Forward Glory Effect Observed in Differential Cross Sections for the One-Electron Capture Process in Ne^{4+} – He System at E_{cm} = 6.3 eV

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State-selective differential cross sections (DCSs) at energies from a few hundred eV to several keV for the one-electron capture process in the Ne^{4+} – He system have been measured by several researchers [1 – 4]. Schmeissner *et al.*[1] and Tunnell *et al.*[2] showed that the main reaction channels were

$$Ne^{4+}(2p^2\ ^3P) + He \rightarrow Ne^{3+}(2p^2 3s\ ^2P) + He^+(1s\ ^2S) + 12.4V, \qquad (1)$$

or

$$Ne^{4+}(2p^2\ ^3P) + He \rightarrow Ne^{3+}(2p^2 3s\ ^4P) + He^+(1s\ ^2S) + 13.1V. \qquad (2)$$

Later, Kamber *et al.*[3] performed high-energy-resolution measurements at 8 keV, and observed that the reaction channel (2) was the dominant process. Furthermore, the DCS showed a forward peak and oscillatory structures [2, 3].

Tan and Lin [5] applied quantal two-channel calculations based on an empirical model potential that ignores the difference in the final states of the reaction channels (1) and (2), i.e., $Ne^{4+}(2p^2\ ^3P) + He \rightarrow Ne^{3+}(2p^2 3s\ ^{2,4}P) + He^+(1s\ ^2S)$. They concluded that the oscillatory structure reported by Tunnel *et al.*[2] could be due to envelopes of fast Stückelberg oscillations. Tan and Lin also studied the origin of the forward peak in the DCS. Although they suggested that the peak was due to the glory scattering, they commented that experimental results could

not conclusively determine the origin, because Tunnel *et al.*[2] could only measure $d\sigma / d\theta = 2\pi \sin\theta \cdot d\sigma / d\Omega$, not $d\sigma / d\Omega$, because of limitations in the experimental settings. When the scattering angle θ becomes small, $d\sigma / d\theta$ is determined by the factor sin θ, and the detailed structure at around $\theta = 0$ is unclear. Thus, whether the forward peak is due to the glory scattering or the finite scattering angle is not yet apparent.

In this paper, we report relative state-selective DCS, $d\sigma / d\Omega$, for the one-electron capture process in Ne^{4+} – He at E_{lab} = 38 eV (E_{cm} = 6.3 eV), and studied the origin of the forward peak also observed in this work.

The experimental method was reported previously.[6] Briefly, $^{20}Ne^{4+}$ ions were produced by an electron beam ion source (EBIS). Energy- and momentum-selected ions were crossed with a supersonic target beam, and the energies of the scattered ions were analyzed by an electrostatic analyzer with a position-sensitive detection system.

The angular distribution was determined from the energy spectrum obtained by rotating the detector in 0.3° steps in the laboratory frame. The accumulation time was approximately 1.5 h at each angle. A peak-fitting program was used to integrate the ion counts under the peak area. The measured signals were then converted to DCS in the center-of-mass system in a standard manner. The elastically scattered ions were recorded simultaneously to determine the collision energy accurately. The accuracy of the collision energy was estimated to be better than ± 0.5 eV in the laboratory frame. The overall angular resolution of about ± 0.8°, at the full width at half maximum, corresponds to approximately ± 0.05 rad at θ_{cm} = 0.35 rad in the center-of-mass system.

We observed the Ne^{3+} ions at an angle of around 0° even when the target beam was not being used. Therefore, we carefully measured the background counts and thus determined the

true signal counts.

A typical energy spectrum obtained at $\theta_{lab} = 4.5°$ is shown in Fig. 1. Although the energy resolution of the apparatus used is insufficient to separate the reaction channels (1) and (2), the energy position of the observed peak coincides with that of the reaction channel (2); this is in good agreement well with the experimental results of Kamber *et al*.[3]. In the following analysis, we only took into account this channel.

The DCS obtained for the reaction channel (2) in the center-of-mass system is shown in Fig. 2. The error bars show the sum of the fluctuations of the ion signal and the imprecision of the peak-fitting procedure. The DCS is prominent at a scattering angle of 0 and shows undulations with maxima at 0.20, 0.40, 0.55, 0.75, 0.95, and 1.40 rad. The angular separations of these peaks are larger than the angular resolution of the apparatus.

To interpret the origin of the forward peak semi-quantitatively, we applied classical trajectory analysis. Since we determined that the reaction channel (2) was the dominant process, we used a two-state approximation. Atomic units are used hereafter unless indicated otherwise.

The *ab initio* potentials reported by Ohtsuki [7] were used to construct a model potential for the analysis. We set up a Morse-type potential for the initial channel: $V_{ini}(r) = 0.0524X(r)[X(r) - 2]$, where $X(r) = \exp[1.074(3.255 - r)]$. Only the Coulomb repulsive potential and the exothermicity were considered for the reaction channel: $V_{final}(r) = 3 / r - 0.4814$.

Using the above model potentials, we calculated the deflection function; the result is shown in Fig. 3. The upper half of the curve corresponds to the reaction that occurs in the incoming part of the trajectory, whereas the lower half of the curve corresponds to the

reaction in the outgoing part of the trajectory. We discussed previously [6] that the angular behavior of the DCS for the reaction was mainly determined by that for the elastic scattering. The classical DCS for the elastic scattering can be evaluated by

$$\frac{d\sigma}{d\Omega} = \sum_{\mathrm{j}} \frac{b_{\mathrm{j}}}{\sin\theta} \left| \frac{d\theta}{db_{\mathrm{j}}} \right|^{-1}, \qquad (3)$$

where b_{j} is the possible impact parameter that would result in the same scattering angle θ in the center-of-mass system. The deflection function shown in Fig. 3 reveals that the scattering angle becomes 0 when the impact parameters are 3.4 and 4.8; therefore, the elastic DCS diverges at these impact parameters. Thus, we conclude that the origin of the forward peak in the DCS is the glory scattering.

Another divergence of the DCS will occur when the factor $d\theta/db$ becomes 0, i.e., the rainbow scattering. In Fig. 3, we see that this occurs when the impact-parameter is 4.0, resulting in a scattering angle of 0.18 rad. At this scattering angle, we see a shoulder of the forward peak in the DCS in Fig. 2. However, this feature is indistinguishable and unclear in comparison with that observed in the N^{5+} - He collisions [6].

Clearly, classical treatment alone cannot analyze the oscillatory structure of the DCS. We compared our DCS with the quantal results reported by Tan and Lin [5]. The lowest energy they applied was 220 eV; therefore, we compared the results using scaled DCS, $\theta \sin\theta \cdot d\sigma / d\Omega$, as a function of $E\theta$. No agreement was observed except that both showed the existence of the forward peak. Tan and Lin[5] already showed that the agreement between the theoretical and experimental results reported by Tunnel *et al.*[2] tended to be worse with lower collision energies. Structures on the DCS are known to be very sensitive to the

interaction potential. Therefore, these disagreements were due to the inaccuracy of the potentials applied.

In summary, we determined that the origin of the forward peak in the DCS is the glory scattering; however, the origin of the oscillatory structure is still unclear. For a better understanding of the reaction mechanism in this collision system, further theoretical work based on an accurate interaction potential is required.

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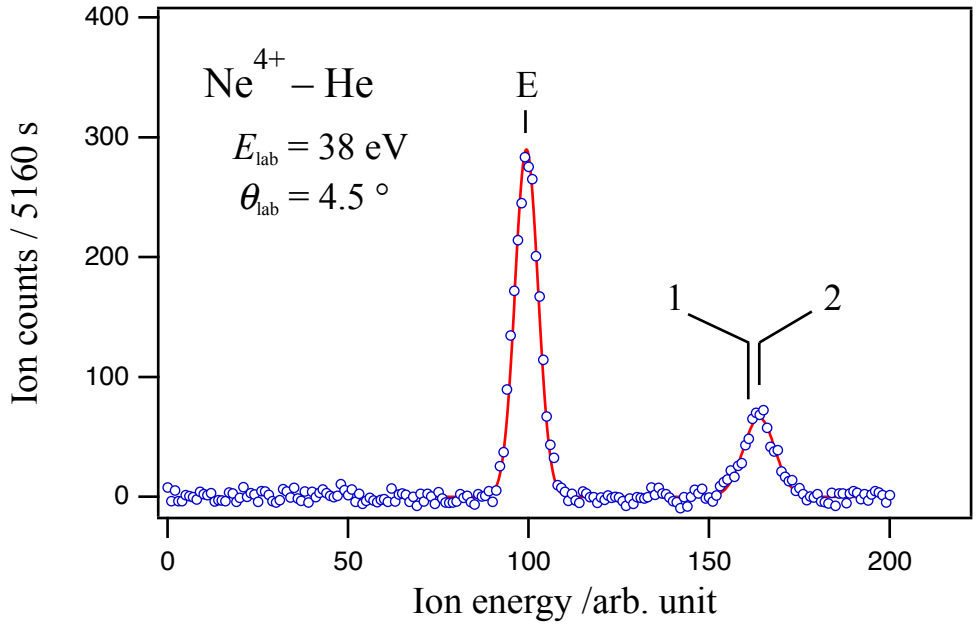

Fig. 1. (Color online) Energy spectrum of the scattered ions in the Ne^{4+} – He system at E_{lab} = 38 eV. The peak labeled E corresponds to the elastic scattering. The energy positions for the reaction channels (1) and (2) are shown by the lines labeled 1 and 2, respectively. The results of the peak-fitting procedure are shown by the curve.

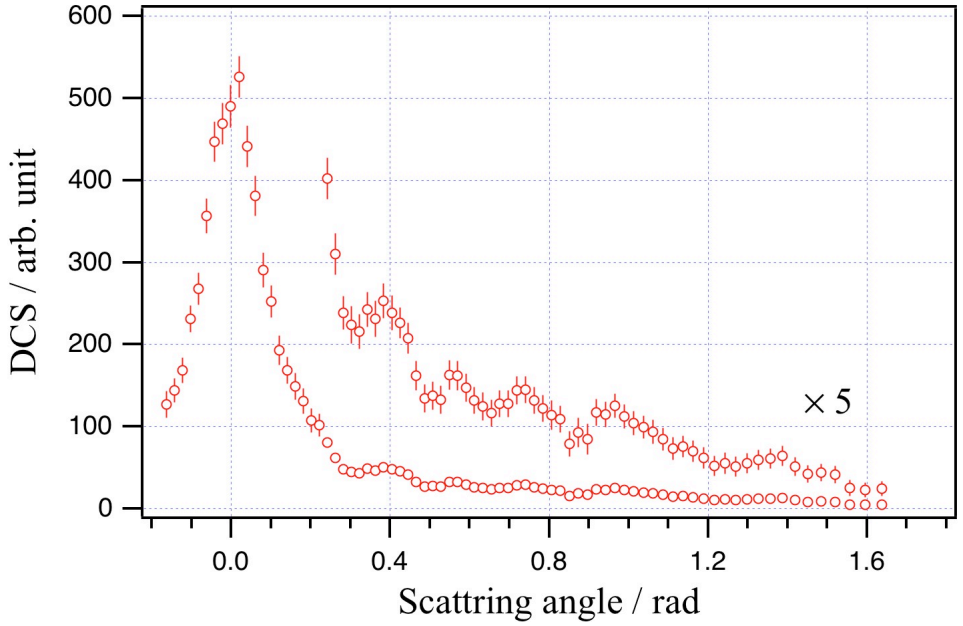

Fig. 2. (Color online) Relative differential cross section in the center-of-mass system for the reaction channel (2).

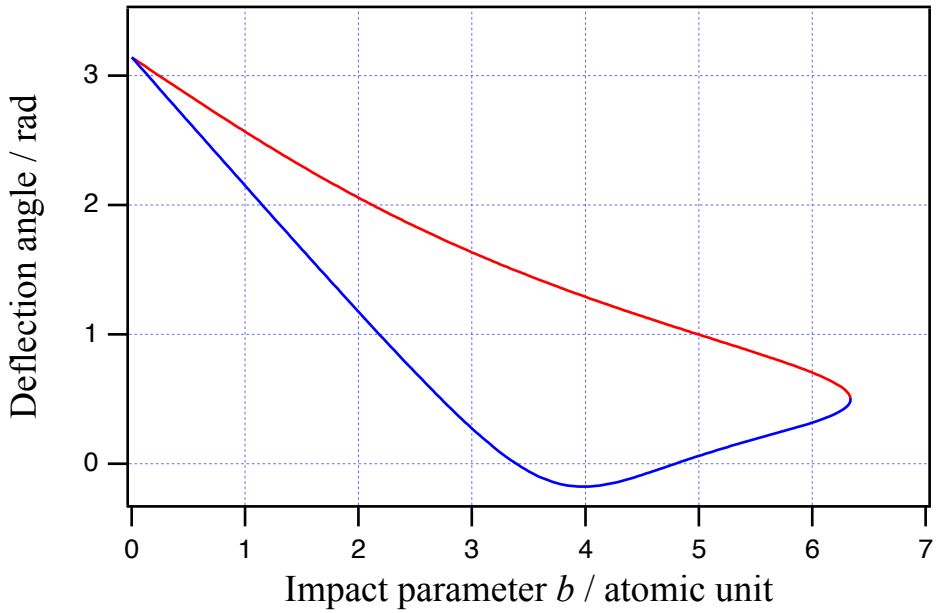

Fig. 3. (Color online) Deflection function for the reaction channel (2) at E_{lab} = 38 eV.