV and the maximum cross section value agree to an

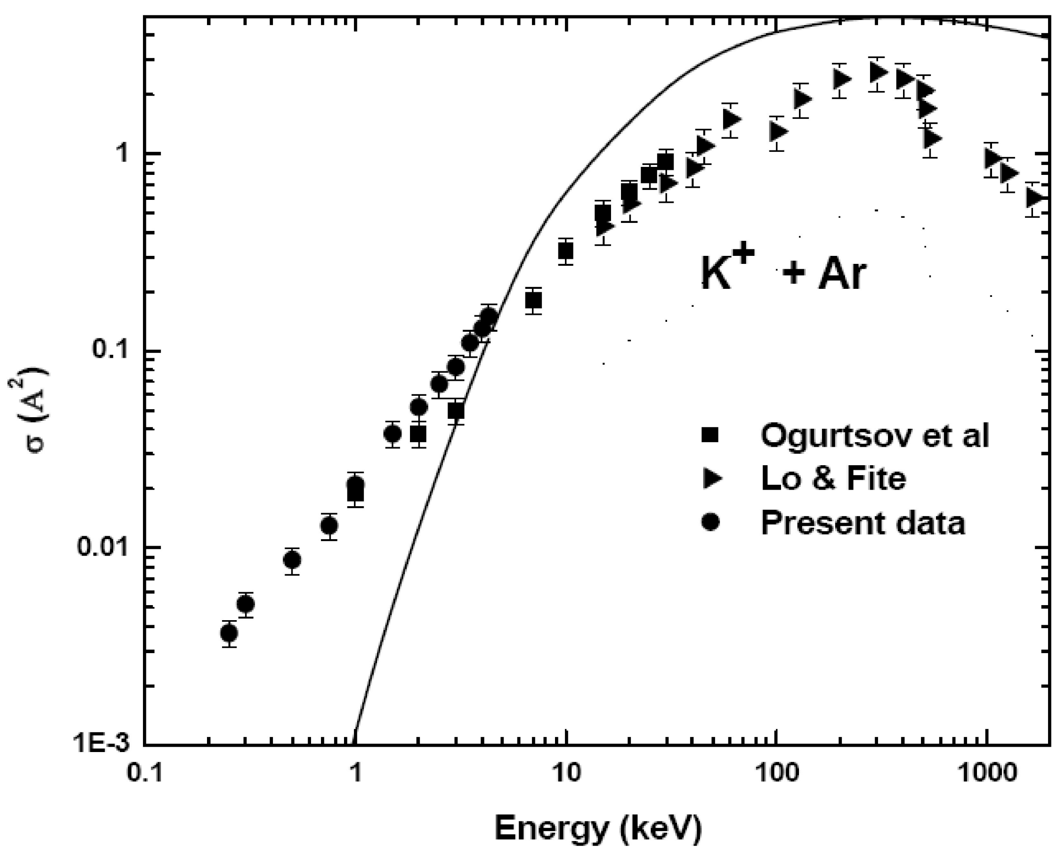

Figure 3 : Total electron-capture cross section for K^+ - Ar collisions.

energy E_{max} predicted by the Massey adiabatic model. The estimated CT cross sections are shown in Figure 3 as a solid line. It should be noted that although the Olson formula[15,16] assumes that the target atom is in the ground state after CT, the calculation of σ_{10} is observed to agree in behavior with the experimental data. At energies lower than 1.5 keV, the experimental data lie above the Olson model calculations. This discrepancy might be due to the simplification of the theoretical treatment; for instance, the model considered only two states.

CONCLUSIONS

Measurements of charge transfer cross sections for the K^+ - Ar system are reported, at impact energies between 0.25 - 4.30 keV.

Good agreement is found between the present experimental results and previous data.

The present results are extending down in energy to 0.25 keV.

The semiempirical calculations were compared with the present experimental data and were found to agree in behavior.

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