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# State-selective electron capture and core excitation in slow $Ne^{6+}$–He collisions

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**Abstract.** We have studied in this paper the competition between (projectile) core-conserving and core-varying single-electron capture processes in $Ne^{6+}$–He collisions for impact energies between 0.07 and 1.2 keV $amu^{-1}$. By deconvoluting the spectra of the VUV radiation emitted by the decaying product ions, absolute state-selective cross sections for these processes were determined. We also obtained capture cross sections for metastable $Ne^{6+}$ ions colliding on helium. Core-conserving capture channels dominate the charge transfer process at the higher impact energies investigated; with decreasing impact energies, however, the core-varying channels gain strength at the expense of the core-conserving channels. Our results show that the capture cross sections for the core-conserving processes involving metastable primary ions are comparable with those for the ground-state primary ions. At lower impact energies, however, the capture cross sections for the metastables are almost three times larger than the cross sections for ground-state primary ions.

## 1. Introduction

Single-electron capture (SEC) almost always constitutes the dominant charge transfer process in slow collisions ($v \leqslant 1$ au) between multiply-charged ions and neutral gas atoms. SEC processes have been studied intensively in the past decade because of their fundamental importance and relevance for plasma physics and astrophysics. For valuable review articles the reader is referred to the papers by Janev and Winter (1985) and Fritsch and Lin (1991).

SEC is normally thought of as a one-electron process induced by the Coulomb interaction between the active target electron and the nuclear charge of the projectile ion. It results in a quasi-resonant capture of the active electron into excited states of the ion with high probability. The basic physics of the process is generally well described by simple models such as the Landau–Zener model (Taulbjerg 1986 and references therein) or the classical overbarrier model (Niehaus 1986 and references therein). Sophisticated close-coupling calculations are needed, however, in order to understand the detailed impact-energy dependence of the various total- and state-selective capture cross sections (Fritsch and Lin 1991). The overall agreement between these theoretical models and the experimental data for many-collision systems illustrates that these simple one-electron processes are fairly well understood.

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Our understanding is generally less detailed for two-electron processes contributing to SEC. For example, very little information exists about absolute, state-selective cross sections for transfer-excitation processes in slow collisions between multiply-charged ions and neutrals. In a transfer-excitation process a target electron is transferred to the projectile ion with simultaneous excitation of the projectile or target core. In previous work we investigated transfer-target excitation processes in slow collisions between $C^{4+}$ and $N^{5+}$ and helium (Hoekstra *et al* 1987, 1992). In this paper we present absolute, state-selective cross sections for transfer-projectile excitation processes in slow $Ne^{6+}$–He collisions. In particular, we have used VUV photon emission spectroscopy to study the competition between the following processes:

$$\mathrm{Ne}^{6+}(1s^2 2s^2) + \mathrm{He} \begin{cases} \nearrow \mathrm{Ne}^{5+}(1s^2 2s^2 3l) + \mathrm{He}^+ & (1) \\ \searrow \mathrm{Ne}^{5+}(1s^2 2s2p3l) + \mathrm{He}^+ & (2) \end{cases}$$

for impact velocities between 0.05 and 0.22 au ($0.07 \leq E(\mathrm{keV\,amu^{-1}}) \leq 1.2$). Reaction (1) results from a pure one-electron process, whereas reaction (2) is induced by a two-electron process. Following Schweinzer *et al* (1988) we will denote reaction (1) as core-conserving (CC)-SEC and reaction (2) as core-varying (CV)-SEC respectively. In both reactions the recoiling $He^+$ ion is in its ground state. The present study was initiated from recent work by us on SEC in slow $C^{6+}$, $O^{6+}$–He collisions (Beijers *et al* 1992). Preliminary results have been published before (Beijers *et al* 1991).

Several groups have already investigated SEC in low impact-velocity $Ne^{6+}$–He collisions. Gordeev *et al* (1983) and Dijkkamp *et al* (1985) at this laboratory reported the 3s, 3p and 3d CC-SEC cross sections for impact velocities between 0.21 and 0.48 au using VUV photon emission spectroscopy. They neglected the small contribution from CV-SEC processes at these velocities. Our results expand the work reported by Dijkkamp *et al* (1985) in the lower impact velocity region. Schmeissner *et al* (1984) and Andersson *et al* (1989) have recorded energy-gain spectra at impact velocities between 0.03 and 0.08 au. However, their interpretation regarding the relative contribution of CC- versus CV-SEC differs. Schmeissner *et al* (1984) found a dominating 3d CC-SEC cross section at an impact velocity of 0.08 au, decreasing in strength at the expense of an increasing CV-SEC cross section for smaller impact velocities. On the other hand, based on multi-channel Landau–Zener calculations, Andersson *et al* (1989) attribute their energy-gain spectra entirely to CV-SEC processes. Hansen and Andersson (1989), however, showed with close-coupling calculations that at an impact velocity of 0.063 au (100 eV $amu^{-1}$) charge transfer in $Ne^{6+}$–He collisions is totally dominated by CC-SEC into the 3d state. We intend to resolve this discrepancy by providing detailed, state-selective cross sections for the various processes.

New results on CV-SEC processes in slow $Ar^{6+}$–He and $Ne^{2+}$, $Ar^{2+}$–Li, Na, K collisions have recently been published by respectively Andersson *et al* (1991) and Schweinzer and Winter (1990). A good review of the work of the Vienna group is given by Winter (1991). These authors describe CV-SEC as being due to an (final-state) exchange interaction following initial capture of the active target-electron by a CC process. We will use this concept to deconvolute our VUV spectra. Finally, it should be mentioned that the (non)resonant transfer and excitation processes observed at higher impact velocities ($v \geq 1$ au) are not caused by the above-mentioned final state interaction. These processes result instead from direct, binary encounters between the electrons and nuclei of the colliding particles (Hahn 1989). Consequently, the cross

sections involved are orders of magnitude smaller than the cross sections of the CV-SEC processes discussed in the present paper.

In the following sections we will briefly describe the experimental method, explain the deconvolution scheme used to analyse the spectra and present and discuss the resulting CC- and CV-SEC cross sections.

## 2. Experimental method

The experimental set-up used in the present investigations has already been described on a number of previous occasions, and we refer the reader to those papers for details (Hoekstra *et al* 1990, Beijers *et al* 1992). Briefly, the $Ne^{6+}$ projectile ions extracted from an ECR ion source are electrostatically decelerated to the desired impact energy and crossed at right angles with an effusive helium beam. The effective target pressure is kept low enough to ensure single collision conditions. VUV photons emitted by the decaying $Ne^{5+*}$ product ions are analysed with a grazing incidence monochromator which is equipped with a position sensitive detector. The monochromator is positioned under the magic angle of 54.7° with respect to the ion-beam axis and tilted by 45° in order to cancel all polarization dependent effects. The wavelength resolution of the optical detection system is approximately 0.6 nm. Lifetime corrections are not necessary since all the observed product states decay within view of the detection system. Two pairs of Helmholtz coils reduce the magnetic field perpendicular to the ion beam to less than a few $\mu$T. The sensitivity of the photon detection system has been calibrated absolutely as a function of the wavelength with an uncertainty of 20% (Hoekstra *et al* 1990).

We have recorded various VUV spectra resulting from SEC in $Ne^{6+}$ + He collisions for impact energies between 1.2 and 0.07 keV $amu^{-1}$. Figure 1 shows two typical spectra observed at 1.2 and 0.11 keV $amu^{-1}$, respectively. The quantitative analysis of these VUV spectra is complicated by two factors: (i) the lines are not resolved and (ii) the primary ion beam contains both ground-state $Ne^{6+}(1s^22s^2)\,{}^1S$ ions and metastable $Ne^{6+}(1s^22s2p)\,{}^3P^o$ ions. Consequently, the core-excited $Ne^{5+}[2s2p({}^3P^o)3l]$ product states (equation (2)), populated by CV-SEC transitions from $^1S$ ground-state ions, can also be populated by CC transitions originating from the $^3P^o$ metastable primary ions. We have estimated the $Ne^{6+}({}^3P^o)$ metastable beam fraction by linear extrapolation of data for Be-like ions with the charge states $q = 2$, 3 and 4 given in the article by Brazuk *et al* (1984). In this way we find a metastable beam fraction of $0.3 \pm 0.1$, which is in accordance with the estimate made by Dijkkamp *et al* (1985) of $0.28 \pm 0.03$.

Before presenting the various state-selective capture cross sections we shall describe in detail the $Ne^{5+}$ VUV spectroscopy and the method used to separate the contributions of the CC-SEC and of the CV-SEC transitions from the spectra.

## 3. Deconvolution of the VUV spectra

### 3.1. $Ne^{5+}$ VUV spectroscopy

The Ne VI spectrum in the 9–18 nm wavelength region results from the decay of the $1s^22s^23l$ singly-excited and $2s2p({}^{1,3}P^o)3l$ doubly-excited $Ne^{5+}$ states shown in figure 2. States denoted with one and two apostrophes have singlet and triplet excited cores, respectively. Binding energies are taken from Kelly (1987). The angular momentum

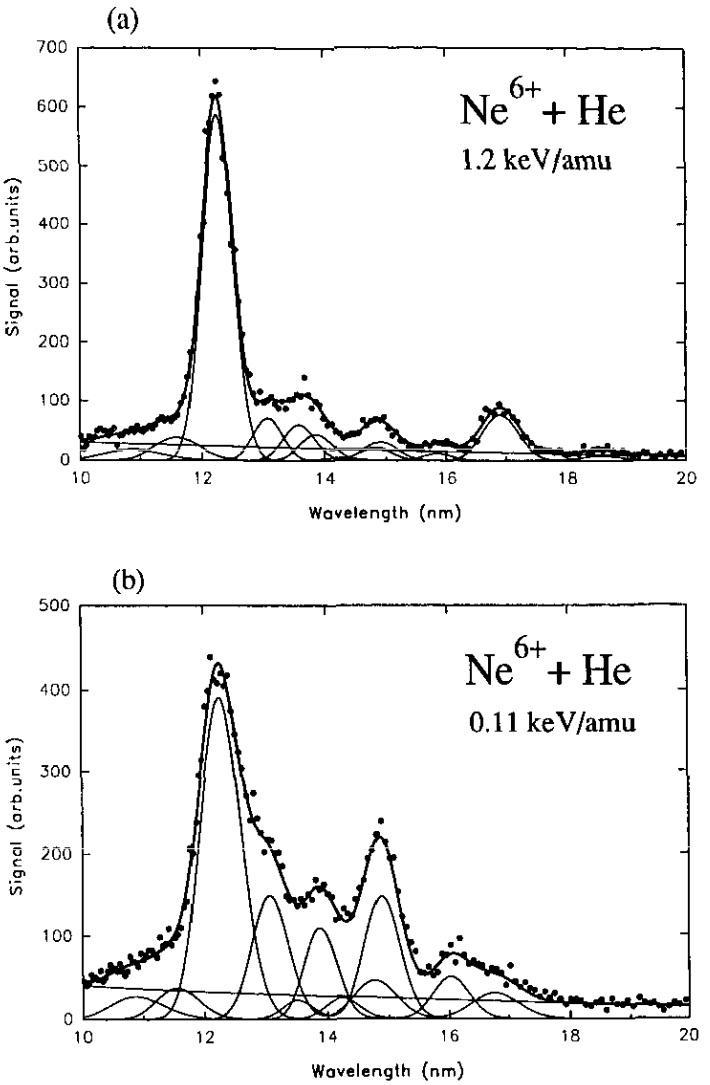


**Figure 1.** Typical VUV emission spectra obtained for collisions of $Ne^{6+}$ on He at impact energies of (*a*) 1.2 keV amu$^{-1}$ and (*b*) 0.11 keV amu$^{-1}$.

coupling between the captured electron and the projectile core produces the doublet and quartet structure of the Ne VI spectrum. Dipole-allowed radiative transitions only couple states with the same spin, as is indicated in figure 2. The wavelengths and branching ratios of the various VUV lines are given in table 1. We have determined the branching ratios from theoretical oscillator strengths which are calculated as part of the Opacity Project using *R*-matrix methods (Seaton 1990).

While at the higher impact energies investigated the spectra are clearly dominated by the 3d → 2p line at 12.26 nm, many unresolved lines appear between 12.5 and 16.6 nm with decreasing impact energies. These lines are emitted by decaying doubly-excited states which are populated by CV-SEC processes with ground-state primary ions or by CC-SEC processes with metastable primary ions. Our observations agree qualitatively

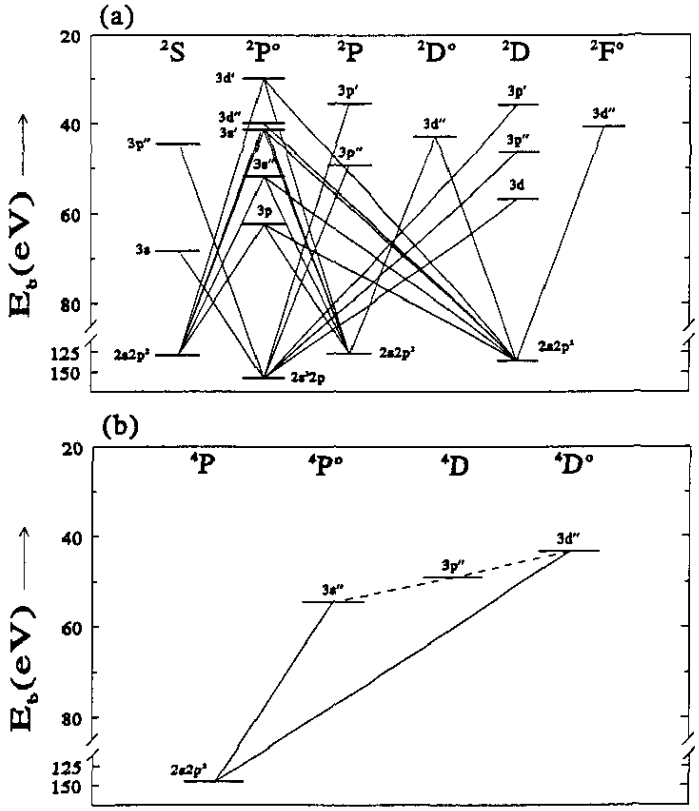


**Figure 2.** Energy level diagram of $Ne^{5+}$: (*a*) doublet system and (*b*) quartet system. States with an excited core are denoted by apostrophes, e.g. $3l' \equiv 1s^2 2s2p(^1P^o)3l$ and $3l'' \equiv 1s^2 2s2p(^3P^o)3l$. Dipole-allowed radiative transitions are designated by straight lines.

with those of Schmeissner *et al* (1984). However, in order to extract more quantitative information from the VUV spectra we have to disentangle the various unresolved lines. This can be achieved by using some basic information on the nature of CC-SEC and CV-SEC processes as will be discussed below.

### *3.2. Core-conserving and core-varying capture processes*

Not all the states shown in figure 2 will contribute to the SEC process in $Ne^{6+}$–He collisions. This can be understood qualitatively for the CC-SEC channels with the classical overbarrier model (see for example Ryufuku *et al* 1980). According to this model the electron is resonantly captured by the projectile ion as soon as the Coulombic barrier, which separates the projectile from the target atom, drops below the active electron's binding energy. This happens for the $Ne^{6+}$–He system at an internuclear distance $R_{cb} = 6.5$ au $= 3.5 \times 10^{-10}$ m, and with a corresponding *asymptotic* binding energy of the electron at the projectile ion $I_q = 45.3$ eV. Mainly those product states which lie around this value will be populated in single-electron capture processes. In figure 3 we have plotted the reaction window (Niehaus 1986) at an impact energy of

**Table 1.** Wavelengths (in nm) of the Ne VI spectrum in the VUV region between 10 and 20 nm. The branching ratios of the various lines are indicated in parentheses.

| | Lower state | | | | |
|---|---|---|---|---|---|
| Upper state | $^2S$ $2s2p^2$ | $^2P^o$ $2s^22p$ | $^2P$ $2s2p^2$ | $^2D$ $2s2p^2$ | $^4P$ $2s2p^2$ |
| $^2S$ 3s | | 13.84 | | | |
| 3p″ | | 10.94 | | | |
| $^2P^o$ 3p | 18.60† (0.19) | | 19.17 (0.02) | 16.88 (0.79) | |
| 3s″ | 15.99 (0.22) | | 16.49 (0.07) | 14.77 (0.71) | |
| 3s′ | 14.10 (0.34) | | 14.48 (0.40) | 13.14 (0.26) | |
| 3d″ | 13.86 (0.87) | | 14.24 (0.12) | 12.94 (0.01) | |
| 3d′ | 12.48 (0.35) | | 12.78 (0.60) | 11.63† (0.05) | |
| $^2P$ 3p″ | | 11.42 | | | |
| 3p′ | | 10.13 | | | |
| $^2D^o$ 3d″ | | | 14.74 (0.23) | 13.35 (0.77) | |
| $^2D$ 3d | | 12.26 | | | |
| 3p″ | | 11.10 | | | |
| 3p′ | | 10.15 | | | |
| $^2F^o$ 3d″ | | | | 13.03 | |
| $^4P^o$ 3s″ | | | | | 13.64 |
| $^4D^o$ 3d″ | | | | | 12.11‡ |

† This line is not given in Kelly (1987).
‡ The 3d″ $^4D^o$ state also decays to the 3p″ $^4D$ state, but with a branching ratio of $1.6 \times 10^{-4}$.

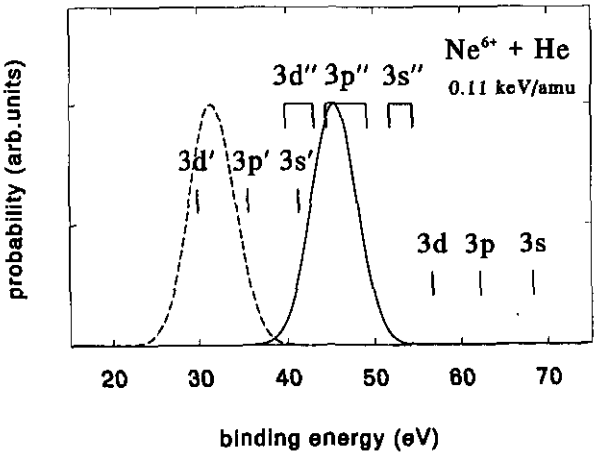


**Figure 3.** Reaction windows for single-electron capture processes in collisions of ground-state (full curve) and metastable (broken curve) $Ne^{6+}$ ions and He at an impact energy of 0.11 keV $amu^{-1}$.

0.11 keV amu$^{-1}$, both for ground-state and metastable primary ions. The reaction window for the metastable projectiles is shifted to lower binding energies according to the metastable excitation energy (13.97 eV) because *total* binding energies are plotted. The positions of the final product states with respect to the reaction windows are also indicated in figure 3. Because of their small binding energies the $n = 4$ levels are completely irrelevant in the present impact energy range.

We use these reaction windows in order to designate the product states which will most likely be populated in $Ne^{6+}$–He collisions. First we consider the CC-SEC processes which can populate the 3*l* states in collisions involving ground-state primary ions and the 3*l*″ states in collisions involving metastable primary ions. From the positions of these states, relative to the reaction windows, we would expect that the 3d and 3d″ states be populated with the highest probability and that the 3s and 3s″ states be populated with much lower probability. In particular we have assumed in our spectral analysis that CC-SEC processes do not populate the 3s″ state, i.e. that this state will only be populated by CV-SEC processes in collisions with ground-state primary ions.

Next we discuss the CV-SEC processes. These processes can in principle populate the 3*l* states in collisions involving metastable primary ions, the 3*l*′ states in collisions involving both ground-state and metastable primary ions and the 3*l*″ states in collisions involving ground-state primary ions. In our analysis, however, we assume that CV-SEC processes will populate *only* those final states which lie inside the relevant reaction windows. This assumption is justified by the fact that the coupling strength between initial and final states is generally much weaker for CV-SEC processes than for CC-SEC processes (see discussion below). Consequently we have neglected CV-SEC processes populating the 3*l* and 3*l*′ states in collisions involving metastable and ground-state primary ions, respectively. The 3*l*′ states can still be populated by CV-SEC transitions from metastable primary ions. Yet we did not observe the 3p′ $^2$P, $^2$D lines around 10.14 nm in any of the spectra. We therefore assumed that the 3s′ and 3d′ states, too, are not significantly populated by CV-SEC processes involving metastable primary ions. This assumption is supported by two factors: (i) the metastable ion flux is less than half of the ground-state ion flux and (ii) the multiplicity of the 3*l*′ states is only one-third of that of the 3*l*″ states. It thus follows that CV-SEC processes will only significantly populate the 3*l*″ states in collisions involving ground-state primary ions.

By using a selection rule for CV-SEC transitions we can entirely separate the CC-SEC from the CV-SEC contributions to the VUV spectra. This selection rule is based on the work of Schweinzer and Winter (1990) and Andersson *et al* (1991) who argue convincingly that CV-SEC processes in slow collisions proceed via a configuration interaction mechanism. If the final core-excited product state contains a large admixture of an active singly-excited configuration the population of such product states could be strongly enhanced. The coupling between these states and the initial state can be written in a Landau–Zener model as the product of a mixing coefficient giving the admixture of the singly-excited configuration (obtained from configuration interaction calculations) and a matrix element connecting the singly-excited configuration with the incoming state (Andersson *et al* 1991). This picture implies, however, that the core-excited product states due to mixing have the same angular momentum symmetry as the active single-electron capture channels. It then follows that for the $Ne^{6+}$–He system only core-excited product states with $^2$S, $^2$P$^o$ or $^2$D symmetry will be populated by CV-SEC processes; the other observed core-excited product states must therefore be populated via CC-SEC transitions from metastable primary ions. With these concepts about CC-SEC and CV-SEC processes we can finally deconvolute the VUV spectra.

### *3.3. Deconvoluting the VUV spectra*

In accordance with the above discussion we excluded the $3s''\,^4P^o$ and all $3l'$ states from the analysis of the VUV spectra, see also table 1. Also excluded from the analysis are the following lines because of relatively low branching ratios: 3p at 19.17 nm, 3s'' at 16.49 nm, 3d'' at 12.94 nm. The remaining lines are fitted by Gaussians with fixed positions and widths. Using the branching ratios given in table 1 proved to be essential for deconvoluting the VUV spectra in a unique way. For the $3d''\,^2F^o$ line at 13.03 nm and the $3d''\,^2D^o$ line at 13.35 nm we used one Gaussian because their separation is too small. The same applies for the $3d\,^2D$ line at 12.26 nm and the $3d''\,^4D^o$ line at 12.11 nm, and also for the $3p''\,^2S$, $^2D$ lines at respectively 10.94 and 11.1 nm. In total we therefore need 12 Gaussians to fit the VUV spectra. Typical fit results are plotted in the VUV spectra shown in figure 1.

All the states in table 1 are exclusively populated either by CC-SEC or CV-SEC processes except the $3p''\,^2S$, $3p''\,^2D$ and $3d''\,^2P^o$ states, which can be populated by both processes (see section 3.2). Furthermore, the dominant $3d\,^2D$ line at 12.26 nm suffers from contamination by the $3d''\,^4D^o$ line at 12.11 nm. However, we have disentangled the various contributions to these lines in the following way. First, because the $3p''\,^2P$ and $3d''\,^2D^o$, $^2F^o$ states are only populated by CC-SEC transitions from metastable primary ions, we determined cross sections for these processes from the corresponding peak areas and the known metastable fraction of the primary ion beam. Secondly, assuming a statistical distribution of the cross sections for capture into the 3p'' and 3d'' multiplet states by CC-SEC transitions from metastable primary ions we subtracted their contributions from the above-mentioned unresolved lines.

The steps outlined above enabled us to determine absolute, state-selective cross sections for both CC-SEC and CV-SEC processes following $Ne^{6+}$–He collisions for impact energies between 0.07 and 1.2 keV amu$^{-1}$. Our results are presented below.

## 4. Results and discussion

### *4.1. Core-conserving capture processes*

The observed VUV spectra clearly indicate that in CC-SEC processes the active target electron is preferentially captured into the 3d orbital of $Ne^{5+}$ both by metastable and ground-state primary ions. The state-selective CC-SEC cross sections for metastable $Ne^{6+}(^3P^o)$ primary ions are given in table 2 and plotted in figure 4 as a function of impact energy. The errors quoted here and in the following tables and figures represent statistical uncertainties of one standard deviation. The total systematic error is estimated to be an additional 30%. Both the dominating 3d'' cross section and the 3p'' cross section stay fairly constant over the entire energy range investigated. Because the 3p'' cross section is determined from a small peak in the wing of the VUV spectra (line at 11.42 nm, see figure 1) the associated statistical error is large. As already discussed we attribute capture into the 3s'' state exclusively to CV-SEC transitions from ground-state primary ions.

The state-selective CC-SEC cross sections for ground-state $Ne^{6+}$ primary ions are given in table 3 and plotted in figure 5 as a function of impact energy. Also plotted are the data of Dijkkamp *et al* (1985) at higher impact energies. These two independent data sets agree with each other in the overlapping energy region. The large 3d cross section with respect to the 3s and 3p cross sections, both for ground-state and metastable

**Table 2.** State-selective and total CC-SEC cross sections with corresponding statistical errors (in units of $10^{-16}$ cm$^2$) for metastable ($^3$P$^o$) $Ne^{6+}$ ions colliding on He.

| $E$ (keV amu$^{-1}$) | $v$ (au) | $\sigma$ (3p″) | $\sigma$ (3d″) | $\sigma_{tot}$ (CC-SEC) |
|---|---|---|---|---|
| 0.068 | 0.052 | 3±3 | 15±5 | 18±6 |
| 0.088 | 0.059 | 3±3 | 15±5 | 18±6 |
| 0.109 | 0.066 | 3±3 | 16±6 | 19±7 |
| 0.137 | 0.074 | 3±3 | 13±6 | 16±7 |
| 0.172 | 0.083 | 3±3 | 14±6 | 17±7 |
| 0.214 | 0.093 | 3±3 | 16±5 | 19±6 |
| 0.304 | 0.11 | 3±3 | 14±5 | 17±6 |
| 0.387 | 0.13 | 4±3 | 15±6 | 19±7 |
| 0.555 | 0.15 | 3±3 | 14±4 | 17±5 |
| 0.739 | 0.17 | 4±3 | 13±5 | 17±6 |
| 0.949 | 0.20 | 5±3 | 13±4 | 18±5 |
| 1.204 | 0.22 | 4±3 | 12±3 | 16±5 |

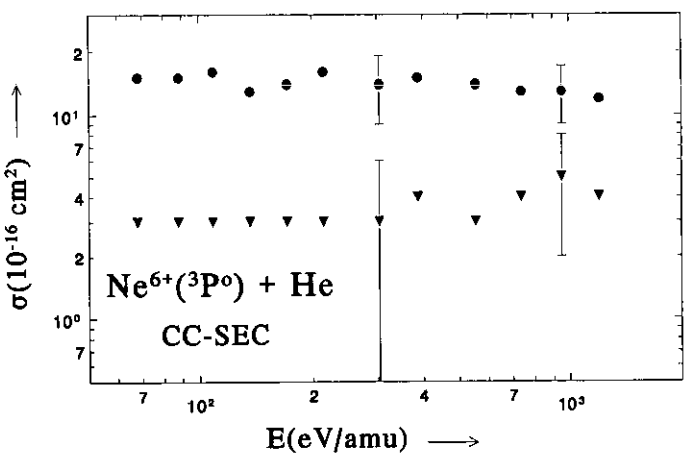


**Figure 4.** State-selective CC-SEC cross sections for metastable ($^3$P$^o$) $Ne^{6+}$ primary ions colliding on He. The error bars represent one standard deviation of the statistical uncertainty. Experimental results: ▼, capture into 3p″; ●, capture into 3d″. The systematic uncertainty is estimated to be 30%.

primary ions, is consistent with the reaction windows of the classical overbarrier model (see figure 3). Also the increase of the 3s and 3p cross sections with increasing impact energies for the ground-state primary ions can be qualitatively understood with the classical model, because the width of the reaction window is proportional to the square root of the impact velocity (Niehaus 1986). On the other hand, the pronounced drop of the 3d cross section at higher impact energies cannot be explained with the classical model. However, in the Landau-Zener model the pseudo-crossing of the relevant potential energy curves is traversed diabatically at these higher energies, both on the way in and on the way out of the collision, resulting in a decrease of the corresponding cross section. It should be noted that although the 3$l''$ states are situated more favourably relative to the reaction window than the 3$l$ states (figure 3), their weaker coupling with

**Table 3.** State-selective and total CC-SEC cross sections with corresponding statistical errors (in units of $10^{-16}$ cm$^2$) for ground-state ($^1$S) $Ne^{6+}$ ions colliding on He.

| $E$ (keV amu$^{-1}$) | $\sigma$ (3s) | $\sigma$ (3p) | $\sigma$ (3d) | $\sigma_{tot}$ (CC-SEC) |
|---|---|---|---|---|
| 0.068 | 0.7 ± 0.3 | 0.6 ± 0.2 | 4.8 ± 1.4 | 6.3 ± 1.4 |
| 0.088 | 0.9 ± 0.4 | 0.6 ± 0.2 | 4.8 ± 1.4 | 6.3 ± 1.5 |
| 0.109 | 0.8 ± 0.3 | 0.7 ± 0.2 | 6.5 ± 1.4 | 8.0 ± 1.5 |
| 0.137 | 1.0 ± 0.3 | 0.6 ± 0.2 | 8.4 ± 1.5 | 10.0 ± 1.5 |
| 0.172 | 1.0 ± 0.3 | 0.9 ± 0.3 | 11.8 ± 1.5 | 13.7 ± 1.6 |
| 0.214 | 0.9 ± 0.3 | 1.0 ± 0.2 | 12.7 ± 1.6 | 14.6 ± 1.6 |
| 0.304 | 1.0 ± 0.3 | 1.1 ± 0.3 | 15.3 ± 1.6 | 17.4 ± 1.6 |
| 0.387 | 0.8 ± 0.2 | 0.9 ± 0.3 | 14.2 ± 1.6 | 15.9 ± 1.6 |
| 0.555 | 1.3 ± 0.3 | 1.2 ± 0.2 | 18.0 ± 1.8 | 20.5 ± 1.8 |
| 0.739 | 1.6 ± 0.4 | 1.6 ± 0.2 | 19.7 ± 1.8 | 22.9 ± 1.9 |
| 0.949 | 1.6 ± 0.4 | 1.9 ± 0.2 | 17.3 ± 1.5 | 20.8 ± 1.6 |
| 1.204 | 1.3 ± 0.3 | 2.7 ± 0.3 | 14.0 ± 1.4 | 18.0 ± 1.5 |

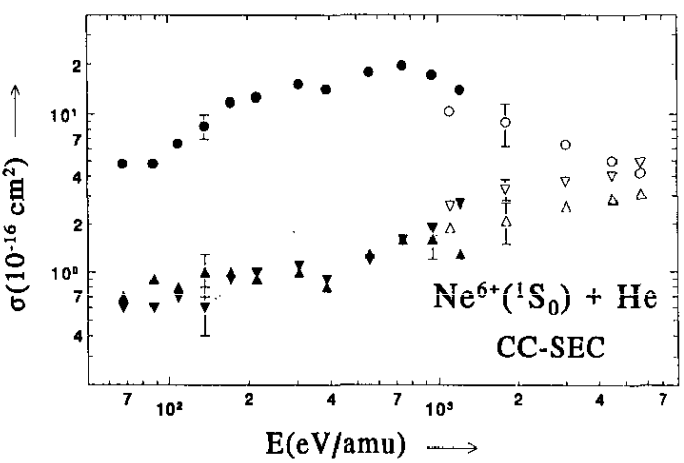


**Figure 5.** State-selective CC-SEC cross sections for ground-state ($^1$S) $Ne^{6+}$ primary ions colliding on He. The error bars represent one standard deviation of the statistical uncertainty. The systematic uncertainty is estimated to be 30%. Experiment: ▲, △ capture into 3s; ▼, ▽ capture into 3p; ●, ○ capture into 3d. Closed symbols denote present results, open symbols denote data from Dijkkamp *et al* (1985).

the initial state prevents a direct comparison of CC-SEC and CV-SEC cross sections solely on the basis of classical considerations.

We notice finally that at the lower impact energies the total CC-SEC cross section for metastable primary ions is almost three times larger than the one for ground-state primary ions, while at higher impact energies the cross sections are more or less the same. Thus the state of the projectile core influences the capture process only at lower impact energies. This pronounced core effect cannot be understood with the classical overbarrier model but requires a realistic, quantum mechanical calculation for its explanation (see for example Larsen and Taulbjerg 1984). These data clearly illustrate the importance of electron capture by metastable primary ions in collisions with neutrals.

### *4.2. Core-varying capture processes*

In CV-SEC transitions from ground-state primary ions only triplet core-excited states are populated, e.g. the spectra do not show any lines from singlet core-excited states (see section 3.2). The resulting 3s″, 3p″ and 3d″ CV-SEC cross sections are given in table 4 and plotted in figure 6 as a function of impact energy. The CV capture process is dominated by the 3s″ cross section, which stays constant with increasing impact energy until it drops sharply around 0.3 keV amu$^{-1}$. This is consistent with the results of Andersson *et al* (1989), who also found capture into the 3s″ state to be the dominant CV-SEC process at 0.1 keV amu$^{-1}$. The large statistical uncertainty of the 3p″ cross sections is caused by the corresponding errors in the contributions of the metastable primary ions to the relevant 3p″ lines.

**Table 4.** State-selective and total CV-SEC cross sections with corresponding statistical errors (in units of $10^{-16}$ cm$^2$) for ground-state ($^1$S) $Ne^{6+}$ ions colliding on He.

| $E$ (keV amu$^{-1}$) | $\sigma$ (3s″) | $\sigma$ (3p″) | $\sigma$ (3d″) | $\sigma_{tot}$ (CV-SEC) |
|---|---|---|---|---|
| 0.068 | $3.2\pm0.8$ | $0.0^{+0.3}_{-0}$ | $1.1\pm0.4$ | $4.3\pm1.0$ |
| 0.088 | $3.2\pm0.8$ | $0.0^{+0.3}_{-0}$ | $1.0\pm0.4$ | $4.2\pm1.0$ |
| 0.109 | $3.4\pm0.8$ | $0.1^{+0.3}_{-0.1}$ | $1.1\pm0.5$ | $4.6\pm1.0$ |
| 0.137 | $3.4\pm0.8$ | $0.0^{+0.3}_{-0}$ | $1.1\pm0.4$ | $4.5\pm1.0$ |
| 0.172 | $4.4\pm0.9$ | $0.1^{+0.3}_{-0.1}$ | $1.2\pm0.4$ | $5.7\pm1.0$ |
| 0.214 | $3.8\pm0.9$ | $0.0^{+0.3}_{-0}$ | $0.7\pm0.4$ | $4.5\pm1.0$ |
| 0.304 | $3.2\pm0.7$ | $0.3^{+0.4}_{-0.3}$ | $0.7\pm0.5$ | $4.2\pm1.0$ |
| 0.387 | $2.6\pm0.6$ | $0.1^{+0.3}_{-0.1}$ | $0.5\pm0.3$ | $3.2\pm0.8$ |
| 0.555 | $2.1\pm0.6$ | $0.3^{+0.4}_{-0.3}$ | $0.1^{+0.3}_{-0.1}$ | $2.5\pm0.8$ |
| 0.739 | $1.9\pm0.6$ | $0.3^{+0.4}_{-0.3}$ | $0.2^{+0.3}_{-0.2}$ | $2.4\pm0.8$ |
| 0.949 | $1.2\pm0.5$ | $0.0^{+0.4}_{-0}$ | $0.2^{+0.3}_{-0.2}$ | $1.4\pm0.7$ |
| 1.204 | $0.8\pm0.2$ | $0.0^{+0.2}_{-0}$ | $0.3\pm0.3$ | $1.1\pm0.4$ |

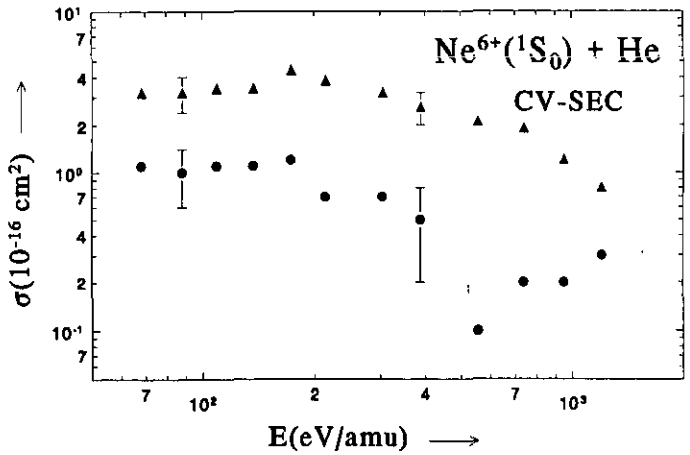


**Figure 6.** State-selective CV-SEC cross sections for ground-state ($^1$S) $Ne^{6+}$ primary ions colliding on He. For clarity the 3p″ cross sections are not shown, see table 4. The error bars represent one standard deviation of the statistical uncertainty. Experimental results: ▲, capture into 3s″; ●, capture into 3d″. The systematic uncertainty is estimated to be 30%.

### *4.3. Total cross sections*

Total $n = 3$ capture cross sections, for both CC-SEC and CV-SEC processes, are plotted in figure 7 as a function of impact energy together with results from other groups. As can be seen we find almost equal contributions from CC-SEC and CV-SEC processes to the capture cross sections in $Ne^{6+} + He$ collisions at the lowest impact energies investigated. With increasing impact energy, however, the CV-SEC cross sections decrease while the CC-SEC cross sections increase. This same global trend was found for CC-SEC and CV-SEC processes in $Ar^{2+} + Na$, K collisions by Schweinzer and Winter (1990). The decreasing importance of CV-SEC processes with increasing impact energies is attributed to the much weaker coupling between the initial and final channels compared with the dominant CC-SEC transitions. With increasing impact energy the CV-SEC channels therefore show pure diabatic behaviour, resulting in decreasing cross sections, before the CC-SEC channels do (Andersson *et al* 1991).

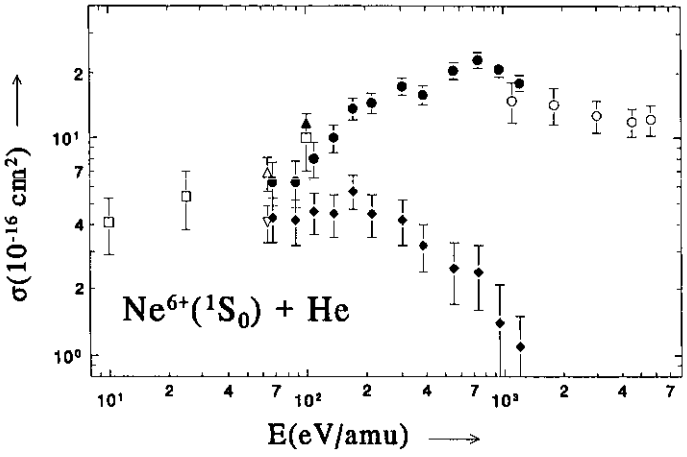


**Figure 7.** Total CC-SEC and CV-SEC cross sections for ground-state ($^1S$) $Ne^{6+}$ primary ions colliding on He. The error bars represent one standard deviation of the statistical uncertainty. Experiment: ● CC-SEC, ● CV-SEC, present; △ CC-SEC, ▽ CV-SEC, Schmeissner *et al* (1984); ○ CC-SEC, Dijkkamp *et al* (1985); □ CV-SEC, Andersson *et al* (1989). Theory: ▲ CC-SEC, Hansen and Andersson (1989).

Also shown in figure 7 are the experimental results of Schmeissner *et al* (1984) and Andersson *et al* (1989) obtained with translational energy spectroscopy. Both groups use recoil-ion sources to determine capture cross sections at low impact energies. Schmeissner *et al* (1984) present energy gain spectra for impact energies between 22 and 157 eV amu$^{-1}$, but only give total CC-SEC and CV-SEC cross sections at 66 eV amu$^{-1}$. At this impact energy their results agree very well with our data. Andersson *et al* (1989) measured energy gain spectra at impact energies of 10, 25 and 100 eV amu$^{-1}$. By comparing these spectra with Landau–Zener calculations they attribute the spectra entirely to CV-SEC processes. However, while we find a decreasing importance of CC capture with decreasing impact energies, at 109 eV amu$^{-1}$ the CC-SEC cross section is still by nearly a factor of two larger than the CV-SEC cross section. A possible reason for this discrepancy was found by Hansen and Andersson (1989) who used an atomic orbital (AO) close-coupling model to calculate capture cross sections in $Ne^{6+} + He$ collisions at an impact energy of 100 eV amu$^{-1}$. The result of their calculation is also

shown in figure 7. They found rotational coupling to be very important for this collision system which is totally neglected in the Landau–Zener model used by Andersson *et al* (1989). Hansen and Andersson (1989) also calculated an energy gain spectrum which showed that the peaks attributed by Andersson *et al* (1989) to CV-SEC processes are actually caused by CC-SEC processes. However, contrary to our experimental results the AO model of Hansen and Andersson (1989) predicts a negligible contribution of CV-SEC channels to the charge transfer process at 100 eV amu$^{-1}$. According to their model the SEC cross section is totally dominated by CC capture into the 3d state of $Ne^{5+}$. Further work is needed to resolve these discrepancies.

## 5. Conclusions

In this paper we present and analyse VUV spectra from excited $Ne^{5+}$ ions which are produced by single-electron capture in slow $Ne^{6+}$ + He collisions. The impact energy ranges between 0.07 and 1.2 keV amu$^{-1}$. The spectra contain contributions from both singly-excited and doubly-excited product states populated by CC-SEC and CV-SEC collisions, respectively. Some doubly-excited states can also be produced by CC-SEC transitions from metastable primary ions. We have succeeded in disentangling these different contributions to the VUV spectra and have determined absolute, state-selective cross sections for the various CC-SEC and CV-SEC processes as a function of the impact energy.

We find that the CC-SEC process is dominated by capture into the 3d state of $Ne^{5+}$ both for ground-state and metastable primary ions in agreement with the classical overbarrier model. The CC-SEC cross sections for both kinds of primary ions are more or less the same except at the lowest impact energies. At these energies the capture cross section for the metastables is larger by a factor of three compared with the cross section for ground-state primary ions. CC-SEC and CV-SEC processes contribute almost equally to the total capture cross section at the lowest impact energies studied, but the CV-SEC cross sections decrease whereas the CC-SEC cross sections increase with increasing impact energy. The explanation of CV-SEC processes falls outside the domain of the classical overbarrier model but can, at least qualitatively, be understood in a Landau–Zener picture. The difference in energy-dependence of CV-SEC and CC-SEC cross sections is caused by the much weaker coupling between the initial state and the $3l''$ states as compared with the $3l$ states. A quantitative calculation is needed to account for the relative magnitudes of the state-selective CV-SEC cross sections.

At the highest impact energies investigated the state-selective CC-SEC cross sections smoothly join the experimental data of Dijkkamp *et al* (1986). Our total capture cross sections agree with the results from energy gain experiments done by Schmeissner *et al* (1984) and Andersson *et al* (1989). However, we disagree with Andersson *et al* (1989) who attributed the total capture cross section entirely to CV-SEC processes. The reason for this discrepancy is that in their analysis Andersson *et al* (1989) neglected rotational coupling which effectively populates the 3d channel by a CC-SEC transition. This was theoretically shown by Hansen and Andersson (1989) with an AO calculation done for an impact energy of 0.1 keV amu$^{-1}$. However, Hansen and Andersson (1989) do not reproduce the significant contribution of CV-SEC processes at this energy. More theoretical work is needed to understand the detailed CC-SEC and CV-SEC contributions to the total capture cross section in $Ne^{6+}$ + He collisions.

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