# Experimental Study on electron Detachment Cross Sections of Cl- in Collisions with Inert Gas Atoms

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Experimental Study on electron Detachment Cross Sections of Cl\(^-\) in Collisions with Inert Gas Atoms

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ABSTRACT
The single-electron and double-electron detachment cross sections of Cl\(^-\) in collision with inert gas atoms (He-Xe) have been measured by the growth rate method. The incident negative ions’ energies are from 5keV to 30keV. It is found that the single-electron detachment cross sections become greater and greater, when the target atoms change from Helium to Xenon. However, double-electron detachment cross sections show more complicated relationship with the target atom changing. The results of this work have been compared with the previous data, and a model based on energy division is used to interpret the trends of cross sections.

Key words: negative ion, collision, single electron detachment cross section, double electron detachment cross section, inert gas

INTRODUCTION
Single electron detachment (SED) and double electrons detachment (DED) would occur in negative-ion-atom collisions. A lot of experimental and theoretical studies of such collision systems have been carried out to explain to mechanism of negative-ion–atom interactions [1–10]. Besides, negative-ion-atom collisions could be used to produce atomic beams for plasma heating and be relevant to the fields of ionosphere physics, structural chemistry and astrophysics. In the past few years, SED cross sections of transition elements negative ions incident on noble gases were studied in our lab [11-15], and some scaling laws of the cross sections have been established.

In present work, SED and DED cross sections for Cl\(^-\) in collision with inert gas atoms are obtained with growth rate method. And the model based on energy division [15] is used to interpret the trends of the cross sections.

EXPERIMENT
Figure 1 shows the setup of collision experimental system. Negative ions are produced by a cesium-sputter negative ion source, and then accelerated, extracted by an electric field. Interested negative ions selected by an isotope separator pass through a vacuum drift tube, a switch magnet and finally reach the collision chamber. The target noble gas atoms are introduced into the chamber by a needle valve, and the pressure of the target gas is measured by an absolute pressure transducer. After collision with the target gas, the incident beam is divided into three parts according to their charged state by adding with electric field. Neutral particles, positive particles

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and negative particles hit on different positions of a multichannel plate position sensitive detector. The same experimental system has been used in our previous experiments [11-15].

In order to obtain SED and DED cross sections, the projectile neutrals, positive ions and negative ions should be counted together with the gas pressure of the collision chamber simultaneously. Under different pressures, several groups of data are obtained.

![Experimental setup for measuring electron detachment cross sections of negative ions and atoms collision](image)

Figure 1 Experimental setup for measuring electron detachment cross sections of negative ions and atoms collision

If the gas density in the collision chamber is low enough to meet the condition of a single collision, the following equations can calculate the cross sections [16]:

$$F_{0,1} = \sigma_{-10,-11}\pi \quad (1)$$

$$F_{0,1} = \frac{I_{0,1}}{I_{-1} + I_0 + I_1} \quad (2)$$

$$\pi = n l = C \frac{P}{kT} l = 7.26 \times 10^{16} \frac{P l}{T}$$

where $I_0$ is neutral particle beam intensity, $I_{-1}$ is negative ion beam intensity, $I_1$ is positive ion intensity; $\sigma_{-10}$ is SED cross section; $\sigma_{-11}$ is DED cross section; $n$(cm$^{-3}$) is target gas density; $k$ is Boltzmann's constant; $P$(Pa) is the absolute pressure of target gas; $l$(cm) is the length of the collision chamber; $T$(K) is room temperature during the experiment. In our experiments, the detection efficiency for particles with different charge state is considered the same. Therefore, the detected beam intensities can represent the projectile beam intensities.

Using different $I_0$, $I_{-1}$ and $I_1$ at different gas pressures, the cross section can be obtained by a linear fitting. This is the so-called growth rate method.
There are four parts in the uncertainty of experimental results: (a) the effective length of chamber, ±2%; (b) the statistic uncertainty of particle counts, ±3%; (c) the gas pressure measurement, 0.25%; (d) the detection efficiency uncertainty, 10.4%, which is the most important error source in present measurement. Thus, the total uncertainty in our experiment is about 11%.

RESULTS AND DISCUSSION

Figure 2 The SED cross sections of Cl$^-$ in collisions with He, Ne, Ar, Kr, Xe.

Figure 3 The DED cross sections of Cl$^-$ in collisions with He, Ne, Ar, Kr, Xe.

Figure 2 shows the SED cross sections of Cl$^-$ impact on noble gases, and Figure 3 gives the DED cross sections of these collisions. It can be seen from figure 2, in 5keV-30keV energy range, the SED cross sections go up with the increase of the incident energy and the SED cross sections become bigger when Cl$^-$ collide with bigger target atoms. For example, in Figure 2, the SED cross sections are the biggest for Cl$^-$+Xe, and the smallest for Cl$^-$+He. For DED cross sections, in Figure 3, the cross sections also increase with the incident energies going up. However, the DED
cross sections for Cl⁺+Xe are no longer the biggest.

Figure 4 Compare of SED cross sections of Cl⁺ in collisions with He, Ne, Ar, Kr, Xe.

Figure 5 Compare of DED cross sections of Cl⁺ in collisions with He, Ne, Ar, Kr, Xe.

In Figure 4 and Figure 5, we compare our results with others’ data [6, 7]. Although there are some minor differences, the relative magnitudes of cross sections remain the same. For SED, cross sections of Cl⁺+Xe collision are still the biggest ones, and those of Cl⁺+He are the smallest. For DED, the data of Cl⁺+Xe locate in the lowest part through our energy region, and the data of Cl⁺+He (Ar) are in the upper part.

The results can be interpreted more by using the same model as in [15].

If a completely inelastic collision happens in classical frame, \( \Delta E_i \) transformed into internal energies of the incident ion and the target atom would reach the maximum and could be expressed by:

\[
\Delta E_i = \frac{m_2}{m_1 + m_2} E
\]
where $m_1$ is the mass of the incident negative ion, $m_2$ is the mass of the target atom, and $E$ is the incident kinetic energy of ion. However, the actual collision is not the completely inelastic one. After colliding with target atom, the kinetic energy of the incident negative ion would be divided into four parts: the residual kinetic energy of the incident ion, the kinetic energy of the target atom, the changed internal energy of the incident ion and the changed internal energy of the target atom. Therefore, a coefficient $k$ which is between 0 and 1 should be introduced into equation (3):

$$\Delta E = k \Delta E_i = k \frac{m_2}{m_1 + m_2} E \quad (4)$$

$\Delta E$ is the part of energy that transferred into internal energies of the collision system. The SED process is known to prefer a large-impact-parameter [17, 18], and it means $k$ is usually a small value. In the following analysis, the variation of $k$ is ignored and $k$ is considered as a constant in equation (4).

$\Delta E$ in equation (4) provides the total energy needed in the ionization of target atom and the detachment of negative ion during the collision. If $\Delta E$ is large enough, it would lead to both negative ion electron detachment and target atom ionization. If the ionization energy of the target atom is lower, the energy remaining for the electron detachment of negative ion is relatively larger, so the probability of electron detachment becomes larger. If the $\Delta E$ is not big enough, only one type of electron loss process could happen (incident negative ion electron detachment or target atom ionization). If the target atom has lower ionization energy, the possibility of ionization of the target atom becomes greater. As a result, the probability of electron detachment of anion becomes smaller.

Now, we can turn to the explanation of the experimental results.

1, the cross sections go up with the increasing of incident energy. From equation (4), it can be found out that $\Delta E$ becomes larger when $E$ in the formula becomes larger. Larger $\Delta E$ provides more energy used in the electron detachment of Cl-. Therefore, incident negative ion has bigger probability to detach.

2, the SED cross sections are bigger when Cl- collides with heavier target atoms. We know, bigger target atom, like Xe, has smaller ionization energy (shown in Table 1) than others. That means, with same $\Delta E$, Cl- could get more energy to detach when colliding with Xenon atom than with other atoms. Helium atom has the biggest ionization energy in the five kinds of inert atoms, it means, with same $\Delta E$, Cl- could get the smallest part of energy used to detach when colliding with He. In addition, from equation (4), it can be found that the values of $m_2/(m_1 + m_2)$ would change with different target atom, 0.10(He), 0.36(Ne), 0.53(Ar), 0.70(Kr), 0.76(Xe). For He, due to the smallest $\Delta E$ and the biggest ionization energy, the SED cross sections would be the lowest. It can be seen in Figure 2, the SED cross section for He is the smallest in the five kinds of target atoms.

3, the DED cross sections show different trend. The DED cross sections for Xe are no longer the biggest in the Figure 3, the data of Xe locate in the lowest part. It is known that DED process prefers small-impact-parameter, so $k$ in equation (4) should be bigger than in SED process. That means bigger $\Delta E$ is obtained. However, in DED process, more energy is needed for the negative ions to detach, due to two electrons
lost. We can assume the above-mentioned situation 2 happening. $\Delta E$ is not enough for both negative ion DED and target atom ionization. Smallest ionization energy is needed for Xe to ionize, so in small-impact-parameter collision, Xe ionization is easy to happen. That is, the double electron detachment has smallest probability to happen for incident Cl$^-$ in such collisions. With the increasing of the ionization energy from Xe to Ar, the DED cross sections go up, because it will be more and more difficult to ionize the target atom. Therefore, DED cross sections become bigger and bigger. For collision with Ne and He, the DED cross sections don’t follow the above deduction. It could be caused by the much different $\Delta E$. When colliding with Ne and He, smaller $\Delta E$ and much bigger ionization energy would produce much bigger probability to detach two electrons from Cl$^-$, instead of ionizing the target. Therefore, much larger DED cross sections are obtained.

CONCLUSION

SED and DED cross sections of Cl$^-$ in collision with noble gases (He-Xe) have been obtained by using growth rate method. The incident negative ions’ energies are between 5keV and 30keV. It is found that SED cross sections become bigger and bigger, when the target atoms change from Helium to Xenon. However, DED cross sections show more complicated relationship with the target atom changing. The results of this work have been compared with the previous data, and a model based on energy division is used to interpret the trends in cross sections.

Table 1 The ionization energy of inert gas atom. [19]

<table>
<thead>
<tr>
<th>Atom</th>
<th>Mass</th>
<th>Ionization Energy (eV)</th>
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<tbody>
<tr>
<td>He</td>
<td>4</td>
<td>24.6</td>
</tr>
<tr>
<td>Ne</td>
<td>20</td>
<td>21.36</td>
</tr>
<tr>
<td>Ar</td>
<td>40</td>
<td>15.8</td>
</tr>
<tr>
<td>Kr</td>
<td>84</td>
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<tr>
<td>Xe</td>
<td>131</td>
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REFERENCES