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Experimental study of single-electron capture in slow collision of Ne^+ and Ne^{2+} ions with Ne rare-gas atoms

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ABSTRACT

One-electron transfer processes resulting from Ne^+ and Ne^{2+}collisions with Ne rare-gas atoms have been studied using the time-of-flight technique for energy range of 0.6–2 keV. The dependence of the total single-electron capture cross-sections on the incident laboratory energy has been reported. The present measurements and earlier high-energy data are compared. Extrapolation of the present low-energy data to the high-energy regime exhibits good agreement. The Ne^{2+}–Ne data were compared with the theoretical calculations. The data agree qualitatively with the theory.

1. Introduction

The study of electron-capture processes in collision between atomic ions (in the eV to MeV energy region) and rare-gas atoms has been the subject of both experimental exploration [1–9] and theoretical discussion [4,10,11] for a number of years. Most of the studies of single-electron capture processes are focused at the collision of light-medium projectiles with atomic and molecular gases. During collision between charged ions and target atoms an electron of the target can be captured by the projectile into the ground or excited states:

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+} \quad (1)$$

The study of the collisions of atomic ions with atoms and molecules is important for several reasons. While studying such phenomena, more can be learned about atomic structure and function. The study of collision related events such as electron capture and Coulomb explosion cannot only provide better understanding of such event, but are also applicable in the study of astronomical problems such as formation of stars and planets. Finally, atomic collision research plays a fundamental role in the areas of energy development, high-temperature plasma, testing theoretical models and understanding the dynamics of these reactions.

In the previous works of Martinez et al. [6], the energy dependence of single-electron capture cross-sections of Kr^+–Ne, Ar^+–Ne and Ne^+–He systems has been measured. A reasonably complete set (He^+–Ne, Ar; Ne^+–He, Ar; Ar^+–Ne, Kr, Xe; and Kr^+–Ar, Xe) of experimental cross-sections at low-energy in collision between atomic ions and rare-gas atoms is reported by Maier [8]. Thus, to extend the single-electron capture studies to Ne ion–atom system, we have measured the total cross-sections for single-electron capture into all states of Ne^+ ions in Ne^+–Ne collision at low-energy. The energy dependence cross-sections were measured by Wittkower and Gilbody [16] in the energy range of 60–450 keV and by Jones et al. [17] in the energy range of 20–100 keV.

Previously; total cross-sections for single-electron capture into all states of Ne^{2+} ions in Ne^{2+}–Ne collision were measure by: Kase et al. [1] in the energy range of 0.5–3 MeV, Suk et al. [2] in the energy range of 55–195 keV, Flaks and Solov'ev [3] in the energy range of 5–60 keV and Bloemen et al. [9] at 100 keV. Thus, to extend the single-electron capture studies to low-energy region, we have measured the total cross-sections for single-electron capture into all states of Ne^{2+} in Ne^{2+}–Ne collision in the energy range of 0.6–2 keV.

Our particular interest in recent studies [7] of the total single-electron capture cross-sections has been focused on the dependence of these cross-sections on the incident laboratory energy and on comparing these experimental results with experimental data and theoretical predictions available in the literature.

2. Experiment

The experimental apparatus, featuring the recoil ion source (RIS); gas target; electrostatic analyzer; and position sensitive

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channel-plate detector and technique needed to generate recoil ions, has been described in details previously [7], so the experimental set-up will be discussed briefly.

Slow Ne^{q+} ions were formed by passing a collimated pulsed F^{4+} beam of energy 1 MeV/amu through the RIS containing Ne atomic gas. The collisions that take place in the RIS between the fast F^{4+} pulsed beam and the gas atoms generate recoil ions that are extracted by the voltage gradient across the RIS electrodes. These recoil ions were extracted, accelerated and passed through the first accelerating unit. Upon exiting the RIS, these ions travel through the first acceleration unit (Einzel-type lens) to which an electric field was applied transversely to the F^{4+} pulsed beam direction. This plate (the Einzel lens) focuses and drifts the primary ions toward the secondary differentially pumped gas target cell, containing the Ne atoms, where capture phenomena took place. The gas target cell was 5.8-cm long cylinder cell with entrance and exit apertures of 1 and 2.5 mm in diameter, respectively. Calculations by Toburen et al. [12] indicate that the effective length of the target cell may be obtained by adding the sum of the diameters of its two apertures to the geometric length. The gas target pressure was kept low enough (typically ∼0.5 mTorr) to ensure single collision conditions. The target cell was field-free to avoid an undesired deflection of slow, highly charged ions. After exiting the gas target cell, the emergent slow ions traveled through the second accelerating unit (analogous to the first unit) and a parallel-plate analyzer to a position sensitive channel-plate detector. The neutral beam of Ne^0 passed straight through the analyzer onto the detector, where as the separation of the charged ions occurred inside the analyzer. The energy resolution of the detector is ∼2 eV full width at half maximum. The analyzer voltage was set to detect the Ne^+ and Ne^{2+} ions and the detector was moved as close as possible to the target cell which has a larger exit aperture. Therefore, the angular acceptance of the apparatus was set such that essentially all fast neutral counting rate Ne^o could be measured. The ions were analyzed according to their time-of-flight which is proportional to the $\sqrt{m/q}$ (mass-to-charge) ratio. The use of the electrostatic analyzer in conjunction with the TOF technique allows one to identify the various events associated with the charged ions.

3. Evaluating of the absolute total cross-section

Thin target conditions were used in this experiment, the absolute total single-electron capture cross-sections for Ne^+, Ne^{2+}–Ne systems were evaluated by the following expression:

$$\sigma = \frac{N}{N_t n \varepsilon l} \tag{2}$$

where N is the measured signal of Ne^o atoms or Ne^+ ions, N_t is the measured number of incident ions Ne^+, and Ne^{2+} for each reaction, n is the number of gas particles per cm^3 in the collision target-cell and is related to the measured pressure p in Pa according to $n = 2.45 \times 10^{14}\, p$ (at 22 °C), ε is the detection efficiency of detector for Ne neutral events to their ions [13–15], and l is the effective length of the target cell.

4. Error estimate

The total uncertainties are estimated at 85% confidence level. The total uncertainty corresponds to quadrature sum of the statistical and systematic errors. The errors mainly originated from the fluctuation of the data, the gas target pressure stability in the measurements, the absolute transmission of the meshes and that of the detection efficiency of the microchannel plate. The signal from the background events was measured without the Ne ions and was usually less than 5%. These counts were subtracted from the data.

Table 1
Lists the measured total cross-sections σ (Å^2) and the total uncertainties s for single-electron capture into all states of Ne^+ and Ne^{2+} ions from Ne atoms

E (keV)	σ_{Ne^+-Ne}	s	$\sigma_{Ne^{2+}-Ne}$	s
0.6	0.15	±0.022	0.0016	±0.0002
0.7	0.21	±0.032	0.002	±0.0003
0.8	0.33	±0.045	0.0028	±0.0004
0.9	0.40	±0.060	0.003	±0.0004
1	0.53	±0.079	0.0037	±0.0006
1.5	0.87	±0.130	0.0059	±0.0009
2	1.04	±0.160	0.0077	±0.0012

5. Results and discussion

Table 1 lists the measured absolute total cross-sections, total uncertainties and collision laboratory energies for single-electron capture into all states by Ne^+ and Ne^{2+} ions from Ne rare-gas atoms.

5.1. Ne^+–Ne system

The energy dependence of single-electron capture cross-section into all states of Ne^+ is shown in Fig. 1. The figure displays the present data and those of Wittkower and Gilbody [16] and Jones et al. [17] over the energy range of 0.6–450 keV. The general shape of the cross-section reported in this paper for low-energy data shows a monotonically increasing behavior as a function of incident energy. Lee and Hasted [10] showed that in low-intermediate range of impact energies the total charge transfer cross-sections of symmetrical collision $A^+ + A \rightarrow A + A^+$ can be calculated using the expression:

$$\sigma^{1/2}(\text{Å}) = k_1 + k_2 \ln[E\,(\text{keV})] \tag{3}$$

where k_1 and k_2 are constants. The total single-electron capture cross-section into all states of Ne^+ ions is shown in Fig. 2 and can be expressed in the form

$$\sigma^{1/2}(\text{Å}) = 0.68 + 0.57 \ln[E\,(\text{keV})] \tag{4}$$

The present data have been fitted using a least-square fit and with a correlation coefficient of 0.99 to obtain this expression. The present measurements are in good accord with Lee et al. prediction.

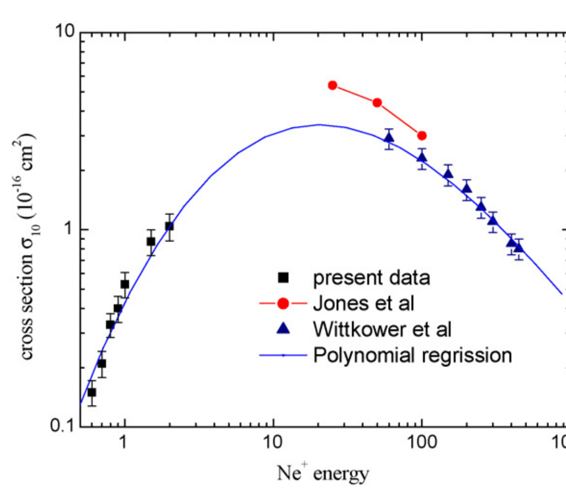

Fig. 1. Total cross-sections for one-electron capture into all states of Ne^+ ions in collision with Ne rare-gas atoms. The solid line is a third order polynomial fit for the present and Wittkower data.

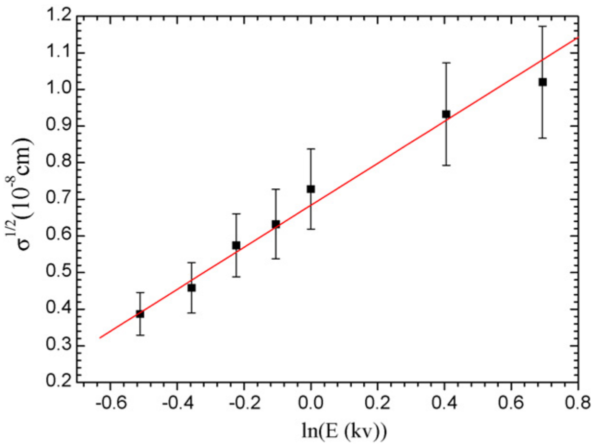

Fig. 2. Cross-sections for one-electron capture into all states of Ne^{+} ions in collision with Ne rare-gas atoms. The solid line is a linear fit for the present data.

The present data and the previous high-energy data [16] display a bell-shaped distribution centered at approximately 20 keV. This behavior is typical for symmetric collision between singly charged ions and neutral atoms for which capture is usually favored between atomic ground states. This behavior can also be seen in the He^{+}–Ne and Ne^{+}–He collisions [6]. A lack of experimental data that cover a wide range 2–20 keV and disagreement between Jones and Witkower data are depicted in Fig. 1. There is evidently further work to be done to resolve these two problems.

5.2. *Ne^{2+}–Ne system*

The recoil ion source used in this experiment is not only capable of producing Ne^{2+} ions in their ^{3}P ground states, but also in the low-lying metastable ^{1}D and ^{1}S states, which are 3.2 and 6.9 eV, respectively, above ^{3}P ground state. These metastable states have long lifetimes to survive the transit time to the collision chamber and consequently no one can rule out the possibility that metastable affect our measurements. In the present measurements it was not possible to determine the exact fraction of metastable ions presents in the ion beam and how much of a role these metastables play in our experiments is uncertain. However, Suk et al. [2] concluded that the fraction of metastables in the beam was insufficient to produce a significant change in the measured cross-sections, Imai et al. [18] in their study of Ne^{2+}–He suggested a mixing fraction of 75% ^{3}P and 25% metastables with equal fractions of each metastable ion. Accordingly, the resulting mixed cross-section is in good accord with the experimental results.

The energy dependence of the total single-electron capture cross-sections into all states of Ne^{2+} are shown in Fig. 3. Previously, Kase et al. [1], Suk et al. [2], Flaks and Solov'ev [3] and Bloemen et al. [9] measured the total single-electron capture cross-sections in the energy range of 5 keV to 3 MeV. Thus, to extend the single-electron capture studies to low-energy region, we have measured the total electron-capture cross-sections of Ne^{2+}–Ne system in the energy range of 0.6–2 keV. Extrapolation of the present low-energy data to the high-energy regime exhibits good agreement. The solid line shows the theoretical cross-section calculated by Rapp and Francis [4] for the ground-state multiplied by a factor of three. Kase et al. [1] mentioned that this difference cannot be reduced by adjusting the input parameters in keeping with the physical meanings, not as for the case of He target. They attributed that to the employment of simple hydrogen 1s wave-function for atomic orbit of Ne, and to the higher value of $|\Delta E|$ for Ne compared to the He. Bloemen et al. [9] in their study of Ne^{z+} with He, Ne and Ar showed the strong influence of ΔE on the capture cross-section.

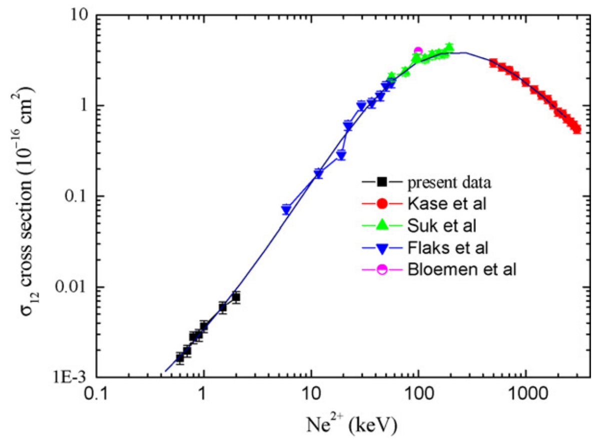

Fig. 3. Plot of total cross-sections vs. the ion energy for one-electron capture into all states of Ne^{2+} in Ne^{2+}–Ne collisions. The solid curve exhibits the theoretical cross-sections of Rapp and Francis for the ground state-ground state multiplied by a factor 3.

6. Conclusion

We have measured the total electron capture cross-sections for collisions of slow Ne^{+} and Ne^{2+} ions with Ne atomic gas at laboratory energy in the range of 0.6–2.0 keV. The major results of this experimental study are summaries as follows:

(a) Experimental measurements of cross-sections are presented, at low-energies, for electron transfer from Ne rare-gas atoms to Ne^{+} and Ne^{2+} rare-gas ions. These cross-sections are in the range of 0.15–1.04 Å^2 for Ne^{+}–Ne system and 0.0016–0.0077 Å^2 for Ne^{2+}–Ne system.
(b) The dependence of the total electron-capture cross-section on the projectile energy is reported for Ne^{2+}–Ne system. These measurements are compared with other available experimental results and theoretical predictions. Overall, the present measurements are in good agreement with the existing data.
(c) The dependence of the total electron-capture cross-sections on the projectile energy are explored for Ne^{+}–Ne system. These measured cross-sections exhibit similar behavior to those experimental studies of single-electron capture cross-sections in collision of Ar^{+}–Ne, Kr^{+}–Kr and Kr^{+}–Xe reported by Martinez et al. [6]. The present low-energy data and previous high-energy data are compared. A lack of experimental data that cover a wide range 2–20 keV and disagreement between Jones and Witkower data are observed. Thus, it is quite conceivable that further work will have to be carried out in order to produce reasonable set of measurements for Ne^{+}–Ne system.

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