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TRANSFER IONIZATION IN COLLISIONS OF BARE IONS WITH NOBLE GAS ATOMS AT KEV ENERGIES\(^{(1)}\)

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Abstract - A time-of-flight technique has been used for investigation of transfer ionization processes of bare B\(^{5+}\), C\(^{6+}\), N\(^{7+}\), 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 \( \text{B}^{5+} \), \( \text{C}_{6}^{6+} \), \( \text{N}^{7+} \), \( \text{O}^{8+} \) and \( \text{F}^{9+} \) ions with q\(\times\)10 keV kinetic energy. The experimental set-up is schematically shown in Fig. 1. The momentum-analyzed ion beam is cleaned by a 90\(^\circ\) 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\(^\circ\) the charge-transfer 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

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

where $k$ is the number of captured electrons and $i \leq k$. 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 $\sigma_{q,i}^{0,i}$ for producing a $B^{i+}$ recoil ion by

$$F_i = \frac{\sigma_{q,q-k}^{0,i}}{\sum_i \sigma_{q,q-k}^{0,i}} = \frac{\sigma_{q,q-k}^{0,i}}{\sigma_{q,q-k}}$$

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 $2 \times 10^{-7}$ 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" $B^{i+}$ 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% - $F_i$) 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 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 \( R = 100\% - F_L \) for one-electron capture collisions of \( A^{Z+}(\circ : B^{5+}, \square : C^{6+}, \diamond : N^{7+}, \triangle : O^{8+}, \bigtriangledown : F^{9+}, \bigcirc : Ne^{10+/2}) \) 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 \( Z \times 10 \) keV bare projectile ions \( \circ : B^{7+}, \square : C^{8+}, \diamond : N^{9+}, \triangle : O^{10+}, \bigtriangledown : F^{11+} \) 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

\[ \langle i \rangle = \sum_i i F_i^i \]  

\( \langle i \rangle \) increases with increasing \( Z_i \), showing no noticeable 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/:

\[ R_i = \left( \frac{1}{2} \frac{q^{i+1}}{2} + i \right) / I_B^{(i)} \]  

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 \( \sigma_q^i \) of capturing \( i \) electrons can be calculated from

\[ \sigma_q^i = \pi (R_i^2 - R_{i+1}^2) \]  

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 \( i \)

\[ p_{i-k}^i (\Delta E) = \left( \frac{1}{i-k} \right) \sum_{j=0}^{m} (-1)^{j} \binom{k}{j} \left( 1 - \frac{i-k+j}{\Delta E / \langle I_B \rangle} \right)^{i-1} \]  

where \( m \) is defined by

\[ i-k+m \leq \Delta E / \langle I_B \rangle \leq i-k+m+1 \]  

and \( \langle I_B \rangle \) is defined by

\[ \langle I_B \rangle = \frac{1}{i-k} \sum_{j=0}^{i-k-1} I_B^{(i+j)} \]
the absolute partial cross sections $\sigma_{q,q-k}^{0,i}$ can be determined from

$$\sigma_{q,q-k}^{0,i} = p_{i-k}^{i}(AE) \sigma_{q}^{i}.$$  \hspace{1cm} (9)

The autoionization probability is only dependent on the maximum potential energy $AE(i)$

$$AE(i) = \sum_{j=q-1}^{q-1} I_{A}^{(j)} - \sum_{j=0}^{i-1} I_{B}^{(j)}.$$  \hspace{1cm} (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 Ne 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/.

![Graph showing normalized recoil-ion charge-state fractions $F_{i}$](image)

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.
Unexplained 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 \( Z = 5, \ldots, 9 \). 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.

REFERENCES