TRANSFER IONIZATION IN COLLISIONS OF BARE IONS WITH NOBLE GAS ATOMS AT kev ENERGIES

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TRANSFER IONIZATION IN COLLISIONS OF BARE IONS WITH NOBLE GAS ATOMS AT keV ENERGIES(1)

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Résumé - Une technique de temps-de-vol a été appliquée pour examiner des processus d'ionisation de transfert des projectiles nus de B^{5+}, $^{13}C^{6+}$, $^{15}N^{7+}$, $^{18}O^{8+}$ et F^{9+} qui s'entrechoquent avec des atomes de gaz rare. Les distributions d'état de charge des ions de recul de gaz rare après un ou deux processus de capture électronique montrent l'influence forte du processus d'ionisation de transfert. Les résultats sont discutés à l'aide d'un approche statistique employant le modèle "over-barrier" classique.

Abstract - A time-of-flight technique has been used for investigation of transfer ionization processes of bare B^{5+}, $^{13}C^{6+}$, $^{15}N^{7+}$, $^{18}O^{8+}$ and F^{9+} projectiles colliding with rare gas atoms. Charge-state distributions of noble gas recoil ions after one- and two- electron capture processes show the strong influence of the transfer ionization process. The results are discussed within a statistical approach involving the classical over-barrier model.

1-INTRODUCTION

Collisions of multiply charged ions on many electron targets are currently a subject of great interest. These collisions are characterized by very large cross sections and they may populate highly excited states which usually decay via autoionization. As a result transfer ionization (TI) processes may occur. Many plasma properties are effected by the large cross sections for transfer and ionization, including the energy and charge-state distributions in the plasma. Hence, many experiments have been performed and various theoretical approaches have been made.

This paper will show experimental results of the charge-state distribution of noble gas recoil ions after one- and two-electron capture by bare projectiles. Because many electrons are involved, a statistical approach based on the classical barrier model is used for describing the experimental results.

(1) excerpt from thesis G. Mank, D26.

2-EXPERIMENTAL TECHNIQUE AND DATA EVALUATION

The experiment was performed at the Giessen electron-cyclotron-resonance (ECR) ion source which provides cw beams of fully stripped B^{5+}, $^{13}C^{6+}$, $^{15}N^{7+}$, $^{18}O^{8+}$ and F^{9+} ions with qx10 keV kinetic energy. The experimental set-up is schematically shown in Fig. 1. The momentum-analyzed ion beam is cleaned by a 90^o cylindrical electrostatic analyzer and is collimated to typically 1.7 mrad FWHM. After intersecting a thin gas target emerging from a narrow tube at an angle of 90^o the charge-transferred projectiles are separated with respect to their charge states from the parent ion beam in an electric field configuration. The scattered ions hit a two-dimensional position-sensitive detection system (PSD) with a resistive anode which has a diameter of 40 mm. The recoil ions are extracted by an electric field (300 V/cm) perpendicular to the collision plane and travel through a drift region before reaching a multichannel-plate detector (MCP). Simultaneously, there is the possibility to extract electrons in opposite direction into a channel-electron multiplier (CEM). The polarity of the extraction field can be changed, so that recoil ions can also be detected in the channel-electron multiplier.

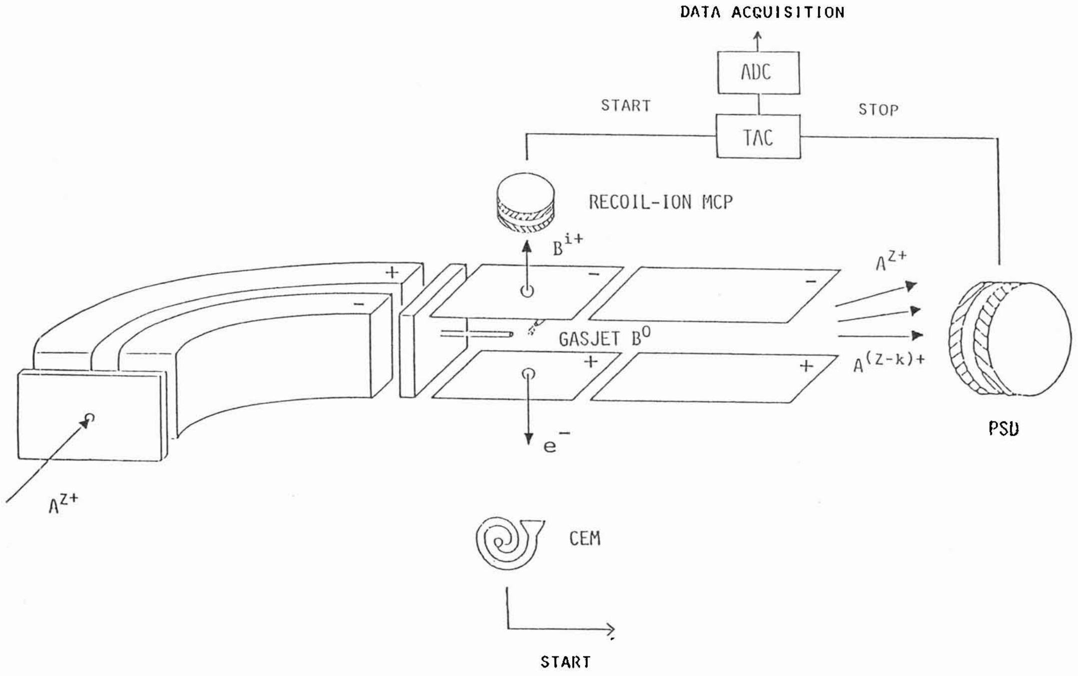

Fig. 1 Schematic diagram of the experimental set up. PSD: position sensitive detector; CEM: channel-electron multiplier; MCP: multichannel-plate detector; TAC: time-to-amplitude converter; ADC: analog-to-digital converter.

The charge-state distribution of the recoil ions is determined from their flight times to the detector. The output pulses of the MCP detector start a time-to-amplitude converter (TAC). The stop signal comes from the position computer which follows the position-sensitive detector. Since all charge-transferred ions hit the PSD, position windows have to be set to determine the different multiple-electron capture processes. The analog flight-time information is digitally converted by an ADC and sent to the data acquisition system.

Different test measurements as described in Ref./1/ were made to ensure the correct determination of the recoil-ion charge-state fractions. The total count rate of the PSD device was less than 10 kHz in order to avoid dead-time corrections resulting from the internal logic of the computer.

The experiments were performed to obtain information about transfer-ionization processes in collisions of bare ions A^{Z+} (Z=5, ..., 9) with the noble gases B = He, Ne, Ar, Kr and Xe

$$A^{Z+} + B \rightarrow A^{(Z-k)+} + B^{i+} + (i-k)e \tag{1}$$

where k is the number of captured electrons and $i \geq k$. Since no absolute measurements of the target thickness and detection efficiency have been made, the measurements yield the fractions F_i (given in percent) of recoil ions B^{i+} in charge state i. F_i is correlated with the total capture cross section $\sigma_{q,q-k}$ and the partial cross sections $\sigma^{0,i}_{q,q-k}$ for producing a B^{i+} recoil ion by

$$F_i = \sigma^{0,i}_{q,q-k} \;/\; \sum_i \sigma^{0,i}_{q,q-k} = \sigma^{0,i}_{q,q-k} \;/\; \sigma_{q,q-k} \tag{2}$$

Since the flight times of the recoil ions B^{i+} are proportional to the square root of their mass to charge ratio, different events can be detected in coincidence and analyzed as described in Ref./1/. No corrections have to be made for residual gas components, since the base gas pressure is about $2x10^{-7}$mbar. Also, the single collision condition was fulfilled as verified by changing the target gas pressure. For the two-electron capture process small corrections of less than 5% have to be made since charge-changing processes before or after the collision region result in "forbidden" B^{1+} recoil-ion peaks. The main source of error is due to statistical uncertainties which usually are less than 10%. Only in the case of F^{9+} projectiles or two-electron capture processes they amount up to 15%. Various test measurements have been made, and the results differ only within the statistical errors.

3-RESULTS AND DISCUSSION

The experimental results demonstrate the important contributions of transfer-ionization processes to electron capture collisions in the low energy range. Figure 2 shows the percentage of TI in one-electron-capture collisions (R = 100%-F_1) of bare ions B^{5+}, C^{6+}, N^{7+}, O^{8+}, F^{9+} and Ne^{10+} /2/ with noble gas atoms B = He, Ne, Ar, Kr, Xe. The percentage of TI increases with increasing target atomic number Z_T and seems to saturate at about 45% for the heavier targets. No significant dependence on the projectile species is observed.

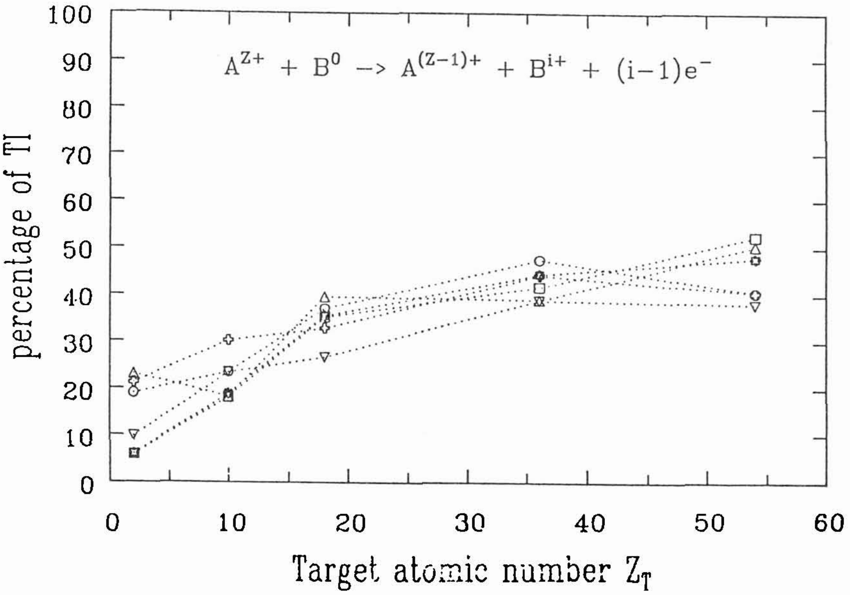

Fig. 2 The percentage of transfer ionization processes (R = 100% - F_1) for one-electron capture collisions of A^{Z+} (○ :B^{5+}, □ :C^{6+}, ✧ :N^{7+}, △ :C^{8+}, ▽ :F^{9+}, ● :Ne^{10+}/2/) with noble gas atoms B (He, Ne, Ar, Kr, Xe) as a function of the target atomic number. Dotted lines are drawn to guide the eye.

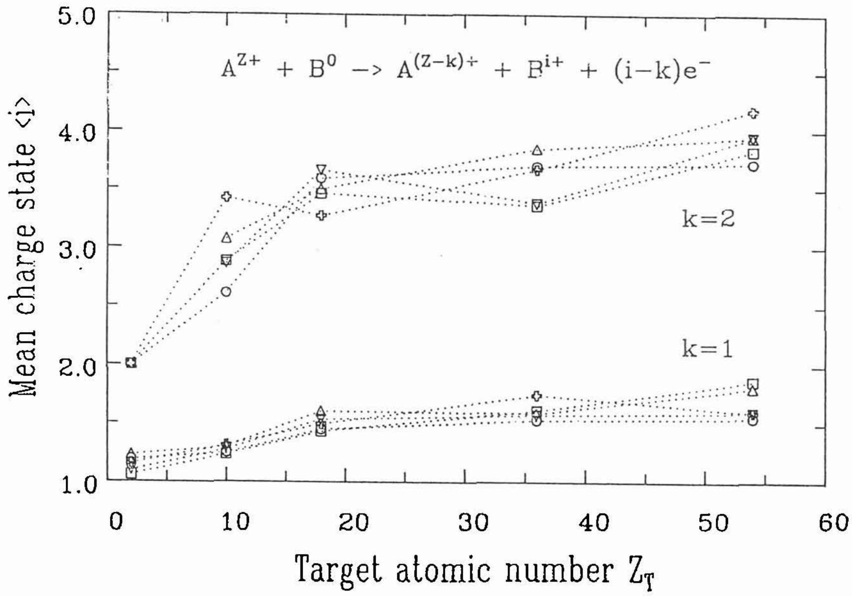

Fig. 3 Mean recoil-ion charge states $\langle i \rangle = \Sigma\, iF_i$ arising from one- and two-electron capture reactions by Zx10 keV bare projectile ions (○ :B^{5+}, □ :C^{6+}, ✧ :N^{7+}, △ :O^{8+}, ▽ :F^{9+}) from the noble gas atoms He, Ne, Ar, Kr and Xe.

Figure 3 shows the influence of the TI processes on the *mean* recoil-ion charge states

$$\langle i \rangle = \sum_i iF_i \quad . \qquad (3)$$

$\langle i \rangle$ increases with increasing Z_T showing no noticable difference for the different projectiles. The slope of increase in the two-electron-capture process (k=2) is higher than in the case of one-electron capture (k=1), similar to results observed before /3/.

A quantum mechanical treatment of TI processes would be extremely difficult due to the complexity of the multi-channel problem. Therefore, there is a need for simple models which give quantitative results. Assuming the transfer of i electrons in an extension /4,5/ of the classical barrier model /6,7,8/ the characteristic capture radii (in atomic units) are given by /5/

$$R_i = (2\, i^{1/2}\, (q-i+1)^{1/2} + i) \;/\; I_B^{(i)} \qquad (4)$$

where q is the projectile charge state and $I_B^{(i)}$ denotes the ionization potential of the recoil ion B^{i+}. Hence, the total cross sections σ_q^i of capturing i electrons can be calculated from

$$\sigma_q^i = \pi\, (R_i^2 - R_{i+1}^2) \quad . \qquad (5)$$

The target is left in the charge state i without any excitation energy, while the highly excited projectile has the possibility to autoionize /4,5,9/. The autoionization probability can be calculated with statistical methods /9/. Introducing the probability to evaporate (i-k) electrons out of i

$$P^i_{i-k}\,(\Delta E) = \binom{i}{i-k} \sum_{j=0}^{m} (-1)^j \binom{k}{j} \left(1 - \frac{i-k+j}{\Delta E/\langle I_B \rangle} \right)^{i-1} \quad . \qquad (6)$$

where m is defined by

$$i-k+m \le \Delta E/\langle I_B \rangle \le i-k+m+1 \quad , \qquad (7)$$

and $\langle I_B \rangle$ is defined by

$$\langle I_B \rangle = \frac{i}{i-k} \sum_{j=0}^{i-k-1} I_B^{(i+j)} \quad , \qquad (8)$$

the absolute partial cross sections $\sigma^{0,i}_{q,q-k}$ can be determined from

$$\sigma^{0,i}_{q,q-k} = P^{i}_{i-k}(\Delta E)\ \sigma^{i}_{q} \quad . \tag{9}$$

The autoionization probability is only dependent on the maximum potential energy $\Delta E(i)$

$$\Delta E(i) = \sum_{j=q-i}^{q-1} I_A^{(j)} - \sum_{j=0}^{i-1} I_B^{(j)} \tag{10}$$

stored as excitation energy of the projectile.

Comparisons between calculated total and partial cross sections and experimental results /10,11/ show that this simple model is able to describe the experimental cross sections quantitatively. Figure 4 shows calculated and measured fractions F_i for one-electron capture in collisions 90keV F^{9+} + B (B=He, Ne, Ar, Kr, Xe). Except for the He target, the experimental data are very well described by the model. Good agreement has been also obtained for the fractions F_i measured with the other bare projectile ions. Only in the case of B^{5+} the model differs very much from the experimental data, which leads to further investigations /12/.

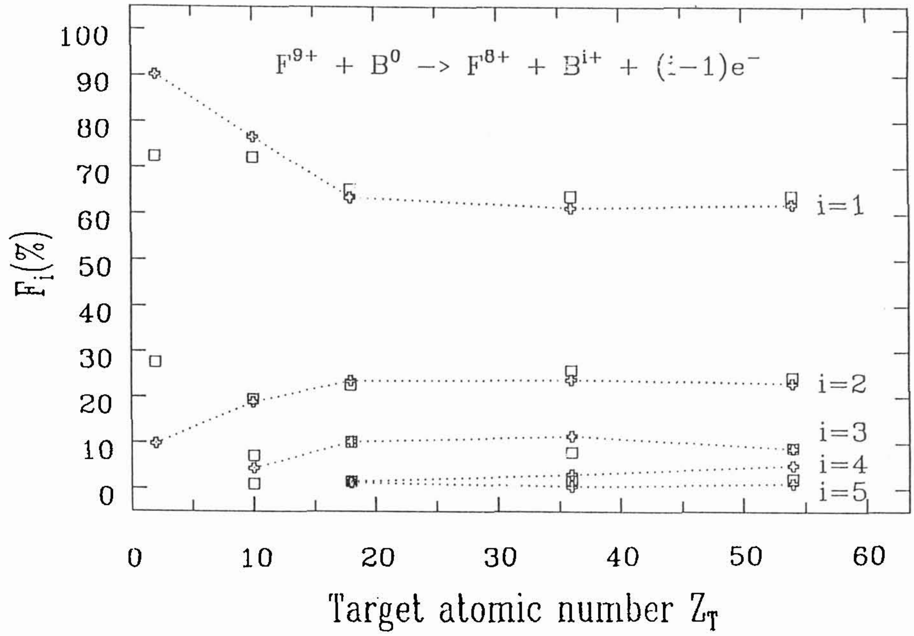

Fig. 4 Normalized recoil-ion charge-state fractions F_i in collisions of 90 keV F^{9+} + B (B = He, Ne, Ar, Kr, Xe). The squares represent the values calculated from the over-barrier statistical model described in the text.

4-CONCLUSIONS

Unexpected in collisions of bare ions with noble gas atoms is the nearly identical behaviour of the mean recoil-ion charge state for increasing charge states Z = 5, ..., 9. Although the potential energy involved in the collision system increases strongly with Z, no difference for the same target can be seen within experimental uncertainties. The simple model presented here predicts recoil-ion charge-state fractions F_i which are in good accord with measured values for one-electron capture processes.

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