Cross Sections for Single electron capture in collisions of N$^{2+}$ with He at low energies

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Abstract. The absolute cross sections of single electron capture during the collision of N$^{2+}$ with He have been measured over the energy range 0.1–300 eV/u. From the plot showing the dependence of cross sections on energy, the following three remarkable observations can be made: (1) the cross sections exhibit an oscillatory structure below 1 eV/u, (2) a bend in the cross sections appears at approximately 1 eV/u and (3) there is a dip in the cross sections at approximately 70 eV/u. The formation of an oscillatory structure is attributed to the glory effect. The bend in the cross sections occurs owing to the attractive potential part of a $1^2\Pi$ state of quasimolecule NHe$^{2+}$. The dip in the cross sections appears as a result of opening a new reaction path above 70 eV/u. The glory effect can be observed for the first time on a total cross section even for slow ion-neutral collisions. The objective of this study is to explore the possibilities of providing a detailed explanation of energy dependence measurements in order to study reaction dynamics for a charge changing process.

1. Introduction

Charge-changing processes involving multiply charged ions are not only fundamentally significant but are also widely used in various fields such as upper atmospheric physics, interstellar science, and fusion plasma science [1, 2]. It is essential to estimate the absolute values of the total charge-changing cross sections in order to successfully carry out charge-changing processes in the abovementioned fields. At present, however, there is a scarcity of experimental and theoretical data on the energy region below 1 keV/u.

Maier et al. [3] have measured single electron capture cross sections for N$^{2+}$-He ions over the low energy range 0.7–6 eV/u. Lennon et al. [4] have also measured the cross sections over the energy range 100–360 eV/u. Even more recently, Ishii et al. [5] have measured the cross sections over the energy range 0.2–260 eV/u. Theoretically, Lafyatis et al. [6] have calculated the potential energy curves for NHe$^{2+}$ using a multiconfiguration self-consistent field method and also estimated the cross sections using the Landau-Zener (LZ) model.

Recently, Ito [7] performed differential cross section measurements; the results of these measurements suggested that the single electron capture cross section could be enlarged at 0 °, which is a result of glory effect. The cross sections mentioned above are not affected by the glory effect. During slow neutral-neutral collisions, an oscillatory structure is observed in total cross sections due to the glory effect [8]. Does the oscillatory structure appear in the total cross sections even during ion-atom collisions? This study investigates the reason for the formation of the oscillatory structure. The absolute values of the total cross sections have been obtained for single electron capture during the
collision of N\textsuperscript{2+} with He over the energy range 0.1–300 eV/u. The present measurements have been performed over a wide energy range with fine energy step, which provide a detailed explanation of the dependence of cross sections on low energy. The dependence of cross sections on energy during ion-atom collisions was observed for the first time as an evidence of the glory effect.

2. Experimental Setup

The experimental apparatus and measuring procedure have been previously described in detail [9]. This section only summarizes the main features. Figure 1 shows the schematic diagram of the experimental setup.

A 300 eV/u mass-selected beam of N\textsuperscript{2+} ions was obtained from an electron beam ion source (EBIS). This beam, which has a measured full width and half maximum (FWHM) energy spread of 0.1 eV/u, was then focused and decelerated to the required energy before it entered a collision cell. The collision cell was equipped with an octupole ion beam guide (OPIG), which prevents the slow moving ions from diverging by means of an RF field [10]. The OPIG has a length of 160 mm, inner diameter of 7 mm, and an RF field strength of \(\sim 100\) V at 14 MHz. Ion energy in the collision cell is defined as the difference between the voltages of the ion source and collision cell. The target gas pressure, which was low enough to ensure single collision conditions at all times, was determined using an MKS baratron pressure gauge, type 690A. Primary and product ions were reaccelerated after the beam passed through the collision cell, and their m/q was determined using the second electromagnet MS2. These ions were detected by a channeltron multiplier. The signal transmitted from the channeltron and fed into an electronic circuit consists of NIM modules, which were transferred to a personal computer.

For low energy collision, it is important to consider the possible effect of large angle scattering, because electron capture processes are exoergic and both products are positively charged. However, the OPIG used in this study can accommodate all the projectiles scattered in the forward direction. Furthermore, in order to check whether back scattering had a significant effect on the observed cross sections, attenuation cross sections were determined over the entire collision energy range. For all cases, the attenuation cross sections were found to be in good agreement with the single electron capture cross sections, within the estimated experimental error. It can be concluded that backward scattering did not have a significant effect on the observed cross sections at all energies. The overall uncertainty in the measured cross sections was estimated to be approximately \(\pm 20\%\). The target gas pressure and collision length were the parameters that significantly contributed to this uncertainty. The uncertainty of the target gas pressure was estimated to be \(10\%\). For the determination of gas pressure gradients, the collision path length was estimated to be \(9.0 \pm 0.5\) cm.

It is also important to consider the possible effect of metastable N\textsuperscript{2+} ions on the primary beam, since such contaminants are known to have significant and dramatic effects on the cross sections [11]. However, it is difficult to produce metastable ions from the EBIS-type ion source used in this experiment [12]. In addition, the pressure in the EBIS under operating collisions and the background pressure outside the source region were of the orders of \(10^{-5}\) Pa and \(10^{-8}\) Pa, respectively. At such low pressures, metastable ions, even if they are produced, will be quenched since they are produced as a
result of multielectron impact collisions. Therefore we conclude that our measurements are valid only for ground state N\(^{2+}\) ions.

3. Results and Discussion

Single electron capture cross sections during the collision of N\(^{2+}\) with He over the energy range 0.1–300 eV/u, are shown in figure 2. Absolute errors of the cross sections are estimated to be \pm 20%.

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\begin{align*}
N^{2+}(2p^2 P) + He &\rightarrow N^+(2p^2, 3P) + He^+ + 5.0eV \\
&\rightarrow N^+(2p^2, 1D) + He^+ + 3.0eV
\end{align*}
\]

Figure 2 shows that the results of our experiment are in good agreement with the previous measurements. The energy dependence of the cross sections has interesting structures. A bend and a dip in the cross sections were clearly observed at collision energy of 1 and 70 eV/u, respectively. The cross sections estimated by Lafyatis et al. [6] using the LZ calculations results in the following reaction paths:

1. \(N^{2+}(2p^2, 3P) + He \rightarrow N^+(2p^2, 3P) + He^+ + 5.0eV\)
2. \(N^{2+}(2p^2, 1D) + He \rightarrow N^+(2p^2, 1D) + He^+ + 3.0eV\)

The ground state of quasimolecule NHe\(^{2+}\) is \(^1\Sigma^+\), which separates to the N\(^+\)(2p\(^2\), 3P)+He\(^+\) (1) limit. The potential energy curve of \(^1\Sigma^+\) has an avoided crossing near 2 Å with the \(^2\Sigma^+\) state and has a potential well of 1.9 eV at an equilibrium separation of 1.3 Å [6]. Above 0.1 eV/u, the reaction path via the avoided crossing represents the main path. In the case of \(^1\Sigma^+\) for N\(^+\)(2p\(^2\), 1D)+He\(^+\) (2) limit, the potential energy curve has an avoided crossing near 5 Å with the \(^2\Sigma^+\) and has a potential well of 0.4 eV at 1.8 Å. Below 0.1 eV/u, the reaction path changes to a path via the avoided crossing. Therefore, it is hard to consider that a cause of the bend in the cross sections at 1 eV/u is changing the main path from (2) to (1) with an increase in collision energies. The bend probably appears as a result of increasing the contribution of an attractive potential of the \(^1\Sigma^+\) state to the reaction below 1 eV/u. It is well known that a dependence of total cross sections on energy for an attractive potential is different from that for a repulsive potential [13]. The dip in the cross sections at 70 eV/u is probably caused by opening a new reaction path via an avoided crossing which is located at a small internuclear distance.
An oscillatory structure was observed in the cross sections below 1eV/u, which can be attributed to the glory effect. If the differential cross section at 0 ° exhibits an oscillatory structure, the total cross section $\sigma$ also exhibits an oscillatory structure according to the following relation:

$$\sigma \approx \frac{4\pi}{k} \sqrt{q(0)}$$

, where $q(0)$ is the differential cross section at 0 ° and $k$ is the wave number. At a collision energy of 1.5 eV/u, an enlargement of the differential cross section at 0 ° for single electron capture has been observed by Ito [7]. However, there is no clearly evidence of an oscillatory structure in our total cross sections around 1.5 eV/u. It is need to observe an oscillatory structure in total cross sections that the differential cross section exhibits a supernumerary rainbow. Peaks of a supernumerary rainbow move to 0 ° and disappear with an increase in collision energies; this is a cause of an oscillatory structure in the $q(0)$. The Peaks increase with a decrease in collision energies. Therefore, it becomes easier to observe an oscillatory structure in total cross sections at rather low energies. Since the collision energy of 1.5 eV/u is not enough low to observe a supernumerary rainbow, the oscillatory structure could not be observed. This can be confirmed to measure differential cross sections below 1 eV/u.

4. Conclusion
In this study, the absolute values of the total cross sections have been obtained for single electron capture during the collisions of N$_2$\(^{2+}$ with He over the energy range 0.1–300 eV/u. The present measurements have been performed over a wide energy range with fine energy step, which provide a detailed explanation of the dependence of cross sections on low energies. Our results are in good agreement with those of the previous measurements. The energy dependence of the cross sections has interesting structures. A bend in the cross sections was observed at a collision energy of approximately 1eV/u; this probably appears as a result of increasing a contribution of an attractive part of $^1\Sigma$ potential curve below 1 eV/u. A dip in the cross sections was clearly observed at a collision energy of approximately 70 eV/u; this can be attributed to the changing of the main path. Below 1eV/u, an oscillatory structure was observed in the cross sections, which can be attributed to the glory effect.

The detailed measurements of energy distribution of total cross sections can serve as a basis for reaction dynamics.

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